Lecture Notes in Mobility

Ciaran McNally · Páraic Carroll · Beatriz Martinez-Pastor · Bidisha Ghosh · Marina Efthymiou · Nikolaos Valantasis-Kanellos *Editors*

Transport Transitions: Advancing Sustainable and Inclusive Mobility

Proceedings of the 10th TRA Conference, 2024, Dublin, Ireland - Volume 4: Clean Energy Transition

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Lecture Notes in Mobility

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Preface

We are pleased to publish the Conference Proceedings of the 10th Transport Research Arena (TRA 2024), held on April 15–18, 2024, in Dublin, Ireland. The conference brought together 4500 delegates from 57 countries who came together to discuss research findings, the latest innovations in policy, technology and practice, and the future directions of mobility and transport.

The conference tagline was *Transport Transitions: Advancing Sustainable and Inclusive Mobility*, and four primary conference themes were defined, namely:

- Safe & Inclusive Transport
- Sustainable Mobility of People and Goods
- Efficient & Resilient Systems
- Collaborative Digitalization.

TRA takes place every two years, and TRA2024 featured an array of plenary sessions, ministerial sessions, strategic sessions, and special sessions which took place alongside the technical programme. A call for papers was issued in early 2023 which resulted in 1182 submissions. A double blind peer review process was initiated, which ultimately resulted in 784 papers that were chosen for presentation at the conference (66% conversion rate). These papers were presented in a combination of oral or poster presentations over the course of the conference.

All accepted papers presented at TRA 2024 are published in a topical collection of the journal European Transport Research Review (ETRR) or within these proceedings. Both are published in a fully open access format.

TRA is a multi-modal conference that draws on the support of key stakeholders. These include the European Commission, ACARE (Advisory Council for Aviation Research and Innovation in Europe), ALICE (Alliance for Logistics Innovation through Collaboration in Europe), CEDR (Conference of European Road Directorates), ECTP (European Construction Technology Platform), ERRAC (European Rail Research Advisory Council), ERTRAC (European Road Transport Research Advisory Council), ETRA (European Transport Research Alliance), and the Waterborne technology platform. Key Irish supporters of the event were Transport Infrastructure Ireland, Enterprise and Ireland and the Irish Government's Department of Transport.

The editors would like to express their thanks to the presenters, authors, reviewers, session chairs, committee members, and sponsors for helping deliver such a successful event. TRA 2026 will take place in Budapest, Hungary.

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Beatriz Martinez-Pastor
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Contents

Impact on Health and the Environment

TOXinTRANSPORT: Project About Toxicological, Chemical and Physical Characterizations of Particles in Railway Environments 3
A. Delater, O. Le Bihan, S. Fable, G. Lacroix, C. Tebby, S. Ngo, G. Brun, H. Carrilho, G. Uzu, and J. Queron

Characterization and Source Apportionment of Particulate Matter in Underground Railway Station 10
Sylvie Ngo, Ghislain Brun, Nicolas Gournet, Fayes Ghozzi, Thomas Boullet, and Heidi Carrilho

Field Study of Pedestrian Crossings Deterioration Over Time: Assessment of Microplastics Emission from Road Markings 17
Tomasz E. Burghardt and Anton Pashkevich

Analysis of Brake Particle Emissions During Laboratory Braking Tests 24
Marwa Ben Taleb Ali, Thomas Schrevere, Vincent Arrigoni, and Thibault Pawlak

Air Pollution at Airport Areas: Magnitude of the Phenomenon and Measures to Mitigate It 31
Maria Vittoria Corazza and Paola Di Mascio

Transport Infrastructure Ireland Roads Emissions Model (REM) and Carbon Tool 38
Dan Brennan, Vincent O'Malley, David Deakin, Duncan Urquhart, Lauren Harrington, and Ian Davies

Road Transport Emission Parameterization for Microscale Applications Based on Macroscale Measurable Traffic Information 45
Christina Quaassdorff and Rafael Borge

On-Board Monitoring of Exhaust Emissions for Euro 7: Effect of System's Tolerances on Monitoring Performance 51
Dimitrios Kontses, Alexandros Papageorgiou-Koutoulas, and Zissis Samaras

Assessing the Perceived Annoyance of High-Speed Trains with an Experience Sampling Method 58
Maël Roux, Guillaume Lemaitre, Chrystèle Philipps-Bertin, Olivier Chiello, Pierre Aumond, and Arnaud Can

Extent of L-vehicles Tampering and Impact on Noise and Emissions 65
Nikoletta Batsalia, Georgios Triantafyllopoulos, Michael Dittrich, Athanasios Tziovas, and Leonidas Ntziachristos

Noise Level and Indoor Air Quality Assessment of Public Transport Buses in Portugal and Nigeria 71
John Omomoluwa Ogundiran, Jean-Paul Kapuya Bulaba Nyembwe, Anabela Salgueiro Narciso Ribeiro, and Manuel Carlos Gameiro da Silva

Transforming Railways into Quiet Neighbours: Pioneering a Global Approach to Noise Reduction 78
Pınar Yılmazer, Jakob Oertli, Lorenzo Franzoni, Alf Ekblad, and Martijn Wolf

biclaR: Estimating the Socio-Environmental Impacts of Car Substitution by Bicycle and Public Transit Using Open Tools 85
Rosa Félix, Filipe Moura, and Robin Lovelace

Strategic Environmental Assessment of Transport Plans and Programs: How to Reach Systematic Monitoring? 93
Elisabete Arsenio, António Lemonde de Macedo, Marta Rodrigues, and Eduarda Marques da Costa

Model-Based Assessment of the Cruising Traffic and Environmental Impact of Parking Restrictions 100
Alexandre Nicolas, Nilankur Dutta, and Léo Bulckaen

Preserving Biodiversity in Railways: Global Strategies for Sustainable Habitat Management 107
Lorenzo Franzoni, Pinar Yilmazer, Thomas Schuh, Neil Strong, and Michael Below

Improvement of SUMP-Methodology for Climate Mitigation 114
Niklas Sieber and Konstantin Krauss

The Ripple Association of Mothers' Non-transport Pro-environmental Behaviours with Adolescents' Travel-to-School Mode Choices 120
Jinpeng Li, David Philip McArthur, Jinhyun Hong, and Mark Livingston

Managing Biodiversity in the Port Sector: Experiences from Three World Ports 127
Michele Acciaro

Model of Societal Cost of Travel for Real Time Urban Traffic Management Supporting V2I Systems 134
Athanasios I. Koukounaris, Konstantina P. Marousi, and Yorgos J. Stephanedes

Driving Toward the Future: Assessing Electric Automated Vehicle Deployment Scenarios in Suburbs: A Case Study of Grorud Valley, Norway . . . 141
Nicole van den Boom, Adrian Boos, Charly Beye, and Guy Fournier

Transport Sectors' Real-World Emissions: From Gaseous Precursors to Secondary Aerosol Formation in Urban Air 153
Päivi Aakko-Saksa, Anssi Järvinen, Topi Rönkkö, Panu Karjalainen, Matti Rissanen, Hilkka Timonen, Luis Barreira, Joseph Woodburn, Wojciech Honkisz, Piotr Bielaczyc, Pontus Roldin, Anna Oudin, Joakim Pagels, Ismael Ortega, David Delhaye, Luoise Ganeau, Jan Topinka, Tereza Cervena, and Michal Vojtisek-Lomgand

Effects of Teleworking in Air Quality During and After the COVID-19 Pandemic: A Spanish Case-Study 160
Jorge Bañuelos-Gimeno, Natalia Sobrino, and Rosa Arce

Walkability as a Catalyst for More Sustainable Mobility Patterns and Urban Rehabilitation in Rome 166
Letizia Appolloni, Maria Vittoria Corazza, and Daniela D'Alessandro

Experiences, Valuable Activities, and Worthwhile Travel: A Comparison of E-cycling and Conventional Cycling Trips 172
Hannah Hook, Yannick Cornet, and Eva Malichová

Estimating the Socio-economic Impacts of Cycling in the EU 178
Holger Haubold

Remote Monitoring of Habitats to Support Management of Biodiversity Alongside Railways Across Britain 185
Neil Strong

Enhancing Biodiversity During the Development of Transport Infrastructure in Ireland 192
Eimear Fox and Vincent O'Malley

Opportunities to Rehabilitate Peatlands via Transportation Projects 196
Paul Kissane, Fiona Patterson, Gerry Baker, Alan Duggan, Patrick Crushell, Willie Crowley, Warren Vokes, Patrick O'Shea, and Rachel Heaphy

Logistics and Sustainable Transport

A Multi-objective Approach to Flight Scheduling and Fleet Assignment in Hub Network 205
Melis Tan Tacoglu, Mustafa Arslan Ornek, and Cemalettin Ozturk

The Single European Sky and Aviation Sustainability 212
Federico Franchina and Cinzia Ingratoci

Enabling Automated Zero-Emissions Air Mobility Trough U-Space Infrastructure 219
J. Camacho, S. Riverso, K. Wadhwani, D. Mobsby, N. Liberko, X. Esneu, U. Houssou, D. Hogan, D. Taurino, A. De Bortoli Vizioli, L. Portoghese, W. Derguech, C. MacCriostail, J. Drysdale, J. Garland, and B. Healy

A New Typology for Classifying European Container Terminals, Considering Their Ability to Green Their Operations 226
Schmidt Wouter, Ferrari Claudio, Vanelslander Thierry, and van Hassel Edwin

Resilience of Inland Waterway Transport: Towards a Practice-Oriented Repository of Common Threats and Hazards 240
Marija Jović, Wiebke Duhme, Patrick Specht, and Nik Delmeire

Modal Shift Potential for Danube Shipping: The Market for Containerized Transport of Dry Bulk 246
Silvia Dopler, Denise Beil, Bianca Duldner-Borca, Lisa-Maria Putz-Egger, and Ricarda Kompp

Development of an Intelligent System for Urban Logistics to Facilitate Sustainable Optimization 253
Paul-Eric Dossou and Jow Irudayaraj

Inefficiency Assessment for Agricultural Commodities in Urban Areas 259
Harshit Talreja and Mayank Dubey

Mobile-Depots and Cargo Bikes Towards a Sustainable Last-Mile Future 267
Vasco Silva, António Amaral, and Tânia Fontes

Assessing the Potential for a European Modal Shift Towards Rail 274
Matthias Prandtstetter, Peter Widhalm, Sandra Stein, and Fritz Starkl

Comparing the Environmental and Economic Impact of the CargoTube System with Road-Based Transport 285
Stephan Wurst, Lukas Eschment, Thomas Schüning, Thomas Nobel, Heiko Duin, and Walter Neu

Full-Scale CargoTube Demonstrator Based on Hyperloop Technologies 292
Thomas Schüning, Lukas Eschment, Christoph Jakiel, Marcel Stamm, and Walter Neu

Benefits, Challenges, and Opportunities of the Digital Automatic Coupling 298
Gabriel Stephan Himmelbauer, Matthias Reichmann, Adrian Wagner, Herbert Wancura, Tobias Hasenleithner, Burkhard Stadlmann, Martin Egger, and Jürgen Zajicek

Comparative Analysis of City-Specific Light Freight EV Applications in Asia, Africa and Latin America 304
George Panagakos, Maria Rosa Muñoz Barriga, Shritu Shrestha, Michael Bruhn Barfod, Vera-Marie Andrieu, Juan Pedro Carriquiry, Emilie Martin, Alvin Mejia, Grace Carolina López Realpe, and Naressa Saripada

Towards Sustainable Urban Freight Transport: Insights from Data Analysis of Receiving and Shipping Behavior in a Technological Development Area in Berlin 311
Greta Hettich, Saskia Seidel, and Carina Kehrt

The Opportunities of Using a Logistics Service Marketplace to Decrease Emissions of Transport and Logistics Industry 318
Markku Mikkola, Jukka Kääriäinen, Ville Hinkka, Harri Pyykkö, Emma Mulhern, and Simo Salminen

Curbside Management: A Digital Solution Space Optimisation 324
Sandra Rothbard, Paola Cossu, Fabio Cartolano, Philippe Rapin, Hernán Mejía, David García Rubio, and Raúl Urbano Escobar

Impacts of Regional Electrified Logistics on Drivers' and Transport Planners' Work Environments 332
Jana Sochor and Frances Sprei

Regional Electrified Logistics System Demonstrator in Sweden - Economic Comparison of Electric - and Diesel-Powered Solutions 339
Andreas Josefsson, Magnus Karlström, Nikita Zaiko, UIrika Colpier, and Lars-Göran Rosengren

A Digital Twin-Based Framework for Evaluating Last-Mile Collaboration Schemes with Electric Modular Vehicles 354
Zisis Maleas, Georgia Ayfantopoulou, and Josep-Maria Salanova Grau

Integrating Logistics Requirements in City District Planning 361
Alexandra Anderluh, Günther Illek, Jonathan Fetka, Martin Berger, Mario Platzer, Emanuel Selz, Maximilian Reimann, and Lucas Reeh

Accounting for Environmental Impact in Air Traffic Network Operations: Carbon Dioxide, Costs and Policies 368
Gustavo Alonso, Arturo Benito, Clara Argerich-Martín, and Rodrigo Álvarez-Lorenzo

Energy Consumption Evaluation of Emerging and Current Vehicle Fleets in Urban Logistics 375
Raphael Andreolli, Mikael Nybacka, Erik Jenelius, Ciarán J. O'Reilly, and Eric Falkgrim

Sustainable Mobility: The Contribution of Railways to Decarbonization 382
Pedro Gaspar, Carina Almeida, and Vítor Antunes

Review of the Algorithms Used in Electric Vehicle Routing Problems for Last Mile Logistics and Shared Mobility Options 388
Cliodhna Ni She, Damian Flynn, and Paula Carroll

Reduction of CO_2 Emissions Through Reusable Packaging 395
Matthias Prandtstetter, Wolfgang Ponweiser, Martin Reinthaler, Bin Hu, Manuela Brandner, and Sarah Pfoser

Overcoming Barriers to Implementing Sustainable Mobility Strategies in Rural Areas: A Case Study in Turkiye 402
Stabak Roy and Hulya Zeybek

Digital Platforms in Localising the Markets and Supply Chains in Rural Areas 409
Veikko Pekkala, Leena Toivanen, Janne Känsäkoski, and Pekka Leviäkangas

15-Minute City: A Holistic Approach in the Frame of SUMPs 415
Andres Monzon, Mari Luz Brownrigg-Gleeson, and Andreia Lopes Acevedo

Sustainable Commuting – An Empirical Analysis of Commuting Considering Changes Due to the Pandemic 421
Claudia Nobis and Viktoriya Kolarova

Hard Shoulder Bus Priority Measures on Motorways and Type 1 Dual Carriageways 427
Stephen Barry, Gerard Hall, Martin Allen, Virginia Kangley, Stephen Cummins, Elizabeth Lawless, and John Bowes

Supercabatteries for a New Sustainable Mobility 433
Maurizio Laschi, Dario Vangi, and Michelangelo Santo Gulino

Medical Applications of Urban Air Mobility: A Study on Acceptance 439
André Teixeira Silva, Sérgio Pedro Duarte, Sandra Melo, and António Lobo

Last-Mile Delivery Through Electric Motorbikes: Modelling Considerations for Parcel vs. Food Delivery 446
Harbil Arregui, Iñaki Cejudo, Iker Arandia, Andoni Mujika, Eider Irigoyen, Laura Rabadan, and Estibaliz Loyo

Digital Automatic Coupling as an Enabler for Rail Freight Innovations 453
Patrick Seeßle, Daniel Wolfram, Andreas Haller, Florian Einsele, Victoria Jäger, and Simon Funke

Data for Shifting to Rail Freight Transport: A Review of Free Online Tools 460
Celestino Sánchez Martín, Francisca Rosell Camps, Aristarco Tomás Úbeda, and Boban Djordjevic

Hyperloop as an Innovative New Mobility Mode: Squaring the Circle in High-Speed Transportation Systems? 467
Walter Neu, Lukas Eschment, Sascha Lamme, and Thomas Schüning

Technological Design Considerations of CargoTube Low-Pressure Tube Transport for High-Speed Sustainable Logistics Networks 474
Lukas Eschment, Heiko Duin, Irina Yatskiv, Thomasz Kublin, Paweł Radziszewski, Thomas Schüning, Stephan Wurst, and Walter Neu

Unlocking Green Maritime Corridors: Lock-Ins, Barriers, and Enablers for Decarbonizing RoPax Maritime Transport in Europe 480
Anastasia Tsvetkova, Magnus Hellström, Henry Schwartz, and Magnus Gustafsson

Integrating Intra-terminal Logistics Optimization and Freight Train Scheduling 487
Georg Brandstätter and Jürgen Zajicek

Critical Analysis of the Main Factors Causing Delays in Various Stages of a Supply Chain and the Relevant Machine Learning Models for Dynamic Lead Time Predictions 494
Afroditi Stamelou, Georgia Ayfantopoulou, and Ioannis Mallidis

A Satellite Image Based Eco-Routing Solution: Requirements Analysis from Industry Interviews 501
Riccardo L. Notarangelo, Petri Helo, and Heidi Kuusniemi

The SEAMLESS Approach to Enabling Fully Automated Waterborne Freight Feeder Loop Services 509
Nikolaos P. Ventikos, Konstantinos Louzis, Vassilis Podimatas, Angeliki Stouraiti, Odd Erik Mørkrid, and Håvard Nordahl

Establishing Living Labs for City Logistics: Scoping and Initial Outcomes 515
Ioannis Karakikes, Vaike Fors, Jesper Lund, and Amalia Polydoropoulou

Adapting MTVRPTW for Small Business: A Simplified Approach to Optimizing Food Delivery Logistics 523
Diego Bandeira de Melo Akel Thomaz, Tassia Carolina Forasteiro Pinto, Rose Campbell, Nicolas Malhene, and Tatiana Graindorge

Data-Driven Decision-Making in Fashion Logistics: A Systemic Approach in the Greek Clothing Industry 529
Vasileios Giannoudis, Elpida Xenou, Georgia Ayfantopoulou, and Vasileios Voulkopoulos

Decarbonising Last Mile Logistics 536
Manon Levrey, Amalia Ntemou, Akrivi Kiousi, Ioanna Fergadiotou, Maria Kampa, Dimitrios Rizopoulos, Babis Magoutas, Athena Tsirimpa, and Panos Georgakis

Integrating Parcel Delivery Services into Public Transport Operations Through a Common ICT Platform 543
Jochen Wendel, Christoph Becker, Andrea Demetrio, Felix Elgner, Hannes Hameister, and Dominic Warzok

Customer and Retailer Expectations from City Logistics: Comparative Analysis of the Market in Thessaloniki, GR 550
Sofoklis Dais and Georgia Ayfantopoulou

A New Concept for Resilient and Green Freight Transport and Logistics Networks Against Disruptive Events 556
Sandra Stein, John von Stamm, Janis Simons, Gerrit Hoeborn, and Tobias Schroer

Estimating a Detailed Trans-European Origin-Destination Matrix of Road Freight Transport 563
Peter Widhalm, Julia Buchegger, and Bin Hu

Data-Driven and Dynamic Land Use for Physical Internet-Led Urban Logistics and Planning 569
Paola Cossu, Paola Astegiano, Ioanna Fergadiotou, Georgia Ayfantopoulou, and Rod Franklin

Food Delivery Services Influence on Urban Mobility – A Systematic Literature Review 576
Amanda Oliveira Mesquita, Zsolt Matyusz, and András Munkácsy

Monitoring and Assessing Heavy Traffic Loads: Feedback from French Initiative and Data Analysis 583
Franziska Schmidt and Eric Klein

Road Freight Models to Accelerate Green Transition in Europe 589
Sheba Nair, Erika Kallionpää, and Heikki Liimatainen

Understanding the Success of Road Freight Decarbonization Strategies. A Case-Study from Spain 596
Genís Majoral and Sergi Saurí

Implementing Sustainable Micro-Logistics Hubs for Innovative Physical Internet Urban Delivery Methods: The Bologna Case 603
Eleonora Morganti, Giuseppe Luppino, Alice Benini, and Francesco Paolo Nanni Costa

Freight Demand Modeling for Green and Digital Logistics 609
Sofia Cerqueira, Elisabete Arsenio, Rui Henriques, and José Barateiro

Road Freight Electrification: Digital Model for Fleet Depot Electric HGV Charging Infrastructure 616
Clive Crewe, Bo Gao, and Alan Walker

Business Model Implications of Innovative Solutions for Sustainable Urban Freight Transport 623
Paul Buijs

Performance Assessment of Multi-articulated Flexible Vehicle Platforms in Realistic Road Infrastructure Models 629
Nikhil Muthakana, Dixon Devasia, Siddharth Ajaykumar, and Karel Kural

Circularity of Reusable Packaging 636
Wolfgang Ponweiser, Matthias Prandtstetter, Martin Reinthaler, Bin Hu, Sarah Pfoser, and Manuela Brandner

Circular Economy and Life Cycle Assessments

Laboratory and Field Study of High-Rate Recycled Asphalt Pavement Rejuvenated with Waste Cooking Oil 645
Silvino Capitão, Luís Picado-Santos Capitão, and Arminda Almeida Capitão

Rejuvenation of High-Content Reclaimed Asphalt Mixtures with Bio-Heating Oil: Laboratory and Plant-Produced Experience 652
Silvino Capitão, Luís Picado-Santos, and Arminda Almeida

Towards a Sustainable Design and Circular Economy for Hybrid EV Batteries 659
Hanna Sahivirta, Diana Arellano, Rodrigo Serna-Guerrero, Benjamin P. Wilson, Tomas Jezdinsky, Georgi Todorov, Yavor Sofronov, Blagovest Zlatev, Victor Ferreira, and Corneliu Barbu

Life Cycle Environmental Performance of Diesel, Fuel Cell, and Battery Electric Long-Haul Heavy-Duty Trucks 680
Linda Ager-Wick Ellingsen and Rebecca Jayne Thorne

Irish Automotive Sector Considerations for Recycling Electric Vehicle Lithium-Ion Batteries 687
Matt McGuinness

Simulation-Based Optimization for Sustainable Textile Waste Collection Routes 695
José Luis López, Shaghayegh Rahnama, David Ciprés, Lorena Polo, and David Escuín

Integrating TCO and Sustainability Requirements: ESCALATE Pro-Active Design and Manufacturing Approach for Enhanced Electric Fleets 703
U. U. Turkan, E. A. Calado, S. Mamarikas-Itsios, D. Kontses, Z. Samaras, and A. E. Hartavi

Uncertainty Sources in the Life Cycle Sustainability Assessment of Transport Infrastructure in the Context of Asset Management 710
Andrea Vargas-Farias, Joao Santos, Andreas Hartmann, and Irina Stipanovic

Environmental Assessment of Components for Trains Based on the Use of Fiber Reinforced Plastic 719
E. de la Guerra, M. Cerdeira, and M. Pérez

Refining Design Approaches and Implementing the Material Matrix Assessment to Foster Structural Components Circularity 726
Engy Ghoniem, Vanesa Ventosinos Louzao, Miguel Moldes Carballal, Matteo Basso, and Ahmed Elmarakbi

Feasibility of Concrete Paving Blocks Produced with By-Products from Construction and Coconut Industries 733
Webert Silva, Luís Picado-Santos, Suelly Barroso, Antônio Eduardo Cabral, and Ronaldo Stefanutti

How Does Circular Economy Disrupt Business Models: The Case of Ballast Reuse in Railway Projects 740
Joseph Mansour Salamé, Yann Leroy, Isabelle Nicolaï, and Michael Saïdani

Life Cycle Analysis of Low Carbon Roller Compacted Concrete Pavements ... 747
Alexandra Telford, Sripriya Rengaraju, Haneen Mohammed, Ahmed I. M. Nassar, and Abir Al-Tabbaa

The Norwegian Approach to Future Design, Construction, Maintenance, and Rehabilitation of Asphalt Pavements 754
Sara Anastasio, Brynhild Snilsberg, Thor Asbjoern Lunaas, and Even K. Sund

Non-Contact Measurements of Wind Turbine Blades Repurposed as Pedestrian Bridges 761
Nathan MacAuley, Alfie Brennan, Hugh Irving, Kieran Ruane, Vesna Jaksic, Abdollah Malekjafarian, Aasifa Rounak, Kevin Nolan, and Vikram Pakrashi

A Contribution for a Sustainable, Resilient Road Infrastructure Management from Brisa, a Portuguese Road Concessionaire 768
Carina Vieira, Eugénia Correia, Daniela Domingues, Maria João Rato, Fernanda Caetano, Henrique Borges Miranda, and Manuela Carvalho

Methodologies for Economic Assessment of Rail Technical Innovations: Challenges and New Perspectives 775
Andrew S. J. Smith and David E. Pierce

Material Supply of Urban Factories Using Circulation Hubs - An Analytical Comparison of the Logistical Effort 782
Marius Dellbrügge, Sina Rudolf, Maximilian Kiefer, Max Juraschek, Christoph Herrmann, and Uwe Clausen

Designing Low Energy Sustainable Asphalt Mixtures Based on Their Mechanical Properties and Performance Characteristics 789
Dimitris Michailidis and Amanda Gibney

Eco-Design of Lightweight Structural Components for Electric Vehicles Made of Advanced Materials 796
Vanessa Ventosinos Louzao, Raquel Ledo Bañobre, Ilya Popov, Jérôme Favero, Fernando Burguera, and Tom Ligthart

The PROCEEDR Tool to Assess Environmental Impacts, Circularity and Life Cycle Costs of Roadside Equipment 802
Holger Wallbaum, Taz Lodder, Simin Tavajoh, Alison Hewitt, Bijan Adl-Zarrabi, Marco Conter, and Giovanni Brero

The Transition to Circular Economy in Transport Infrastructure - CERCOM and LIAISON Progression 809
Emma Sheils, Lorcan Connolly, Alan O'Connor, Martin Lamb, Helen Viner, Helen Bailey, Vijay Ramdas, Avishreshth Singh, Aikaterini Varveri, and David Garcia-Sanchez

Contribution to Incorporation of Non-recyclable Plastics in Bituminous Mixtures 816
João Clérigo Fonseca, Vitor Antunes, and Ana Cristina Freire

Luas Finglas – Delivering a Sustainable Infrastructure – Sustainability, Circular Economy, Active Mobility 823
David Weldon, Eimear Fox, and Joseph Martin

Sustainability Considerations in the Design of Earthworks for Road Projects ... 831
John O'Connor, Cathal Mac an tSearraigh, Kevin Berthet, and Miles Friedman

Evaluation of Lignin-Bitumen Blend as a Sustainable Alternative for Asphalt Binder 838
Sayeda Nahar, Dave van Vliet, Alan Lynch, and Amir Tabakovic

KPI Framework for Assessing Pavement Sustainability 845
Concepción Toribio-Díaz, José Solís-Hernández, and Noemi Jiménez-Redondo

Facilitating Choice of Long Haul HD Environmental-Friendly Drivetrains: LONGRUN Life Cycle Analysis Tool 852
Shantanu Pardhi, Michael Schwingshackl, Mohamed El Baghdadi, Stefan Hausberger, and Omar Hegazy

Reducing Carbon Through Transport Investment – Transport Infrastructure Ireland Pavement Renewal Programme 859
Stephen Smyth, Gerard O'Dea, Olivier Mainardis, Alan Lynch, Peter Adams, and Mike Evans

Low Energy Bound Materials: A Sustainable Solution for Regional and Local Road Pavement Renewal? 868
Alan Lynch, Kevin West, Declan Toner, Brian Mulry, John Coppinger, Edward Winterlich, Alan Kavanagh, Alan Anderson, and Simonas Ignatavicius

Circular Economy Transition Actions by a Major Transport Agency–Transport Infrastructure Ireland 876
Esther Madden, Janet Lynch, Mike Evans, Kimberley Perry, Alice Halpenny, and Ann-Marie Gallagher

Towards Standardized S-LCA: Identification of Relevant Stakeholder and Social-Impact Categories for Autonomous Electric Car-Sharing Fleets 885
Davis Jose, Ashik Rahim, Rose Nangah Mankaa, and Marzia Traverso

Author Index 891

Impact on Health and the Environment

TOXinTRANSPORT: Project About Toxicological, Chemical and Physical Characterizations of Particles in Railway Environments

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Abstract. When studying the toxicological effects of pollutants, mostly this is achieved examining their action one at a time whereas in real life, many pollutants act together in a given period of time. This is well known as the cocktail effect. In addition, the close interactions between numerous physico-chemical and toxicological effects are not always scrutinized. In this framework, the TOXinTRANSPORT project was set up. It aimed at examining in-depth the close relationship between the physico-chemical and toxicological effects and the way the former impacts the latter. The context was that of railway transport where this link between physico-chemistry and toxicology was made. Numerous instruments were used to determine the physico-chemical properties of two environments, namely an underground platform and a railway rolling stock. This characterization was made along with toxicological analyzes. The originality of this project was to resort to a biosampler to collect aerosols prior to toxicological analysis. This eliminates the tedious step of filter processing, technique usually used for sampling. Among the main results, toxicological effects have been linked to the presence of certain physico-chemical parameters and their concentration levels. Inflammation seems to be linked to high concentrations of metals (particularly iron). The obtained results are presented and discussed.

Keywords: railway transport · aerosols · toxicology

1 Presentation of TOXinTRANSPORT

1.1 Context

Air pollution and especially its particulate fraction is known to be detrimental to human health. Cardiovascular and respiratory diseases, even lung cancers may be caused by such pollution [1]. The main difficulties the scientists are faced with when trying to estimate people exposure are the complexity of the physico-chemical composition of

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this pollution and its spatial and temporal variability [2]. The pollution depends not only on the emission sources but also on the photochemical processes taking place in the atmosphere and on the meteorological conditions [3]. Most of toxicological studies imply assessing the impact of pollutants one after the other, taken separately. They usually do not consider the cocktail effect involving many substances acting together at the same time. The TOXinTRANSPORT project deals with particulate pollution in railway rolling stocks and in the underground stations.

1.2 Objectives

The main objective of the TOXinTRANSPORT project is to assess the cocktail effect by measuring many variables about particulate matter using both real-time and integrative measurements with the idea in mind to find correlations between all the gathered data. The project targets the travelers and workers in environments such as railway rolling stocks or underground stations. It aims at providing new data on toxicity test responses to particles (PM) correlated to their physico-chemical compositions with sampling made where exposure is critical, namely a station platform or a railway rolling stock. One of the most delicate issues to deal with is to assess the impact of the physico-chemical composition on the toxicological effects considering particle numbers, morphologies, compositions, mass concentrations and so on. In order to improve current knowledge in the field, a new way to sample the aerosols for further in-vitro tests was achieved using a biosampler (Coriolis from Bertin Technology). This sampler using a cone as a receptacle and a cyclone avoids the delicate use of filters, rendering particle collection trickier than with the Coriolis. Finally, using a complete battery of instruments described below in Section 2.2, one of the objectives was to assess several metrics and to determine their impact and therefore possible use in this context.

1.3 Description of Experimental Campaigns

Two campaigns of experiments were organized during the project. The platform of an underground station was designated as the site for the first campaign. Sampling took place in Paris suburb from the 4th to the 17th of March in 2020. Data were recorded from 5 AM to 1 AM the next day. The second campaign of experiments unfolded in a railway rolling stock. Sampling was achieved from the 15th to the 25th of September in 2020. The choice of the sites was proposed by the railway operator. Nevertheless, it presented all the aspects to be taken into account for this study.

2 Sampling Methodology

2.1 Sampling Objectives and Principles

The methodology set up in the framework of this project aimed at achieving both physico-chemical and toxicological characterization of the particles in suspension in these two environments. It differed from one campaign to the other to take into account the different constraints of each environment. The list of the equipment used during the campaign of experiments is given in the section below.

2.2 Experimental Instruments for the Two Campaigns of Experiments

Many instruments were used during the TOXinTRANSPORT project, and many results were obtained from these. Only the main results will be presented in this paper.

For the first campaign on the platform, a DA80 (Digitel) sampler (sampling on filters) allowed measuring metals, PAHs (Polycyclic Aromatic Hydrocarbon), elemental and organic carbon, ions. A MPS (Mini Particle Sampler, Ecomesure) sampling particles on TEM (Transmission Electron Microscope) grids made possible morphology and elemental composition analysis using a TEM (Jeol 1400). All these instruments were meant to achieve integrative sampling. Real-time monitoring was made using Grimm (Dust Monitor 1.108, Grimm Aerosol Technik), NanoScan (TSI Nanoparticle Sizer 3910) for particle number monitoring. A TEOM (TEOM 1405-D Thermo Scientific) and a Canarin sensor [4] were utilized to determine PM2.5 and PM10 masses. A Cairsens (ENVEA) measured NO2 gas levels. Black carbon quantification was estimated with MicroAeth® MA350 and AE51 (Aethlabs) instruments. The cellular toxicology measurements were assured resorting to two biosamplers, namely Coriolis Micro (wet sampling) and Compact (dry sampling). Toxicity tests were performed on a co-culture of human lung cells. From there, cytotoxicity, oxidative stress, endotoxins, and inflammation were studied. Cytotoxicity was assessed through metabolic capacity and membrane integrity. Oxidative stress was dealt with by measuring intracellular ROS (Reactive Oxygen Species). For inflammation, pro-inflammatory cytokines were measured. Acellular toxicology assessment was made possible with a laboratory made oxidative potential analyzer for real time monitoring and sampling with a DA 80 for integrative measurements.

For the second campaign in the coach, a HPEM (Harvard Personal Exposure Monitor, Ecomesure) was used to measure PM10 (mass), metals and ions. A Microvol (Ecomesure) quantified PAHs, elemental and organic carbon. These gather the integrative instruments. Real-time measurements were made using Grimm, NanoScan, Canarin, Cairsens, MA 350 all these playing a role identical to that played in the first campaign. For cellular toxicology, only the Coriolis Micro was used, and the tests performed on lung cells. Acellular oxidative potential measurement was made with the Microvol with integrative evaluation.

For toxicology analysis, the particles collected in the cone are poured directly on the lung cells with a physiological fluid or mixed with a solution close to lung fluid for acellular toxicological tests.

3 Results

3.1 First Campaign: Underground Platform

Physico-Chemical Results

Average PM10 concentrations are of about 62-138 $\mu g/m^3$ which is consistent with values usually found in France [5]. Iron is the main metallic element with a concentration of 69 $\mu g/m^3$ and this value does not vary much from one day to the other. The main PAH found are phenanthrene, pyrene, fluoranthene. The average carbon (elemental and organic) concentration is of about 37 $\mu g/m^3$ with values not varying much throughout the weeks. Sulphate is the main ion found on the platform with a value of around 1.32 $\mu g/m^3$.

Mass contribution of the ions is rather low in comparison with carbon and metals. TEM observations reveals that there are particles with sizes ranging from 50 nm to several micrometers. Most of the sampled particles are made of iron oxide as may be seen in Fig. 1. The analyze of DA80 filters showed a proportion of iron of 81 ± 2% in average (n=18). An example of iron particles collected during the campaign is shown in Fig.1.

Toxicological Results

Cellular toxicological analyzes evidence different effects and three parameters have been examined: cytotoxicity, oxidative cellular potential, inflammation. Regarding toxicity, the sampled particles seem to act on the cell functionality rather than on the cell membrane. The number of particles does not seem to influence cellular toxicity results. The oxidative cellular potential seems to be sensitive to particle concentration. Measurements in the station show that particles are prone to induce ROS formation [6]. As to inflammation, sampled particles in underground stations do not display significant pro-inflammatory potential under the experimental conditions of this study. However, a multivariate analysis performed on the data suggest a link between proinflammatory potential and high concentrations of iron, zinc, manganese, and aluminum.

Acellular oxidative potential evidenced values higher than those usually found in French cities [7].

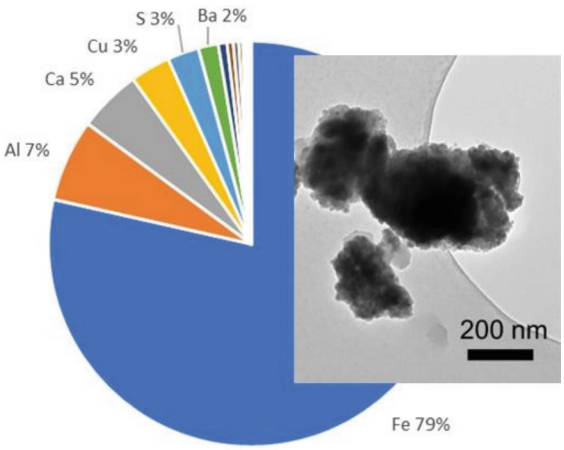


Fig. 1. Diagram showing the prevalence of iron in the sampled particles and picture showing a particle made of iron and oxygen.

3.2 Second Campaign: In the Railway Rolling Stock

Physico-Chemical Results

Average PM10 concentrations range from 40 to 70 $\mu g/m^3$ with a maximum value of 133 $\mu g/m^3$ found during the first test. These values are consistent with those usually found in France [5].

Again, for this campaign, the main element sampled during the experiment is iron with an average concentration of 21 $\mu g/m^3$. This time, concentration varies significantly throughout the tests. The PAHs display very low concentrations in the coach. The average carbon concentration is of about 60 $\mu g/m^3$ with organic carbon concentration five times higher than that of elemental carbon. Mass contribution of the ions is rather low in comparison with metals and carbon. There is a greater diversity in particle morphology in the railway rolling stock than on the platform. Many of these particles are agglomerates made of iron alone or combined with carbon and oxygen. There is a large number of particles with a diameter of about 200 nm mainly composed of carbon and iron. The air conditioning seems to influence particle concentration and the observation of particles with various morphologies. Sampling while traveling without air conditioning displays large amounts of micrometric-sized particles made of iron and probably connected to the opening of the windows while rolling. Particles whose morphologies were different from those of the first campaign were also observed.

Toxicological Results

Cellular toxicological analyzes were made here again through cytotoxicity, oxidative cellular potential and inflammation. Regarding cytotoxicity, tests made using particles sampled in a railway rolling stock proved low toxicity. The oxidative cellular potential was assessed by sampling in the railway rolling stock and evidenced a significant formation of intracellular ROS for the longer sampling times (100 lpm, 8 hours). Using Coriolis micro with a sampling time of ten minutes and a maximum flowrate of 300 lpm, it was possible to differentiate the samples inducing ROS in the underground station from those (no ROS induced) of stations in the open. This result is promising to study different kind of environments. As to the pro-inflammatory potential, sampling made in a railway rolling stock displayed higher endotoxin contents than on the platform, though no connection with PM mass could be demonstrated. Eventually, sampling did not display significant pro-inflammatory potential under the conditions of this study.

The acellular oxidative potential is 4 to 10 times higher than that found in urban areas [7, 8]. Observations suggest that this may be connected to carbon, copper, and iron concentrations.

4 Conclusion and Perspectives

The objective of the TOXinTRANSPORT exploratory project was to assess the impact of particle pollution on toxicological characterization. To reach this goal, a battery of various instruments was utilized for physico-chemical characterization of particles together with assessment of cellular and acellular responses. One original feature of the TOXinTRANSPORT project was particle sampling using the Coriolis biosampler to expose in-vitro cells and physiological fluids close to lung fluids directly to the particles without using tedious particle extraction from filters. These analyzes were made both in underground stations and in the railway rolling stock. Regarding the physico-chemical results, measured particle concentrations in the framework of this study proved to be consistent with other measurements made in France [5]. The measurements made on the platform showed that their variability is low whereas it is higher in railway rolling

stock. This may be caused by air-conditioning, heat if the air conditioner is down, the number of people in the coach and so on. This project brings about joint answers both physico-chemical and toxicological. Toxicological effects could be related to physico-chemistry and particle concentrations. Thus, inflammation seems to be connected to high concentrations of metals (4 to 10 times higher than average concentrations found in urban ambient air background). The acellular oxidative potential was found quite high both in the underground station and in the railway rolling stock. In both environment (platform and coach), intracellular ROS were produced when exposing cells to the sampled particles. However, the pro-inflamatory potential was found rather low both on the platform and in the train whereas endotoxin concentrations were higher in the railway rolling stock than on the underground platform. In terms of perspectives, it could be envisaged a standardization of sampling conditions of the particles for the study of the cellular and acellular toxicological impact. This should require mastering the use of the biosampler to make the best connection between physico-chemistry and toxicology.

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Characterization and Source Apportionment of Particulate Matter in Underground Railway Station

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Abstract. This study presents the chemical characterization and the source apportionment of particulate matter (PM10) in an underground railway station. The sampling site is the platform of an underground station operated by SNCF in France. Outdoor PM were also sampled on the roof of this station.

During the 5 measurement campaigns conducted for 8 months, the mean concentration of PM10 was 129.78 $\mu g/m^3$ in this underground station. PM10 sampled on the platform was composed of 52% metals and elemental compounds, mostly iron, silicon, and barium. Elemental carbon and organic matter represent respectively 8% and 14% of the mass of PM10.

Source apportionment using Positive Matrix Factorization (PMF) analysis shows that in this underground station, 82.1% of PM10 is emitted by railway traffic. 17.9% of the PM10 comes from the outdoor air.

However, railway sources have similar chemical compositions, and emissions from these sources occur simultaneously. Consequently, this study reveals the difficulty of further separating emissions from railway traffic using the PMF model. It underlines the need to expand our knowledge of the chemical composition of railway emissions and to define more specific tracer compounds of each railway source of PM.

Keywords: Particulate matter · underground railway station · chemical characterization · physical characterization · source apportionment · PMF

1 Introduction

Air pollution due to fine particles is a major issue because of its impact on human health. Indeed, the mortality rate due to long-term exposure to outdoor fine particles is estimated to reach 40,000 people per year in France [1]. In the meantime, European regulations about outdoor air quality are being reinforced. However, there are no specific regulations or requirements on particulate matter (PM) levels in underground railway stations where PM concentration levels are known to be often higher than outdoor PM levels [2]. In this context, this research aims to increase our knowledge of the physical and chemical

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composition of PM10 in an underground railway station. The second objective of this research is to identify PM10 emissions sources in an underground station and their contributions. The outcomes of this research will enable the identification of solutions to prevent and protect workers along with passengers from fine particle pollution in those underground environments.

2 Experimental Methods

2.1 Measurement Sites

The measurement site is an underground station operated by SNCF and located in the Ile de France region in France. This station has a central platform and two concrete rail tracks without rail ballast. It is known for its high PM concentration levels as PM concentrations are monitored here since 2018. Operating hours are from 5:00 a.m. to 1:00 a.m. Measurements and PM10 samplings were conducted in the middle of the platform. An extra sampling site is located on the roof of the station to provide information on outdoor ambient air PM near the station.

2.2 Instrumentation

On the platform of the station, PM10 and PM2.5 mass concentrations were monitored with a TEOM-FDMS analyzer (Thermo Scientific). Sampling of PM10 was conducted using simultaneously two Partisol samplers (Thermo Scientific). The first one was equipped with quartz filters (Tissuquartz Pallflex) which were dedicated to the analysis of elemental carbon (EC), and organic carbon (OC) by thermo-optical transmission method using EUSAAR2 protocol and Cl^-, $NO_3{}^-$, $SO_4{}^{2-}$, Na^+, $NH_4{}^+$, K^+, Mg^{2+}, Ca^{2+} by ion chromatography. The second Partisol sampler was equipped with mixed cellulose esters filters (MF-Millipore, Merck). This second type of filter was used for the analysis of Al, Ba, Ca, Cr, Cu, Fe, Mn, S, Si, Zn by ICP-OES and As, Cd, Ni, Pb, Sb, Sn, Ti by ICP-MS. Concentrations of metals and elemental components of platform PM were measured with an Xact 625i metals monitor (Cooper Environmental). An Electrical Low-Pressure Impactor ELPI + (Dekati) was used to study underground PM size distribution and monitor concentration of PM in number for particles size ranging from 6 nm to 10 μm. Samplings of outdoor PM were performed with two portable filter sampling devices: a PEM 200 personal impactor (MSP-TSI) and a CAThIA sampling head (Tecora). The same chemical compounds as platform PM10 were analyzed in outdoor PM10 samples.

2.3 Measurement Period

On the platform, 5 one-month measurement campaigns were conducted between September 2020 and May 2021. PM10 samplings were performed during weekdays and operating hours whereas TEOM-FDMS measurements were carried out for 24 h, 7 days a week during each campaign, with a 15-min time resolution. Xact measurements started on the third campaign. This monitor was set for the measurement of hourly concentrations for 24 h a day, 7 days a week. ELPI measurements were conducted in February

(1 session) and April 2021 (2 sessions). A total of three sessions of 24-h measurements were carried out with a 1-s time resolution. On the roof of the station, 8 h of sampling per measurement campaign was performed for a total of 5 sessions of sampling of outdoor PM.

2.4 Source Apportionment

Positive Matrix Factorization (PMF v.5.0) was used to identify PM10 sources on the platform and their contribution. PMF analysis was applied to data from chemical analysis of platform PM10 samples (26 chemical compounds) and PM10 concentrations measured by TEOM-FDMS. A total of 96 samples built up this dataset. Organic matter (OM) was considered rather than organic carbon (OC). To do so, a conversion factor of 1,8 [3] was used to convert OC to OM concentrations. Although this factor is defined for outdoor PM, it was still considered in this study as there is no conversion factor specific to PM in underground railway environments.

3 Results

3.1 Physical and Chemical Characterization

For the 5 measurement campaigns, the average daily concentration of PM10 and PM2.5 is respectively 126 $\mu g/m^3$ and 53 $\mu g/m^3$.

In this paper, only ELPI measurements from February 24th to February 25th, 2021, are shown as measurements during the 2 other sessions have similar results. Regarding particulate number concentration on the platform of this station, the mean concentration was 11 553 #/cm^3. Size distribution of particulate number concentrations (Fig. 1) shows that the particles with an aerodynamic diameter inferior to 30 nm represent a major part of particles in this underground station.

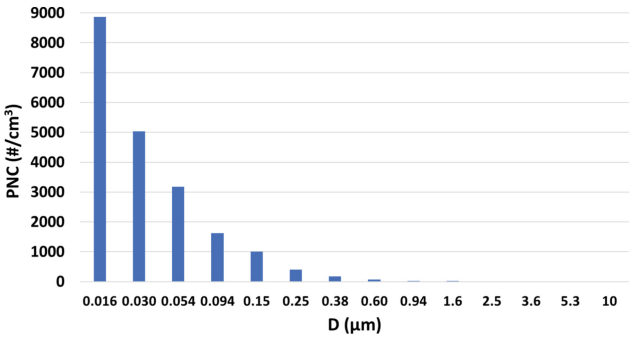


Fig. 1. Particulate size distribution of average number concentration (PNC #/cm^3) measured every second for 24 h from February 24th to February 25th, 2021.

According to the results of the 5 campaigns on the platform of this underground station, PM10 is composed of 52% metals and elemental components mainly Fe, Si, and

Ba. EC and OM represent respectively 8% and 14% of the PM10 total mass. SO_4^{2-}, Ca^{2+}, and NO_3^- are the major ion components in PM10. They represent 2% of the mass of PM10. Although a significant number of chemical components were investigated, 24% on average of the mass of PM10 couldn't be identified. This proportion called "Other" (Fig. 2) seems to be comprised of oxygen. Indeed, several studies [4–6] on the chemical composition of PM in European underground railway stations reveal the presence of oxidized forms of metals and elemental components such as hematite (Fe_2O_3) or quartz (SiO_2).

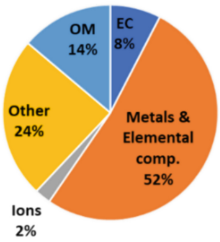


Fig. 2. Mean chemical composition of PM10 on platform

An example of the 24-h temporal evolution of metal and elemental components contained in PM10 is illustrated in Fig. 3 as it is representative of the measurements performed for 3 months. Their concentrations compared with PM10 concentrations measured with TEOM-FDMS (Fig. 3) indicate a similar temporal evolution. During rush hours in the station, both PM10 and metal concentrations increase as train traffic increases. Conversely, when PM10 concentrations decrease during off-peak hours and non-operating hours, metals and elemental component concentrations also decrease.

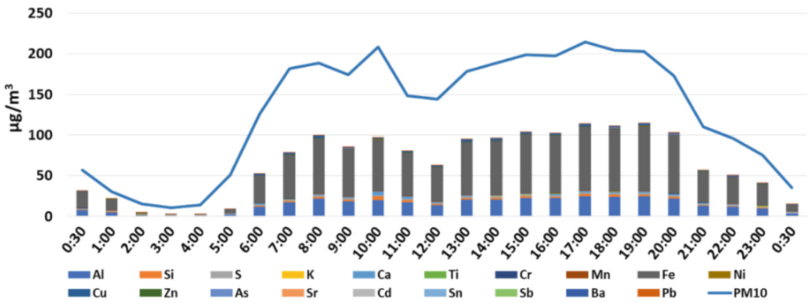


Fig. 3. Elemental compounds and metals concentration measured by Xact monitor and PM10 concentration measured by TEOM for 24 h on February 8th, 2021.

3.2 Source Apportionment

To identify emissions sources of PM in underground railway stations, two types of sources were investigated: elements from railway rolling stock and infrastructure and

particles from outdoor air. Regarding the railway elements, PM is known to be emit-ted by the brake pad and brake block, the contact wheel rail, and the contact between the catenary and the pantograph. The chemical composition of these railway rolling stock elements [7, 8] and these railway infrastructures [9, 10] bring out that Fe, Mn, Cu, and carbon are present in many of these elements. Therefore, particles emitted by railway rolling stock and railway infrastructures are expected to be mainly composed of metals. Chemical analysis of PM10 sampled on the roof of the station reveals a typical urban PM chemical composition. The presence of NO_3^- and NH_4^+ are related to a mix of traffic road and agricultural spreading emissions. Anthropized sea salts are characterized by the presence of Na^+ and Cl^-.

Among the different PMF solutions obtained, the five-factor solution was the most stable solution (Fig. 4) with bootstrap mappings ranging from 77% (factor 2) to 100% (factor 1 and 5). Moreover, this solution gives a good reconstitution of PM10 concentrations by the PMF model (correlation coefficient R2 = 0.84). Based on the chemical composition of the various parts of the railway rolling stock and the railway infrastructures that emit particles and the chemical composition of outdoor PM10, factor 1 "Na-Cl", factor 2 "NO_3" and factor 5 "NH_4-SO_4" were assigned to sources coming from outdoor ambient air. Factor 3 "EC-Metals" and factor 4 "OM-Metals" are related to emissions originating from railway activities. The contribution of these 5 factors to the concentration of PM10 on the platform (Fig. 4) indicates that 44.3% of PM10 is related to the third factor "EC-Metals" and 37.8% of PM10 is associated with factor 4 "OM-Metals". Factors attributed to outdoor air emissions represent 17.9% of platform PM10 concentrations. Thus, the PMF model shows a strong impact of emissions from

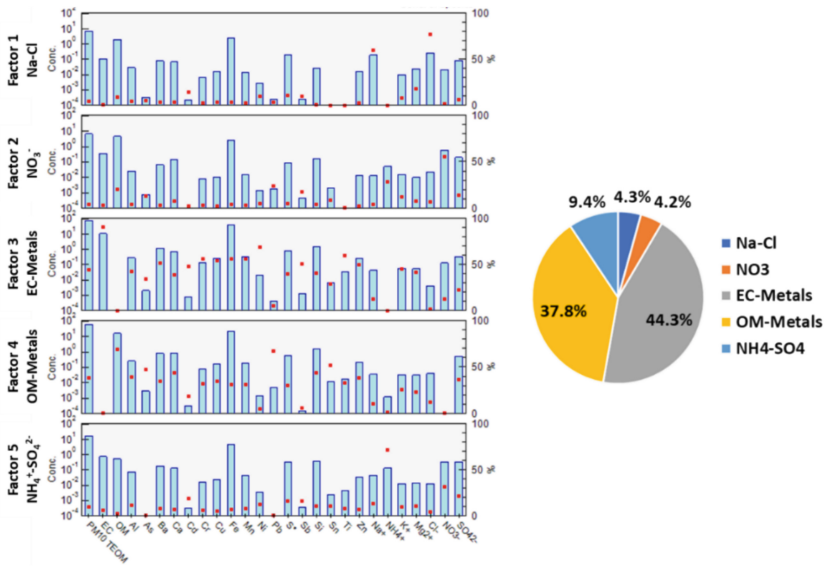


Fig. 4. Factor profiles identified by PMF (on the left, red dots represent percentage of each species and blue bar chart represent concentration of species) and their contribution to the concentration of the PM10 on the platform (on the right).

railway activities on this underground environment as it represents the major source of PM10 on this platform.

4 Conclusion

During the 5 measurement campaigns, mean concentration of PM10 was 129.78 $\mu g/m^3$ in this underground station. PM10 sampled on the platform were composed of 52% of metals and elemental compounds. EC and OM represent respectively 8% and 14% of the mass of PM10. Source apportionment using Positive Matrix Factorization (PMF) analysis shows that in this underground station, 82.1% of PM10 is emitted by railway traffic. 17.9% of the PM10 comes from the outdoor air. However, railway sources have similar chemical compositions, and emissions from these sources occur simultaneously. Consequently, this research stresses the difficulty of further separating emissions from rail-way traffic using the PMF model. It underlines the need to expand our knowledge of the chemical composition of railway particles emissions and to define more specific tracer compounds of each railway source of PM. It would be interesting to reiterate this work in another underground station to confirm or not these first tendencies.

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Field Study of Pedestrian Crossings Deterioration Over Time: Assessment of Microplastics Emission from Road Markings

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Abstract. The issue of road marking deterioration (loss of functional properties, followed by abrasion) is of profound importance, so appropriate maintenance of roadway infrastructure is required. When road markings are used past their intended functional service life, they can undergo abrasion, which negatively affects their visibility for drivers and also leads also to emission of microplastics. This study was undertaken to fill the knowledge gap related to the rate and extent of abrasion that could be expected from road markings exposed to heavy traffic after the loss of functional properties. Analysis of luminance loss over three years was utilised as an indirect measurement method. The outcome, based on assessment of three pedestrian crossings, indicated average abrasion of 2.1% per 1 million weight-adjusted vehicle passes when cold plastic, a durable material containing hard coarse fillers, was used. However, it could exceed 20% if paint, unsuitable for such jobs, was utilised instead. Thus, the polymer quantities released from the analysed zebra stripes during the three years of usage past their functional service life varied from 10.3 to 25.9 g per 1 million weight-adjusted vehicle passes. Such relatively large measured abrasion and emissions was a result of grossly negligent maintenance. Hence, appropriate selection of materials for a particular road and their correct maintenance were shown as necessary to not only assure visibility of the road markings for drivers, but also to minimise the emissions to minimise the environmental impact.

Keywords: service life · luminance · abrasion · retroreflectivity · environmental pollution

1 Introduction

Road markings (RM) are necessary basic road safety elements – they are used by both human drivers and by the machine vision technology utilised in driver assistance systems and as such are currently irreplaceable [1]. However, RM are deteriorating systems that require renewals, so they would maintain their functional properties. Upon reaching the end of functional service life, RM remain on the road and normally should be renewed

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(not replaced). Their extended use, past the intended and designed functional service life, leads to the decrease in visibility for drivers and then abrasion, which causes contribution to microplastic (MP) pollution.

There were reports about enormous emissions of MPs originating from RM, but closer examination revealed them to be fundamentally wrong [2]: in the theoretical estimates not only the functional parameters of RM, but also the protective role of the drop-on glass beads and the common practices associated with RM maintenance were disregarded. Several reports of finding RM particles amongst collected MPs were traced to either extraordinary abrasion conditions (like the use of studded tyres) [3, 4] or to unacceptably negligent maintenance (i.e. permitting for complete abrasion or crumbling instead of prompt renewal upon the loss of functional properties) [5, 6]. Based on field assessment in several countries, it has been demonstrated that at pedestrian crossings, which are the most used areas as all of the vehicles encroach on them, annual abrasion was $< 5\%$ (with the exception of Sweden, where studded tyres are used; abrasion there exceeded 20%) [7].

Whereas based on prior research it was possible to estimate the extent of complete loss of RM at a particular moment, absent was a systematic study to correlate the rate of abrasion (which can occur only after the loss of functional properties) with the traffic load. Hence, this effort was undertaken with the goals of providing the results from such assessment and proposing an easy methodology for this type of evaluations. For demonstration, periodically taken images of three pedestrian crossings were analysed for road marking erosion (i.e. complete abrasion) based on the loss of luminance, according to previously established methodology [7, 8]. The outcome was envisaged to be a clarification of the issue of RM deterioration for environmental scientists seeking apportionment of roadway sources of pollution, but foremost should assist road administrators in selecting optimum solutions to simultaneously maximise the benefits for drivers and minimise contamination of the environment.

2 Methodology

The evaluation protocol was explained in detail elsewhere [7]. The key assumption was that the marked area had much lighter colour than the area of underlaying roadway exposed due to a complete abrasion of RM.

Evaluation was done on representative ‘zebra’ pedestrian crossings at national road 2 in Poland, a two-lane section between towns Kałuszyn and Siedlce. Two of the assessed crossings were marked with structured cold plastic (a material designed for withstanding heavy traffic loads, containing hard coarse fillers) and one initially with paint (material of relatively low durability that should be used only on edge lines that are not heavily trafficked). Analyses were repeated at least twice a year for three years (but not necessarily all on the same day). One has to note that it is not known how long exactly the RM were in service before the analyses commenced; while it may be important and this weakness is acknowledged, for the presented assessment it was considered irrelevant because of the extended evaluation period. The annually average daily traffic, per data published recently by the road administrator, is provided in Table 1 (assumed was equal traffic in both directions). For easy comparison, the marking loss was expressed per 1 million of weight-adjusted vehicles per lane (MWAVL).

Table 1. Traffic load (per lane).

—	Crossings A and B	Crossing C
Light vehicles (≤3.5 t gross weight rating)	7703	7716
Heavy vehicles (>3.5 t gross weight rating and buses)	1621	1381
Weight-adjusted annually averaged daily traffic	20,667	18,764

3 Results

Pictures of one of the analysed pedestrian crossing at the beginning and at the end of the evaluation period are shown in Fig. 1 and Fig. 2, correspondingly; increase in the abraded area is clearly visible.



Fig. 1. Exemplary area (crossing B) at the beginning of analysis: circa 2% marking loss since last application (period on the road unknown).



Fig. 2. Exemplary area (crossing B) after 3 years and 23.0 million weight-adjusted vehicle passes: circa 43% marking loss.

The results of the evaluation are summarised in Table 2 and visualised in Fig. 3. One should note the superior performance of cold plastic that was used to mark pedestrian crossings A and B, loss of 1.4–1.8% per MWAVL was measured, which corresponded to estimated polymer emissions of 10.3–12.9 g per MWAVL. At pedestrian crossing C, marked initially with paint, loss of 20.2% per MWAVL was measured (within just several months, average abrasion was 75.5%, but if one excluded the least-used 'zebra' stripe, on which almost no vehicles encroach, it was > 97%) for polymer release reaching 14.5 g per MWAVL. Subsequent switch to cold plastic resulted in significantly higher abrasion resistance; however, after another renewal the abrasion rate increased to 3.6% per MWAVL, which indicates that the renewal was not done properly (poor workmanship and/or use of a substandard material).

Table 2. Marking loss.

Period	MWAVL[(a)]	'Zebra' A[(b)]	Zebra' B[(b)]	'Zebra' C[(c)]	'Zebra' C[(b)]
Initial	0.0 / 0.0	0.6%	1.8%	75.2%	–
about 3 months	2.3 / 1.9	1.6%	4.6%	3.5%[(d)]	–
about 6 months	4.5 / 3.6	3.8%	12.1%	65.5%	–
about 1 year	5.8 / 5.5	8.4%	19.2%	75.5%	–
about 18 months	9.8 / 8.0	13.7%	24.6%	–	2.7%[(d)]
about 2 years	16.2 / 12.5	22.9%	33.8%	–	9.6%
about 30 months	20.5 / 14.7	31.1%	41.2%	–	1.0%[(d)]
about 3 years	23.0 / 20.5	33.5%	43.1%	–	22.1%
Average marking loss per MWAVL		1.4%	1.8%	20.2%[(d)]	1.5 / 3.6%[(d)]
MP emissions per MWAVL [g][(e)]		10.3	12.9	14.5[(d)]	10.9 / 25.9[(d)]

(a) First value applies to crossings A and B, second value applies to crossing C. (b) Marked with cold plastic. (c) Marked with paint. (d) Renewal was done. (e) Calculated assuming the material losses given herein and: cold plastic – applied at 3.5 kg/m^2 containing 20.5% of polymeric material, and paint – applied at 0.6 kg/m^2, containing 12.0% of polymeric materials

4 Discussion and Conclusions

Evaluation of pedestrian crossings for marking loss (i.e. complete abrasion) revealed that its rate was strongly correlated with the selection of materials for the RM. The use of properly applied cold plastic (a good choice for this type of location) resulted in average abrasion rate of 1.6% per MWAVL and mean MP release rate of 11.4 g per MWAVL. The selection of paint (a very poor choice for pedestrian crossing) resulted in abrasion rate more than ten times larger. Because life cycle assessments done on various types of RM revealed that the parameter controlling their sustainability was their functional service life, so appropriate materials selection is critical [9–11] which was demonstrated herein again.

Validity of this approach and consistency of the collected data was confirmed through comparison of the trendlines drawn through the data points (Cf. Figure 3), where almost parallel trendlines ($y = 0.015x$ – $y = 0.018x$) and good data point fits, with $R^2 > 0.95$, were observed for crossings A and B. Similar result was also seen for the initial application of cold plastic at pedestrian crossing C. Because of apparently poor quality of its renewal, the subsequent slope was steeper ($y = 0.032$; loss 3.6% per MWAVL was measured instead of 1.4–1.8%). The differences between the most used and least used stripes were disregarded for this preliminary assessment, even though they were meaningful; this aspect may be needed for optimisation of the maintenance schedule.

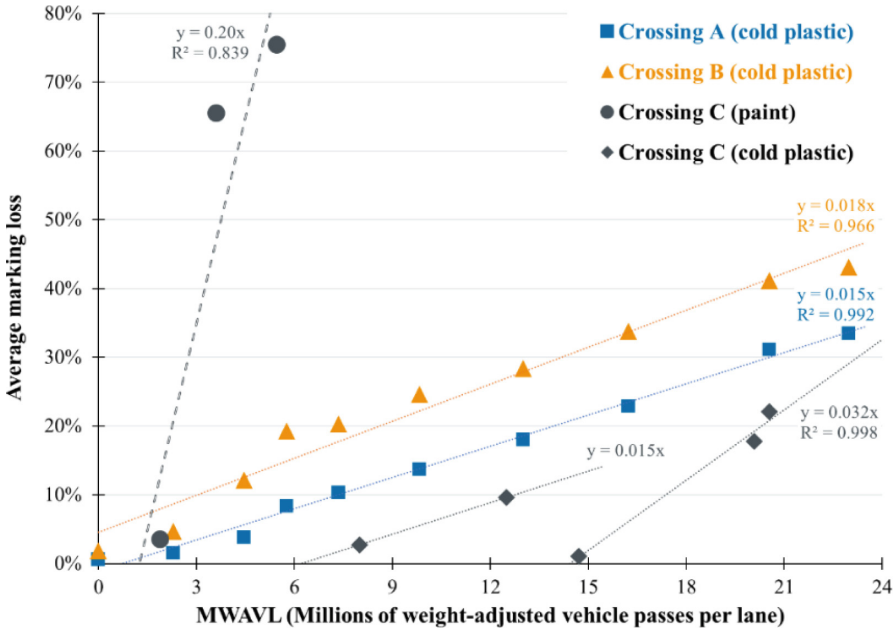


Fig. 3. Marking loss (abrasion) at the analysed pedestrian crossings as a function of traffic load.

From the perspective of MP emissions, this assessment indicated larger annual abrasion than was previously reported based on other field estimate [7]; however, herein very heavy traffic load was combined with grossly negligent maintenance – the RM were not renewed upon the loss of functional properties, but were permitted to be significantly abraded [2, 7]. The relatively high rates of marking loss should not be treated as an inherent weakness of RM and their propensity to undergo abrasion, but were a results of very poor maintenance practice (combined with erroneous choice of material in one of the cases).

One should additionally note that structured RM, such as those present on the pedestrian crossings marked with cold plastic, are providing much better visibility at night during rainy conditions [12], which should translate to an increase in road safety. Therefore, the measured grossly inadequate maintenance could be a factor contributing to very poor road safety in Poland. If the RM are simultaneously reflectorised with glass beads capable of furnishing retroreflectivity under wet conditions, additional benefits could be realised; successful use of such high-end RM at pedestrian crossings was recently reported [13]. Furthermore, it was calculated that the use of high-end materials for RM, despite their high unit costs, from a long-term perspective was not more expensive than low-end RM due to improved durability [14]. Because of enormous expenses associated with vehicular accidents, the use of inexpensive and readily available solutions like properly visible RM should bring meaningful social advantages, so it is surprising that some road administrators neglect such easy solutions to improve road safety.

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Analysis of Brake Particle Emissions During Laboratory Braking Tests

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Abstract. Particulate matter (*PM*) is one of the most problematic pollutants in the world because of its harmful impact on human health and the environment. Rail rolling stock braking can contribute to air pollution. Therefore, studying these emissions can help to develop cleaner and more sustainable rail transportation systems.

The aim of the work conducted by the Rolling Stock Engineering Department of SNCF Voyageurs at the Railway Testing Agency (AEF) is to establish a comprehensive understanding of the connection between braking conditions and the particles concentrations. The insights gained from this research can lead to the development of a model that accurately predicts and quantifies the amount of particles released during braking. The research also involves comparing different types of brake pads to better identify which ones emit fewer particles during the same barking conditions.

The article presents the analyses conducted on the parameters measured during bench brake testing. These parameters include speed, application and tangential force, braking distance, energy dissipation, and PM concentration.

Keywords: Air quality · Airborne particles · Railway brake · Variance-based sensitivity analysis · Correlation analysis · Principal component analysis · Random Forest for prediction · Cluster analysis

1 Introduction

Reducing atmospheric pollution in underground railway installations is a challenge faced by rail systems around the world. Underground stations and tunnels may have important levels of pollutants and particulate matter due to factors such as train operations, insufficient ventilation systems and the enclosed environment.

Regularly, the Railway Testing Agency (AEF) conducts measurements of particles concentrations in railway environment. The results show the presence of dust which consists of metal particles resulting from the wear of railway components such as braking systems, wheels, rails, pantographs, and overhead power lines. Since brake events have a significant contribution, tests are conducted by means of bench course simulation (real braking cycles) to measure and analyze brake system pollution.

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The brake test rig of AEF enables monitoring different parameters affecting the braking such as forces of application, initial speeds, masses involved, temperatures,…

Additionally, it is equipped with an air flow system designed to capture the dust released during brake application. The collected dust is analyzed to track the PM concentration based on different braking parameters.

Traffic-related PM can be divided into 3 categories based on the particle size: coarse particles PM_{10} with diameters below 10 μg; fine particles $PM_{2.5}$ with diameters below 2.5 μg; ultrafine particles PM_1 with diameters below 1 μg.

In the light of the above, the main objective of this study is the analysis of PM_{10}, $PM_{2.5}$ and PM_1 concentrations as a function of braking parameters and chemical composition brake pad or shoe. Different test programs composed of several brake events each were conducted on the test rig to simulate the brake performance of a railway vehicle during a typical route. The analysis has been conducted using two brake pad materials.

2 Methodology

2.1 Data Collection and Experimental Setup

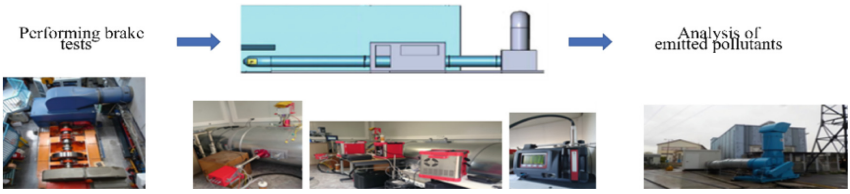


Fig. 1. Brake test rig

The brake test rig is used to test and evaluate the braking performance of monobloc wheels. It allows control of braking conditions, including the force applied to the brakes, wheel rotation speed, and other key parameters. Various braking scenarios can be simulated. During tests, important data such as braking distance, braking force, brake temperature is gathered through a measurement system. Additionally, an air caption system placed around the braking system enables PM analyses, conducted in a small laboratory located just next to the brake bench. Figure 1 illustrates the complete procedure.

2.2 Analysis Techniques

Variance-Based Sensitivity Analysis

The approach is divided into four main parts. Firstly, variance-based sensitivity analysis is conducted to quantify and understand how changes in input parameters (braking parameters and brake pad composition) affect the output variability (in this case, particle concentration). Calculating the first-order Sobol indices reveals the parameters with the

most significant impact on the variability of the output. Mathematically, the first-order Sobol index for the *i-th* parameter (S_i) is calculated as follows:

$$S_i = \frac{\mathbb{V}\left(\mathbb{E}_{X_{\sim i}}(Y|X_i)\right)}{\mathbb{V}(Y)}$$

where:

- Y represents PM_{10}, $PM_{2.5}$ and PM_1
- X_i is the *i-th* input parameter and $X_{\sim i}$ represents all input parameters except X_i;
- $\mathbb{E}_{X_{\sim i}}$ is the expected value of Y given X_i while keeping $X_{\sim i}$ constant;
- $\mathbb{V}$ represents the variance.

Principal Component Analysis

Next, a principal component analysis is conducted followed by a correlation analysis to capture the relationship between uncorrelated variables (principal components) and the original variables. Following these steps provides insights into how the original variables contribute to the principal components.

The main objective of PCA is to transform high-dimensional data into a lower-dimensional space while preserving as much of the original variability as possible.

Principal components extracted through PCA can be used as input variables for the prediction model and the clustering algorithm. After performing PCA on the original data, a subset of the principal components is selected that capture most of the variance in the data. Thus, noise and irrelevant information is reduced and potentially leading to better-defined clusters and prediction.

Clustering Algorithm

Agglomerative clustering, a hierarchical technique, is applied in this study. It works by iteratively merging similar data points to form larger clusters.

The choice of similarity metric and linkage criterion plays a crucial role in determining the quality and characteristics of the clusters produced. In this study, Ward's method is used to determine the distance between clusters.

By doing so, the final clusters are formed by minimizing the variance within each cluster after merging, resulting in compact and well-separated clusters.

Additional analysis is being conducted to provide insights into the cluster's properties.

Prediction Model

To simplify the model, reduce overfitting, and speed up training, the reduced number of principal components is employed for predicting concentrations of particulate matter PM_{10}, $PM_{2.5}$ and PM_1.

In this study, random forest is employed which is a popular algorithm for regression tasks as it can handle non-linear relationships and interactions among features effectively. Hyperparameters have a crucial impact on the results of regression. They control its behavior. One way to find the optimal set of hyperparameters is by applying a random search across a defined parameter space, commonly referred to as a hyperparameter value range.

This study follows a step-by-step process. First, a variance-based sensitivity analysis is conducted to identify key input variables. Subsequently, a Principal Component Analysis is applied to reduce dimensionality and enhance interpretability. Following this, similar data points are grouped, providing valuable insights into how each brake pad behaves within the same cluster. Finally, a predictive model is trained to estimate PM concentration for unknown brake conditions.

3 Results and Discussion

The aim of this section is to provide an overview of the outcomes derived from the conducted analysis. As part of data exploration process, a correlation analysis (see Fig. 2) is conducted which provides valuable insights into the data and captures linear relationships.

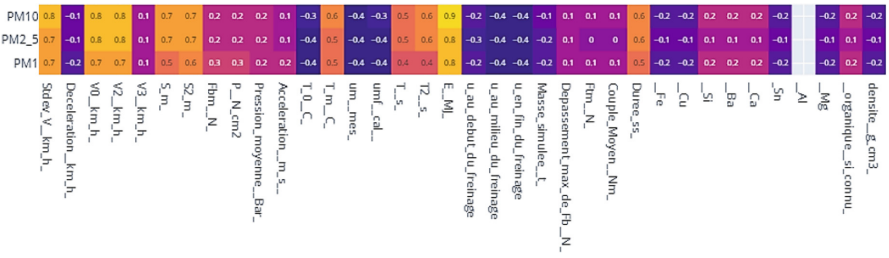


Fig. 2. Correlation analysis of particulate matter and input parameters

The results reveal intriguing insights into the links between air quality and Braking test conditions. The correlation coefficient for PM and speed ranges from 0.7 to 0.83, suggesting a strong linear relationship. The same interpretation applies to the energy dissipated by braking. This finding aligns with the notion that higher speeds tend to contribute to elevated levels of particulate matter. Or higher speeds require intense braking, resulting in increased energy dissipation and braking duration through the braking system. Correlation analysis highlights also a moderate linear relationship between particulate matter and various parameters, such as total braking distance, average temperature, and friction coefficient.

To comprehend variable contributions to particulate matter variability, variance-based sensitivity analysis is conducted. It is way to capture complex relationships and avoid the limitations of linear associations.

The result represents the proportion of output variance that can be attributed to each input parameter individually. Higher Sobol indices indicate greater influence on the output. Based on Fig. 3, the highest contributions are generated in a decreasing order by start speed, speed standard deviation, energy dissipated, total braking distance, braking duration and average temperature. Higher temperatures can accelerate chemical reactions and increase wear rates. Consequently, at elevated temperatures, it could contribute to the production of PM .

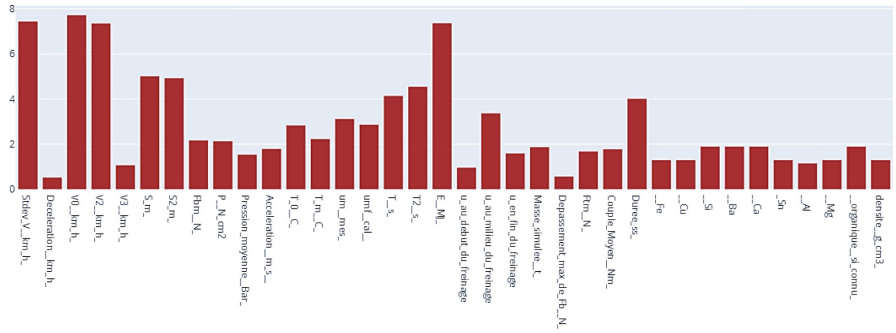


Fig. 3. Sobol Sensitivity Analysis: Impact of input parameters on $PM_{2.5}$

To simplify the dataset while preserving much of the important variance, PCA is performed on braking parameters as a method of dimensionality reduction. Selecting four principal components retains 83.82% of the explained variance.

Because PCA transforms the original variables into orthogonal (uncorrelated) principal components through linear combinations, performing a correlation analysis provides insights into the connections between original variables and principal components.

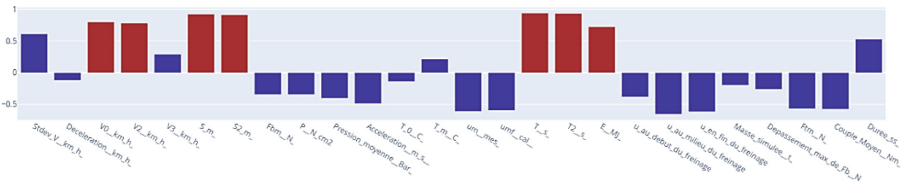


Fig. 4. Contribution of the braking parameters to the first principal component

Based on Fig. 4, the first component can be interpreted as the dynamic braking performance component capturing characteristics related to higher speeds, greater energy dissipation, and longer braking distances.

Following the same strategy, the second component captures the complex relationships between various factors influencing braking dynamics. It represents how application force, friction pression, air pressure, vehicle acceleration, tangential force, and braking torque collectively contribute to the braking process.

The third principal component can be linked to friction characteristics, average temperature, and braking duration.

Performing agglomerative hierarchical clustering on the principal components leads to 8 well-separated clusters with a higher silhouette score.

Analyzing the statistical characteristics of the data within each cluster enables the identification of the cluster with the highest PM production.

Figure 5 highlights three clusters characterized by elevated *PM* production (cluster 1, 7 and 4). These clusters share common characteristics related to high-speed levels, high braking distance, average temperature, dissipated energy.

Based on Fig. 5, it appears that the first brake pad material generates more PM production under similar braking conditions compared to second one. This finding confirms the hypothesis that the type or composition of brake pad materials can have a significant impact on PM emissions during braking.

To further address this insights, additional research is necessary to be better identify the specific factors within the material composition that contribute to elevated *PM* production.

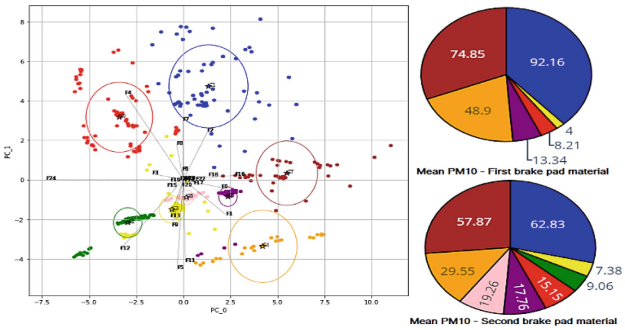


Fig. 5. Clustering Analysis and Impact on Similar Braking Conditions

By employing the random forest algorithm on braking conditions and material composition, the test phase results in a 78% accuracy in predicting particulate matter (PM) levels. The predictive model affirms that *PM* production is related to high-speed levels, high braking distance, average temperature, dissipated energy.

4 Limitations and Future Work

Due to the similarity of the tested brake pads within the material composition, the prediction model does not effectively emphasize the impact of the chemical composition. Efforts are currently underway to gather data from a wider range of brake pad manufacturers, and compositions. The completeness of the current database is expected to enhance the accuracy of the prediction model.

5 Conclusions

The main novelty of this project is to design a model capable of predict *PM* production using braking parameters and material composition. This research employs algorithms used in different contexts but compatible to this study case. The investigations have yielded significant conclusions regarding various variables and their impacts.

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Air Pollution at Airport Areas: Magnitude of the Phenomenon and Measures to Mitigate It

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Abstract. Airport areas generate large amounts of air pollution due to the air and surface traffics. However, this issue is often addressed by just considering single contributions, i.e. either the emissions generated by rubber-tired vehicles traffic or aircraft's. Obviously, the two contributions overlap and to understand the magnitude of the phenomenon it is important to calculate the emission package generated by each mode. For a given airport area, this raises three research questions: i) which is the major contributor between surface and air traffic?; ii) how big are these contributions? and iii) which can be the mitigation measures for the major contributor? In reply, two Italian case studies are considered. The first is a medium-size airport, as a case to estimate emissions generated both by surface vehicles and aircraft. Simulations stress that the contribution of the latter is not even comparable to that of the former, thus replying to the third research questions by studying four mitigation measures at take-off and landing at an another airport (as second case study), to decrease ground-operations' emissions. The paper describes the methodology adopted and elaborates the results and implications of air operations at ground level in urban airports within local mobility policies.

Keywords: Airports · Air Emissions · LTO Cycle

1 Introduction

The aviation industry has historically faced criticism for its environmental impact, but it now prioritizes environmental concerns. In this study field, initially numerous researchers have extensively documented the assessment of emissions produced by aircraft at ground level from various perspectives [1]. These studies include specific evaluations of Landing and Take-Off (LTO) cycles in different case scenarios, highlighting the importance of considering factors such as detailed flight data, dynamic time during climb and approach modes, aircraft performance, runway availability, specific inventories, large-scale benchmarks, and case-specific assessments [2, 3]. All of these studies emphasize how LTO operations can impact air quality and increase noise levels, potentially affecting public health [4]. It is important to note that emissions in the aviation sector are not solely generated by aircraft engines' exhaust; ground facilities and operations, such as refueling, maintenance, and heating, also contribute. Additionally, airports

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themselves, acting as attractors and generators of rubber-tired traffic, play a role in emissions [5]. Environmental concerns have spurred research into innovative aircraft design concepts, focusing on specific components or processes [6], as well as improvements in aircraft engine fuel efficiency [7]. This has led to the revision of existing practices, including route optimization, which has resulted in substantial reductions in carbon dioxide emissions. The policy implications of these findings are extensive and the subject of ongoing debate [8, 9]. The aviation industry is also exploring electrification as a means to reduce its environmental footprint, following trends seen in other sectors like transit [10, 11].

Airports generate air pollution from both rubber-tired vehicles and aircraft. Policymakers often focus on one aspect, overlooking the combined impact. To understand the full picture, it's vital to calculate emissions from both modes, acknowledging their overlapping influence. For a given airport area, this raises three research questions: i) which is the major contributor between surface traffic and air traffic?; ii) which is the magnitude of this contribution ? and iii) which can be the mitigation measures for the major contributor?

The paper addresses these research questions using two Italian case studies. The first, a medium-sized airport, reveals that aircraft emissions are significantly smaller than those from surface vehicles (Sect. 2). The second study explores four mitigation measures for ground emissions during LTO cycles (take-off and landing), calculating emissions with the same methodology and assessing their potential in decreasing pollution (Sect. 3), with the research goal to advance knowledge (Sect. 4).

2 Estimating Surface and Air Emissions at a Medium-Large Size Airport

To reply to the first research question, i.e. which is the major contributor in generating emissions, a scenario has been built simulating daily air and surface traffics and the emissions produced by each, in a medium-large airport in central Italy. Prior to the pandemic, this facility operated yearly around 53,000 air movements, for a passenger traffic of more than 5.5 million units. The modal share to commute to this facility rely on private cars (26.5%), chartered buses and coaches (53.5%), taxis and rentals (20%). Traffic surveys corroborated these figures and enabled to associate the annual demand with different European average occupancy rates, i.e., 1.25, 1.5, 2 and 3 for passenger cars [12] and full occupancy for buses and coaches. The scenario employed consolidated modeling methodologies (more specifically COPERT for the surface traffic and the EEA for the air traffic, both fully described in [13]), treating airside and landside areas as a unified space known as the "Airport Envelope," given their proximity and the low altitude of LTO operations. This envelope was defined based on a 3000 ft altitude for the LTO cycle and a 2.5-km radius surface catchment area, encompassing nearby road traffic from two major arterials. Data on both air and surface traffic were gathered to simulate fuel emission models, assessing their impact on the Airport Envelope. Consistency in both types of simulations was maintained by adhering to EEA regulations [14]. Results (Table 1) reply to the second research questions by showing that the rubber-tired traffic

emission contribution is virtually negligible if compared to that of aircraft, thus implying the urgency to look for more environmentally-friendly solutions to manage ground operations in air traffic.

Table 1. Yearly emissions comparison.

Mode	Traffic	Pollutant Emitted, Mass (kg)			
		CO	CO2	HC	NOx
Aircraft	26,128 LTO cycles	64,278,872	129,778	13053	314,200
Car	2,102,508 vehicles (1.25 occupancy)	299,931	1766	71	794

3 Improving Ground Operations: Four Solutions

With aircraft being the major emissions contributor, to reply to the third research questions, i.e. which can be the mitigation measures, a strategy to reduce environmental impacts at LTO operations has been identified. This considers four different taxiing solutions, taking as a case study an Italian airport, operating at a larger scale than the one previously considered (in this case 70,000 movements/year and around 9 million passengers, in the pre-pandemic period).

The four mitigation measures are:

- Single-engine taxiing (ST), i.e. using half of the aircraft engines for ground operations, with the reduction in emissions equating to the number of pollutants that the turned-off engines would have produced during operations;
- Dispatch towing (DT), i.e. aircraft being towed on taxiways from parking to runway without engine power. The auxiliary power unit (APU) provides power. In this case emissions from APU and towing vehicle must be considered, according to three traction options: diesel (DT diesel), petrol (DT petrol) fueling or electrification (DT electric)
- Taxing with onboard systems (TOS), with onboard systems using electrification of landing gears for parallel traction, ensuring autonomous aircraft movement with main engines off, except for heating/cooling periods, and operating APU at maximum power [15];
- Reducing taxiing time (RTT), within a business-as-usual scenario, but via the optimization of ground handling procedures and modifying aprons and taxiways layouts. This can be operated by reducing taxiing by 1, 2, and 3 min (giving rise to RTT1, RTT2, RTT3, respectively)

For each, fuel consumptions and emissions have been calculated with the same ICAO methodology as in the previous case (fully detailed in [16]), and presented in Table 2.

In terms of LTO cycles all taxiing solutions give rise to a marked emission decrease. However, specific taxi in and out phases provide additional considerations. More specifically, during the taxi-in phase, various strategies lead to significant reductions in pollutant emissions. Implementing Surface Electric Taxiing (ST) results in a 10.1% decrease, while improved surface traffic management yields reductions of 16.0%, 31.9%, and 47.9% for RTT1, RTT2, and RTT3, respectively. These strategies affect all pollutants similarly due to reduced aircraft engine taxiing time. However, dispatch towing with internal combustion vehicles, whether diesel or petrol-powered, increases pollutant concentrations due to emissions from the towing vehicle and APU. Diesel towing raises NO_X by 109% and PM by 240%, while petrol towing increases CO by 344%. Electric towing vehicles are a more favorable option, with only a 25% increase in HC emissions. Onboard systems, operating in TOS mode result in pollutant reductions, except for an 18.3% increase in NO_X, with a minimal 1.2% rise in fuel consumption. During the taxi-out phase, which has a longer operating time than taxi-in, the containment of emissions is more effective when the aircraft's main engines remain off, significantly reducing fuel consumption. ST conditions result in a notable 30.2% emission reduction, while improved ground operations reduce emissions by 7.9%, 15.8%, and 23.8% for RTT1, RTT2, and RTT3, respectively. Onboard systems reduce fuel consumption by 39.0%, along with a 57.6% decrease in HC and a 60.4% drop in PM. Electric-powered towing systems generate good fuel savings at 41.3% but are less advantageous due to increased taxiing time. Towing with internal combustion vehicles, whether diesel or petrol, during taxi-out generates emissions exceeding mitigation objectives, with diesel towing causing a 199.8% PM increase and a 73.4% NO_X increase, and petrol towing leading to a 308.6% CO increase.

Table 2. Emission scenarios per LTO cycle.

Taxiing solution at LTO phase	Pollutants (ton)						Fuel consumption (ton)
	HC	CO	NO_x	SO_x	PM	CO_2	
BAU	19	193.1	267.0	21.4	2.6	67,668	21,448
ST	15	151.3	259.0	19.6	2.4	61,489	19,603
RTT1	17.2	174.3	263.4	20.6	2.5	65,047	20,617
RTT2	15.4	155.4	259.8	19.8	2.4	62,427	19,787
RTT3	13.6	136.6	256.2	19.0	2.3	59,806	18,956
DT diesel	23.9	166.6	295.8	19.2	4.1	62,499	19,161
DT petrol	30.0	762	269.0	19.8	2.3	62,470	19,161
DT electric	19.9	153.2	258.8	18.6	2.2	60,453	19,161
TOS	11.4	117.6	264.1	19.4	2.2	61,313	19,434

4 Analyzing Costs

Strategic choices must consider costs, including purchase and fuel consumption. This allows quantifying economic savings compared to the baseline scenario, guiding planners toward technically sound and profitable strategies. To this end, the total fuel cost T_c for each strategy have been calculating according to:

$$Tc = F_c \, \text{x} Unit\, fuel\, price \tag{1}$$

with F_c being the fuel consumption of each solution considered and the Unit fuel price assumed from grey literature [17, 18]. Results are showed in Table 3 and evidence that the most significant cost reductions occur when surface handling operations within the airport are properly optimized during entry and exit. Both electric vehicle towing and onboard systems offer similar savings. In contrast, the petrol option results in higher overall costs than the BAU case.

Table 3. Yearly fuel costs

Taxiing solution	Kerosene (Euro)	Diesel/Petrol (Euro)	Total	Difference with BAU
BAU	11,825,396	0	11,825,396	
ST	10,808,411	0	10,808,411	− 1,016,985
RTT1	11,367,408	0	11,367,408	− 457,988
RTT2	10,909,420	0	10,909,420	− 915,976
RTT3	10,451,432	0	10,451,432	− 1,373,963
DT diesel	10,564,583	1,236,851	11,801,434	− 23,961
DT petrol	10,564,583	1,460,274	12,024,857	199,461
DT electric	10,564,583	0	10,564,583	− 1,260,813
TOS	10,714,738	0	10,714,738	− 1,110,658

5 Concluding Remarks

The four alternative ground handling measures provides environmentally friendly solutions for airports and their surroundings, thus helping decision makers to address the problem of airports polluted environments in the right way. The four taxiing modes (single-engine taxiing, dispatch towing, onboard systems, and reduced taxiing time) if compared to current operations can mitigate HC, CO, CO_2, NO_X, SO_X, and PM pollution. However, it's crucial that the success of these strategies depends on airline carriers' acceptance, operational policies, regulatory frameworks, and collaboration among stakeholders, emphasizing the need for long-term structural solutions aligned with transport policies and sustainability goals.

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Transport Infrastructure Ireland Roads Emissions Model (REM) and Carbon Tool

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Abstract. Transport Infrastructure Ireland (TII) provide and maintain transport infrastructure and services in the Republic of Ireland. TII is committed to the sustainable delivery and operation of its transport networks and supporting Ireland's ambitious emissions reduction targets, with a goal to reduce greenhouse gas emissions by 51% by 2030.

It is within this context that TII has developed the TII Roads Emissions Model (REM) and complementary TII Carbon Tool to quantify and visualise the greenhouse gas emissions (carbon dioxide (CO_2) and CO_2-equivalent (CO_2e)) of vehicles on the National Road Network (NRN) both in the existing situation and future years. The Carbon Tool quantifies carbon impacts of road and light rail projects over the full lifecycle from high level early design to construction, use, maintenance, and end of life.

The Carbon Tool assists TII and its contractors in complying with the greenhouse gas (GHG) reporting requirements as per the revised Environmental Impact Assessment (EIA) Directive 2014/52/EU and allows for the identification of emissions hotspots to understand where carbon savings can be made.

Keywords: Carbon · air quality · emissions · transport

1 Introduction

Transport Infrastructure Ireland (TII) provide and maintain transport infrastructure and services in the Republic of Ireland. This includes the development and operation of the strategic National Roads Network (NRN), light rail infrastructure and greenways. TII is committed to the sustainable delivery and operation of its transport networks. Like other European countries Ireland has ambitious emissions reduction targets, with a goal to reduce greenhouse gas emissions by 51% by 2030 compared to1990 levels.

It is within this context that TII has developed the TII Roads Emissions Model (REM) and complementary TII Carbon Tool to quantify and visualise the greenhouse

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gas emissions (CO_2 and CO_2e) of vehicles on the NRN both in the existing situation and future years, and to quantify carbon impacts of road and light rail projects over the full lifecycle from high level early design to construction, use and maintenance, and end of life.

The TII REM Tool has been designed to work with the TII National Transport Model (NTpM) providing TII with integrated economic, safety and emissions outcomes to facilitate informed decision making. The TII REM is a modular tool developed using R programming language consisting of four main elements: traffic data, a fleet mix database, an emission rate database and an ambient air quality model.

The TII Carbon Tool assists TII and its contractors in complying with the greenhouse gas (GHG) reporting requirements as per the revised Environmental Impact Assessment (EIA) Directive 2014/52/EU and allows for the identification of emissions hotspots to understand where carbon savings can be made. The tool allows users to model carbon impacts of different design options for varying levels of design information to provide an understanding of relative carbon impacts to influence decision making and reduce carbon emissions of new infrastructure developments.

2 Methods

The development of the REM and Carbon tools involved a literature review and liaison with stakeholders to develop tool requirements and identify potential data sources. After this calculation algorithms were developed, with coding carried out using the R programming language and R Shiny. Model validation has also been undertaken.

3 Results and Discussion

3.1 REM Benefits and Uses

The TII REM differs from contemporary national scale approaches to emission calculations. These typically estimate total national emissions for the existing situation without showing on a local scale where emissions are generated; e.g. based on a simplified fleet and / or average speed across whole journeys. Furthermore, national emissions estimates are also often undertaken separately for GHGs and non-GHG harmful to human health and designated ecosystems, including oxides of nitrogen (NO_X) and particulate matter ($PM_{2.5}$ and PM_{10}).

3.2 REM Tool Description

The REM includes an Emissions Rate Database and a Fleet Mix Database which are used with traffic data to generate vehicle emissions for individual roads (or sections of roads known as links), individual counties, or for total national emissions. The tool does this by multiplying together the classified vehicles in the Fleet Mix Database with the speed-based emission rates in the Emissions Rate Database and traffic flows. Traffic flows are inputted by the tool user through the Traffic Data File, whilst the Fleet Mix Database and Emissions Rate Database are embedded within the tool.

The last module is the air quality algorithm which takes the link-based emissions to calculate pollutant concentrations. This module incorporates calculations of background pollutant contributions and the conversion of NOx to nitrogen dioxide (NO_2).

The TII REM has clear advantages over current alternative tools, such as Transport users benefit appraisal (TUBA) as it is a link-based model rather than an average speed journey model, and it enables differentiation of discrete geographic areas, road types, vehicle classifications, etc, to match the resolution of traffic models.

This link-based emission calculation approach avoids the smoothing out of emissions that can occur in TUBA. Also, as the TII REM uses detailed fleet predictions for age, fuel technology, engine size and weight it also enables the user to gain additional insights to inform possible interventions for different scenarios.

3.3 REM Emissions Rates Database

The TII REM utilises available information to create a bespoke Emission Rate Database which defines a speed-based emission rate for multiple pollutants for each vehicle classification.

The REM is designed to replicate the emissions output by The Department for Environment, Food and Rural Affairs (DEFRA) Emissions Factors Toolkit (EFT), which utilises emissions profiles for NO_X and PM_{10} published in COPERT5 by the European Environment Agency (EEA) [1] along with additional scaling for use in the UK. CO_2 is calculated with reference to emissions rates published by TRL on behalf of the UK Department for Transport (DfT) [2].

The REM utilises scenario settings, such as year and region, that refer to fleet composition and age profiles, with further detail incorporated on an individual link basis. This means that each link in a model can be run within a larger model network to determine the total or individual link emission rates.

To create the Emissions Rate Database, emissions were calculated for each pollutant at 5 kph speeds (up to 140 kph for light vehicles and 90 kph for heavy vehicles) and per each vehicle classification, fuel type, engine size, vehicle weight and Euro class.

3.4 REM Fleet Mix Database

The fleet mix is a core aspect of the tool, as this determines what the proportions of the different vehicle classifications (e.g. Euro classification) are to be applied from the classified database to the number of vehicles being modelled.

The proportions of the different vehicle classifications are also expected to change over time. This is because it is expected the fleet will move towards increased adoption of newer and relatively lower emission vehicles in the future, including greater uptake of hybrid (HEV), battery-electric (BEV) and alternative fuelled vehicles.

The fleet mix considers Euro classifications from pre-Euro to Euro 6c for light duty vehicles (LDVs), such as cars and Light Goods Vehicles (LGVs), and up to Euro VI for Heavy Duty Vehicles (HDVs) such as Heavy Goods Vehicles (HGVs) and buses.

Data from the Central Statistics Office (CSO) [3] data for vehicle registrations for each county for cars and nationally for freight has been used to define the existing fleet mix. A county is assigned to each road link to determine the fleet breakdown.

Future predictions of vehicle emissions are provided by a vehicle stock model (predicting future composition of vehicle fleet).

The fleet projection figures which underpin the vehicle fleet projections used in REM are derived from CSO registered vehicles [4] and the car stock model developed by University College Cork (UCC) [5] derived from predecessor research [6–8]. UK Dept. For Transport (DfT) data [9] has been used to infill data gaps in the fleet model, where necessary.

The projected stock models for non-goods vehicles (i.e. cars) are extrapolated from the UCC stock model for several core scenarios. For goods vehicles (i.e. LGVs and HGVs) there are no stock model projections and so a bespoke projection was created using CSO data for the registered goods vehicle fleet.

3.5 REM Traffic Data File and Other User Inputs

The NTpM is a core module that focuses on highway demand. Users input traffic data using a data input template file provided with the tool. The user also selects in the tool whether just emissions are required or if pollutant concentrations are required, for which pollutants and the year calculations are required.

3.6 REM Air Quality Module

The air quality tool predicts the atmospheric pollutant concentration resultant from the road-source emission rate as a product of dispersion, which increases with distance, calculating an ambient pollutant concentration. The ambient pollutant concentration is reported as a mass per volume of air as $\mu g/m^3$. Rates of nitrogen and acid deposition are modelled as kg/yr to consider effects on designation ecological sites.

The dispersion algorithm is derived from of the Design Manual for Roads and Bridges (DMRB) screening tool [10]. The results from this algorithm are combined with background contributions to determine the overall concentration.

3.7 TII Carbon Tool Drivers and Audience

The need for climate change impacts to be assessed as part of EIAs, was a key driver behind TII wanting to develop a bespoke mechanism for calculating and assessing carbon emissions associated with their projects in an efficient, simple, and accurate way. Recognising the potential limitations of existing 'off the shelf' tools for carbon calculation that were either too generic to inform decisions or too specific to one sector or geography, a custom tool was developed for TII and its contractors that could be applied to road, light rail and greenway projects in Ireland. This tool would also help TII to achieve its strategic goal to *"facilitate further the integration of environmental issues into transport infrastructure planning, construction and operation"*.

The TII Carbon Tool was designed to be used primarily by climate practitioners as well as project designers, engineers and lead contractors as part of the early design and planning process for road, light rail and greenway projects.

3.8 TII Carbon Tool Development

Technical knowledge and experience undertaking carbon assessments, infrastructure projects, and in-depth understanding of challenges of delivering EIA and infrastructure projects in Ireland were used to critique available tools and develop an effective solution. Through collaboration with local transport engineers the tool was developed to be as relevant and specific to Ireland as possible. Shortfalls of existing tools for example included insufficient consideration of the effect of carbon loss from peat removal.

An added challenge was to design a tool with built-in longevity to reflect the current and future availability of environmental information about construction products and materials in Ireland. To accommodate this, flexibility was built-in to the tool to enable it to adapt to different project types while having the capacity to evolve as new data becomes available in the future.

3.9 TII Carbon Tool Description and Scope

The TII Carbon Tool has several key functions as described below:

1. To calculate the carbon footprint associated with road, light rail and greenway projects in Ireland.
2. To allow the user to assess the main sources of carbon emissions throughout the lifecycle of a project to identify emissions hotspots and carbon savings.
3. To model carbon impacts of different design options (up to 8 options) for varying levels of design information and enable understanding of relative carbon impacts to influence decision making to reduce carbon emissions.

The tool is useable at TII's different project phases from initial outline design and option selection through to detailed design and final implementation and allows users to assess major new projects like Dublin's rapid expansion of the light rail systems, as well as relatively minor infrastructure upgrades in a consistent way.

The tool's reporting aligns with the Publicly Available Standard (PAS) 2080: 2023 (Carbon Management in Buildings and Infrastructure) which provides good practice for lifecycle carbon quantification in infrastructure projects.

To produce carbon emissions outputs, the tool uses a series of calculations based on material quantities, greenhouse gas emission factors and assumptions. Extensive carbon and infrastructure experience informed the design of the tool to capture the likely activities, products and materials involved over the life of an infrastructure project (with aspects such as travel distances and construction practices tailored to Ireland) but it is also designed so that new emerging carbon emission factor data (from Environmental Product Declarations (EPDs) can be added.

The tool also captures where opportunities exist for carbon mitigation, which in later project phases can be quantified as carbon savings.

Finally, the tool provides a range of output types and outputs that can be readily exported to excel, with the default outputs consistent with EIA requirements.

4 Conclusions

It is understood that there has been a keen uptake of the TII REM and Carbon Tool across Ireland with over 180 users.

Feedback has indicated that the Carbon Tool has been successfully used to quantifying the carbon associated with EIA Reports including Ireland's high-capacity, high-frequency, metro rail line 'MetroLink'. Furthermore, the TII Carbon Tool has been used for bespoke studies including a carbon benchmarking assessment undertaken on as-built data from the N22 Baile Bhuirne to Macroom Road Development to develop a series of carbon benchmarks for TII road projects.

The REM was used to inform the National Roads Network Indicators 2022, including the Annual Road Travel Emissions of CO_2, NO_X and PM_{10} from 2018 to 2022, and disaggregated by vehicle class.

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Road Transport Emission Parameterization for Microscale Applications Based on Macroscale Measurable Traffic Information

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Abstract. The road transport sector significantly contributes to urban air pollution globally. City-scale inventories, relying on regional (macroscale) traffic emission models, attempt to grasp the spatial and temporal road transport emissions distribution. However, understanding high pollution levels in specific urban microenvironments requires more detailed information. Efforts have been made to integrate traffic details into emissions models at the microscale with a focus on high-resolution air quality solutions for polluted urban areas. The increased data demands and longer processing times of microscale tools, makes it crucial to reconcile this detail with a comprehensive city-scale view for effective policy actions. This study provides insights to understand how relevant microscale variables vary when they are aggregated over time. Objectives include testing the integration of microscale features into macroscale emission assessments and evaluating how microscale data align with coarser scales for inclusion in a parameterization. Utilizing one Hz microscale data for speed, road grade, and estimated Vehicle Specific Power for light-duty gasoline vehicles, the study evaluates macroscale approaches' capability to capture microscale high values. Results indicate a decay in accuracy for all factors with increasing time aggregation. While speed preserves the highest accuracy, falling below 90% only after 1200 s (20 min) or more of aggregation, accuracies of over 80% are achieved for all factors with a notable inflection point at 300 s (5 min) average. This study emphasizes the importance of balancing accuracy and computational efficiency when parameterizing microscale applications based on macroscale information.

Keywords: air pollution · modelling · road-transport · emissions · multi-scale

1 Introduction

The road transport sector continues to be one of the main contributors to air pollution in many cities around the world. In Europe in 2020, the main contributor to NO_X (nitrogen oxides) was road transport, accounting for 37% of these emissions [1]. To understand the spatial and temporal distribution of the emissions, city-scale inventories are compiled from the most detailed information available. They typically rely on regional

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(macroscale) traffic emission models. This level of detail is not enough to understand the high pollution levels that occur on specific urban microenvironments [2], which are often related to very local characteristics. Important efforts have been made towards the integration of detailed traffic and emissions with high-resolution air quality models to understand pollution hotspots [3] and their implications on exposure [4]. These microscale tools require a significant amount of data and longer processing times due to the high detail of inputs and the model outcomes. However, it is crucial to reconcile this level of detail with a comprehensive city-scale view to undertake suitable policy actions.

To understand the spatial and temporal distribution of the emissions at city level, typically, regional (macroscale) traffic emission models are used. Available traffic activity data usually include traffic volumes (number of vehicles per hour from gauging stations), traffic fluxes (through traffic cameras or origin-destination matrices), and vehicle fleet composition (trough country specific databases or fleet composition studies); which are used in macroscale traffic models to resolve vehicle movements and composition over a city for predefined road segments (link level). How to robustly use this information for microscale analysis is unsolved [5].

At local level, microscale tools and/or measurements provide the needed information to resolve highly detailed road traffic emissions processes. One of the challenges involved in microscale modelling is to capture fast changes in vehicle emissions that can lead to emission peaks. These fast changes in vehicle emissions occur very locally and in short periods of time (seconds) depending on the vehicle activity [6, 7].

Second-by-second (1Hz) speed, acceleration and road grade have been identified as key factors to define microscale traffic activity and emissions [8]. From these key factors, speed and road grade can be directly measured whereas acceleration can be estimated from the instantaneous speed data. Vehicle specific power (VSP) is an estimate of the power demand on the engine during driving based on the instantaneous speed, road grade and acceleration. Consequently, VSP is often the central concept in road transport emission models [9].

The main goal of our study is to understand how to increase the resolution of emission estimates based on macroscale measurable traffic activity information. We explore experimental 1Hz microscale data to reveal a trade-off between computational efficiency and accuracy in microscale parameterization and identify potential options to overcome the limitations of city-scale inventories. This study provides insights to understand how relevant variables such as VSP or average speed (often used to estimate emissions) vary when they are aggregated over time (/space). That may inform methods to derive microscale emissions starting from mesoscale input data, i.e. through parameterizations. This would allow to improve current modelling systems and thus provide better support for urban air quality managers. The specific aims of this study are to perform a test of concept to understand whether microscale features can be integrated on macroscale emission computation assessment; and to evaluate how microscale data relate to higher scales to estimate microscale features from macroscale inputs that could be included into a parameterization.

2 Methods

To evaluate the potential to perform microscale estimates from mesoscale information, the step by step flowchart is presented in Fig. 1 and further explained below.

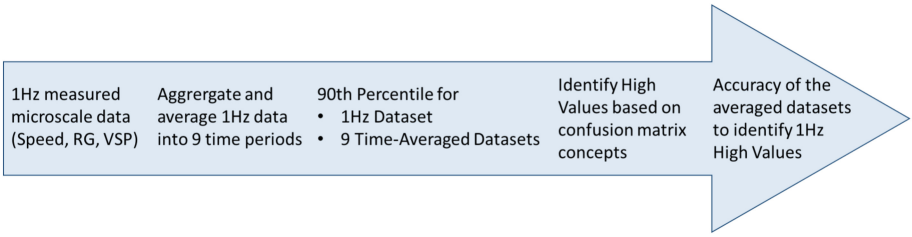


Fig. 1. Flowchart of key steps involved in evaluating the potential of macroscale information for microscale analysis, including data acquisition, aggregation, identification of high values (HV), and assessment of accuracy using confusion matrix concepts.

1 Hz measurements include speed and road grade (RG) and estimated VSP for a sample of 10 light duty gasoline vehicles measured in previous studies over the same set of routes of 170 km in length [10].

One Hz microscale measured data of speed and road grade for the sample of 10 light duty gasoline vehicles were aggregated and averaged in 9 time periods. The original 1 Hz measured data of speed, road grade and VSP were averaged for the time periods of 10, 30, 60, 300, 600, 900, 1200, 1800 and 3600 consecutive seconds to consider different time aggregations of macroscale approaches that can minimize maximum values occurrences.

To identify the capabilities of macroscale approaches to capture microscale high values (HV) of speed, road grade and VSP, the 90th percentile values were estimated for the 1 Hz data and for each of the 9 the time averaged datasets. This is the top ten percent of the highest values in the dataset are considered HV.

To evaluate the capability of the averaged datasets to predict HV, confusion matrix concepts were used [9]. Second-by-second measured data of speed, RD and VSP were classified into true positives (TP), true negatives (TN), false positives (FP) and false negatives (FN). TP are instantaneous values that the time averaged datasets identified as HV and are HV in the 1 Hz dataset too. TN are instantaneous values that the time averaged datasets identified as non-HV and are 1 Hz non-HV. FP are instantaneous values that the time averaged datasets identified as HV but are 1 Hz non-HV. FN are instantaneous values that the time averaged datasets identified as non-HV but actually are 1 Hz HV.

The accuracy concept from confusion matrix [11] was used to assess how well time averaged datasets identify HV. Accuracy is defined as the ratio of time averaged values correctly classified as HV and non-HV to the total number of values in the 1-Hz dataset as shown in Eq. 1.

$$\text{Accuracy}\ (\%) = \left(\frac{\text{TP} + \text{TN}}{\text{TP} + \text{FN} + \text{TN} + \text{FP}}\right) \times 100 \tag{1}$$

3 Results

The outcomes of this study are the identification of time aggregated macroscale speed, road grade and VSP information and the evaluation of their capability to capture HV.

Figure 2 shows that there is a strong decay in the accuracy to detect HV when increasing the time aggregation for the three analyzed factors. Speed is the factor that preserves the highest accuracy values for the 9 averaged datasets falling below 90% of accuracy when averaging for 1200 s or more (60 s for road grade and 30 s for VSP). This points out the importance of 1 Hz information to predict HV.

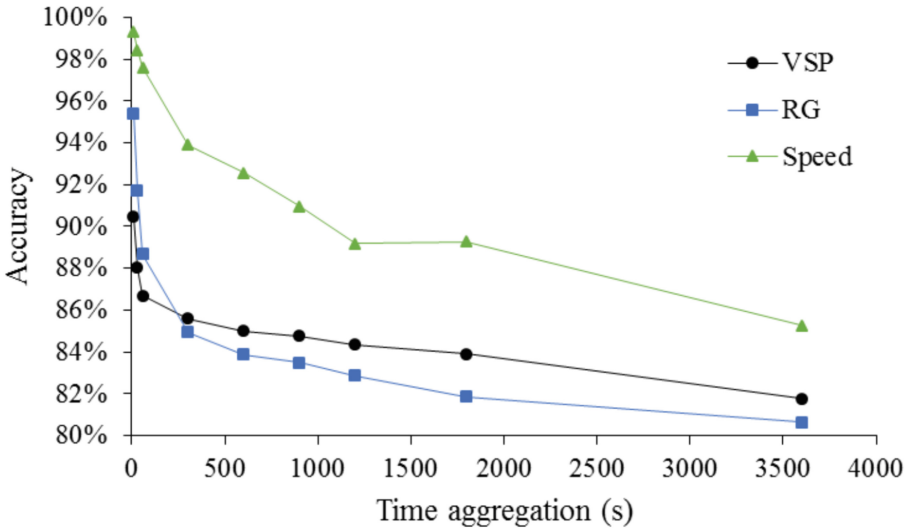


Fig. 2. Speed, road grade (RG) and VSP accuracy to identify high values (HV) for the 9 time averaged datasets.

Nevertheless, accuracies of over 80% are reached for the three factors over all the averaging periods with an inflexion point at 300 s average (5 min). After this point the lost in accuracy is stabilized, especially when using VSP and road grade. Speed is the factor that keeps the highest values of accuracy over all averaging periods showing the lowest accuracy at 3600 s (1 h) with 85% accuracy in comparison to 82% and 81% for VSP and RG respectively. Thus, macroscale data that consider 300 s average or more up to 3600 will have smaller changes in accuracy from 4% to 9% to predict HV. Lower averaging periods than 300 s will result in a significant increase of accuracy of 5% up to 10% depending on the factor. Parameterizations for microscale applications based on macroscale information should consider time aggregated data accuracy lost over increasing time averaged periods to provide more accurate results.

4 Discussion

The findings suggest that aggregation periods of 300 s or more (up to 3600) exhibit smaller changes in accuracy (4% to 9%) in predicting HV. Conversely, lower averaging periods than 300 s yield a significant increase in accuracy (5% to 10%), depending on the variable. For microscale applications using macroscale information, it is crucial to consider the accuracy loss over increasing time-averaged periods for more precise results. The study reveals that accuracies up to 80% can be achieved, even with 1-h averaged data. However, an important boost in accuracy (5% to 10%) is observed when aggregating data for less than 5 min.

Implications of this study include the trade-off between computational efficiency and accuracy in choosing the appropriate time aggregation period for parameterizing microscale applications. Future research could explore refining these time aggregation parameters, potentially incorporating real-time data streams and advanced machine learning techniques for enhanced accuracy in predicting microscale high values. Additionally, investigating the applicability of these findings to different urban settings and diverse vehicle fleets could broaden further research lines.

5 Conclusions

This work aims at refining the understanding of the integration between macroscale and microscale information, and ultimately allowing comprehensive and accurate assessments of road traffic emissions in urban environments.

In conclusion, this study offers valuable insights into the multi-scale analysis of road traffic emissions. The identification of time-aggregated macroscale speed, road grade, and Vehicle Specific Power (VSP) information, along with an evaluation of their capability to capture HV, enhances our understanding of emissions dynamics at different scales. One Hz data are needed for precisely identifying microscale HV. Remarkably, the study reveals that accuracies up to 80% can be achieved, even with 1-h averaged data. Notably, there is a noteworthy increase in accuracy (5% to 10%) when employing averaged data for less than 5 min. This highlights a potential trade-off between computational efficiency and accuracy in selecting the appropriate input data resolution to successfully apply microscale parameterizations.

To further advance research in this field, similar analyses may be done with measurements in different routes or driving patterns that may be representative of a wider range of urban areas. Additionally, validating the findings with different types of vehicle fleets, including variations in size and fuel type assess the generalizability of the proposed approach.

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On-Board Monitoring of Exhaust Emissions for Euro 7: Effect of System's Tolerances on Monitoring Performance

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Abstract. Direct and continuous On-Board Monitoring (OBM) is a key part of future Euro 7 emission standards. An OBM system can track emission-related data for each vehicle using on-board physical sensors and - if necessary- calculation models. This study focuses on the inherently highest uncertainty of OBM systems compared to Portable Emission Measurement Systems (PEMS) or laboratory emission measurements. The uncertainty of the system is expressed as OBM tolerance, and it should be considered in the relevant under-development Euro 7 implementing legislation. For the currently available monitoring technologies and representative Euro 6 RDE trips (CLOVE database), OBM tolerance is 28% (average) and up to 75% (maximum) of the selected Euro 7 NOx emissions limits for 1 trip. Sensors' element accuracy is the greatest contributor to the final NOx uncertainty. Lower tolerances could be achieved either by the usage of improved sensors and correction algorithms or by selecting a slightly lower confidence level.

Keywords: Euro 7 · OBM · Uncertainty · NOx · NH_3 · PM

1 Introduction

Tailpipe vehicle emissions' On-Board Monitoring (OBM) is a significant part of ongoing investigation and discussions on Euro 7 implementing regulations [1]. Via physical (sensors) and virtual (models) means, an OBM system monitors emissions performance, ensures compliance and induces necessary repairs. Validation of the OBM system will be conducted during the In-Service Conformity (ISC) procedure by comparing its emissions results with those from ISC's more sophisticated and accurate systems. The average difference (Δ) and the spread (σ) of the two measurements should be below a threshold that expresses the inherently highest uncertainty of OBM systems. The latter is the subject investigated in this study focusing on Nitrogen Oxides (NOx) emissions.

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2 Methodology for Uncertainty Estimation

A standardized methodology for uncertainty calculation of OBM systems is currently not available. Therefore, methods used for Portable Emission Measurement Systems (PEMS) uncertainty calculation [2], and International [3] and European [4] guidance were utilized. 4 steps are identified for the methodology followed (Fig. 1):



Fig. 1. General methodology of expressing uncertainty in measurement

2.1 Identification of Uncertainty Sources

As seen in Eq. 1, instantaneous emission concentration ($c_{p,i}$ [ppm]), exhaust mass flow (q_i [kg/s]) and covered distance (d_i [km]) should be tracked to estimate gaseous and particulate emissions for a vehicle trip.

$$MassEmissions_p = \frac{\sum u_p \times c_{p,i} \times q_i \times 1000}{\sum d_i} \left[\frac{mg}{km}\right] \quad (1)$$

Note: u_p is the ratio of the density of pollutant p and the overall density of the exhaust gas. u_p is constant and thus, not a source of uncertainty. The uncertainty sources for NOx emissions monitoring are summarized in Tables 1 and 2.

Raw uncertainty values were extracted based on Type B evaluation [4]. This means that the uncertainty of a measured variable is expressed as an approximation to the corresponding multiple of standard deviations (K_j) from the real value assuming a probability distribution based on all the available information including manufacturer's specifications, data provided in calibration or other reports and handbooks, previous measurement data, etc. Element accuracy expresses the aged amperometric sensor accuracy tolerances from the average mass-production. When physical sensors cannot measure (typically 60 s after key-on), emissions models' measurement could be deployed. The expected emissions models' uncertainty is greater than the sensors' uncertainty. Also, the amperometric sensor is sensitive both to NOx and Ammonia (NH_3) emissions. NOx and NH_3 separation is possible but not always effective. The other real-world effects express the reference system (i.e. PEMS for current analysis) measurement uncertainty and the uncertainty introduced due to sensor dependencies to exhaust gas conditions (e.g. temperature and pressure). Exhaust gas flow uncertainty is introduced based on Mass Air Flow (MAF) sensor performance specifications including aging effect while travelled distance uncertainty is estimated based on PEMS GPS specifications. Finally, uncertainty due to time misalignment between NOx concentration and exhaust flow signal is also considered.

Table 1. Sources of OBM system NOx uncertainty

Source	Raw uncertainty values (rj)	Type, distribution, and corresponding standard deviations (K_j)
Sensor element accuracy	7 ppm <100 ppm, 10% ≥ 100 ppm	Systematic-varied, normal distribution (4σ)
Emission models (for first 60s)	2 × element accuracy	
NOx/NH_3 separation algorithm	8 mg/km	Random variation, uniform distribution (3σ)
Other real-world effects	13 mg/km	Systematic-varied, normal distribution (3σ)
MAF sensor accuracy	3.5%	Random variation, uniform distribution (3σ)
GPS/speedometer/smart tachograph accuracy	4%	Random variation, uniform distribution (2σ)
Time alignment	3%	

Table 2. OBM NOx standard relative uncertainties estimation

Source	Standard relative uncertainty (εj [%])
Sensor element accuracy	$\boldsymbol{\varepsilon_{c_{NOx},1}} = \frac{u_{NOx} \times NOx_{tol,abs,1} \times 1000 \times EFD_1 \times \frac{d_1}{d_1+d_2}}{L} + \frac{NOx_{tol,rel,1} \times m_{NOx,1}}{m_{NOx,1}+m_{NOx,2}}$
Emission models (for first 60s)	$\boldsymbol{\varepsilon_{c_{NOx},1}} = \frac{u_{NOx} \times NOx_{tol,abs,2} \times 1000 \times EFD_2 \times \frac{d_2}{d_1+d_2}}{L} + \frac{NOx_{tol,rel,2} \times m_{NOx,2}}{m_{NOx,1}+m_{NOx,2}}$
NOx/NH_3 separation algorithm	$\boldsymbol{\varepsilon_{sep}} = \frac{\text{usep}}{L}$
Other real-world effects	$\boldsymbol{\varepsilon_{rw}} = \frac{\text{urw}}{L}$
MAF sensor accuracy	$\boldsymbol{\varepsilon_{q,acc}} = u_{q,acc}$
GPS/speedometer/smart tachograph accuracy	$\boldsymbol{\varepsilon_{d}} = u_d$
Time alignment	$\boldsymbol{\varepsilon_{t}} = u_t$

2.2 Conversion of Statistical/Measured Data to Standard Uncertainty

Raw uncertainties (r_j) are converted to standard uncertainties (u_j) (i.e. values corresponding to 1 standard deviation) as follows:

$$u_j = \frac{r_j}{K_j} \tag{2}$$

2.3 Calculation of Combined Uncertainty

To enable the combination of uncertainties, the standard uncertainties are transformed into relative uncertainties ($\boldsymbol{\varepsilon_j}$ **[%]**) of distance-based pollutant emissions.

where.

- **1 index**: Refers to the period (i.e. after the first 60 s) with the amperometric sensor measuring
- **2 index**: Refers to the period (i.e. first 60 s) with only models measuring
- $\mathbf{NOx_{tol,abs,j}}$ [ppm]: $u_{c,\,NOc}$ when NOx concentration <100 ppm in period *j*
- $\mathbf{NOx_{tol,rel,j}}$ [%]: $u_{c,\,NOx}$ when NOx concentration ≥100 ppm in period *j*
- **L** [mg/km]: Level of distance-based NOx emissions based on reference equipment (e.g. PEMS)
- $\mathbf{EFD_j} = \frac{\sum q_i}{\sum d_i}$ [kg/km]: Exhaust gas flow over distance rate in period *j*
- $\mathbf{m_{NOx,j}} = \sum u_{NOx} \times c_{Nox,i} \times q_i \times 1000$ [mg]: NOx mass emissions produced in period j

Since errors are random and uncorrelated to each other (e.g. the error of the mass flow is not correlated to that of the emission sensor), combined uncertainty ($\delta_{C,\,E_{NOx}}$) is estimated based on error propagation of the individual uncertainties as follows:

$$\delta_{C,E_{NOx}}[\frac{mg}{km}] = L \times \sqrt{\left(\left(\varepsilon_{c_{NOx,1}} + \varepsilon_{c_{NOx,2}}\right)^2 + (\varepsilon_{sep})^2 + (\varepsilon_{rw})^2 + (\varepsilon_{q_{acc}})^2 + (\varepsilon_d)^2 + (\varepsilon_t)^2\right)} \tag{3}$$

2.4 Calculation of Uncertainty Margins for Various Confidence Intervals

The combined uncertainty is multiplied by a coverage factor (k) providing a final uncertainty ($\delta_{F,\,E_{NOx}}$ or from now on δ) that is believed to include the true value with a certain confidence e.g. 95% (for k = 2) or 99.7% (for k = 3). Final uncertainty refers to one vehicle trip and follows normal distribution ~ N(0, δ) since it is a combination of individual uncertainties that mainly follow a normal distribution in which the average value converges to zero. Dividing δ by the NOx Eu7 limit (i.e. 60 mg/km), NOx OBM uncertainty over limit (δ/limit) can be estimated.

3 OBM NOx Uncertainty Over Real-World Conditions

For the evaluation of OBM NOx uncertainty over real-world conditions, the Consortium for ultra–LOw Vehicle Emissions (CLOVE) Euro 6 Light-Duty Vehicles (LDV) database was utilized [5]. Apart from basic estimations (based on original data), scenarios were also created to quantify the effect in the final uncertainty (δ) of each uncertainty component (Table 1) and the associated physical parameters. As shown in Sect. 2.3 these include:

- Exhaust gas flow over distance rate (EFD): Higher EFD results in higher uncertainty of NOx concentration measurement ($\varepsilon_{c_{NOx}}$) and therefore higher δ. EFD depends on both the test (higher in short-distance trips with high exhaust gas flow e.g. urban trips with traffic jams) and the vehicle [higher in vehicles with high engine displacement and power e.g. large diesel Sports Utility Vehicle (SUV)].
- Level of NOx distance-based emissions (L_{NOx}): Greater L_{NOx} results in greater δ due to the uncertainty sources expressed as a gain (% of emissions measured) instead of an offset.
- Share of NOx mass emissions measured from models [i.e. $m_{NOx,2}/(m_{NOx,1} + m_{NOx,2})$ or MR_{models}]: Since models are less accurate than sensors, δ increases proportionally to this share. The same goes in case the share of distance covered with sensors inactive increases but this parameter was not further analyzed in this study since no significant variability was encountered in real-world tests.

As seen in Fig. 2, for 9 out of 10 trips (original data), δ is below 50% of the NOx limit while average and max δ are 28% and 75% of the limit, respectively. Based on the scenarios results the effect of each physical quantity can be quantified as follows:

- For 1 kg/km increase of *EFD,* δ/limit increases 3% on average and up to 14% (abs)
- For 60 mg/km increase of L_{NOx}, δ/limit increases 9% on average and up to 26% (abs)
- For 40% (abs) increase of MR_{models}, δ/limit increases 0.3% on average and up to 6% (abs)

The variability of δ/limit can be mainly attributed to the variability of real L_{NOx} since it is greatly reduced when a predefined L_{NOx} is set (scenarios B1 and B2). Uncertainty is maximized in the case of combined maximation of all three parameters. In real-world trips, however, this is a rare case. For example, high cold-start emissions and MR_{models} are mainly possible in non-diesel applications. These applications though, lead to low exhaust mass flow and EFD.

The effect of each uncertainty source in the final uncertainty can be seen in Fig. 3. The most significant effect can be attributed to sensor element uncertainty (u_cNOx,1) and it is strongly dependent on EFD and L_{NOx}. For NOx concentrations below 100 ppm (100 ppm is far higher than the expected average for Euro7 vehicles), $u_{cNOx,1}$ is expressed as an offset in the real concentration. In a trip with high EFD (2 kg/km) and near-limit emissions (60 mg/km), 1 ppm offset increases final NOx emissions by ~ 3 mg/km. This is explained by NOx high molecular weight (and thus higher density and u_p). The real-world effect is the next greatest contributor while the rest uncertainties (as illustrated in Fig. 3) indicate a similar effect in the final uncertainty.

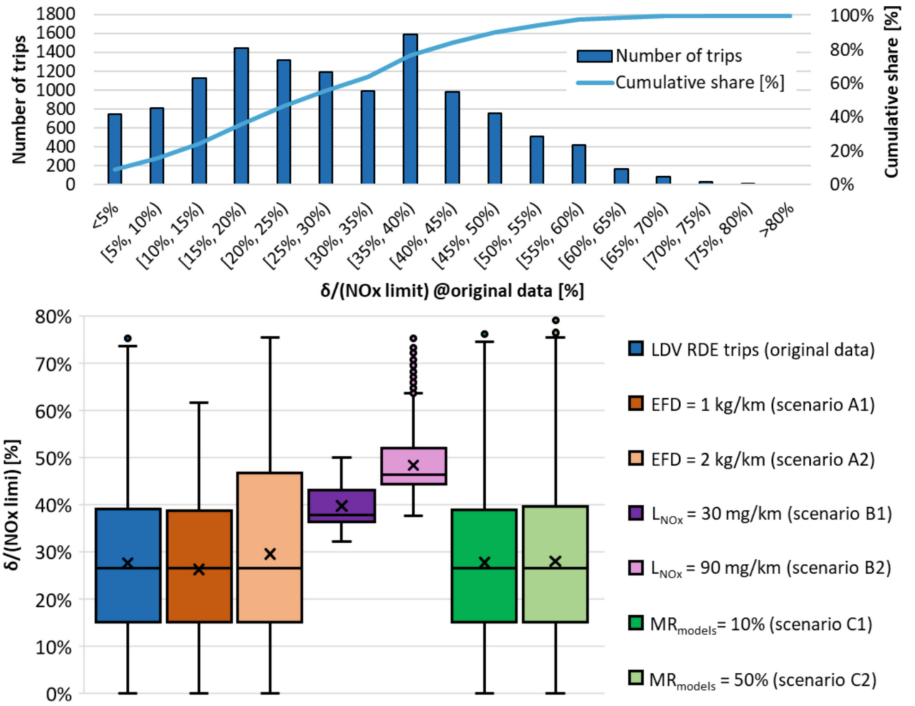


Fig. 2. NOx OBM uncertainty over RDE trips with normal driving conditions and effect of physical quantities. Notes: Results represent a confidence level of 99.99% (a lower level will result in lower uncertainty). Physical parameters values in scenarios A1, B1, C1 and A2, B2, C2 are selected based on original trips average and 95th percentile respectively

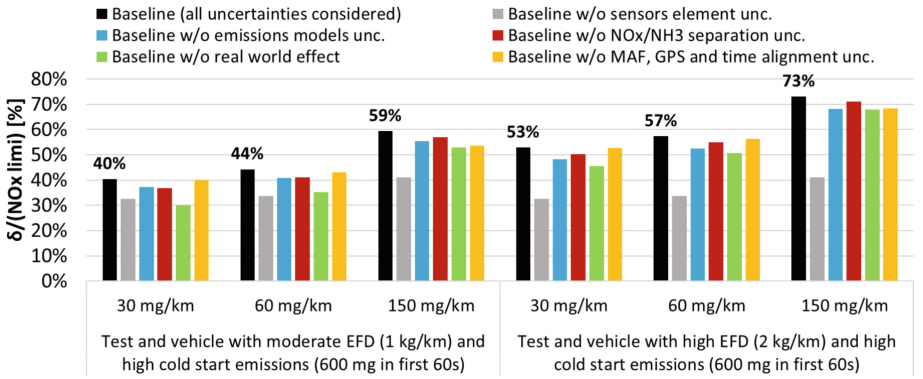


Fig. 3. Effect of each uncertainty source in the final uncertainty. Notes: Results represent a confidence level of 99.99% (a lower level will result in lower uncertainty). Since individual uncertainties are not simply added, it was by principle dictated to conduct such a type of analysis.

4 Conclusions

The calculation of the OBM uncertainty is considered an important element of the development process of Euro 7 regulation. For RDE trips with normal driving conditions, OBM NOx uncertainty can be up to 75% of the limit mainly in case of high exhaust gas flow over distance rate and high levels of NOx emissions (e.g. large diesel SUV in short trip with traffic jam). The sensor element accuracy has the greatest effect on the final NOx uncertainty but this may differ for other pollutants with lower density (e.g. NH_3). Even if the uncertainty seems high, it can be greatly improved by statistical means in case multiple trips (N) are considered in the ISC procedure. Similar δ values are also expected for NH_3 emissions (lower sensor element accuracy but also lower emissions limit), while higher uncertainty (on average ~ 100% over limit) is expected for PM/PN emissions where sophisticated OBD models are used. Nevertheless, as seen in recent research [5], more accurate sensors and emission models and thus better OBM uncertainty are expected after a few years of OBM implementation. For current systems though, other options to mitigate uncertainty could be also investigated [e.g. $NOx + NH_3$ (sum) emissions monitoring to eliminate NOx/NH_3 separation algorithm uncertainty].

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Assessing the Perceived Annoyance of High-Speed Trains with an Experience Sampling Method

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Abstract. Annoyance caused by high-speed trains (HST, >250 km/h) seems to be not completely modelled by current indicators (e.g., L_{DEN}). For example, the suddenness, spectral content, temporal fluctuations of pass-by noises, and the density of peaks seem to play a significant role that is not fully understood [1]. To better understand these effects, we report on the results of a pilot study aiming to test experimental protocol that allows for a detailed analysis of short-term annoyance due to high-speed trains. We used an experience-sampling method (ESM): volunteer participants living nearby French high-speed lines were instructed to report their annoyance level right after a train pass-by with a remote device. This method has the potential to combine ecological validity with a precise control of the sound experienced by participants. As this method has never been used for railway noise assessment, residents were recruited to take part in the study and received two protocols in two different periods, to determine which ESM parameters are the most efficient.

Keywords: High-speed trains · noise · annoyance · experience sampling method

1 Introduction

One drawback of railway transportation is noise pollution for communities living close to railway infrastructures. In France, the social cost of railway noise pollution has been estimated to be 11.2 billion euros per year [2]. After years of constant progress in decreasing noise levels around railway infrastructure (rolling stock design, noise barriers, dwelling insulation), further global level reductions are becoming increasingly costly. It is therefore utterly important for railway stakeholders to better understand which aspects of noise emissions impact people living near high-speed lines (HSL) the most, to focus noise abatement measures more precisely.

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Two main approaches are reported in the literature to assess annoyance caused by railway noise: in-situ social surveys and laboratory experiments. *In situ* social surveys ask residents living alongside railway tracks to rate annoyance experienced (retrospectively) at home over a long time period. In contrast, laboratory experiments are designed to focus on the characteristics of a small number of acoustic events, in a laboratory setting. Despite their differences in scope and methods, both social surveys and laboratory experiments have yielded the following results:

- Loudness indicators are often the main factor contributing to annoyance [1, 3–7]
- Annoyance if higher for high-speed (HST) than for conventional trains [1, 8–10];
- The number of passages also influences annoyance [7, 11–13]
- There is no clear consensus as to whether indicators based on averaged or maximal levels better model long-term annoyance [1, 14, 15];

Here, we focus on the short-term annoyance caused by HST and a method combining the advantage of in-situ and laboratory experiments: the experience sampling method (ESM). It involves the repeated measurements of human beings' daily-life experiences, perceptions, or behaviors in situ at different moments over a certain period of time [16]. To our knowledge, this method has mostly been used to assess aircraft noise annoyance [17–19] but not for railway noise. Through this diary study methodology, participants evaluate annoyance from pass-by noise in response to notifications. Responses are then associated with data on sound exposure.

The study reported here is part of a larger project aimed at better understanding the acoustic factors contributing to annoyance experienced by people living alongside an HSL. Overall, its goal was to compare different parameters of an ESM. Particularly, we sought to identify the best method to send notifications to participants so that they can assess the annoyance of specific train passages. More precisely, we wanted to select protocol settings that: generates enough data, allows to study the influence of the number of passages on perceived annoyance, allows to combine annoyance judgements with trains' acoustical characteristics, is acceptable for participants (not too burdensome, not too intrusive), is easy to use, and does not interfere with participants' daily life. Therefore, two protocols (A and B) with different parameters were compared in a pilot study.

2 Materials and Methods

2.1 Selection of Participants

This pilot study was conducted in the vicinity of the French HSL "Atlantique" (West of France). We selected 122 residential buildings with a railway noise exposure L_{DEN} >55 dB(A) (corresponding to a maximum of distance of about 1 km). The selected dwellings had also to be not exposed to other sources of transportation noise. Topography and noise barriers were also considered in the simulation. A recruitment agency contacted potential participants by phone or by visiting them in person. As the aim of this pilot was purely methodological, we were not looking for significant quantitative results. We were therefore aiming for around ten participants. Some of the selected dwellings were in fact not canvassed. Eight people between 26 and 67 years old with no reported

hearing issue were finally hired (3 women and 5 men). Each participant received financial compensation of 150 €.

2.2 Setup

A remote response device made of a LCD with Bluetooth Low Energy and a buzzer was used to send out notifications at predefined times based on theoretical train passages. Participants used it to fill in an annoyance questionnaire, either by scanning QR code that sent them to a web page (protocol A), or directly on the device (protocol B).

2.3 Procedures

The first 3 days, participants used protocol A. On the 4th day, a telephone interview took place to debrief the first three days. The next 3 days, participants used protocol B. A last telephone interview was scheduled at the end of this week. The whole study will lasted 7 days for each participant.

Protocol A was designed to interfere as little as possible with participants' daily lives. They selected a two-hour slot each day, and notifications were sent after certain train passages (that were preselected) during these slots. The notification times were selected to vary the number of train passages experienced before each judgement.

Participants were instructed to carry on their daily activities as usual. When they received a notification, they were invited to fill in a brief online questionnaire. The first two questions concern whether the participant heard the train passing before the notification, and whether they were inside their home. Then, the questionnaire presents an ISO 11-points numerical scale of annoyance (focused on the last train passage). Three additional questions concern the activity being carried out at the time of the passage, whether the window was opened or closed, and the level of noise inside the dwelling.

Protocol B required participants to stop their activities during a 15-min slot each day and listen carefully and assess noise annoyance for every train passing by during this slot. It used only the annoyance scale. In this protocol, participants answer directly on the remote response device, using physical buttons to move a cursor on the ISO 11-points numerical scale.

3 Results and Discussion

3.1 Amount of Data and Statistics

For protocol A, considering only participants with no impediments or technical issues (5 participants out of 8), 74 notifications were sent during the study. Sixty-five answers were obtained (87.8%). Forty-two answers (64.6%) mentioned that the participant had not noticed the train (and hence could not rate annoyance). It may be partly due to the poor synchronization of the notification with the actual train passages, based only on train schedule. Details are given in Table 1. For protocol B, a total of 20 quarter-hours were studied and 38 annoyance ratings were collected. Details are given in Table 2.

Table 1. Quantitative results for protocol A

Participant	1	2	5	6	8	Total
Number of notifications received	13	12	21	12	16	74
Number of answers provided	13	12	16	8	16	65
Number of "no train heard" answers	7	12	10	3	10	42
Number of annoyance ratings	6	0	6	5	6	23

Table 2. Quantitative results for protocol B

Participant	1	2	3	4	5	6	7	8	Total
Number of slots	3	3	2	1	2	3	3	3	20
Numb. of ratings	5	7	4	2	5	8	1	6	38

3.2 Acceptability, Ease of Use and Interference with Daily-Life Activities

The analysis of the interviews highlighted that asking for two hours a day may have scared participants away (protocol A). This protocol can be perceived as more restrictive as it requests participants to stay in their main room during the whole time slot. Moreover, seven participants express a preference for protocol B, because of the shorter time slot, the careful listening, and the response directly on the device.

During the interviews, six out of eight participants mentioned that the notification was not loud enough, so they had to change their habits (e.g., not listening music or TV) to detect it. Discussions with the participants also revealed that most of them have become accustomed to the noise of trains and hardly notice them in their daily life. Only certain passages were perceived as very annoying. In their opinion, the potential sources of annoyance are the weather, the speed, the vibrations, and the type of train.

4 Conclusion

This pilot study aimed at testing different methodologies to develop an in-situ study of the acoustic factors driving the short-term annoyance experienced by residents living close to HSL. It compared two variations of the Experience Sampling Method. Protocol A was designed to interfere as little as possible with the situation: it requested participants to carry out their daily activities as usual and rate the annoyance of train passages signaled by notifications sent throughout 2-h periods, whenever they had noticed them (signal contingent). In contrast, in protocol B requested participants to stop their daily activities for 15 min, listen carefully and rate the annoyance of every train passing by (event contingent). The main methodological results are:

- Protocol A seems to be more representative of participants' real-life annoyance than protocol B. It allows to consider the number of passages that participants did not notice, and thus, to study its influence on annoyance, considering not only the scheduled number of train passages but also the number of passages heard by participants. This will allow us to determine the acoustic characteristics of the passages heard by the residents as well as other external factors such as weather conditions.
- Consequently, in protocol A, many notifications did not yield any annoyance rating, as participants had not noticed the train passage. In contrast, in protocol B, participants rated every single passage. This striking contrast suggests that protocol B was clearly not representative of the annoyance experienced by participants
- However, protocol A also has some drawbacks: for example, participants were often not in the same room as the response device when they received notifications. In addition, participants found it difficult to be available 2 h each day (and preferred the shorter protocol B).

These methodological results will now be used to design a new protocol at a larger scale, which will combine annoyance ratings and acoustical characteristics.

Protocol A seems to be more representative of participants' real-life annoyance as it allows to consider the passages that participants did not notice. However, the drawbacks it presents could be improved in the future. First, the 2-h' time requested in protocol A is restrictive. This may explain why recruiting eight participants was already difficult. In order to roll out an experiment on a larger scale, we will have to reduce the constraints by letting them choose their time slots from day to day. Moreover, a louder notification will be developed to ensure that participants' lifestyle is not changed. Finally, annoyance responses would be synchronized to trains' passages thanks to a microphonic device (equipped with a Raspberry Pi) who automatically detects trains' passages. The goal of our next studies will be to develop a new protocol including these improvements, and then to relate and analyze the impact of the acoustical characteristics of the trains passing-by on annoyance judgements.

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Extent of L-vehicles Tampering and Impact on Noise and Emissions

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Abstract. L-category vehicles (LVs) may result in numerous harmful effects, due to more relaxed emission standards and higher peak noise levels, compared to other types of vehicles. LV tampering further contributes to the deterioration of pollutant and noise emission performance since these modifications often take place without considering any potential negative consequences. This paper aims to present the most common LV tampering methods within the European Union (EU) and to assess their undesirable effects by using a qualitative approach. The impacts of each method on noise and pollutant (including CO, NO_x, and HC) emission levels are determined in the form of an effects table, which could be used as a guide and contribute to identifying LV tampering attempts, as well as assessing any negative impacts more effectively. This study is part of the L-vehicles Emission and Noise mitigation Solutions (LENS) project, funded from the EU's Horizon Europe research and innovation program under grant agreement No 101056777. The main aim of LENS is to assist law enforcement and regulatory authorities to reduce the contribution of LVs to air and noise pollution.

Keywords: L-category vehicles · tampering · road transport emissions · air pollution · noise pollution

1 Introduction

LVs comprise mopeds, motorcycles, tricycles, and quadri-mobiles. Their contribution to air pollution and traffic noise [1–3] is significant, despite their low seating capacity. Before Euro 5, they had more relaxed emission standards than cars and they did not face as strict controls by legislation as other types of vehicles. Their general sound characteristics and peak sound levels are also distinct compared to other types of vehicles [4].

According to the EU, tampering refers to "inactivation, adjustment or modification of the vehicle emissions control or propulsion system, including any software or other logical control elements of those systems, that has the effect, whether intended or not, of worsening the emissions performance of the vehicle" [5]. Tampering thus further

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contributes to any negative impacts of LVs [6–10], especially since such practices are more common among LVs than other types of vehicles.

The present study is part of the LENS project. LENS is a three-year Horizon Europe research and innovation programme, funded by the EU under grant agreement No 101056777. It aims to investigate the contribution of LVs to both air and noise pollution and assist enforcement authorities, cities, and regulators to decrease any of their negative impacts. This work presents a first assessment of the effects that the most common LV tampering methods have on both pollutant and noise emissions. This at first is done using a qualitative approach, while a quantitative one is also set to be done as part of the LENS project.

2 Methods

Various methods were used in conducting the present study. These included a literature review, utilization of own engineering judgment, as well as delivering online questionnaires and face-to-face interviews with Original Equipment Manufacturers (OEMs), service shop owners, and motorcycle or LV owners and enthusiasts from more than 20 EU countries. The objective was to identify the most common LV tampering methods and create an effects table that documents their impacts on pollutant and noise emission levels by using a qualitative approach.

By reviewing previous studies that focused on tampered LVs, it was possible to collect data regarding the observed changes in air pollutants and noise level emissions of LVs before and after applying different tampering techniques. The partners included in the project also contributed to this work with their own experience and expertise.

In total, 602 online questionnaires were completed within the EU and, additionally, 64 in-person interviews took place in Greece. The target group of both was LV owners and enthusiasts, repair shop owners, and online motorcycle sellers. The questionnaires included a variety of questions referring to vehicle characteristics, such as brand and type, year of registration, and usage, as well as information about any tampering attempts and the reasons behind them. The main aim was to identify the most common LV tampering methods and find out how frequently these take place on an EU wide scale.

3 Results

Table 1 reports the 25 most common LV tampering methods as resulted from the questionnaires that were used in the scope of the LENS project. The table includes the percentage of total participating vehicles that had implemented each modification, as well as the category of each modification based on which vehicle system it aims to modify.

The replacement of the original silencer with an after-market (certified or not) one turned out to be the most popular modification. Next in the ranking is the after-market air filter, followed by after-market fairing and software modifications to the ECU. On the other hand, the least common modifications include the crankshaft weight reduction and the increase of the wheelbase.

Table 1. Ranking of most common LV tampering methods.

No	Percentage of total vehicles	Category	Modification
1	48.8%	Exhaust	After-market silencer
2	31.7%	Air Intake	After-market air filter
3	21.2%	Fairing	After-market fairing
4	17.5%	ECU and electronics	Software modifications to ECU
5	15%	Exhaust	Removal of silencer, silencer modifications
6	14.4%	Exhaust	Catalyst removal
7	14.1%	Exhaust	Modifications to exhaust manifold (tubes)
8	11.4%	Transmission	After-market final drive gear
9	9.3%	ECU and electronics	After-market spark plugs
10	8.1%	Exhaust	Adjustable exhaust valve/dB killer
11	7.9%	Fairing	Removal of fairing parts
12	6.6%	ECU and electronics	After-market ECU
13	6.4%	Transmission	After-market clutch (slip clutch or regular)
14	5.2%	Engine	Porting cylinder head
15	5.1%	Air Intake	Air filter removal
16	4%	Engine	After-market camshafts
17	4%	Engine	Increased engine displacement (after-market cylinder, pistons, rods, etc.)
18	3.9%	ECU and electronics	Engine speed limiter removal
19	3.6%	Fuel System	After-market carburetor
20	2.7%	Engine	Flywheel weight reduction
21	2.4%	ECU and electronics	After-market ignition coils
22	2.2%	Transmission	After-market gearbox gears
23	2.2%	Fuel System	After-market fuel injectors
24	2.1%	Engine	Crankshaft weight reduction
25	1.8%	Transmission	Wheelbase increase

From the questionnaire results, it can also be concluded that most modifications target the exhaust system, the ECU and electronics and the air intake system of a vehicle, while tampering is most frequently motivated by the need to increase engine power.

In the scope of LENS, the effects of all the abovementioned modifications in air and noise pollution were investigated. Table 2 presents only the effects of the modifications that resulted in having the most significant impact either on pollutant (CO, NO_x, HC) or noise level emissions in a qualitative way. More specifically, out of the 25 most common LV tampering methods (see Table 1), the removal of a vehicle's catalyst, the use of an after-market ECU or an after-market carburetor affect pollutants in the most negative way. Using an after-market silencer or air filter and the complete removal of them, as well as applying an adjustable exhaust valve or dB killer results to the highest noise levels. The modifications that are not outlined in Table 2 have a comparatively less pronounced effect on the pollutant and noise emission performance of LVs.

Table 2. Effects table of most common tampering methods in pollutant and noise emission levels.[1]

Category	Modification	Effect in				
		CO	CO_2	NO_x	HC	Noise level
Exhaust	After-market silencer	-	-	-	-	↑↑
Exhaust	Removal of silencer, silencer modifications	-	-/↓	-	-	↑↑↑
Exhaust	Catalyst removal	↑↑↑	↓	↑↑	↑↑↑	↑
Exhaust	Adjustable exhaust valve/dB killer	-	-/↓	-	-	↑↑
Air Intake	After-market air filter	-/↑	↓	-/↑	-/↑	↑/↑↑
Air Intake	Air filter removal	↓	-	↑	-/↓	↑/↑↑
ECU and electronics	After-market ECU	↑/↑↑	↑↑	↑	↑↑	↑
Fuel System	After-market carburetor	↑↑	↑↑	↓	↑↑↑	↑

A silencer is used to reduce the noise emissions of a vehicle. The replacement of the OEM silencer by an after-market one, certified or not, can lead to higher noise levels, while its complete removal results in a significant increase in noise.

The fundamental function of a catalyst is to purify noxious exhaust emissions by converting them into less harmful substances. Hence, its removal leads to a remarkable increase in pollutant emissions, while noise levels may increase as well. Fuel consumption and thus CO_2 emissions may also decrease due to the lower backpressure.

By having an adjustable exhaust valve, the driver can adjust the noise levels of the vehicle. There are various systems that can be used, as well as various ways to place them in the vehicle. The most common one is after the catalyst. While driving with the valve opened, noise emissions increase significantly, while having the valve closed does not affect them.

[1] (-): no effect, (↑): increase (on a scale of one to three), (↓): decrease (on a scale of one to three), (-/↑): slight or no increase, (-/↓): slight or no decrease.

An air filter is responsible for filtering the air in the intake before entering the engine so as to improve the combustion. Both its replacement and removal aim to enhance air intake flow, leading to alterations in the vehicle's pollutant emissions, while concurrently increasing noise emissions.

The ECU consists of both hardware parts and software and affects various systems of a vehicle. After-market parts are mainly applied to pre-Euro 5 vehicles in order to achieve richer combustion and increase power and noise. As a result, there is an observed rise in pollutant emissions and fuel consumption.

The carburetor works by controlling and mixing the air and fuel that enters the engine. Its replacement leads to a richer combustion and thus CO, HC, CO_2, and noise emissions are increased, while NO_x ones are decreased.

4 Conclusions

LV tampering poses a severe problem that may lead to harmful effects, as it deteriorates the pollutant and noise emission performance of LVs. The aim of this study was to identify the most common LV tampering methods within the EU and to assess their effects on both noise and air pollution by using a qualitative approach. The main output of this work is an effects table documenting the impacts of these methods on pollutant (CO, NO_x, HC), CO_2, and noise level emissions in a qualitative way. It could be used as a guide so as to identify different tampering types and reduce any negative effects on air and noise pollution more effectively.

The following can also be concluded from the present study:

- The most common LV tampering modification in the EU is the replacement of the original silencer of a vehicle with an after-market one.
- The removal of the catalyst, using an after-market ECU or an after-market carburetor has the most significant effects on pollutant emissions of a LV.
- The removal of the silencer, using an adjustable exhaust valve or removing the air filter of a LV affects its noise levels the most.

Acknowledgment. This work is part of the LENS project, funded by the EU's Horizon Europe research and innovation programme under grant agreement No 101056777. The main objective of LENS is to assess the contribution of LVs to both air and noise pollution and contribute to the restriction of any negative impacts.

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Noise Level and Indoor Air Quality Assessment of Public Transport Buses in Portugal and Nigeria

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Abstract. Cabin air quality and noise are essential parameters of indoor environmental quality (IEQ) that impact the comfort, safety, and well-being of exposed occupants. Daily, many passengers and drivers are exposed to the indoor climate in bus and coach microenvironments, which, if inadequate, pose significant risks to health, comfort, and safety, including annoyance and stress, thus necessitating the present study's interest.

A real-time assessment of cabin noise levels and air quality parameters (CO_2, VOCs, and $PM_{2.5}$. PM_{10}) in city buses was conducted during 46 bus trips in Lagos, Nigeria, and Coimbra, Portugal. Results have been analyzed and discussed regarding IEQ requirements in EU, WHO, ISO, and Portuguese regulations, inciting suggestions to mitigate risks in cabins based on IEQ, and gaps by the current study.

In the investigated Coimbra buses, the CO_2 levels (2630 to 5079ppm $\pm$ 653) did not follow the requirements of EN16798-1 standard, whereas, for Lagos BRT buses, particulate matter (PM) levels exceeded the WHO Limit. Noise equivalent (L_{eq}) level ranged from 69 to 81 dBA ($\pm$ 4) for Lagos, and 59 to 88 dBA ($\pm$ 8) dBA, for Coimbra. Only 40% of all the L_{eq} exceeded the 75 dBA limit, considering Portugal's NP 1674 regulation.

These findings suggest that IEQ gaps in mass transit vehicles still exist, necessitating broader assessment and intervention in future IEQ studies. Also, the current study sensitizes transport operators on IEQ gaps in mass transit vehicles, while informing preliminary conclusions regarding IEQ gaps in the EU and developing tropics with limited IEQ studies.

Keywords: Indoor air quality · Noise · Buses

1 Introduction

The choice of mass transit transport vehicles will continue to increase on account of comparatively lower CO_2 per passenger per km emission and the energy intensity, thus, ensuring safer and more comfortable cabins for commuters remains imperative. Indoor

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environmental quality (IEQ) is determined by five main parameters, indoor air quality (IAQ), thermal, visual, acoustic comfort, and ergonomics. Meanwhile, for transport microenvironments, besides indoor climate, noise, vibration, and harshness (NVH) also affect passenger comfort and safety. Also, the recent COVID-19 pandemic has highlighted the implicit risk of poor IEQ in transport cabins (TC). The current study has evaluated the IAQ and noise in mass transit buses of Lagos City, Nigeria, and Coimbra, Portugal, during real-time journeys.

1.1 Literature Review

Although several studies have assessed the IEQ of vehicles in the EU, very few studies have been reported for developing sub-Saharan countries, including Nigeria [1]. Notably, no study has been reported regarding IEQ study in buses of Coimbra municipality during real-time journeys. Meanwhile, exposure to poor IAQ has been reported to affect human health, including discomfort. In Lisbon, [2] assessed commuter exposure to physiochemical and microbiological pollutants in vehicles, concluding that ventilation primarily affects cabin IAQ. Similarly, [3] assessed commuter exposure to particulate matter (PM) in different transport modes, concluding that ventilation lowered PM concentration but raised increased black carbon (BC). In Lagos, two studies assessed PM levels in various transport modes with common conclusions of unacceptable in-cabin PM levels while [4] found pedestrians were most exposed but reported higher PM in cars than buses, including exposure to high noise levels in all modes assessed. Similarly, the findings by [5] affirm commuter exposure to elevated noise and PM levels, especially comparatively higher PM levels for closed window settings in larger buses than cars. However, the study by [6] did not report the IAQ, rather only thermal comfort and ventilation in commercial buses of Lagos were discussed. Noise, which is described as unwanted sound, can be found, or generated in indoor or outdoor spaces. Commonly in cities, noise from Industries, socio-economic activities, and traffic contributes significantly to indoor noise [7]. According to WHO, around 466 million people globally live with disabling hearing loss due to various causes including noise, and these figures will rise if there are no interventions. There is no doubt that cabin passengers and drivers are in proximity to high levels of traffic noise, which poses a significant risk due to the high chance of daily exposure [8]. Studies have discussed noise sources and the negative outcomes of human exposure [9, 10], while others have evaluated the noise, its sources, and interventions to mitigate the noise and its burden [11]. Noise exposure can increase annoyance, irritation, and health problems [12], and reduce cognitive performance in drivers [13]. A preliminary review of accessible literature suggests that more focus has been given to outdoor noise in Nigeria affirming outdoor noise is in exceedance of recommended limits. Hence the relevance of the current study assessment of indoor noise levels in public mass transport vehicles.

2 Methods

The current study has objectively assessed IAQ and noise levels in city buses of Lagos (Nigeria) and Coimbra (Portugal) during 46 real-time journeys within the cities between 2021 and 2023. This study data and report form part of the authors' ongoing and broad-scope IEQ investigations in mass transit vehicles. IAQ measurements including CO_2, VOCs, $PM_{2.5}$, and PM_{10} performed in 18 trips (Lagos City) and 14 trips (Coimbra), are reported. The IAQ parameters were measured using an IEQ multiprobe device, connected to a computer for data logging, while PM was measured using a FLOW air quality measuring device. The IEQ multiprobe device measures temperature, humidity, atmospheric pressure, CO_2 (ppm), and IAQ index using VOC level. Measurements were done by the EN16798-1 [14] requirements and the VOC index was delimited following the BME 68O [15] as in the methods used by [16]. The RH, CO_2, and VOCs have been analyzed and categorized following the EN16798-1. The noise levels have been measured following ISO 5128 [17] using a pre-calibrated TROTEC SL400 class 2 sound meter. A total of 28 trips have been presented, 14 trips for each city. The main sound descriptor reported in the current study is the noise equivalent level, L_{eq} in dBA, which was calculated from the measured sound pressure level (SPL) during each investigated trip using Eq. (1).

$$\text{Leq} = 10\log 1/\sum_{i=1}^{n} 10\frac{\text{SPLi}}{10} \tag{1}$$

Average vehicle speed and distance traveled were monitored using a mobile phone speedometer application. Statistical analysis was performed on the data samples, using Microsoft Excel, whereas the mean and standard deviation (SD), T-Test; Paired Two Sample for Means, was performed on the noise data set. Some IAQ parameters have been graphically represented for evaluation, discussions, and preliminary conclusions.

3 Result and Discussion

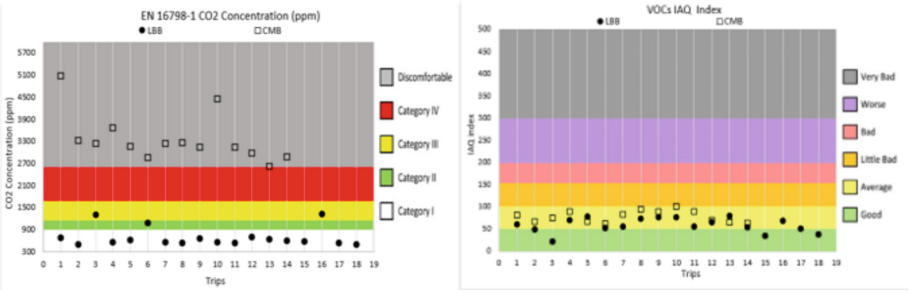


Fig. 1. IAQ parameters of Lagos BRT buses and Coimbra municipality buses.

IAQ is critical in assessing the indoor climate conditions of the investigated bus cabins to which passengers and drivers were exposed. All trips surveyed may be regarded as short-haul trips within the studied cities. Trips assessed on the Lagos BRT buses were

from Ikorodu, mainland to CMS, Lagos Island. In Fig. 1 the IAQ parameters for Lagos Coimbra buses are shown. The mean CO_2 levels computed for the 18 Lagos BRT bus trips ranged from 504 to 1338 ppm (± 262), while for the 14 Coimbra bus trips, CO_2 ranged from 2630 to 5079 ppm (± 653), Regarding the VOCs Index, the mean values for the Lagos trips ranged from 22 to 81 (± 16), and 63 to 101 (± 13) for the Coimbra trips, meanwhile, the referenced VOCs index has a maximum of 500. The average RH (%) computed ranged from 41 to 71% (± 8), for Lagos trips, and from 70 to 89% (± 6) for the Coimbra trips. The operative temperature averages (T_O) ranged from 27 to 31.6 °C (± 1.4) for Lagos trips, and from 20.7 to 25 °C (± 1.3) for the Coimbra trips, suggesting poor thermal environments in the BRT buses of Lagos. Figure 1, graphs a and b, show the IAQ parameters for the investigated Lagos BRT trips while images c and d represent IAQ in Coimbra city bus trips. For Lagos, the mean CO_2 levels computed show that all trips were suitable according to the EN167981 requirement, given that 15 trips were found in Category I, one in Category II, and two in Category III. In contrast, all trips exceeded the recommended limits for the Coimbra trips. Most were found in the discomfort zone. In both locations, the VOCs index was within the permissible range. Notably, most of the BRT cabins of Lagos trips had no use of HVAC but natural ventilation from open windows although fully occupied. Hence the significantly low averages in CO_2 levels. Furthermore, BRT buses were traveling at speeds of 60 to 70 km/h, due to dedicated travel lanes and minimal stops for most of the journey times except for congested traffic conditions. For Coimbra, the travel speeds were typically less than 60 km/h, punctuated by several stops by traffic light controls and passenger stops. Other stops might have been due to ongoing road maintenance and mild traffic.

Particulate Matter: The average mass concentration of $PM_{2.5}$ ranged from 15 to 35 $\mu g/m^3$ (± 6), and PM_{10} ranged from 46 to 115 $\mu g/m^3$ (± 18) for the Lagos trips, while for Coimbra trips, it ranged from 2 to 28 $\mu g/m^3$ (± 7), and PM_{10} ranged from 9 to 107 $\mu g/m^3$ (± 29). For $PM_{2.5}$, only one of the 14 trips was in exceedance of recommended limits (The WHO and Portaria No. 353 - A/2013 PM limit, $PM_{2.5}$; 25 $\mu g/m^3$ and PM_{10}; 50 $\mu g/m^3$), as no record was found of any Nigerian regulation for PM by the authors, at the time of the current study report. Mean PM_{10} levels were in exceedance in all but the 6th cabin ($PM_{10} = 46\ \mu g/m^3 \pm 20$), for the Lagos trips; meanwhile, for Coimbra trips, only five trips were in exceedance. In all Lagos trips, the unrestricted intrusion of ambient air accounts for high PM levels in the cabin, while the few cases of high PM levels in Coimbra trips can be linked to the frequent stops for passengers enhancing increased PM intrusion and/or particle resuspension. Also, during the survey months in Coimbra, road maintenance activities were ongoing along some of the study journey routes, although most of their bus windows were seldom open during the trips due to the winter season or rain, as well as for HVAC in use. Moreover, the high in-cabin CO_2 levels could be linked to the partially/fully closed cabin, the fully occupied bus cabins (high commute due to students and residents in the city), and the risks of inadequate fresh air supply. In both cities, on account of PM's exceedance in all the assessed Lagos buses and CO_2 levels of discomfort category according to EN16798-1 for all Coimbra buses gives a preliminary conclusion that IAQ was inadequate in most of the studied bus cabins. Also, the mean T_O (°C) reported for the Lagos buses, suggests thermal discomfort according to EN16798-1 limits.

Noise Measurement: The L_{eq} presented for 14 Lagos trips ranged from 69 to 81 dBA (± 4) while the 14 Coimbra trip L_{eq}, ranged from 59 to 88 dBA (± 8). The T-Test on the paired independent L_{eq} samples showed statistical significance, whereas we obtained the respective statistical means of 75 and 70 and variances were 13 and 56 for Lagos and Coimbra trips. Also, $P = 0.02$, t-Stat = 2.36 (with $\alpha = 0.05$). The results show that noise levels were higher in the Lagos BRT buses. Moreover, the in-cabin L_{eq} ranges suggest the need to improve the acoustic environments in the studied cabins of both cities. The in-cabin L_{eq} (dBA) values were below or slightly higher than the NP 1674 limit of 75 dBA for vehicles moving at 40 km/h ± 5 or 80 dBA for higher speeds within cities [18], except in bus trip 12 (L_{eq} of 88 dBA). For Lagos, 50% of the surveyed trips exceeded the 75 dBA limit, whereas only trips 6 and 11 exceeded 80 dBA. However, considering the speed limit of 40 to 50 km/h, applicable to in-city roads of Coimbra and the BRT speed limit, 40% of trips surveyed had inadequate noise levels while only 12% of trips were inadequate considering higher driving speeds. Meanwhile, by Bryan's 1976 criteria [19] the L_{eq} ranges imply that noise levels in the investigated buses are mostly quiet (67 dBA), noticeable (73 dBA), intrusive (79 dBA), but not annoying (85 dBA) nor very annoying (91 dBA).

4 Conclusion

The study assessed IEQ parameters of bus rapid transit (BRT) buses in Lagos (Nigeria) and the urban buses in Coimbra (Portugal) in 46 real-time journeys within the city. The Measured IAQ parameters exceeded the relevant limits of the EN16798-1, WHO, and Portuguese regulations. Noise levels were comparatively more adequate on the Coimbra buses than the Lagos BRT buses but adequate in 60% of all 28 assessed bus trips. The findings indicate that IEQ gaps still exist in short-haul passenger mass transit. Moreover, in Lagos BRT buses, the continuous intrusion of ambient outdoor air lowered in-cabin CO_2 levels. Still, it enhanced the PM penetration at the elevated levels in-cabin, due to open windows in the studied BRT buses. Meanwhile, poor IAQ is linked to elevated levels of CO_2 and closed crowded cabins of Coimbra buses. Closed cabins with adequate HVAC use will improve IAQ. Avoiding overcrowded cabins for better IEQ and good vehicle maintenance can enhance cabin IEQ, including less interior noise and reduced vibration.

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Transforming Railways into Quiet Neighbours: Pioneering a Global Approach to Noise Reduction

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Abstract. Railways play a pivotal role in modern transport systems, contributing significantly to economic growth and societal connectivity. However, railways rank as the second most significant noise polluter, following roads, and noise stands as the second largest environmental factor impacting health, after air pollution caused by particulate matter [1, 2]. Thus, integrating a low-noise approach into rail asset management is crucial for operational optimisation and promoting railways as good neighbours aligning with UN Sustainable Development Goals (SDG) and the EU Green Deal.

Addressing railway noise and vibration requires well-thought-out harmonised strategies, supporting good health and global UN SDG Target 3. The technical approach should centre on curbing environmental impacts as rail traffic and transport infrastructure grow. The International Union of Railways (UIC) acknowledges this challenge and emphasizes cross-border collaboration to reduce noise and vibration levels through its Noise and Vibration (NV) Sector, promoting sustainable development.

This paper presents recent reports, including preliminary studies on nuisance [3] and parked train noise management [4], addressing to global concerns. It also highlights outcomes from the LOWNOISEPAD project [5], offering innovative solutions for noise reduction through optimised rail pads in Europe. These results guide sustainable investments and enable the railway sector to embrace its responsibility as good neighbours, amidst environmental, societal, and economic turmoil. This approach underlines the urgency of noise mitigation for a more sustainable involvement of railways in communities.

Keywords: Nuisance · Parked trains · Optimised rail pads

1 Introduction

UIC, through its NV sector, leads the drive for a more quiet railway sector, identifying key issues and focusing on solutions through the convening of a series of technical projects and roundtables. The goal is to comprehend the mechanisms that generate noise

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and vibrations, aiming to make tangible progress in advancing responsible practices. UIC's vision integrates sustainability into railway operations and maintenance, aiming to better manage noise emissions and minimise the health burden impact. Tackling noise at source is often seen as the most cost-effective and time-saving method, and the development of strategic approaches is of paramount importance in this regard. In particular, the Phenomena study, which has been the motivation for these efforts, has shown that quieter tracks and vehicles on the railways will lead to a 37–52% reduction in health burden by 2030 and a cost/benefit ratio of 0,9 – 3,1 between 2020 and 2035 [6]. Therefore, recent focus has been on railway system-wide optimisation, measurement methodologies and evidence-based indicators to determine the noise nuisance levels of line-side residents.

2 Mitigating Noise and Enhancing Community Well-Being

Railway noise arises from diverse sources across varying speeds: power/traction/auxiliary noise at lower speeds (<50 km/h), rolling noise at most speeds, and aerodynamic noise at higher speeds (> 250 km/h). This noise can disrupt sleep, induce stress, and lower residents' quality of life, with potential long-term health effects. As rail traffic is expected to increase, noise mitigation approaches gain significance. Rail authorities and communities adopt measures like improved track design, quieter rolling stock, and noise barriers. Case studies and best practices demonstrate effective noise mitigation approaches.

In collaboration with subcontractors in the NV sector framework, UIC conducts technical studies involving worldwide infrastructure managers and operators. Continuous feedback and peer reviews ensured robustness and a collaborative approach within the UIC NV Sector. The studies shed light on sector efforts through literature reviews and research, addressing gaps and shaping the sector's direction.

2.1 Harmonising Approaches for Mitigating Nuisance

Despite monitoring noise complaints and adhering to regulatory thresholds (e.g., TSI NOI), the number of noise complaints is on the rise. UIC's scoping study explored health effects of railway noise exposure, encompassing annoyance, sleep disturbance, and long-term physiological conditions. The study assessed existing research, mitigation methods and economic factors. Moreover, it investigated the correlation between arousal responses, nuisance, and complaints linked to railway noise, offering insights to guide government authorities in adopting pertinent indicators. It explored noise nuisance indicators and offers pragmatic solutions in collaboration with infrastructure managers.

2.2 Managing Parked Train Noise

Noise from stationary or parked trains remains an issue due to complex mechanical components in contemporary multiple units (EMU/DMU). A UIC-led study aimed to understand parked train noise management and provide insights for the global railway community. It established a foundation for potential regulatory changes (e.g., TSI NOI) regarding parked train noise. Challenges in measuring parked train noise are addressed,

and strategies to harmonise operational needs, infrastructure capabilities, and ecological concerns were identified. The study delved into ISO-compliant measurement methods and contributes to ISO 3095 advancement [4].

2.3 Enhancing Noise Mitigation Through Asset Optimisation

Improving track component design and material properties enables quieter train operations. Ongoing research approaches focus on engineering solutions for noise mitigation, particularly concerning rail pads. The UIC LOWNOISEPAD project analyses rail pad properties' impact on train noise emission such as stiffness, geometric distribution, and damping impact, and target noise reduction in pass-by levels. The study focused on the track decay rate (TDR) in the frequency range of 800 Hz–2 kHz, with emphasis on the 1 kHz energy band representing the pin-pin mode of vertical rail vibration. The study also led to the development of a harmonised methodology for measuring and comparing noise emissions during train pass-bys, which enables it to be used for optimising asset performance.

3 Adding Value to Future Noise Mitigation

3.1 Noise Abatement in Residential Areas: Nuisance Factors

A survey of 18 operators and infrastructure managers, covering 64% of Europe's rail network, explored noise regulation, complaints, and mitigation. Despite regulatory actions and innovations, a third of respondents reported persistent complaints despite railway noise pollution remaining stable or decreasing. This indicates an arousal response to noise, highlighting the need for short-term noise indicators like L_{Amax} for awakening reactions. Intermittent high noise events or sounds of distinct character cause more arousal than steady noise, leading to complaints. Robust and realistic indicators must be developed to represent the noise perception of lineside residents. This is an interdisciplinary endeavour including health experts, legislators and the railway representatives.

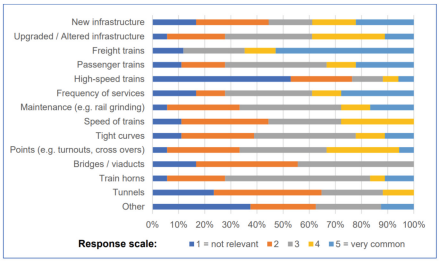


Fig. 1. Railway features and how common they are in causing complaints.

Figure 1 illustrates railway features and their association with complaints. Various components, including compressors, HVAC systems, power converters, and traction

units, contribute to disturbances for lineside residents. Furthermore, freight trains and atypical noise sources (e.g., tight curves) correlate with higher complaint rates, indicating connections to noise changes and heightened sensitivity. Nuisance correlated with both noise exposure and arousal, while complaints were directly linked to arousal. Given qualitative variations in complaints arising from diverse sources, influenced by perceptions and concerns, and recognising that various factors influence complaining behaviour, it cannot be concluded that only people who are annoyed complain. Thus, conducting further research involving stakeholders becomes essential to refine noise exposure-response relationships, recommended by WHO.

3.2 Addressing Noise from Stationary and Parked Trains

When it comes to noise emissions, stationary trains prove noisier than parked ones due to their active technical components.

- Stationary train: A fully operational train temporarily halted, often awaiting signals or station activities, ready to accelerate, possibly with passengers, emitting noise from operational components.
- Parked train: Train out of commercial service, in a depot or yard, no passengers, undergoing phases of preparation, resting (with reduced noise), and reactivation for return to service.

While noise limits exist for moving or stationary trains, limit values for parked train noise lacks standardised requirements. A UIC study found 45% increased complaints about parked trains, with critical noise from locomotives and DMUs. EMU trains have moderate noise, and coaches/wagons creates minimal problems. It's worth mentioning that this study excluded an analysis of on-track machinery, also called "yellow vehicles," which may require further investigation, as shown in "others" in green colour (see Fig. 2).

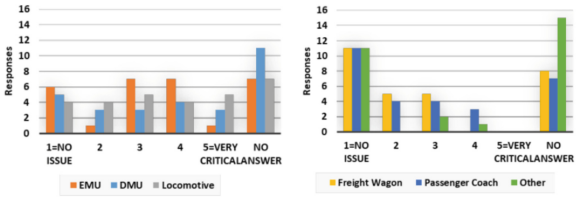


Fig. 2. Criticality of rolling stock with regards to parked train noise

Developing noise limits needs a reliable database, which is lacking despite in some countries (e.g., NL & CH) having acoustic databases. Moreover, the analysis varies due to differing train types and unclear guidelines. The development of noise solutions for parked trains among suppliers poses a competitive environment, so that open dialogue between the actors is hardly achievable. Existing technical specifications formulated by rail operators (VDV, EuroSpec, NSW) are not deemed pivotal by suppliers and are even considered a source of confusion. As a result, developing a database requires a standardised approach (in line with ISO3095) with a well-defined measurement protocol.

Vehicle side limit values can then be developed to address gaps without being overly restrictive and can encourage the development of innovative activities to make the entire railway system better neighbours.

3.3 Optimising Noise Control Through Asset Managements

Balancing the demands of track engineers and acoustic engineers in track asset design represents an ongoing challenge. For instance, softer rail pads ensure load distribution and long-term stability, while stiffer pads with low TDR reduce noise emissions. This apparent conflict of aims was addressed with the development of optimized soft pads with high damping. These pads were successfully installed and measured under real operating conditions by 12 European railway infrastructure managers within the LOWNOISEPAD project. Tailoring the rail pad optimisation process to accommodate individual partner requirements, including input from track engineers, contributed to a collaborative and effective approach throughout the project's implementation. Standardised procedures and a harmonised guideline (IRS 75717 [7]) offer a common framework for measuring noise emissions during train pass-bys. Despite challenges in deriving definitive conclusions due to the variances in operational activities, train types, speeds, and track assets such as rail pads and fastening systems, significant noise reduction could be achieved.

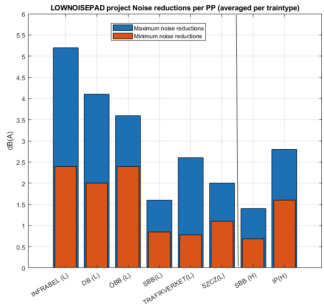


Fig. 3. Overview of achieved minimal and maximal noise reduction by comparing optimised rail pads with standard rail pads (L): Soft rail pad, (H) Stiff rail pads.

The results, shown in Fig. 3, demonstrate that optimised rail pads with higher TDR demonstrate reduce overall noise by 1–2 dB if compared to stiff pads and 3–5 dB when compared to soft pads while mostly retaining "soft" qualities often associated with better track protection. The development of long-term monitoring programmes and the promotion of optimisation studies can help to assess the effectiveness of the noise abatement obtained with rail pads and encourage continuous progress in railway noise minimisation. This should be followed up by cost benefit analyses allowing for a whole system optimisation including track life-cycle cost, noise and vibration.

4 Conclusion and Recommendations

Advancing the greenest mode of transport, railways should be further promoted to meet global climate targets. While the EU's zero pollution action plan aims to reduce chronic annoyance from transport noise by 30% by 2030 from 2017 level [1]. However, the projected 36% increase in disturbed individuals due to traffic increases must be addressed to avoid potentially undermining the railways' status as a sustainable transport option. The promising potential of supplementary technologies and innovative approaches, such as those subsidised by ERJU, offers substantial potential to combat railway noise pollution. Implementing efficient noise mitigation strategies holds the key to creating quieter and more livable environments, contributing to a sustainable transport system. The following recommendations stem from the projects discussed:

- **Optimisation approach:** The LOWNOISEPAD project provides solid scientific evidence through extensive data collection and standardised measurement methods and analysis techniques to support the idea of noise reduction through asset optimisation. Demonstrated noise reduction of up to 5 dB through acoustically refined track pad designs underscores the project's potential as a catalyst for forthcoming innovations and partnerships. Accordingly, the sector's overarching goal should encompass a collaborative pursuit of an optimized rail system, incorporating noise, vibration, and life-cycle-cost analyses. Pioneering noise-solving designs from the outset offers a cost-effective mean to tackle long-term noise issues.
- **Quieter stationary and parked trains:** Prioritising HVAC system enhancement involves developing technical solutions and software adjustments to diminish vehicle noise through reduced fan speeds, encapsulation of noisy components, silencing exhaust valves, and optimized fresh air intakes. Collaborative efforts with suppliers, during initial design or retrofitting, accounting for practical, financial, and regulatory factors, can guide rail operators toward seamless integration within procurement processes. Enhanced engagement with subcontractors and suppliers will maximize efficacy. To mitigate due to depots and stations, infrastructure managers should be incentivised to install noise barriers and introduce specialised parking schemes for noisier trains. Additionally, proactive consultation with local authorities can avert challenges stemming from non-expert train set commissioning.
- **Initiatives for community well-being:** Comprehensive noise exposure assessment must consider uncertainties in data from regulatory noise maps and emphasize stakeholder collaboration. Further exploration should yield regional and local estimates of the impact of passenger, freight, and high-speed trains on global disease burdens. The ineffectiveness of complaint rates as a metric was evidenced by UIC's analysis. Alternative noise indicators like L_{Amax}, SEL and TEL should be evaluated as supplementary health indicators to assess waking responses. Acknowledging the limitations of noise exposure-response relationships is pivotal in accurately representing actual values.

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biclaR: Estimating the Socio-Environmental Impacts of Car Substitution by Bicycle and Public Transit Using Open Tools

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Abstract. This paper estimates the potential for cycling combined with public transit (PT) as a substitute for car trips in the Lisbon metropolitan area and assesses its socio-environmental impacts using open data and open source tools. A decision support tool that facilitates the design and development of a metropolitan cycling network was developed (*biclaR*). The social and environmental impacts were assessed using the *HEAT for Cycling* and the *HEAT as a Service* tools. The impacts of shifting car trips to PT were also estimated and monetized. The results indicate that 10% of trips could be made by bicycle + PT combination. Shifting to cycling for the first-and-last mile stages can reduce annual CO_2eq emissions from 3,000 tons/day, with benefits over 10 years of at least €125 million. For the PT leg, the transfer from car avoids up to 20,500 tons of CO_2eq emissions per year. This evidence can support policymakers to prioritize interventions that reduce the reliance on private motor vehicles.

Keywords: Active transport · Intermodality · First and last mile · Health economic assessment · Environmental impacts · Open methods

1 Introduction

Combining public transportation (PT) and cycling for the first and last mile in metropolitan areas can significantly replace private car trips [1,2]. This approach requires interventions and programs to make bicycling more appealing, and the resulting public investments can have significant social and environmental benefits.

According to the latest mobility survey conducted in 2018 [3], the LMA registered a total of 5.3 million daily trips, with only 0.5% by bicycle. Car modal

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share was 58.4%, while PT accounted for 15.5%. The number of intra-municipal trips—with origin and destination in the same municipality—amounts to 3.5 million trips. This exceeds the number of inter-municipal trips (1.8 million trips), involving travel between different municipalities. Cars and public transport are the most used modes for intercity trips, with cars being the predominant choice for all journeys.

To achieve the cycling targets set by the Portuguese national cycling strategy for 2025 and 2030 (4% and 10%, respectively), the Lisbon's Metropolitan Department of Transport introduced *biclaR*[1], a decision support tool that facilitates the design and development of a metropolitan cycling network [4].

biclaR builds on the Propensity to Cycle Tool[2] (PCT), a web application and research project funded by the UK's Department for Transport in 2015 which launched nationally in 2017 as part of the government's Cycling and Walking Investment Strategy. The PCT initially used only origin-destination data for commuting trips as the basis of estimates of cycling potential at zone, route and route network levels [5]. However, to the best of our knowledge, this is the first time that the method has been integrated with public transport data using multi-modal routing to estimate the potential and benefits of multi-stage cycling and PT trips.

This paper estimates the potential for combining cycling and PT to substitute car trips in the LMA. After presenting the methods used, it assesses its socio-environmental impacts using open data and open-source tools.

2 Methods

2.1 Modeling Origin-Destination trips

The mobility survey data [3] is the basis for this project and defines the baseline scenario. Despite being conducted in the pre-pandemic period (2017), this dataset represents the most comprehensive and up-to-date information on urban mobility in Portuguese metropolitan areas (Lisbon and Porto).

We used a method for disaggregating the origins and destinations of trips between the centroids of two districts (same as "parish") to ensure that a district is not solely characterized by a single point of origin and destination for its trips. The OD Jittering method breaks down a single point (i.e., the centroid of an area) into multiple random points on the existing and neighboring road network, using OpenStreetMap as a reference [6]. Using the odjitter R package, we employed a maximum disaggregation level of 100 trips per O-D pair for this project. Although this method provides a more realistic representation of the trips undertaken compared to the traditional approach, it does not fully align with the actual O-D pairs of trips, which remain unknown due to data privacy regulations.

[1] See biclar.tmlmobilidade.pt.
[2] See pct.bike.

2.2 Modeling Routes

The mobility survey collects the origin and destination of trips but does not include the respective routes. Modeling the realistic cycling + PT routes between OD pairs depends on assumptions regarding the characteristics of the cycling and road networks and the location of public transport interfaces.

The selected route choice algorithm was the r5r R package [7], which allows for great flexibility in configuring estimated route types. `r5r` can calculate multimodal routes using PT combined with other modes. It enables the identification of the most direct or safest cycling routes, using the Level of Traffic Stress[3] (LTS) scale. The routes were estimated for the base scenario for both types of networks: *direct* and *safe*, using LTS 4 and LTS 3, respectively.

The `r5r` model used the OpenStreetMap road network and the GTFS metropolitan data aggregated and validated. This information is crucial for an accurate PT trip and route estimation.

2.3 Modeling Intermodality

The intermodality scenario considers trips combining PT and cycling for the first and last legs. In a conservative approach, we have restricted our analysis to the first and last legs with a combined length of up to 5 km (for instance: 1 km from origin to interface A plus 4 km from interface B to destination) or up to 25 min on bike. Furthermore, we have imposed restrictions on PT usage to include only trips with no PT transfers, and up to 2 h (120 min). Additionally, we have only included PT modes that can easily accommodate bicycles, such as trains, ferries, trams, and inter-municipal bus lines equipped with bike racks (Fig. 1). Figure 2 illustrates the resulting bicycle routes to access the main PT interfaces in the LMA.

2.4 Assessing Socio-Environmental benefits

For the cycling legs of the journey (first and last legs), socio-environmental impacts were estimated on the shifting from car to cycling, using the HEAT for Cycling tool v5.0 [8] from the World Health Organization, and the HEATaaS R package[4]. We considered two dimensions: *social*—including the physical activity of cyclists, air pollution exposure, and road casualties; *environmental*—including CO_2eq emissions and other pollutants.

For the second leg of the journey, we estimate the additional environmental impacts of shifting car trips to PT (between the PT interfaces).

To estimate the car emissions, we used the EMEP/EEA's COPERT software v5 methods and reference values [9] for a Tier 3 detail level. Regarding PT, we considered the emission factor values reported in the environmental and sustainability reports of the PT operators in the LMA. The conversion of avoided

[3] see docs.conveyal.com/learn-more/traffic-stress.

[4] `HEATaaS` is under development. For more information contact heatwalkingcycling.org.

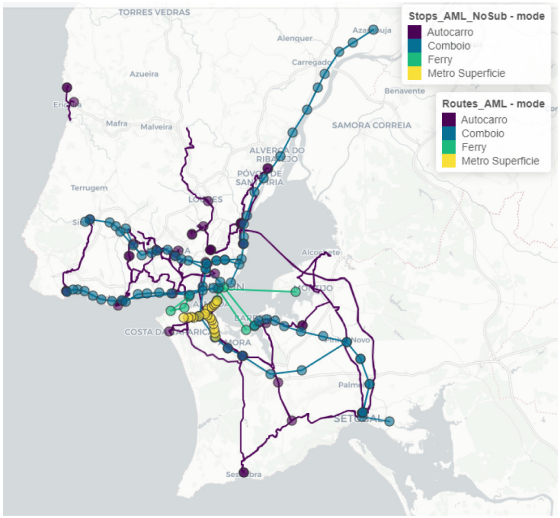


Fig. 1. Interfaces and lines considered, by transport mode, in the Lisbon metropolitan area

emissions into avoided welfare loss and respective monetary valuation was based on the EU Guide to Cost-benefit Analysis [10] and the best up-to-date reference values for the various gases.

3 Results and Discussion

Table 1 presents the LMA total daily trips that can be made with cycling + TP combination (with the aforementioned restrictions), the trips in the baseline scenario and corresponding new trips to achieve the national strategy targets (4% and 10%), for different route profiles. For the cycling legs of the journey (first and last legs), the environmental avoided emissions and monetized socio-environment (SE) benefits are also presented, resulting from replacing car trips with cycling.

For both *direct* and *safe* route profiles, 10% of the daily trips have the potential to be made by a combination of PT and cycling (up to 5 km on bike). This unveils the potential of cycling as a complementary mode of PT, with the potential to uptake the number of PT trips within the LMA area by as much as 6.3% (in addition to the 825 thousand PT trips reported in the mobility survey).

Regarding the PT mode to replace the second leg of the journey, in combination with cycling, trains offer the greatest potential for substitution (88%). When comparing the existing PT interfaces (Fig. 1) with the bike routes with highest potential to serve as first and last legs (Fig. 2) it becomes clear that the Train interfaces are the ones that have the highest potential to attract car-to-PT substituting trips, if their accessibility by bicycle is improved to be safe.



Fig. 2. Bike routes with highest potential to serve as first and last leg when replacing cycling and PT from car trips (screenshot of the interactive online tool).

Table 1. Summary of the cycling potencial of intermodality scenario and its socio-environmental benefits for the cycling legs.

Target	Routing	Total trips	Baseline Cycling + PT	Potencial Cycling + PT	Avoided CO2eq (ton/yr)	SE Benefits for 10 years (thousand €)
4%	safe	538 514	2 312	20 385	2 958	115 780
4%	direct	500 880	2 274	18 944	3 004	113 030
10%	safe	538 514	2 312	52 323	7 590	297 510
10%	direct	500 880	2 274	48 609	7 694	289 290

Regarding the PT segment, the shift from private car usage would lead to the mitigation of CO_2 equivalent emissions to 8,500 to 20,800 tons annually, valued in €1.4 million to €3.5 million yearly.

The sum of CO_2eq avoided emissions from the potential car trips shifted to bike (first-and-last legs) in combination with PT (second leg) in the LMA is presented on Table 2, for both national cycling strategy targets and routing profiles, and the socio-environmental benefits monetized in €, for a 1-year and 10-year time periods.

Shifting from car to cycling + PT can reduce annual CO_2eq emissions emissions by 11,500 to 28,500 tons per year, and the 10-year socio-environmental benefits account for €125 million to €325 million, depending on the cycling targets

The environmental impacts represent less than 2% of the socio-environmental benefits (in value) from replacing car trips to bicycle in first-and-last legs. For

Table 2. Summary of the avoided CO2eq emmissions (ton/year) and the estimated social and environmental benefits (monetized in thousand €) by replacing car trips with cycling in combination with PT.

Target	Routing	Avoided CO2eq (tons)	SE Benefits 1yr (k€)	SE Benefits 10yrs (k€)
4%	safe	11 551	14 380	127 534
4%	direct	11 706	14 135	125 016
10%	safe	28 217	36 861	325 814
10%	direct	28 487	35 905	318 062

the PT segment, we did not estimate the social impacts from substituting car trips, although its health benefits would not be as high as shifting to cycling.

The emissions of CO_2eq that are avoided during both the initial and final journey segments account for about 74% of the emissions avoided during the PT segment. This finding, while expected – due the zero cycling emissions, should not be overlooked when promoting the PT use. Improving the safe accessibility to PT interfaces to cyclists and providing bicycle-friendly amenities such as parking facilities can potentially lead to a higher reduction in CO_2eq emissions, compared to a scenario where individuals shift from car travel to car + PT combination.

Our findings show that cycling *in combination* with PT could replace 10% of current LMA trips, with an additional 6% of PT journeys prone to further substitution, based on conservative assumptions.

4 Conclusion

The information on socio-economic benefits can support policy-makers in prioritizing interventions to reduce the reliance on individual motorized transportation, and to better communicate their decisions by providing the expected avoided GHG and air pollutant emissions and the monetized socio-economic benefits for short and long terms.

The information available at *biclaR* tool – an open access website – can be downloaded and used with any GIS software. This allows users to, for example, gain insights into which potential cycling connections have the highest socio-environmental impacts, quantified in tons of avoided CO_2eq emissions, or in long term social benefits.

By making the research process publicly accessible in a code repository, this research enables the replication of similar estimates for socio-environmental impacts, resulting from a modal shift from car to bicycle in combination with PT, in other metropolitan areas.

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Strategic Environmental Assessment of Transport Plans and Programs: How to Reach Systematic Monitoring?

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Abstract. The Strategic Environmental Assessment (SEA) Directive of plans and programs represents a key tool for enabling an earlier integration of environmental issues into the preparation, adoption and implementation of plans and programs that are likely to have significant effects in the environment. Nevertheless, recent research in impact assessment and project appraisal noted that monitoring is still poorly performed, more than 20 years after the launch of SEA in Europe.

Given the above context, this paper aims to address the following research questions: a) Which are the factors that hinder the SEA process and in particular the monitoring of environmental impacts in transport plans and programs? and b) Can any good practices be identified in terms of monitoring frameworks of transport impacts worldwide?

The methodology includes a comprehensive review and in-depth analysis of available SEA studies in main scientific databases and use of data mining tools to enable mapping the range of factors and existing frameworks within the transport domain.

Research results are expected to shed light on further SEA updates to facilitate an effective monitoring and follow-up in implementing transport plans and programs, to enable transitions to the sustainable mobility of people and goods.

Keywords: Strategic Environmental Assessment · Transport · Monitoring

1 Introduction

1.1 SEA of Transport: A Legal Procedure and Enduring Challenge

The European Directive 2001/42/CE, of 27th June, known as the Strategic Environmental Assessment (SEA) Directive [1] envisaged strategic thinking in planning for the earlier integration of environmental issues into the preparation, adoption and implementation of plans and programs that are likely to have significant effects on the environment. In Europe, the implementation of the SEA of transport plans and programs was also driven

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by the launch of this Directive which was transposed to the internal law by all Member States. In Portugal it was transposed in 2007 through the Law Decree 232/2007 of 15th June, rectified by the Law Decree 58/2011, of 4th May, and issued the National guidance on SEA [2].

The SEA comprises several main steps such as scoping, preparation of the environment report (taking into consideration the baseline information and the alternatives), public consultation and participation, decision making, monitoring and evaluation of the impacts, the latter also known as the "follow-up" component. Recent research reveals that monitoring is still poorly performed today, more than 20 years after the SEA Directive was launched, being the "enduring forgotten sibling" in the process [3].

Although the SEA Directive (article 10) refers the need for Member States to monitor the significant environmental effects that result from the plan or programme implementation, it does not recommend any methods or procedures to apply. This fact may have contributed for policymakers to overlook the benefits of demanding a smart monitoring framework, deterring from learning from impact datasets generated through the process that could save resources and be used to future planning [4]. SEA in transport is still understood by policymakers as a legal procedure rather than a collaborative tool for the integration of policies and the capacity building of the complex ecosystem of stakeholders to address jointly common sustainability targets. Given the interdisciplinary nature of SEA, advancing its effectiveness requires a continued research agenda focused on improving the traditional SEA approach [5].

1.2 Research Goals and Methodology

This paper aims to shed light on how to improve the effectiveness of SEA of transport plans and programs through focusing on the analysis of the follow-up process. More specifically, it addresses the following research questions:

a) Which are the factors that hinder the SEA process and in the particular the monitoring of impacts in transport plans and programs?
b) Is there any good practice in terms of solving current gaps and improving SEA monitoring frameworks? What are the remaining challenges?

The methodology includes a comprehensive review and in-depth analysis of SEA studies in main scientific databases and use of data mining tools to enable mapping the research developed over the last five years (2019–2023). The sample of cases shown in this paper enables the provision of insights from worldwide countries on the range of SEA weaknesses and possible common gaps across cases related to monitoring and follow-up activities within the transport domain.

Considering the earlier launch of the SEA Directive in Europe, the existing national SEA guidance across member states was then screened to identify any updates that could be considered a good practice to solve some of the identified monitoring and follow-up gaps. A case example comprising a multi-level monitoring framework developed in the context of a recent multidisciplinary SEA of transport, energy, environmental and irrigation study in Portugal is used to illustrate not only the inclusion of good practice in the monitoring concept, but also the remaining challenges to be addressed at the follow-up and implementation phases.

2 SEA in Transport and Monitoring Practice: Mapping Factors Hindering Effectiveness

2.1 SEA Monitoring in Transport

The previously cited review [3] that covered international research on SEA monitoring available in the Scopus database, gathered 195 publications between 2003 to 2021, which were then filtered to 30 publications for in-depth analysis.

In this paper, bibliographic data or text data mining tools are applied to the Scopus database to understand the research network related to the domain "SEA monitoring in transport", focusing on the last five years (2019–2023). The search strings ["Strategic Environmental Assessment" OR "SEA"] AND ["Monitoring" OR "Follow-up" OR "Follow up"] AND ["Transport"] were applied to meet the purpose. Additionally, the domain was restricted to the above period for all environmental, planning and policy related Journals, rendering 65 publications. Results using VOSviewer show that the "SEA monitoring in transport" research landscape includes six main clusters (Fig. 1, left).

The analysis of the inter-cluster link strengths, measured through the number of publications in which two terms occur together (Fig. 1, right), reveals conceptual approaches of SEA (dark blue) to have stronger relatedness to environmental impact assessment, mitigation and monitoring (red), implementation studies in Europe (light blue), in the Global South and Australia (violet), effectiveness of environmental assessment (green), and policy making, stakeholders and sustainable development goals (yellow).

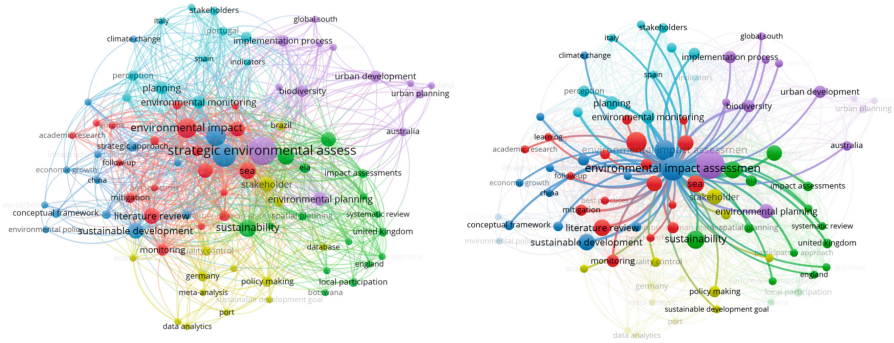


Fig. 1. Network visualization of SEA monitoring in transport research in the period 2019–2023 (left); network with the co-occurrence links between publications' keywords in Scopus (right).

2.2 Factors Hindering the SEA Implementation and Monitoring Practice

Table 1 outlines the main weaknesses that were found to hinder the SEA implementation and the environmental assessment effectiveness using a sample of study cases covering different geographies. Results show that monitoring and follow-up weaknesses in SEA are global concerns across countries.

3 Transport Case Studies with Inspiring SEA Monitoring Frameworks

3.1 Addressing Monitoring Gaps in SEA Guidance

Recently, the Environmental Protection Agency in Ireland (EPA) has updated the national SEA guidance [17] to address previously identified monitoring weaknesses [3, 9], which is an example of good practice. For national-level plans and programs the Irish guidance recommends monitoring five strategic indicators - Biodiversity, Climate, Air Quality,

Table 1. Factors that hinder the SEA implementation and monitoring practice.

Country/Region [Study sources]	Main SEA monitoring/follow-up gaps	SEA study scope/case studies
Italy, Portugal, Spain [Soria-Lara et al., 2020]	Difficulties in implementation; monitoring systems are irrelevant for guiding actions	EU country-cases (Southern Europe); EIA process analysis through online survey
Ireland [González et al., 2019; EPA, 2020]	Unclear monitoring responsibilities; data quality; indicators' adequacy; thresholds; monitoring periodicity; mitigation actions; transparency	National; 15 SEA studies (1 SEA in transport - Greater Dublin Area Transport Strategy 2011–2030)
Germany [Führ, M. et al., 2023; Rehhausen et al., 2018]	Screening practice, transparency, management quality; sources of information, integration into the planning cycle, cumulative effects, monitoring results need to be available in health and environmental agencies	National; 143 SEA studies (2005 to 2018); case study analysis- Federal Transport Infrastructure Plan 2030
Poland [Tokarczyk-Doroczk et al., 2019]	Climate and landscape factors/environmental impacts are insufficiently addressed, lack of monitoring	National; online survey to assess SEA effectiveness (43 stakeholders)
Estonia [Peterson and Vahtrus, 2019]	Monitoring/follow-up stage is missing in SEA due to non-legal requirements	National; database of public SEA notices; semi-structured interviews (12 SEA stakeholders)
New Zealand [Kabier and Morgan, 2021]	Baseline data with inadequate socioeconomic information; no responsibilities for monitoring and reporting results, no recommendations made to deal with residual impacts	Regional; Urban Plan (Christchurch District)

(*continued*)

Table 1. (*continued*)

Country/Region [Study sources]	Main SEA monitoring/follow-up gaps	SEA study scope/case studies
Mexico [Gutierrez et al., 2023]	Novelty of the SEA (lack of knowledge) gives a perceived resistance to recommendations and follow-up (monitoring, evaluation, management, and communication activities); limited institutional capacity of environmental agencies	Municipality; SEA of Puerto Vallarta Urban Development Plan, assessment using stakeholder interviews and reflexive thematic analysis
Botswana [Matome and Mulale, 2023]	Monitoring arrangements are not sufficiently tiered down to link SEA and EIA monitoring plans to avoid duplication of efforts	Regional; 3 Development plans

Water Quality and Land Use, due to their significance and existing European requirements. Nevertheless, the guide recognizes that there is no one-size-fits-all solution to all SEA cases. Different layers of monitoring (tiering monitoring) should be aligned with level in plan hierarchy and make use of global (SDGs), regional and local datasets.

3.2 SEA of Transport Follow-Up: An Exemplification of Remaining Challenges

The National Investments' Program in Portugal - PNI 2030 addresses four thematic areas of intervention (transport and mobility, energy, environment and irrigation) and envisages the implementation of 85 programs/projects until 2030. Transport and mobility projects cover five subsectors (railways, mobility and public transport, road, aviation, maritime-ports) and represent around 52% of the total investment. The SEA study of the PNI 2030 Program [18] proposed a multi-level monitoring framework which was driven by sustainability goals and targets set in national and European strategies. In that context a meaningful set of multi-level indicators and baseline data (including the set of data sources) were selected for the continuous monitoring of project impacts within the scope of five critical decision factors: 1) environmental quality; 2) climate change and energy transition for decarbonisation; 3) natural capital, landscape and cultural heritage; 4) territorial cohesion, mobility and accessibility; 5) competitiveness and innovation. A set of recommendations were thereafter outlined for ensuring an effective monitoring process based on systematic data collection along each project lifecycle, to enable exploring synergies and getting results for possible cumulative environmental effects from projects of different areas and subsectors. The governmental entity responsible for the overall implementation of the Program is responsible for the allocation of monitoring, evaluation and reporting responsibilities to the main intervening entities in the context. The allocation of responsibilities along with the joint commitment of entities are expected to act as key influential factors for the SEA effectiveness.

4 Conclusion

Considering the range of weaknesses identified across the cases analyzed, monitoring and follow-up emerge as global challenges to be tackled, encompassing technical, managerial, legislative, and regulatory issues. Overall, the SEA tool has not yet been implemented to fully met the sustainability goals for which it was designed. Tackling the set of remaining challenges can include further R&D&I to smarten this tool.

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Model-Based Assessment of the Cruising Traffic and Environmental Impact of Parking Restrictions

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Abstract. In many large metropolitan areas, cars cruising for parking significantly contribute to congestion and pollution. At the same time, parking restrictions are contemplated to encourage the use of greener transport alternatives. We give a short overview of a versatile modelling framework for parking search, which can be solved by both numerical simulations and theoretical developments, and we illustrate its applicability in Lyon, France. Then, we show how this framework can be leveraged to assess the environmental impact of parking restrictions, weighing the antagonistic effects of the thus-induced excess cruising vs. mode shift.

Keywords: urban traffic · parking search · graph theory · pollution

1 Introduction

In many large metropolitan areas, parking is a central issue for transport authorities as well as for individual drivers (Shoup [2018]). The latter may spend several dozens of hours every year searching for parking, according to INRIX survey data (Cookson and Pishue [2017]), while cars cruising for parking may represent more than 10% of the total traffic in many large cities (e.g., 15% in central Stuttgart (Hampshire and Shoup [2018])) and thus significantly contribute to congestion and pollution in city centres. In parallel, parking is increasingly regarded as a lever to enforce transport policies.

In particular, over the last ten or twenty years, restrictions on the parking supply have been implemented, or are under active consideration, in various cities across Europe, including Amsterdam, Copenhagen, Lyon, Munich, Paris, Stockholm, and Zurich (Kodransky and Hermann [2010]). This begs the following question: are exhaust emissions increased by such (actual or hypothetical) restrictions because they make parking search longer on average, or reduced because the elasticity of the parking demand curbs trips by car?

We start by underlining the relevance of parking-related studies using the concrete example of curbside parking in Lyon, France. Then, after recapping the general modelling framework that we recently put forward for the parking

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search problem and the insight provided by Statistical Physics and Graph Theory, we show how these considerations can enable transport engineers to assess the impact of hypothetical parking-related measures.

2 A First Case Study: On-Street Parking in Lyon, France

Context. To set the problem in a concrete context, let us illustrate it with the example of Lyon, France, as of 2019. The city belongs to the second urban area in France, with a municipal population around 500,000 people, and it had more than 80k on-street parking spaces, excluding garages and private parking. Curbside parking was either free or charged at one of two rates, depending on the zone; residential offers were available. Besides, the city has efficient transit services in the centre, with 4 metro lines, plus many tramway and bus lines.

On-Street Parking. Difficulties to park in the city centre of Lyon have consistently been reported (Belloche [2015]). To evaluate them objectively, we analyse the results of massive travel survey conducted by Cerema (CEREMA [2015]) in 2015, in which the respondents were asked about their parking search times, among other questions. We focus on the 1,608 reports of on-street parking (regardless of the time of the day). The survival function $P(T \geqslant T_s)$ of parking search times T_s is shown in Fig. 1(left) and has a mean value between 2 and 3 min. While most motorists found a parking space almost instantly, a fraction of drivers had to cruise for more than 10 min, which drives upwards the mean search time. The issue of parking was considered a priority by many of the respondents.

Effect of Parking Restrictions. Given this context, one may wonder about the impact of various hypothetical modifications of the on-street parking plan, notably the (ongoing and prospective) restrictions on the parking supply. We purport to show that this question about hypothetical scenarios can be tackled using a generic methodology relying on a suitable modelling framework.

3 Modelling Framework

We have recently introduced a modelling framework (Dutta et al. [2023]) which encompasses several existing models (Benenson et al. [2008]). It takes as input a network of streets, with parking spots located along them. Car drivers are grouped into distinct categories $\alpha = 1, 2, \ldots$ depending on their destination, trip purpose, etc. At an intersection, they turn into an outgoing street with a probability given by a category-dependent turn-choice matrix $\underline{\underline{T}}^{(\alpha)}$, giving the probability that an α-car moves along an edge of the graph in one arbitrary time step, *if* it does not park in the meantime. When driving by a spot i, drivers park there with probability $p_i^{(\alpha)}$ if it is vacant. Parked cars pull out at a rate $D^{(\alpha)}$, which is the reciprocal of the average parking duration.

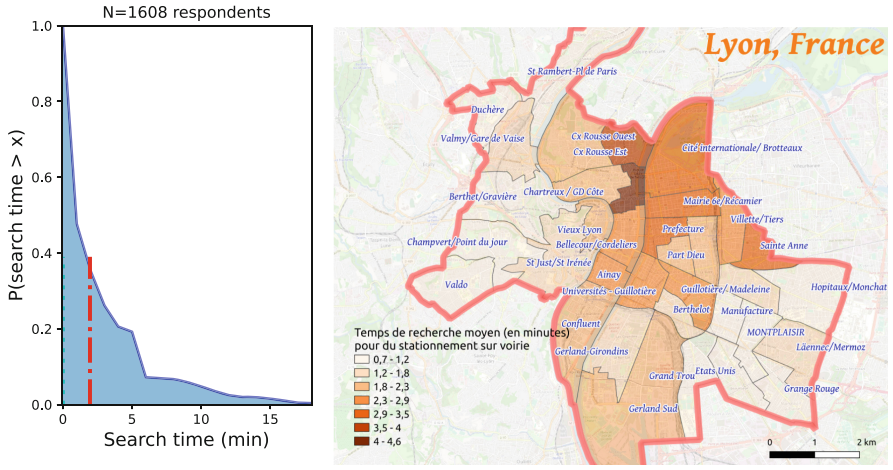


Fig. 1. On-street parking search times in Lyon, France, as declared by respondents to the 2015 survey. (Left) Survival function of search times; vertical cyan and red lines represent the median and mean values, respectively. (Right) Average search time by geographic district. Source of the data: (CEREMA [2015]).

The on-site parking probability $p_i^{(\alpha)}$ may depend on a variety of explanatory variables (rate, distance to destination, etc.); here, these are subsumed into two generic variables: (i) an attractiveness $A_i^{(\alpha)}$ reflecting how attractive a spot i is perceived to be *intrinsically*, (ii) the driver's perception of how easy it currently is to park, $\beta^{(\alpha)} \in [0, \infty)$, viz., $p_i^{(\alpha)}(t) = f(A_i^{(\alpha)}, \beta^{(\alpha)}(t)) \in [0, 1]$. At very low occupancy, when parking seems extremely easy, the driver will refuse to park anywhere but in their preferred spot ($\beta \to \infty$). To the opposite, at extremely high occupancy, virtually any admissible spot will be deemed acceptable ($\beta \to 0$).

Theoretical Insight. On top of its versatility, a major asset of the model is that it can be addressed not only by means of direct numerical simulations, but also more theoretically. For that purpose, the street network is handled as a graph, considering that every street position associated with a parking spot as well as every intersection are nodes of this graph. The instantaneous number of cars of category α, α-cars, passing by each node, averaged over random realisations, is then represented by a vector $\underline{V}^{(\alpha)}(t)$. The transition matrix $T_{ij}^{(\alpha)}$ is useful to locate cars after an arbitrary number o steps, *if they do not park in the meantime*. However, to account for cars pulling in, $T_{ij}^{(\alpha)}$ is substituted by $M_{ij}^{(\alpha)} = (1 - p_i^{(\alpha)}\, \hat{n}_i) \cdot T_{ij}^{(\alpha)}$, where $\hat{n}_i = 1 - n_i = 0$ if the spot is vacant (else, 1).

The average 'driving, searching, and parking' time $\mathrm{T}_s^{(\alpha,j)}$ of an α-car parking at spot j (in arbitrary time steps) can then be derived (Dutta et al. [2023]),

$$\mathrm{T}_s^{(\alpha)} = V_i^{(\alpha)}(0) \cdot \left[\underline{\underline{M}}^{(\alpha)} \cdot \left(\underline{\underline{\mathbb{I}}} - \underline{\underline{M}}^{(\alpha)} \right)^{-2} \right]_{ij} \cdot p_j^{(\alpha)}\, \hat{n}_j. \tag{1}$$

To get the mean occupancy $\underline{n}$, we resort to a mean-field approximation in the stationary regime; a conservation equation yields the desired mean-field stationary occupancy $\langle n_j \rangle$, as detailed in Dutta et al. [2023].

Application to Lyon. Next, we apply the foregoing generic framework to our example of on-street parking in Lyon in the morning peak hour (7am to 10am). Origin-Destination matrices were constructed based on population and employment data and parking occupancy data were measured locally; further details about the specification of the model are provided in (Dutta et al. [2023]).

The average total travel times (including parking search) simulated numerically are shown in Fig. 2, distinguished between destinations. Remarkably, no matter how complex the network is and how many different categories of drivers there are, the theoretical reasoning exposed above (Eq. 1) allows us to quantitatively reproduce most of the numerical results. From the total travel time, the parking search time can be deduced by subtracting the travel time for *vanishing* parking demand from the travel time with the *actual* parking demand. We observe that these search times are also satisfactorily predicted by the analytical formulae (Fig. 2), although some inaccuracies due to the mean-field approximation can be spotted. Still, globally, the zones of high parking tension are well captured by the model, except that it predicts more tension in the North West than what is actually reported.

4 Environmental Impact of Parking Restrictions

Armed with this framework, let us now address the question raised in the introduction, namely, if reducing the parking supply (say, from S parking spaces to $S' = S + \Delta S$, with $\Delta S < 0$) will be environmentally noxious (in that it generates additional cruising traffic) or beneficial (by curbing traffic). We will start by exposing the methodology in a deliberately very stylised way (somewhat akin to (Gragera et al. [2021])), in which only *one period* and one category of drivers (i.e., *one destination* and trip purpose) are considered.

First, let us study the impact of this measure, *ceteris paribus*, on the parking search time $T_{\text{search}}(N, S)$, where the parking demand $N = N(T_{\text{search}})$ is the number of cars aiming to park around the destination:

$$T_s(S') - T_s(S) \approx \Delta S \cdot \frac{dT_s}{dS} = \Delta S \cdot \left[\frac{\partial T_s}{\partial S} + \frac{\partial T_s}{\partial N} \cdot \frac{dN}{dS} \right]. \tag{2}$$

Since $\frac{dN}{dS} = (\frac{N}{T_s}\epsilon_N) \cdot \frac{dT_s}{dS}$, where $\epsilon_N := \frac{\partial \ln N}{\partial \ln T_s} < 0$ is the elasticity of parking demand to search time, we arrive at

$$\frac{dT_s}{dS} = \frac{1}{1 + \frac{N}{T_s} \cdot |\epsilon_N| \cdot \frac{\partial T_s}{\partial N}} \cdot \frac{\partial T_s}{\partial S} \tag{3}$$

Here, we notice that the expected hike of T_s, $\partial T_s / \partial S$, is mitigated by the dip in demand that it induces, via ϵ_N. If the public transit network is accessible and

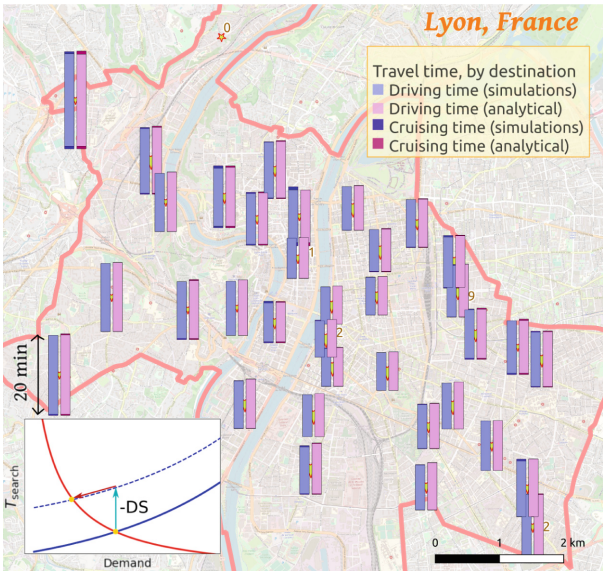


Fig. 2. Mean travel times (driving and cruising) in Lyon: comparison between simulations (in blue) and theory (in pink) for all destinations, irrespective of the entry point, for a global injection rate of 30 cars/min. (*Inset*) Schematic relation between the search time afforded by the street network and the parking demand, and the effect of a reduction DS in parking supply.

efficient, we expect a high elasticity $|\epsilon_N|$, hence a modest impact of the parking supply reduction on the search time because of mode shift.

Finally, the environmental impact of the measure is assessed by expressing the variation in the total exhaust emissions $V_p = V_p(N, T_s, \text{traffic cond.})$ (neglecting the carbon footprint of alternative transport modes, for simplicity) as

$$\frac{dV_p}{dS} = \frac{V_p}{N} \cdot \frac{dN}{dS} + \frac{\partial V_p}{\partial T_s} \cdot \frac{dT_s}{dS} + \text{congestion effect} \tag{4}$$

$$= \frac{dT_s}{dS} \cdot \Big[\underbrace{\epsilon_N \frac{V_p}{T_s}}_{\text{traffic evaporation}} + \underbrace{\frac{\partial V_p}{\partial T_s}}_{\text{excess cruising}} \Big] + \text{congestion effect} \tag{5}$$

Besides the possible (higher-order) backlash on congestion, there are two antagonistic effects between the square brackets. The first one, the demand elasticity to search time, represents the evaporation of part of the traffic following the measure, it indicates how many motorists have switched to another transport mode or given up their journey altogether. The second one is the adverse effect due to the excess cruising generated by tighter parking supply. Both effects are magnified by the sensitiveness of parking search times to these constraints.

Caricatural Examples. Let us illustrate these findings with two antipodal, caricatural examples: (A) Consider a city with sprawling suburbs and extensive motorised commuting (large V_p) despite competitive transit services (large $|\epsilon_N|$), then the first term will largely prevail and the parking supply reduction will be environmentally beneficial, as often found empirically (Kodransky and Hermann [2010]). (B) Conversely, should there be no competitive alternative to driving, the reduction in the parking supply is likely to increase pollutant emission, especially if the induced cruising may represent a significant portion of the total trip.

Conclusion and Broader Applicability. In summary, thanks to a recently proposed quantitative model to estimate parking search times, we have been able to assess in generic terms the environmental impact of parking restrictions, depending on the motorists' propensity to modal shift; the results are qualitatively compatible with observations on travel practices in zones with different degrees of parking tension (Merle and Verry [2009]). Of course, practical cases will never be as clear-cut as the above two examples. More quantitative evaluations are therefore needed, and this is where the framework introduced above can be particularly instrumental, notably for the evaluation of the search time T_s and its partial derivatives, even without resorting to intensive agent-based simulations. (In parallel, the elasticity ϵ_N can be estimated by local (e.g., phone) surveys.) Moving towards these more realistic situations requires relaxing the one-driver-category assumption, but this is readily done in our model, by replacing the scalars N, T_s, S with vectors $\underline{N}$, $\underline{T_s}$, $\underline{S}$ whose components correspond to the destinations (α). The idea can even be further generalised by substituting the variation in parking supply $\underline{\Delta S}$ with modified attractivenesses $A_i^{(\alpha)}$ for the individual parking spaces i, to account for changes in e.g. parking rates. These more realistic situations will be dealt with in an upcoming manuscript.

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Preserving Biodiversity in Railways: Global Strategies for Sustainable Habitat Management

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Abstract. Railways should clearly demonstrate the contribution to the support of healthy ecosystems, and the gains obtained by connecting grey and green/blue infrastructures. This relevance stems from the pivotal role that railways play in striving towards meeting the need for decarbonisation of transport by 2030. The contribution to such progress requires the harmonised integration of biodiversity targets into asset management activities to deliver sustainable infrastructures without loss of value. Within the framework of the International Union of Railways (UIC), several strategies and actions for railway stakeholders have been developed to minimise biodiversity loss, and to value the railways' natural capital. In this article, the UIC's strategy and vision on sustainable habitat management will be outlined through the recent activities and outcomes of several technical projects. Moreover, the development of the future of vegetation control on railways is also illustrated to develop a multi-method holistic approach for tackling the invasive species along railway network. Finally, a guideline to link each railway asset with UIC's biodiversity strategy by mean of implementation of the mitigation hierarchy has been developed for railway infrastructures. As the focus extends to the development of sustainable construction for new rail lines, UIC, together with its members, has initiated the "Ecosystem Valuation for Railways" (ECOV4R) project. This ambitious global approach is aiming to assess, evaluate and monetise the ecosystem services before and after the development and construction of new railway lines.

Keywords: Railways · Biodiversity · Land Use · Habitat Management

1 Introduction

The importance of a shift to rail in the transport sector is widely acknowledged in the international panorama due to the rail's performances in moving people and goods in a safe, reliable and sustainable manner. With the aim of a European net zero scenario [1], the climate and biodiversity crisis should be addressed. Carbon sequestration in natural ecosystems, where carbon is locked up in plants and soils helps railway stakeholders

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in both decarbonisation efforts and habitat creation and restoration through smart and sustainable land use [2]. Within the transport sector, which in totally accounts for approximately 25% of all greenhouse gas emissions [3], railways hold a sustainable advantage due to their electrification status, minimal greenhouse gasses (GHG) emission and efficient land use [4]. Indeed, railways require only 7 m^2 of land per passenger transported compared to 100 m^2 per car passenger [2]. Nevertheless, the amount of land designated to railways, including infrastructure and real estate, is expected to increase. In Europe, targets to double high-speed rail by 2030 and rail freight by 2050 are set [5], while several projects for five world regions are being implemented [6]. Well-managed green infrastructures will bring dual benefits by promoting biodiversity while providing safe and reliable railways operations. Through its green/blue infrastructure railways provide relatively undisturbed corridors including a mosaic of habitats such as embankments, ditches, and woodland providing linear habitat features for dispersal and foraging for a broad range of species [2]. In this article, the UIC's strategy and vision on sustainable habitat management will be outlined through the recent activities and outcomes of the technical projects "TransItion STRategy on vegetAtion Management" (TRISTRAM) [7], "Ecological Effects of Railways on wildlifE" (REVERSE) [2, 8] and the current activities undertaken with the ECOV4R project [9], all managed and delivered by the UIC Sustainable Land Use (SLU) sector.

2 Method: Collaborative Approach

The UIC SLU sector, part of the UIC Sustainability Platform, serves as a global hub for railway organisations to exchange knowledge on how to manage and build railways in a way that also helps to halt the global biodiversity loss. The work programme of the sector is centred on three main topics: vegetation management, biodiversity, and soil quality. Therefore, UIC has established working groups and facilitated knowledge exchange platforms for three successive projects, namely TRISTRAM, REVERSE, ECOV4R. Each of these projects has been undertaken with similar methodologies, supported by UIC members, partners, and other organisations, engaging with more than 25 active stakeholders worldwide. The general framework encompasses round table discussions, desktop research and literature reviews, online surveys and external consultation seeking experts' advice on specific matters and reports production to reach further interested parties. The motivation behind these methods is to provide a global sectoral perspective, promoting the importance of assessing global biodiversity and ecosystem services and ecological corridor connectivity in the construction, operation and management of railway projects.

3 Key Milestones and Themes

The three UIC projects support a common vision of the role the railway sector in biodiversity conservation, providing stakeholders with an understanding on how railways can play a role to overcome the biodiversity crisis. Throughout five years of research, key activities have been performed and important outcomes have been achieved underlining the importance of an internationally standardised approach. These are summarised in the following sections.

3.1 UIC Global Strategy for Habitat Management

Observing the lack of consistent and harmonised vision and strategies for biodiversity management within the railway sector, and among UIC members, it was necessary to implement an internationally agreed approach. A clearly defined set of goals for protecting and enhancing wildlife emerged as essential in effecting positive change in railways. For instance, several railway companies, mainly driven by national targets, paved the way to set global strategies in place across habitats in Austria, France, Germany, and the UK (e.g., [10, 11]). Vegetation management on railways, although carried out regularly for safe and reliable operations, was far from a holistic approach. Strategies were needed to shift from traditional chemical herbicides to a diverse array of innovative alternative methods. The TRISTRAM project provided guidance for this transition and provided best practices to support stakeholder [7]. UIC's strategy centres on optimising herbicide use, and it supports diverse vegetation management methods, promoting multi-method combinations as operative and preventive habitat management. It encourages integrating digital solutions like BIM, GIS, and GPS into new habitat management contracts. Building on this consensus, the UIC Biodiversity Strategy was further developed in the REVERSE project. This initiative aligns with TRISTRAM's vision, outlining ambitions and commitments to manage, enhance and value biodiversity across the railway networks. A core component is a set of thirteen recommendations to minimise the potentially adverse impacts that railways can have on wildlife and boost the direct and indirect positive effects that railways have on biodiversity [2].

3.2 Management Plans: Biodiversity Enrichment

As illustrated in Fig. 1, the sector places top priorities for biodiversity management in the protection and conservation of rare species and habitats (as shown by case studies on transport corridors creation [12] or animals and habitat translocation [13, 14]), the safety and reliability of the rail network, and the elimination of invasive plant species. The project working group supports the application of the mitigation hierarchy, stressing the value of integrating consideration of biodiversity at the earliest stages of planning, and considering it one of the most important recommendations of the Biodiversity Strategy. The four levels should be applied in the following order: Avoid Impacts, Minimise (or reduce) Impacts, Restore (or mitigate) and Offset (compensate).

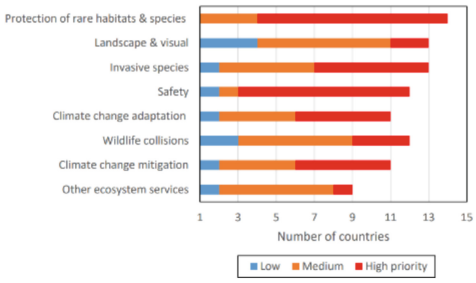


Fig. 1. Priorities of European rail infrastructure managers for biodiversity

3.3 Monitoring Progress

Railways need to monitor and report on their natural assets in order to measure, evaluate and effectively manage them. The monitoring process should encompass two interlinked activities: a stocktake of the biodiversity and habitats present on the railway network, and assessments of the changes of these biodiversity assets over time. The collection of standardised comparable data over time allows to fulfil and put into practice the Biodiversity Strategy [2]. Over 80% of the European railway companies surveyed stated that some aspects of biodiversity are currently monitored, and the progress and accounting for activities that positively and negatively impact is tracked. Our research found that members most commonly monitor habitat type and quality change over time. Numerous companies also monitor ecologically important groups (see Fig. 2) but only 25% of the companies carry out systematic and repeat monitoring [2]. Due to differing geographical and legal factors, there was found to be a lack of consistency with rail network, monitoring different aspects of biodiversity. UIC's biodiversity strategy targets this lack of consistency suggesting consistent biodiversity monitoring and benchmarking.

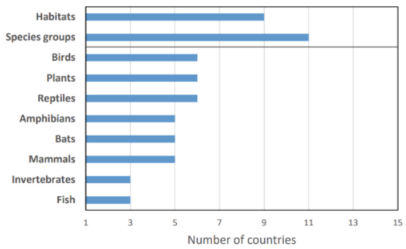


Fig. 2. Results of REVERSE survey - monitoring distinct aspects of biodiversity

3.4 Delivering Net Gain

Biodiversity Performance Indicators (PIs) are important outcomes aimed at assessing the changes in biodiversity assets over time throughout the rail network. They should be reported systematically, as to monitor progress over time and be used as a valuable instrument to measure the achievement of biodiversity targets. In Table 1, a list of PIs proposed by UIC was endorsed with the advice and support of railway experts. Recommendations were made to the sector to report the values in their annual corporate social responsibility reports. Using metrics to minimise impacts on nature and tracking progress will ensure that objectives such as net gain or no net loss are achieved. This requires interdisciplinary collaboration and UIC's joint agreement with WWF-CEE has provided an important direction for the sector. Project members' progresses highlight how UIC strategy has not only come to fruition, but it has also materialized into tangible outcomes. Examples of PIs can be found in ÖBB's work, where in 2021, compared to 2020, an increase in 0.3% of tracks that underwent vegetation inspection has been recorded, and 15% less glyphosate has been used. Overall, 6% less controlled area than in the previous year had to be treated [15]; and in DB's network where the

glyphosate consumption dropped by 50% between 2018 and 2021, with a goal from 2023 of a glyphosate-free railway. Moreover, in 2021, DB applied 4.9t of herbicidal compounds across their 61,000 km rail lines, treating approximately 16% of the tracks, which translates into less than 0.5 kg of active substance per km of treated track [16].

Table 1. Objectives and potential Performance Indicators of biodiversity for railways

Objects	Potential Performance Indicator
Expanding the amount of wildlife habitat	• Area of biodiverse habitat created or restored (ha) • Proportion of sealed and unsealed railway real estate -%
Increasing the connectivity	• Positive trend in habitat connectivity indices • Active monitoring of rare and threatened species and habitats,
Protection of rare species and habitats	• Areas of invasive (plant) species treatment, • Evidence of population growth within railway land,
Reduction in number of wildlife collision	• (Wild) animal collisions: % of identified hotspots or identified line length [km] equipped with protection measures • Permeability - number of culverts per km • Bird protection at the overhead lines of tracks: % of track network or line /track length [km] equipped with bird protection measures
Improved ground water and water quality	• Use of herbicides: % of tracks treated with herbicides /non-chemical methods or track length [km] /track area [ha]/ areas [ha] treated with herbicides /non-chemical methods
Management of invasive alien species	• Areas of invasive (plant) species treatment

4 Conclusions

Railways hold a crucial role in aligning sustainable mobility priorities with ecological conservation, aiming to reduce emissions and support nature. UIC's Biodiversity Strategy highlights that the European rail network intersects over 2,500 protected areas, with over 400,000 km^2 of these areas (16% of the total protected areas in Europe) lying within 1 km on either side of the rail network. These numbers highlight the vast potential for biodiversity. The knowledge and experience gathered from UIC projects needs to be integrated and applied to railway asset management regarding the already existing and to-be-upgraded lines. The thirteen key UIC biodiversity targets are addressed and expanded in the UIC guideline, published in May 2023 [8]. The report presents guidance on the application of the mitigation hierarchy and key design considerations for each grey

asset. The document also includes detailed solutions for various elements of the railway network: track beds, drainages, bridges and tunnels, overhead and high-voltage lines, communication and cable channels, fencing and boundaries, stations and lineside buildings and lineside habitats. The case studies will help the sector to create green corridors with the best habitat connectivity, and enhance the green, blue and grey infrastructures. In the context of new infrastructures development, it is necessary to consider a broader picture in terms of ecological impacts and opportunities for railway. Ecosystem-based approaches and ecosystem services valuation are key features for sustainable railways evolution in line with the 2030 and 2050 targets. For this reason, UIC is targeting ecosystem services valuation for the railway sector with the ECOV4R project, since railways manage large land estates benefitting of, and providing, several ecosystem services. The aim for the railway sector is to value and monetise the ecosystem services related with railway infrastructure projects, mainly concerning new lines. This will possibly lead to solutions to increase the ecosystem services on the used land, ensuring transport network development in compliance with local habitats and natural assets.

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Improvement of SUMP-Methodology for Climate Mitigation

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Abstract. The European transport sector is not keeping on track to reach the Paris Climate Goals. Transport's CO_2-emissions in the EU increased by one third during the past 30 years. This is diametrically opposed to the EU Commission's goal of reducing emissions by 55% in 2030 and completely decarbonizing transport by 2050. Since urban mobility accounts for 40% of all CO_2 emissions, the question arises on how the EU can achieve its goal to decarbonize these and further create 100 climate neutral cities by 2030. This paper analyses Sustainable Urban Mobility Plans (SUMP), promoted by the Commission to solve urban transport problems, and finds major deficits with regard to climate mitigation. The authors propose a reversal of the SUMP methodology by setting climate targets and backcasting in order to identify appropriate measures for climate protection.

Keywords: Sustainable Urban Mobility Planning SUMP · Climate Mitigation in Transport · Planning Methodology

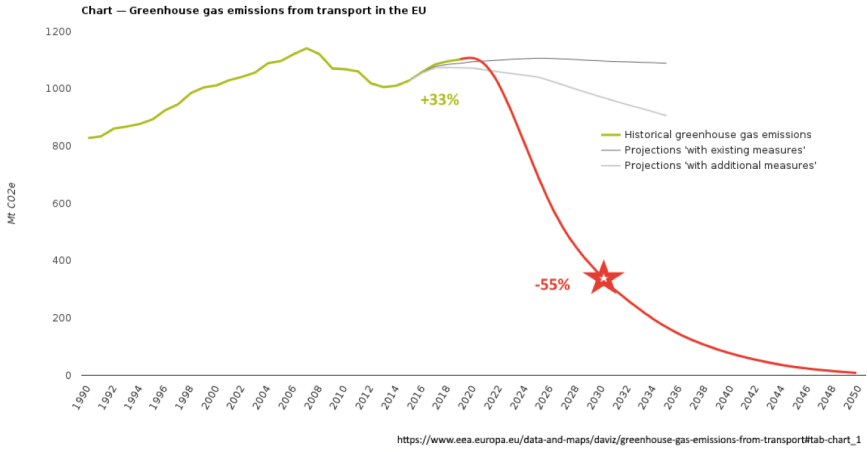
1 Climate Targets in Transport Not Achieved

The European transport sector is not keeping on track to reach the Paris Climate Goals (Fig. 1). While most the other sectors have reduced their emissions, the transport sector increased the output of CO_2 by 33% since 1990. This is diametrically opposed to the EU Commission's new goals of reducing GHG emissions by 55% in 2030 and completely decarbonizing transport in 2050. This target implies that emissions from transport need to be curbed and, arithmetically, decreased annually by more than 10% to reach the 55% reduction goal until 2030. This is a tremendous task – particularly considering the past performance of the sector. The EU Commission (2020, p. 2) consequently demands, "we must shift the existing paradigm of incremental change to fundamental transformation".

The electrification of the cars' drive system is a necessary but not sufficient condition for a Paris-compatible path in the transport sector. Therefore, "traditional" transport planning, using the avoid-shift-improve approach, has to contribute significantly to climate mitigation.

The new TEN-T regulation (EU) 2024/1679 provides guidance on how climate goals can be achieved on the communal level. "All major cities along the TEN-T network will develop sustainable urban mobility plans (SUMPs) to promote zero and low-emission mobility".

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Own graph, data EEA

Fig. 1. Greenhouse gas emissions from transport in the EU 1990 -2050

2 Communal Practice: Muddling Through Instead of Goal-Oriented Planning

A special report by the European Court of Auditors (2020) criticizes that "there is no clear indication that cities are fundamentally changing their approaches. Although cities have put in place a range of initiatives to expand the quality and quantity of public transport, there has been no significant reduction in private car usage". The evaluation of the 2013 Urban Mobility Package (2021) states, "current trends in urban transport do not indicate a significant improvement in terms of modal share, traffic volume and greenhouse gas emissions".

To shed light on the communal practice, Sutter et al. (2022) have screened 190 Sustainable Urban Mobility Plans (SUMP). The results reveal major planning deficits:

- climate targets are often not compatible with the Paris Climate Goals and are insufficiently quantified or not quantified at all;
- planned transport interventions are often not examined regarding their climate impacts;
- long-term and strategic investment planning is often lacking;
- ex-post evaluation of target achievement and implementation of measures is foreseen in less than half of the SUMPs studied; and
- even if ambitious targets are in place, there is a lack of implementation. So far, ambitious climate change targets have not been achieved in almost all cases.

The political and administrative conditions in the municipalities imply that local transport planning is often not very systematic and geared towards solving short-term problems. Political cycles usually comprise four to five years, strategic long-term plans 10 to 20 years, while the Paris agreement is even focusing on 2050. In their totality, the planned measures are usually not suitable for bringing about substantial reductions in

traffic-related GHG emissions. Thus, the next sections develop an approach with a new paradigm and the reversion of the planning process.

3 The New Paradigm Requires the Reversal of the Planning Methodology

Mobility planning is usually determined by future transport demand that is estimated by trend extrapolation. Infrastructures are designed according to this future demand and environmental impacts are merely a byproduct of the process. Instead of influencing future transport demand, the plans generate traffic by supplying additional infrastructures. Thus, transport plans have rather the character of a self-fulfilling prophecy but not enabling a vision of a sustainable mobility.

In order to meet the challenges of climate change, a rethinking in municipal planning is needed. Instead of planning according to "where will we go?", the question is "where do we want to be in 20 years?". A number of cities[1] have already changed their planning philosophy across transport mode boundaries with evaluable objectives as part of an overarching urban and spatial development strategy. E.g., the German State of Baden-Württemberg has developed a SUMP-based planning methodology called Climate Mobility Plans[2]. The goal is to create incentives for communities to develop plans that meet the state's climate targets.

We call this methodology a "Climate SUMP". Focusing on climate mitigation does not mean that the existing SUMP methodology (Rupprecht Consult 2019) should be entirely altered. On the contrary, SUMPs tackle a large number of important issues, such as accessibility, pollution reduction, traffic safety and urban livability that are indispensable for sustainability. However, the achievement of climate targets should be a "conditio sine qua non" for the approval of the plan. Which means, if total future CO_2 emissions do not decline according to a pathway defined by the Paris goals, the whole plan is not considered as sustainable, even though it might include many positive aspects.

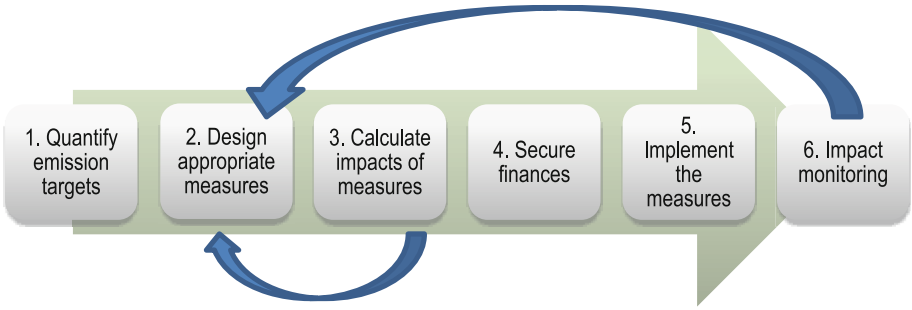


Fig. 2. Procedure for planning and implementation of a Climate SUMP

[1] Zurich (2023), Vienna (2023), Paris, Pontevedra, Umeå (2018).

[2] https://www.klimaschutz-bewegt.de/klimaschutzorientierte-verkehrsplanung/klimamobilitaetsplan/.

4 Methodology of Climate SUMPs

This new paradigm requires a reversal of planning procedures, from forecasting to backcasting, as depicted in Fig. 2. The backcasting approach (Gemeinsame Forschungsstelle 2008) sets future maximum emission levels as target values. This implies to cap future CO_2 emissions from transport, for example by setting an allowable annual CO_2 budget that is reduced over time and finally leads to decarbonization of the transport sector by 2050. The salient planning question is which measures can most efficiently reduce CO_2 emissions to the required level. Six planning steps may be identified:

1. Quantification of emission targets: The basis for a successful Climate SUMP is a political agreement on the climate goals for communal transport planning. The communal council agrees on quantitative targets for the transport sector, which may be based on the 55% goal of the European Commission or a national target. This refers to Phase 2, Step 4 in the official SUMP guidelines (Rupprecht Consult 2019, p.81ff).

2. Design transport measures according to climate goals: The planned transport interventions should focus on the achievement of the goals set in step 1.

3. Calculation of the impacts is imperative since a qualitative assessment of the effects is mostly not sufficient. If impacts are not compliant with the targets, measures need to be reformulated.

4. Secure finances: The planned transport measures need to be included in long-, medium- and short-term investment plans. Adequate financial plans should be developed that include budgeting of future households, credit uptake and donor financing. Good planning needs to assess financial sustainability of the system, including integration into existing programs and assurance of operations and infrastructure maintenance. Werlan and Rudolph (2019), Werlan et al. (2019) and Rupprecht Consult (2019) discuss the complex procedures of funding and financing of SUMPs.

5. Implement the measures. Here a political backlash might occur, since often political agreements taken before do not hold when it comes to implementation.

6. Plan for monitoring: Monitoring is not regularly included in many SUMPs, but may be important, especially if climate targets are not met. The cities of Vienna (Stadt Wien (2023), Zürich (Stadt Zürich 2023), Paris and Umeå (Umeå Kommun 2018) have already implemented a monitoring and feedback processes. These processes check at previously defined intervals whether the planned measures have been implemented and whether the measures have achieved climate targets. If the monitoring reveals that the climate targets have not been met, it is necessary to refine the previous plans in order to achieve the targets. In our approach, this implies a switchback to Step 2.

The SUMP revision process identified a number of important methodological issues that shall not be concealed to the reader since they are important for sustainability (Fig. 3).

5 How Can National and Regional Governments Support Climate SUMPs?

First, municipalities must be motivated to draw up a Climate SUMP. For this purpose, federal and state governments should create incentives for the implementation of Climate SUMPs through funding programs, which include not only contributions to planning

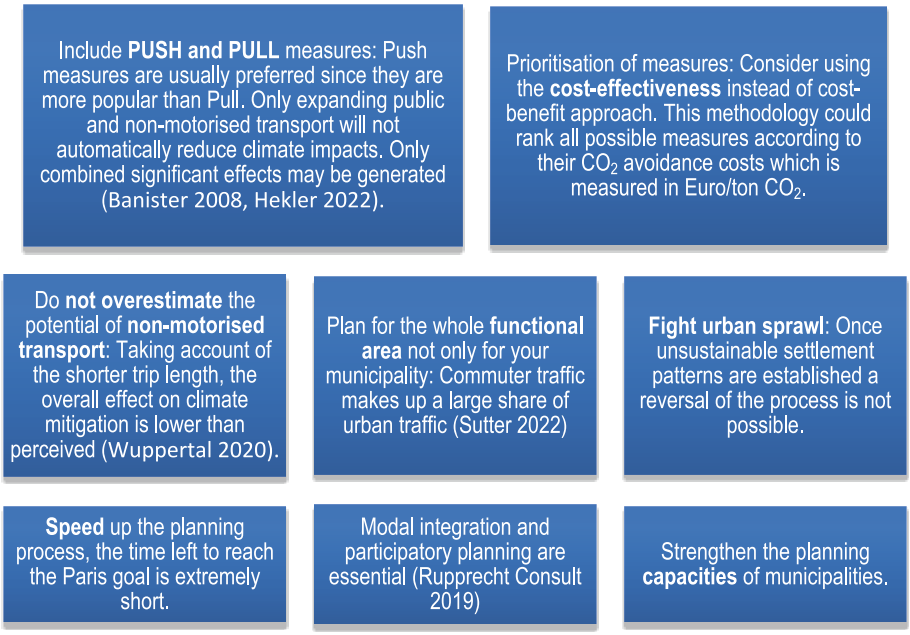


Fig. 3. Recommendations for SUMP improvement

costs, but also investments. Funding should be only provided if the plan proves that its impacts comply with climate targets. The achievement of climate targets may be quantified using the SUMI indicators. Additionally, monitoring of implementation and impacts is necessary. Municipalities need support and guidance for a moderated process to establish a Climate SUMP and implement it. For this purpose, sufficient funds and qualified personnel is necessary.

Federal governments should create a legal basis for Climate SUMPs including binding planning standards and determine how climate targets are defined for federal states and municipalities. This may be done by defining CO_2 budgets. Consequently, larger public subsidies for municipal investments should only be granted if a Climate SUMP is in place. This also means, for example, that no local bypass should be built without a climate mobility plan.

The EU may support this transition process, by funding support to the development of Climate SUMPs. This would at the same time ensure that the mobility planning is not an end in itself but fulfills the needs of the local community.

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The Ripple Association of Mothers' Non-transport Pro-environmental Behaviours with Adolescents' Travel-to-School Mode Choices

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Abstract. This study investigates the relationship between maternal non-transport pro-environmental behaviours, such as energy conservation and environmentally friendly purchases, and adolescents' sustainable transport to school and its temporal changes. Data from waves 4 and 10 of the UK Understanding Society survey (3,022 and 1,890 mother-adolescent pairs, respectively) were analysed using logistic regression to explore the relationship between factor scores for mothers' non-traffic pro-environmental behaviours (derived from confirmatory factor analysis) and adolescents' sustainable transport to school. This study also explored the interaction between maternal non-transport pro-environmental behaviours and survey year to assess temporal variations. The findings indicated substantial correlations between myriad variables, including adolescents' age, mothers' occupational and transport behaviours, and the number of household vehicles, with the adolescents' mode of travel to school consistent across both waves. Moreover, a declining yet positive correlation was found between maternal non-transport pro-environmental behaviours and adolescents' sustainable school transport. Hence, encouraging a range of sustainable behaviours among mothers is crucial to promoting adolescents' sustainable school transport. Additionally, when evaluating the effectiveness of sustainable behavioural interventions targeting adults, considering the ripple correlation with adolescent child behaviours is essential.

Keywords: Sustainable school transport · Pro-environmental behaviour · Maternal factor

1 Introduction

Adolescents choosing sustainable transport modes like walking, cycling, or public transport to school have known health and environmental benefits [1]. However, recent trends in European countries like the Czech Republic and England have shown an increase in the use of cars, accompanied by a decrease in sustainable commuting [2], necessitating investigating the factors influencing school transportation choices to guide effective interventions. Research has indicated that parental factors, including employment status,

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educational level, pro-environmental attitudes, and safety concerns, significantly affect adolescents' school transport choices [3]. However, the relationship between parental behaviours and adolescents' commuting choices has not been fully explored.

Notably, social learning theory suggests correlations between parent-adolescent behaviours like conservation, recycling, and green shopping [4, 5]. This theory is supported by a study linking parents' pro-environmental transport behaviours to their children's active school transport behaviours [6]. However, the question remains whether only parents with pro-environmental transport behaviours influence their children's sustainable transport choices or whether parental non-transport pro-environmental behaviours, like green purchasing and energy conservation, correlate to adolescents' sustainable transport preferences. Considering the high engagement and susceptibility to intervention in such parental environmental behaviours [7], these might hold the potential to promote sustainable transport to school among adolescents.

No direct evidence has established links between parents' non-transport pro-environmental behaviours and adolescents' sustainable commuting choices. However, research has suggested that parental behaviours shape adolescents' pre-environmental psychological constructs, such as attitudes and values [8, 9]. As adolescents develop these psychological constructs, they lead to various green actions extending beyond the behaviours initially learned from parents. Hence, a potential relationship between the non-transport pro-environmental behaviours of parents and the travel-to-school sustainable mode choices of adolescents is proposed and constitutes the initial hypothesis of this study.

Most prior research on adolescents' school commute choices has primarily relied on single cross-sectional studies [3], limiting the exploration of temporal variations in the relationships between determinants and adolescents' transport choices. For instance, how the growing prevalence of parental non-transport pro-environmental behaviours [10] impacts the relationship with adolescents' school transport choices is uncertain, suggesting another hypothesis: as parental non-transport pro-environmental behaviours increase, the correlation between these parental behaviours and adolescents' sustainable transport choices strengthen. This study tests these hypotheses with UK-based adolescents aged 10–15 and their mothers. The focus on mothers in this study is informed by three key reasons. First, mothers are predominantly in charge of their children's education [11]. Second, adolescents' pro-environmental and transport behaviors are more influenced by their mother's behaviours than father's [4]. Third, mothers are usually the primary caregivers responsible for children's school trips [12]. However, it is important to acknowledge the limitation of not fully exploring fathers' influence, suggesting a potential area for future research.

2 Method

This research utilised two cross-sectional studies with data from the UK's Understanding Society dataset. Two distinct periods, 2012/14 (wave 4) and 2017/19 (wave 9), were analysed to examine the relationship between maternal non-transport eco-behaviours and teenagers' eco-friendly school commuting, with any temporal changes. The 2018/20 (wave 10) data supplemented missing information on maternal pro-environmental attitudes and behaviours in wave 9. The dependent variable in this study, school commute

mode, was categorized into sustainable transport and cars by merging responses from the original survey with "sustainable transport" grouping "Walk", "Bike", "Bus/Tube", and "Train" responses. The response "By Car" remained intact as the "Car" category. Notable, the dependent variable is derived from the Wave 9, which was gathered between January 2017 and May 2019. Consequently, the transport choices for school during this period remain unaffected by the pandemic.

The final sample consisted of 3,022 and 1,890 mother-adolescent pairs from waves 4 and 9, respectively. The research measured maternal green purchasing and energy-saving behaviour using a six-question set, with responses scored on a scale from 1 (never) to 5 (always). Mothers' eco-friendly attitudes towards climate change were assessed with six questions scored on a 5-point Likert scale, and higher scores indicated stronger support for environmental conservation. Confirmatory factor analysis (CFA) was performed in the preliminary phase of this research. Table 1 presents distribution of 12 questions on mothers' non-transportation-friendly behaviours and attitudes in waves 4 and 9/10 with their factor loadings. The model, run in an R environment, used the weighted least squares mean and variance-adjusted estimator appropriate for the observed variables, which were ordered categorically with non-normal distributions [13]. The model's goodness-of-fit was evaluated, meeting standard criteria for a well-fitting model. After CFA, factor scores for each mother's non-transport, pro-environmental behaviours and attitudes were calculated. These scores were used as independent variables in the binary logistic regression model dedicated to analysing the factors related to adolescents' modes of transport to school. Based on previous research, eight other control variables (e.g., student demographics, household aspects, maternal socio-demographics, and travel behaviours) were also included.

Odds ratios of each variable were calculated for sustainable vs car transport modes (reference). Next, the datasets from the two waves were combined to assess temporal variations in the influence of mothers' non-transport pro-environmental behaviours on adolescents' modes of transport to school. A two-way interaction term involving behaviours and the survey year was evaluated.

3 Results and Discussion

Table 2 outlines the descriptive statistics of two distinct wave samples with comparable proportions of male and female adolescents. The age distribution was largely similar across both cohorts. Moreover, an increase was evident in the percentages of mothers possessing a degree and working mothers when examining the mothers' sociodemographic traits and travel behaviours. Conversely, weekly bus usage and biking decreased. Considering household factors, there was a nearly 10% increase in households owning more than one car and a rise in those with a net monthly income exceeding £2,000. Regarding adolescent transport methods, car use slightly increased.

Considering the logistic regression results, several control variables (i.e., adolescent age, mother's job status, bicycle and bus use frequency, and car ownership) were consistent across all models. These research findings aligned with previous studies on the subject [3]. Furthermore, Models 1 and 2, based on the fourth wave data, demonstrated that adolescents with mothers holding a degree or higher were less likely to use sustainable transport for school, corresponding with prior research [3]. Model3 and 4 indicated

Table 1. Descriptive Statistics and CFA Factor Loadings for Maternal Non-Transport Pro-Environmental Behaviors and Attitudes across Wave 4 (N = 3022) and Waves 9/10 (N = 1890)

Indicator	Definitions	Wave 4		Wave 10	
		Mean (SD)	Loadings	Mean (SD)	Loadings
Non-transport Pro-Environmental Behaviours					
Mlight	Turns off unused room lights	4.42 (0.882)	1	4.37 (0.931)	1
Mtv	Avoids leaving TV on standby overnight	3.26 (1.79)	2.476	2.81 (1.74)	2.091
Mwater	Avoids leaving tap on while brushing teeth	3.33 (1.66)	3.706	3.60 (1.50)	2.943
Mpack	Avoids over-packaged purchases	1.79 (1.02)	2.141	2.02 (0.997)	2.936
MrecP	Buys recycled paper products	2.51 (1.29)	2.999	2.53 (1.25)	3.126
Mbag	Brings shopping bag	3.65 (1.44)	3.617	4.46 (0.936)	1.416
Pro-Environmental Attitudes					
EA1	Environmental actions must fit lifestyle	2.77 (0.881)	1	2.90 (0.888)	1
EA2	'Environmental crisis' is exaggerated	3.06 (0.880)	1.255	3.42 (0.947)	1.618
EA3	Climate change is beyond control	3.39 (0.896)	1.533	3.58 (0.890)	1.792
EA4	Climate change effects too distant	3.48 (0.923)	1.864	3.68 (0.962)	1.921
EA5	Environmental help depends on others' actions	3.40 (1.03)	2.06	3.57 (0.992)	1.971
EA6	UK climate action futile against others' inaction	3.41 (0.994)	2.132	3.60 (0.998)	2.046
Model fit indices					
GFI			0.99		0.99
AGFI			0.99		0.98
RMSEA			0.04		0.05
CFI			0.96		0.95

that children from households with net incomes ranging from £1,000 to £2,000 were less inclined to use sustainable transport than those below £1,000.

Models 1 and 3 focused exclusively on the role of mothers' eco-friendly attitudes, while Models 2 and 4 expanded to include both attitudes and actions. Models 1 and 3 showed a positive connection between mothers' pro-environmental attitudes and their

Table 2. Distribution of Variables between Wave 4 and Wave 9/10 Samples, and Odds Ratios from Binary Logistic Regression 1–5

Variable Name	LEVEL	Wave 4 sample			Wave 9/10 sample			Wave 4 + 9/10
		Distribution	Model 1	Model 2	Distribution	Model 3	Model 4	Model 5
School transport choice	Car	866 (28.7%)			1327 (70.2%)			
	Sustainable modes	2156 (71.3%)			563 (29.8%)			
Adolescents' sex	Male	1542 (51.0%)			946 (50.1%)			
	Female	1480 (49.0%)	0.98	0.98	944 (49.9%)	1.15	1.15	1.05
Adolescents' age		12.6 (1.7)	1.19***	1.19***	12.4 (1.7)	1.18***	1.18***	1.18***
Mother's education	No Degree	1805 (59.7%)			937 (49.6%)			
	Degree	1217 (40.3%)	0.84*	0.82*	953 (50.4%)	1.01	1.01	0.9
Mother's job status	Working	2159 (71.4%)			1443 (76.3%)			
	Not working	863 (28.6%)	1.21*	1.23*	447 (23.7%)	1.64***	1.64***	1.38***
Mother's bus use	At least once a week	476 (15.8%)			252 (13.3%)			
	Less	2546 (84.2%)	0.47***	0.48***	1638 (86.7%)	0.51**	0.51**	0.50***
Mother's bike use	At least once a week	220 (7.3%)			81 (4.3%)			
	Less	2802 (92.7%)	0.66*	0.68*	1809 (95.7%)	0.38**	0.38**	0.61**
Number of cars	None	376 (12.4%)			150 (7.9%)			
	One	1204 (39.8%)	0.24***	0.24***	645 (34.1%)	0.41**	0.41**	0.28***
	More than one	1442 (47.7%)	0.19***	0.19***	1095 (57.9%)	0.24***	0.24***	0.19***
Net household income	£ < 1000	873 (28.9%)			396 (21.0%)			
	£ 1000–2000	1695 (56.1%)	1.03	1.03	1074 (56.8%)	0.71*	0.72*	0.9
	More than £ 2000	454 (15.0%)	1.07	1.05	420 (22.2%)	0.72	0.72	0.92
Pro-environmental attitudes			1.03*	1.01		1.04*	1.01	1.02
Non-transport pro-environmental behaviours				1.11*			1.06*	1.09*
Non-transport pro-environmental behaviours* Wave								0.97*
n		3022			1890			
AIC			3423.492	3420.155		2187.535	2185.582	5604.631

children's use of sustainable transport to school after accounting for other factors. However, this outcome changed in Models 2 and 4, where the influence of mothers' eco-friendly attitudes on adolescents' sustainable transport choices lost its statistical significance. Instead, the influential factor shifted to mothers' non-transport pro-environmental actions, positively linking adolescents' sustainable transport to school.

These outcomes confirmed hypothesis 1: It is not just attitudes but also the mothers' non-transport pro-environmental behaviours that significantly shape adolescents' sustainable transport to school. This discovery has significant implications for assessing measures to promote sustainable behaviours in parents and adolescents. Thus, it may be essential to consider shifts in various sustainable behaviours among mothers and children when evaluating an intervention targeting maternal sustainable behaviours. For instance, assessing changes in the offspring's sustainable travel behaviours and changes in maternal and adolescent energy-saving-related actions could be beneficial when evaluating an intervention's impact on maternal energy-saving behaviour.

Model 5 examined alterations in the connection between mothers' non-transport-related pro-environmental actions and adolescents' school transport preferences from waves 4 to 9/10. Notable, the diminishing effect of parental non-traffic-related eco-friendly actions on adolescents' inclination towards active transportation modes over time since this finding contradicted the previously formulated second hypothesis. Hence, as eco-friendly actions become more common among adults, adolescents may perceive them as normal rather than exceptional. Consequently, the potency of these actions to shape adolescents' environmental awareness and attitudes may lessen, ultimately influencing their transportation decisions. This research also highlights that as these actions become more common and are perceived as the norm, their novelty and potential to influence adolescent transportation choices may be diluted. This finding emphasises the importance of ongoing dialogue about the value of sustainable behaviours. Even as these actions become commonplace, consistently highlighting their environmental significance and the rationale behind them to adolescents is crucial. Thus, this research broadens insights into factors influencing adolescents' transportation decisions to school and provides direction for potential interventions.

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Managing Biodiversity in the Port Sector: Experiences from Three World Ports

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Abstract. The biodiversity crisis, highlighted for example by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), indicates that up to one million species face extinction risks. Biodiversity's significance is paramount for ecosystem functionality, offering vital services like clean air, water, food, and medicine. Port and coastal areas, often of regional or national importance, benefit from biodiversity. Ecosystems such as wetlands and dune fields around ports maintain water quality, filter pollutants, offer habitats for various species, and act as buffers against industrial pollution.

However, port activities can negatively affect regional flora and fauna, disrupting ecological equilibrium. Some port authorities, like Rotterdam, have initiated measures to monitor and conserve regional biodiversity. The increasing responsibility of port authorities to preserve biodiversity necessitates further research to comprehend ports' impact on biodiversity and devise sustainable management strategies.

This paper examines the sufficiency of current port governance models for biodiversity conservation, proposing a framework based on the experiences of Vancouver, Brisbane, and Rotterdam ports. The analysis reveals that biodiversity loss poses significant challenges for ports. Despite best practices, biodiversity conservation faces hurdles like target fragmentation, interaction with climate change policies, financial constraints, expanding port authority responsibilities without appropriate governance tools, and intricate local stakeholder cooperation.

Keywords: Biodiversity · Port Management · Case Studies · Green Ports · Port Governance · Case Studies

1 Introduction

The biodiversity crisis, driven by human activities like habitat destruction and climate change, is leading to rapid species loss, with a million species facing extinction [1]. This loss is alarming as biodiversity underpins vital ecosystem services, including clean air, water, and food. It also has economic repercussions, impacting agriculture and fisheries, and poses heightened risks to vulnerable communities. Biodiversity is crucial in port and coastal areas, supporting fisheries and mitigating climate effects. Wetlands and marine ecosystems around ports maintain water quality and act as buffers against industrial pollution. However, urbanisation, industrialisation, and transport in port areas threaten

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biodiversity. Activities like habitat conversion and shipping can introduce non-native species and disrupt the environment. Effective management is vital to minimise these impacts and preserve biodiversity in port regions. The importance of biodiversity in ports has been extensively studied [2]. Borja et al. [3] highlight that ports often have areas of salt marshes, wetlands, dune fields, or other important intertidal or marine ecosystems that are locally, regionally, or even nationally important. These areas are crucial for maintaining the ecological balance of the region and provide important ecosystem services, such as carbon sequestration and water filtration. Moreover, they also serve as habitat for various species of flora and fauna, making them a critical component of the biodiversity of the region.

Ports play a pivotal role in shaping the biodiversity of their surrounding environments. Activities, such as cargo handling, can lead to environmental disturbances like spills, which in turn can alter seabed conditions, increase organic loads, and heighten turbidity, thereby affecting marine life [4]. Additionally, noise pollution emanating from port operations has been identified as a detrimental factor for marine species [5].

Recognising the environmental implications of port activities, global regulators have been proactive in their efforts to safeguard biodiversity in these areas. The European Union (EU) stands out in this regard. It has rolled out the EU Biodiversity Strategy, aiming to halt and reverse biodiversity loss by 2020. This strategy encompasses targets and actions centred on ecosystem restoration, sustainable agriculture promotion, and the prevention of invasive species introduction. Furthermore, the EU has established Natura 2000, a vast network of protected areas that spans over 18% of the EU's land and 9% of its marine territories. These sites, designated under the Birds Directive and the Habitats Directive, are geared towards the protection of rare species and habitats. The EU also enforces regulations like the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) to control endangered species trade. Additionally, funding programmes like Horizon Europe and the LIFE programme support research and innovation related to biodiversity, aiming to understand and address the multifaceted challenges of biodiversity loss.

In the United States, efforts to address biodiversity losses in port areas have been significant. The National Oceanic and Atmospheric Administration (NOAA) leads initiatives to protect coastal habitats crucial for marine species. The Coastal Zone Management Act of 1972 established a national framework, balancing coastal economic development with environmental conservation. States like California have implemented regulations to reduce ship emissions, and the Port of Los Angeles introduced a Clean Air Action Plan to mitigate port-related air pollution.

Australia prioritizes port biodiversity management, given its distinct marine and coastal ecosystems. The Department of Agriculture, Water and the Environment (DAWE) oversees national biodiversity conservation policies. The Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) assesses the environmental impacts of significant projects, including port activities. The Australian Maritime Safety Authority (AMSA) implements measures against invasive marine species introduced via ballast water and ship hulls. State environmental agencies collaborate with maritime authorities, ensuring port operations align with both national and local environmental standards, emphasizing a harmonized approach to biodiversity conservation in coastal regions.

Despite the critical role that biodiversity plays in ports and coastal areas, it has received relatively little attention in port management studies. Traditionally, ports have viewed biodiversity primarily as a cost, rather than a valuable asset to be conserved and managed sustainably. As a result, the environmental impacts of port activities on biodiversity have been largely overlooked, and strategies to mitigate these impacts have been limited. This is particularly concerning given the growing recognition of the urgent need to protect and restore biodiversity worldwide, and the potential economic and social benefits of doing so. While some efforts have been made to promote sustainable port development and biodiversity conservation, more research is needed to better understand the relationship between ports and biodiversity, and to identify effective strategies for managing this relationship in a sustainable and socially responsible manner.

2 Anchoring Biodiversity in Management Theory

Biodiversity, while extensively studied, has seen limited integration into management discourses. In this paragraph a brief overview of theories that lend themselves to the application in the context of port biodiversity are discussed. **Natural Capitalism** [6] emphasises efficient resource use through *Radical Resource Productivity*. *Biomimicry*, another principle, suggests businesses draw inspiration from nature's efficient processes. The *Service and Flow Economy* concept advocates for a shift from selling products to offering services, while Investing in Natural Capital emphasizes the value of conserving ecosystems.

Another approach is rooted in the concept of **Stewardship** [7], that encourages firms to prioritize long-term sustainability. This approach extends beyond mere financial gains, encompassing broader social, environmental, and ethical responsibilities. It emphasizes *transparency*, *stakeholder engagement*, and *resource guardianship*. Practical stewardship applications include sustainable supply chain management and proactive environmental restoration efforts.

Ecosystem services have also been theorised and significantly impact human well-being [8]. While economic perspectives often equate value with monetary metrics, a broader understanding includes ecological significance and human well-being aspects, such as freedom of choice and inherent values. Ecosystem services also encompass cultural and spiritual benefits, highlighting the bond between society and nature.

Hart's **Natural-Resource-Based View** (NRBV), rooted in the Resource-Based Theory (RBT), underscores the importance of internal resources in achieving competitive advantage. Hart [9] expanded RBT by considering the interaction between organizations and their environment. He proposed strategies like *Pollution Prevention* for waste reduction, *Product Stewardship* for holistic value chain consideration, and *Sustainable Development* for balanced growth. Over three decades after the NRBV was conceptualised, still little attention had been paid to Nature in management. These theories offer new perspective on biodiversity in ports, highlighting its value instead of presenting biodiversity as a boundary condition for port operations.

3 Methodology

The methodology chosen for this paper is rooted in a comprehensive literature review, where bibliographic databases were searched for peer-reviewed publications centred on biodiversity in ports from a managerial perspective, giving precedence to studies spotlighting ports at the forefront of biodiversity initiatives. To ensure a broad spectrum of insights, cases were chosen from diverse geographic regions, capturing varied ecological, economic, and socio-political landscapes. This included representation from North America through the Port of Vancouver, Europe via the Port of Rotterdam, and Oceania with the Port of Brisbane. The leadership of these ports in biodiversity initiatives was assessed by examining their commitment to biodiversity preservation, manifested in policies, initiatives, and tangible actions. To bolster the robustness of the selection, researchers in biodiversity were consulted to validate the representativeness of the chosen ports. The information collected was complemented with conversations with port representatives. It is worth noting that case study research offers valuable insights for generalisations, providing depth and context often missed in broader studies [10].

4 A Case of Three World Ports

While a detailed account of the case studies is beyond the scope of this section, I will briefly highlight the biodiversity characteristics and actions in the studied World ports.

Port of Brisbane (Oceania): The Port of Brisbane emphasises the coexistence of commercial activities with local ecosystems, initiating various marine life conservation projects. Since 1991, the port has witnessed a 200% growth in its adjacent seagrass bed, expanding from 4.4 km^2 to 13.9 km^2. Surrounding the port are approximately 352 hectares of mangroves, vital for coastal protection and marine biodiversity. The FPE seawall, extending 4.6 km, stands as one of the longest intertidal and subtidal rocky habitats within western Moreton Bay. In terms of weed management, the port has successfully ensured that no priority, prohibited, or invasive weed species are present on PBPL land. Real-time air quality monitoring stations have been strategically placed around the port, and continuous ambient water quality monitoring is conducted to ensure that port operations have no adverse impacts on the environment.

Port of Rotterdam (Europe): The Port of Rotterdam, home to over 200 unique plant and animal species, including orchids, Highland cattle, seals, and pipistrelle bats, has innovated with eco-friendly infrastructures. Integrating biodiversity into its expansive harbour developments, the port's Nature Vision, developed in line with the Port Vision 2030, outlines its approach to incorporating nature into plans and projects. This vision recognises the port's hectares of nature as a vital ecosystem. Nature-friendly management practices are applied throughout the port area, ensuring a harmonious balance between plants, humans, and animals. These initiatives encompass nature-friendly banks, ecological mowing management, and monitoring of protected flora and fauna. The port also undertakes efforts to control exotic or foreign species that could threaten native species or infrastructure. By managing these problem species, the Port Authority aims to restore the natural ecosystem. The port's unique geographical location in a river delta on the

coast serves as a biotope for various species, and 'ecological stepping-stones' have been constructed to facilitate the movement of plants and animals across the port.

Port of Vancouver (North America): The Port of Vancouver operates within an ecologically rich environment, home to a diverse range of aquatic and terrestrial species, including marine mammals and riverine ecosystems. Demonstrating leadership in habitat restoration and enhancement, the port aligns its initiatives with Canada's biodiversity conservation goals. To support species at risk, the port has implemented protections under the Species at Risk Act for species such as sturgeon, bats, bees, and turtles. The Enhancing Cetacean Habitat and Observation (ECHO) Program specifically targets the reduction of the shipping industry's impact on the vulnerable southern resident killer whales. Collaborative efforts with port tenants and the broader community aim to reduce underwater noise, mitigating its effects on marine life. The port also prioritises the prevention of invasive plant species introduction and spread, recognising the threat they pose to native biodiversity. Through responsible land and water management, the port monitors local water quality, ensuring the protection of wildlife and addressing contamination on leased sites. The Habitat Enhancement Program (HEP) further exemplifies the port's commitment, focusing on balancing port development with environmental health by creating and rehabilitating habitats beneficial to regional fish and wildlife.

5 Findings and Conclusion

The Port of Vancouver, Rotterdam, and Brisbane each demonstrate distinct approaches to biodiversity management, reflecting their unique ecological, economic, and sociopolitical contexts. Vancouver's focus on habitat restoration, underwater noise reduction, and invasive species prevention showcases a proactive stance towards biodiversity conservation, aligning with national conservation goals. Rotterdam, on the other hand, integrates eco-friendly infrastructures and nature-friendly management, emphasising the coexistence of industrial activities with natural ecosystems. Brisbane's efforts centre on marine life conservation, with significant emphasis on seagrass monitoring, mangrove conservation, and seawall maintenance. While each port has made efforts in biodiversity management, their strategies vary, reflecting regional priorities, challenges, and stakeholder expectations.

The NRBV underscores the importance of internal resources in achieving competitive advantage. Vancouver's habitat restoration and Rotterdam's eco-friendly infrastructures can be seen as leveraging internal resources for long-term sustainability. The Natural Capital Theory, which values ecosystems for their tangible and intangible benefits, is evident in Brisbane's emphasis on seagrass and mangrove conservation, recognising their ecological and economic worth. The Ecosystem Services theory, focusing on the benefits humans derive from ecosystems, aligns with Rotterdam's nature-friendly management and Vancouver's efforts to balance port development with environmental health. Lastly, the Stewardship Theory, which prioritises long-term sustainability over short-term gains, resonates with each port's commitment to biodiversity. Vancouver's proactive measures, Rotterdam's integration of nature into port developments, and Brisbane's marine conservation initiatives all reflect a stewardship mindset, prioritising long-term ecological health and sustainability.

The role of ports is undergoing a transformative shift. No longer viewed as isolated operational entities, ports are emerging as stewards of expansive ecosystems. Their sphere of responsibility now goes beyond their immediate proximities, often including ecosystems that lie beyond the confines of port areas. This evolution underscores the need for novel business models that empower ports to harness the distinctive biodiversity resources they oversee. As connecting points between human activity and natural ecosystems, ports hold a crucial position in both protecting and capitalising on ecosystem services. Acknowledging the value of these services is not just beneficial but indispensable for sustainable port management strategies and informed decision-making processes.

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Model of Societal Cost of Travel for Real Time Urban Traffic Management Supporting V2I Systems

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Abstract. This work develops and tests a model that estimates the societal cost of travel by automotive vehicles in real time urban traffic conditions, as a function of mean velocity and acceleration. The research goes beyond the existing literature and studies the societal cost of travel in urban road networks to support real time urban traffic management via V2I systems. Travel time, traffic accidents, fuel consumption and pollutant emissions are the four factors that affect the societal cost; and thus environmental and economic facets of society. The societal cost reduction was studied and optimal values of mean velocity and acceleration of vehicles were estimated to minimize the cost. Experimental, field and simulation data were used. The methodology was applied to two traffic case studies at an urban coastal road in Patras city, Greece. The first case refers to the estimation of the mean velocity value that results in the minimum societal cost of travel, when controlling the network to achieve a constant-speed mode. The second case refers to the estimation of the deceleration values resulting in the minimum societal cost of travel, when a network is operating in a constant-speed mode and a red light is going to be imposed. Model integration into V2I system is tested via simulation.

Keywords: Societal Cost of Travel · Urban Road Traffic Systems · V2I Systems

1 Literature Review

The problem of the increased societal cost of travel is intense in urban environments, since citizens are directly affected by the negative social, economic, environmental and health impacts [1]. However, literature deals mostly with societal cost modelling for speed limits definition and assessment in motorways; whereas urban road networks have not been studied adequately. Researchers were focused on minimizing the societal cost of travel, consisting of the cost of travel time, vehicles' operation, traffic accidents, air and noise pollution, to define the speed limits of a road segment. The optimal limits were calculated from four different perspectives. The results showed that the speed limits were higher for the perspective of the individual user and the taxpayer, while they were lower for the resident perspective. Regarding the results obtained for the social point of view, the speed limit values were not far from the limits in force. Also, in some study cases of motorways with travel speeds of 70 km/h to 110 km/h, the effect of the

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travel time factor was low [2]. In another research, the relation of private and societal cost of travel was examined considering three factors; travel time, traffic accidents and fuel consumption as function of velocity. To apply their method, it was necessary to quantify specific parameters such as the value of travel time, loss of human life and injuries, and the rates of each type of traffic accident. To do so, the researchers followed an alternative method based on observing drivers' behavior and average speed where no speed limit was proposed. This method can be satisfactorily applied to all types of roads, regardless of whether they applied it to motorways. They concluded that a speed limit should be determined based on the combination of private and social optimum speed [3]. Further, the non-obedient behavior of drivers when choosing travel speed was studied to optimize variable speed limits based on the societal cost of travel. It was considered that drivers decide the speed at which to travel by considering the journey cost in terms of time, the risk of crashing and being fined for exceeding the speed limit. Further, a separate analysis was carried out for drivers with uniform driving behavior and non-uniform driving behavior, as researchers believed that driving behavior is differentiated according to the social and economic characteristics of users [4]. Researchers studied the optimal speed limits on motorways estimating the private and societal travel costs, concluding to a higher travel speed when private perspective is assessed. They used traffic data where the applicable speed limits were increased recently. Increase of the speed limit by 16 km/h, would result in 2 to 7 times higher societal cost compared to social benefit [5]. There are several studies determining optimal traffic speed of a road network based on pre-defined factors and criteria. Each study follows different models and defines speed depending on the priorities of the researchers. Societal cost of travel can be reduced through implementation of more intelligent traffic management solutions, based on a spatiotemporal reservation scheme supported by V2V and V2I communications, allowing the exchange of information among vehicles and infrastructure [6].

2 The Proposed Model

The proposed model for the estimation of the societal cost of travel by automotive vehicles results in the improvement of traffic and citizens living conditions in urban environments; having an impact on critical social sectors such as health, quality of life, safety, environment and economy. In this paper, the societal cost of travel [€] consists of four factors, the cost of: a) travel time (TTC), b) traffic accidents (TAC), c) fuel consumption (FCC), and d) pollutant emissions (PEC) as shown in Eq. 1. These are considered as the most important [2, 5] determinants in the estimation of the societal cost of travel.

$$Societal\ Cost\ of\ Travel = k_1 * TTC + k_2 * TAC + k_3 * FCC + k_4 * PEC \quad (1)$$

As for the weighting coefficients k_i, different values can be assigned when one or more factors are chosen to have a higher effect. During the literature review, it was observed that these coefficients should take different values if the researcher studies the societal cost from the perspective of the individual user travelling on the road network or from the perspective of the society that is directly or indirectly affected by the traffic on the road network [2]. In the present research, society's perspective is studied; thus the weighting coefficients are all equal to 1.0.

2.1 Travel Time Cost

The cost of travel time (TTC) significantly affects the estimation of the total societal cost of travel, as road-users immediately consider it to be wasted time away from their work or daily activities. This cost depends on user's purpose of travel, which is divided into two main categories, work/pleasure. In Eq. 2, T(V) is the travel time per traversed distance [sec/m] and vehicle as a function of velocity V [m/sec]; U is the unit cost of travel time depending on travel purpose of [€/sec-person]; d is the traversed distance per vehicle j [m]; and x is the number of passengers per vehicle [persons].

$$TTC(V) = \sum_{j=1}^{n} T(V) * U * d * x \tag{2}$$

2.2 Traffic Accidents Cost

The cost of traffic accidents (TAC) is estimated based on Eq. 3 which derived from [7–9]. In this study, the accidents are either property damage only (PDO) or all injuries (AI). V is the velocity [m/sec] of the vehicle(s) involved in the accident; V_{Ref} is the mean velocity [m/sec] of the vehicles moving on the road network when the accident took place or the velocity limit of the road network; n is the number of traffic accidents per type of accident, U is the unit cost of traffic accidents per type of accident [€/accident], and exp1/exp2 are exponents of the power model of [10].

$$TAC(V) = \left(\frac{V}{V_{Ref}}\right)^{\exp 1} * n_{AI} * U_{AI} + \left(\frac{V}{V_{Ref}}\right)^{\exp 2} * n_{PDO} * U_{PDO} \tag{3}$$

2.3 Fuel Consumption Cost

The societal cost of travel in an urban environment is significantly affected by the fuel consumption, as in urban road networks traffic is usually controlled by traffic lights that force drivers to stop and restart frequently while moving. FC_f is the fuel consumption [ml] per type of fuel f (petrol, diesel, LPG, etc.) as function of the velocity (V) and acceleration (a) depending on the moving conditions of the vehicle; idling, travelling at constant speed, accelerating or decelerating [11–13]. U is the unit cost of fuel f [€/ml] and Eq. 4 presents the cost of fuel consumption (FCC).

$$FCC(V, a) = \sum_{f=1}^{n} \left(FC_f(V, a) * U_f\right) \tag{4}$$

2.4 Pollutant Emission Cost

The pollutant emissions cost (PEC) is calculated based on Eq. 5 following Panis et al. [14] model for the estimation of $PE_{p,f}$ which are the pollutant emissions [g] per pollutant p (Carbon Dioxide-CO_2, Nitrogen Oxides-NO_x, Volatile Organic Compounds-VOC, Particulate Matter-PM) and type of vehicle f (petrol/diesel/LPG/etc.) as a function of velocity (V) and acceleration (a). U is each pollutant emission unit cost [€/g].

$$PEC(V, a) = \sum_{p=1}^{m} \sum_{f=1}^{n} \left(PE_{p,f}(V, a) * U_p\right) \tag{5}$$

3 Model Integration into V2I

Since technology is being developed offering new opportunities to road operators and users, the integration of the proposed model into Vehicle-to-Infrastructure (V2I) systems is imperative, supporting dynamic traffic management in real time conditions.

Through V2I system, the proposed model for the estimation of the societal cost of travel is implemented using real time data collected directly from the vehicles moving on the under study road segment (e.g. travel distance, moving conditions of the vehicle; idling, travelling at constant speed, accelerating or decelerating). The function of the societal cost of travel (Eq. 1) is estimated in real time per pre-defined time interval resulting in optimal values of velocity and/or acceleration that minimize the societal cost. The V2I system imposes, in real time, to every vehicle that enters or moves on the under study road segment the optimal velocity and/or acceleration to minimize societal cost; managing traffic in the most efficient way.

4 Case Studies

The reduction of the societal cost of travel was studied, and optimal values of mean velocity and acceleration of the vehicles moving on a section of Othonos - Amalias Avenue were determined to minimize the cost. This Avenue is the major coastal road of Patras city, Greece; connecting the city with the main port, serving also daily thousands of vehicles as one of the main city exits, while heavy vehicles are obliged to use this road when crossing the city.

The methodology was applied to two traffic case studies. The first one refers to the estimation of the value of the mean velocity that results in the minimum societal cost of travel, when controlling the network to achieve a constant-speed mode. The second one refers to the estimation of the value of deceleration resulting in the minimum societal cost of travel, when a network is operating in a constant-speed mode and a red traffic light is going to be imposed.

Experimental, field and simulation data were used to determine how the mean velocity and acceleration of a road segment affect the four factors, and consequently the societal cost of travel. Field data (traffic flow, volume, turning percentages, traffic accidents, traffic lights cycle, public transport data) were collected during a two hours' period of a weekday morning including peak hours.

5 Results

5.1 Constant-Speed Mode

After data collection, through microscopic traffic simulation, from vehicles moving on the under study road segment, the function of the societal cost of travel (Eq. 1) was estimated for pre-defined time interval of 5 s. The value of mean velocity that minimizes societal cost is 10.7 m/sec = 38.5 km/h, as shown in Fig. 1, when no mean acceleration occurs and the road segment is in constant-speed mode. For this value, societal cost is approximately 0.62 €. It is noted that this velocity is under the speed limit of 50 km/h of the road under study. Figure 1 demonstrates that when mean velocity is low, and in particular below 1 m/sec, the societal cost of travel rises at a high rate.

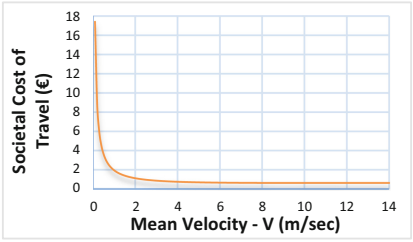


Fig. 1. Societal cost of travel and mean velocity for the constant-speed mode case study.

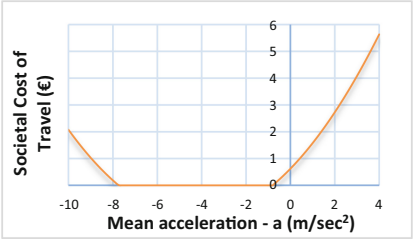


Fig. 2. Societal cost of travel and mean acceleration for the red traffic light case study.

5.2 Deceleration Prior to Red Traffic Light

For the second case study, when a network is operating in constant-speed mode and a red traffic light is to be imposed, the values of acceleration resulting in the minimum societal cost of travel are estimated as shown in Fig. 2. It is noted that for acceleration from -0.9 till -7.7 m/sec^2 societal cost of travel is 0. On the contrary, societal cost is being increased at a high rate for acceleration values not included in this interval.

5.3 Testing Model Integration into V2I

In Fig. 3 the relation between mean velocity and traffic flow is presented. It is shown that the points of the case in which the model was integrated into V2I system via microscopic traffic simulation are slightly shifted further to the right than the points of the case without the integration. It denotes that when the model is integrated into V2I system the traffic flow is higher for the same mean velocity; thus the traffic flow is improved and more vehicles are served.

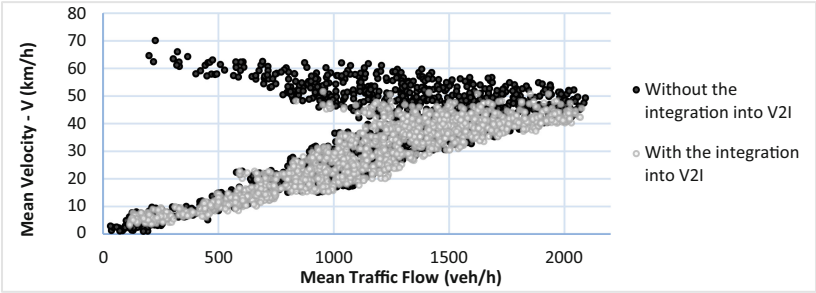


Fig. 3. Mean velocity and traffic flow for a study period of two hours.

6 Conclusions

It is concluded that the societal cost of travel is being increased considerably for low velocity or high acceleration values. High acceleration values result in increased cost of fuel consumption and pollutant emissions, affecting respectively the overall societal cost; as noticed in other studies too [5]. Low velocity values result in decreased cost of traffic accidents, fuel consumption and pollutant emissions which should imply positive influence on the overall societal cost in accordance to [2]. However, this implication is not valid since velocity is inversely proportional to travel time, meaning that low velocity values result in high travel time cost; affecting respectively the overall societal cost. Furthermore, when the model was integrated into V2I system, the traffic is smoother; since the velocity values vary in a smaller range compared to the case without integration and the extreme velocity values are notably less. Also, the traffic flow is higher for the same velocity values; thus the traffic flow is improved enabling the road segment to serve more users.

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Driving Toward the Future: Assessing Electric Automated Vehicle Deployment Scenarios in Suburbs

A Case Study of Grorud Valley, Norway

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Abstract. This study evaluates electric automated vehicle deployment scenarios in suburban areas, using Grorud Valley in Norway as a case study. It aims to determine the best deployment scenario compared with the current situation. Four scenarios were evaluated for global warming potential, air pollution emissions, and accidents. Each parameter was weighted with an external cost factor to calculate the aggregated total external costs for each scenario. This study revealed that electric automated vehicles with ridesharing integrated into Mobility-as-a-Service networks yielded the best results. With 100% market penetration, external costs can be reduced by 66%, and even with 30% market penetration, they can be reduced by 20%. Climate change costs were the main contributors, accounting for more than half of the costs in all scenarios. Although introducing automated vehicles in combination with public transport and ridesharing in a Mobility-as-a-Service concept helps reduce external costs, most of the benefits are derived from the electrification of the vehicle fleet and not from the new mobility concept.

Keywords: Electric Automated Vehicles · External Costs · Externalities · Mobility Scenarios

1 Introduction

1.1 Context

The rapidly evolving urban transportation landscape has introduced new possibilities for sustainable mobility systems. Among these innovations, automated vehicles (AVs), in combination with changes in the current mobility paradigm, have recently attracted interest. As cities strive to minimise greenhouse gas (GHG) emissions and improve transportation efficiency, AVs offer a possible solution. This study aims to investigate the potential benefits of integrating electric AVs into mobility networks with a focus on achieving a more sustainable mobility system in the suburban Grorud Valley.

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The research question is as follows: How do different deployment scenarios of electric automated vehicles impact external costs caused by transportation/mobility in suburban areas? A literature review was conducted to identify scenarios and quantitative indicators for scenario analysis. This analysis evaluated the indicator magnitude and selected the best strategy for the Grorud Valley. Grorud Valley is a suburb northeast of Oslo, Norway, and includes four districts. It houses approximately 140,000 residents with an annual growth trend likely to persist in the future [1]. Its Public Transport (PT) system struggles to compete with private cars, particularly for internal trips in the valley, which constitute 41% of all journeys, owing to abundant parking and extended transit durations by PT [2]. Few studies have explored the impact of AV on suburbs, despite simulations in major European cities. Since PT is often not adequately present in suburbs and face different challenges, the lack of research underscores a gap in suburban AV research, which this study attempts to fill. Its findings can guide the local Public Transport Authority (PTA) in assessing electric AV effects on mobility and the environment, informing implementation decisions, and aiding similar suburbs.

1.2 Scenarios, Externalities and External Costs

Scenario planning, a strategic tool, helps entities and institutions forecast and strategize for future events. Although there is no single definition, it is widely accepted as a useful way to anticipate and respond to possible future developments [3].

Externalities arise when one's actions impact another third person´s welfare without compensation and without being reflected in user prices [4]. Assessing the implications of AVs in different deployment scenarios is vital, as shown by the recent increase in the number of studies on AV scenarios and externalities. These studies delve into aspects including emissions, traffic, land use, energy, and societal aspects. Notably, Miskolczi et al. [5] developed urban mobility scenarios based on a literature review focusing on automation, sharing, electric vehicles, congestion, social attitudes, and GHG emissions, while Milakis et al. [6] developed four scenarios for AV implementation in the Netherlands and assessed them based on market penetration rate, road capacity, user implications, travel behaviour, and transport planning. While optimism surrounds many findings, cautionary voices such as Litman [7] highlight potential AV drawbacks such as heightened congestion and pollution. Additionally, May et al. [8] found that AVs that are not integrated with PT might escalate both vehicle kilometre (vkm) and passenger kilometre (pkm). The local PTA studied six AV implementation scenarios in urban Oslo using the approach of the ITF´s Lisbon studies [9–11], evaluating their impacts on fleet size, vkm, and network efficiency [12]. Although the Lisbon studies methodology has also been used in other cities, only one has incorporated suburban areas into their models [11]. Externalities expressed in specific units, such as CO_2eqivalents (CO_2eq), can be challenging to communicate. By converting these impacts into external costs, a single monetary value, it becomes more accessible and allows for comparison with economic instruments such as taxes and incentives [13]. Methodological frameworks such as the damage cost approach, avoidance cost approach, replacement cost approach, or willingness-to-pay can be used to calculate external cost factors for transportation [14, 15].

2 Methods

2.1 Deployment Scenarios

The deployment scenarios selected for further evaluation (Table 1) are based on the studies of Lisbon and Oslo [9–12] and research of Miskolczi et al. [5]. They were selected based on their interaction with existing PT. AVs were either used as substitutes for current PT options, additions to enhance existing PT or as alternatives competing with it. A team of PTAs, researchers, and project partners assessed them for their applicability and relevance. For vehicle sharing, AVs were modelled as SUVs and without onboard security drivers; for ridesharing, Automated Minibuses (AMs) were used to provide increased capacity. AVs and private cars were assumed to have the same average occupancy. AMs had an average occupancy factor of 5 [16]. Users of trains, metros, cyclists, and pedestrians maintained their behaviour, whereas bus and car users adapted. All scenarios benefit from supportive governmental policies and regulations.

2.2 Externalities Calculation

The transportation sector, responsible for 30% of GHG emissions in developed nations and 23% globally [18], plays a crucial role in influencing climate change and is a prime source of urban Air Pollution (AP) [19]. Additionally, accidents notably influence external transportation costs and are a key metric of mobility in Oslo. These factors justify the importance of the mentioned externalities in this study. In a second step, their impacts were aggregated into external costs to produce a single value.

The Global Warming Potential (GWP) calculation considers the entire life cycle (LC) emissions per scenario because the emission generation of internal combustion engine vehicles (ICEV), battery electric vehicles (BEV), and plug-in hybrid electric vehicles (PHEV) differs. ICEV emissions mostly come from the use phase, whereas BEV emissions originate from energy generation or production, depending on the energy source. To obtain the full GWP value per scenario, the GWP in CO_2eq in Table 2 was multiplied by the vehicle performance data per scenario in vkm and then totalled. For electric vehicles these factors were adapted to the Norwegian electricity mix. Cyclists and pedestrians received a value of zero because their impact is negligible. For the external climate change costs (CCC), we used a damage cost factor of 215 €/tCO_2eq for 2030 and a 1% time preference, as suggested by Matthey and Bünger [20].

Air Pollution emissions include NOx, NMVOC, and exhaust and non-exhaust PM_{10} emissions. The latter includes road vehicle tires, brake wear, and road-surface wear. First, the emission factors (Table 3) were multiplied by vehicle performance and totalled for the complete AP emissions per scenario. Pedestrians and cyclists were again excluded from this study. For AMs, the PM_{10} non-exhaust parameter of light-duty trucks was used, as no special data is yet collected for the PM_{10} of minibuses. Subsequently, the emissions were multiplied by the cost factors adapted for Norway to obtain the total external costs using a damage cost approach that includes health effects, crop loss, material and building damage, and biodiversity loss. These cost factors in €/ton were 17 250 for NO_x (rural), 1 643 for NMVOC (all areas), 95 833 for PM exhaust (rural) and 30 530 for PM non-exhaust (average) [15].

Table 1. Deployment scenarios

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)
Description	AV Shuttle as a Bus Line	AV in MaaS[1]	Robotaxi in MaaS[1]	Robotaxi in Competition with PT
PT interaction	Substitute	Enhance	Enhance	Compete
	AMs[2] replace buses while maintaining the same stops and timetable	AMs[2] offer ride-sharing and on-demand, door-to-door services	AVs[2] offer vehicle-sharing and on-demand, door-to-door services	AVs offer taxi services with only vehicle sharing
Market Penetration Rates	100%	30% and 100%[3]	30% and 100%[3]	30% and 100%[3]
Changes in vkm	±0	−15% [9, 10, 12]	+5%[4]	+25% [9, 10, 12]

[1] Mobility-as-a-Service (MaaS)

[2] AMs were used in S2 because they offer a more spacious environment for shared journeys, while smaller, passenger car sized AVs may inadvertently compel passengers into more confined and less comfortable seating arrangements in the backseat. S3 focuses on an individual solution and privacy and therefore reduces the size of the vehicle to a passenger car sizes AV

[3] The market penetration rates of private car trips transitioning to AVs or AMs are set at 30% to represent expected figures in the near future [17], and at 100% to demonstrate the highest level that could potentially be reached

[4] The current pkm demand remained constant across scenarios, with a redistribution of vkm between transport modes and assumptions on changes. Rebound effects were excluded from the analysis. This means that for example in Scenario 1, 100% of the pkm driven by the bus were redistributed to AMs. In Scenario 2, either 30% or 100% of all pkm driven by private cars were redistributed towards AMs. In accordance with the Oslo and Lisbon studies, Scenario 2 additionally experienced a 15% decrease in the vkm because of ridesharing and integration into PT. Scenario 4 resulted in a 25% increase in vkm owing to deadheading from individual trips. Scenario 3 was not examined in the aforementioned studies. Given that individual trips tend to increase vkm while PT integration typically decreases it, we've projected a 5% rise in vkm for this scenario, positioning it between S2 and S4

Table 2. GWP per vehicle category and vkm in $gCO_2eq/$ vkm

	LC emissions
ICEV-$G_{asoline}$ [21]	269
ICEV-D_{iesel} [21]	229
BEV [21]	59
PHEV [21]	180

	LC emissions
Bus-D_{iesel} [21]	1396
Bus-$E_{lectric}$ [21]	228
AM [16]	170
AV [22]	45

Table 3. AP emission factors per vehicle category and vkm [23]

	NO_x	NMVOC	PM_{10} exhaust	PM_{10} non-exhaust
ICEV-G	0.6594	0.40353	0.00068	0.026
ICEV-D	0.3318	0.01392	0.01187	0.026
BEV	0	0	0	0.026
PHEV	0.0133	0.00074	0.00061	0.026
Bus-D	5.7855	0.20286	0.20143	0.097
Bus-E	0	0	0	0.097
AM	0	0	0	0.035
AV	0	0	0	0.026

The accident calculation was based on the actual number of casualties corrected for under-reporting and the seriousness of accidents. This correction (fatalities = 1, severe injuries = 1.25, slight injuries = 2) accounts for accidents that have not been officially reported and therefore do not appear in statistics. Studies have shown that 93.5% of all accidents are caused by human error, whereas the remaining 6.5% are weather-related or caused by technical problems [24]. As AVs and AMs are assumed to be driverless, they are expected to cause only of all current under-reporting-corrected accidents caused by the transport mode they replace. This assumption is further discussed in the limitations of this study because of its hypothetical nature. The number of accidents is then multiplied by the external cost factors of van Essen et al. [15] which include human costs, production loss, medical costs, and administrative costs not covered by insurance. To represent Norway´s external costs for accidents, the following rates in cent/vkm are proposed: 2.358 cents for cars, 14.004 cents for busses, 0.910 cents for AMs, and 0.153 cents for AVs [15]. In the absence of data specific to Grorud Valley, data on accidents in Norway were used and adjusted to reflect its population distribution.

3 Results

To compare the scenarios and their impacts, we used the Status Quo (SQ) as a reference.

Figure 1 displays the modal split of passenger transport in Grorud Valley, excluding long-distance train trips outside the valley. The totals were 1,450,311 pkm and 929,037 vkm. We excluded metros in further calculations, as they do not belong to road passenger transport and AVs do not intend to replace them. All calculations are the author´s own work based on data from [15, 16, 20–23, 25, 28]. Each scenario reduced the GWP compared to the SQ, with 100% market penetration scenarios showing the greatest decrease owing to the electrification of private cars and renewable hydro energy in Norway. Emissions such as NO_x, NMVOC, and exhaust PM_{10} disappeared in the full electrification scenarios, making them the most appealing option. S2 (100%) had the largest reduction in non-exhaust PM_{10} emissions, while S3 and S4 scenarios caused increases compared to the SQ. When exhaust PM_{10} emissions were included, S2 (100%)

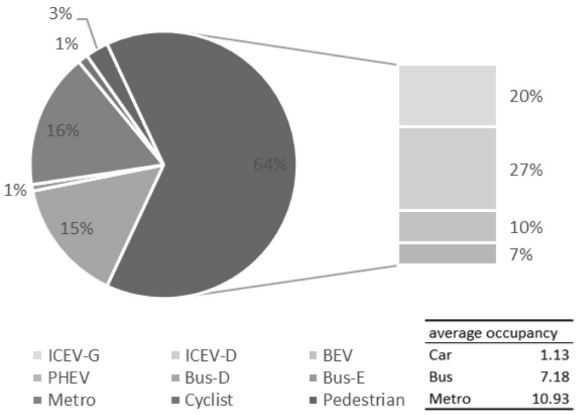


Fig. 1. Modal split SQ in pkm (own calculation based on [25–27])

remained the best option, but the added emissions from ICEVs in the SQ resulted S3 (30% and 100%) now performing better and only S4 (30% and 100%) performing still worse than the SQ. The non-exhaust PM_{10} emissions are dependent on vkm. Given that S2 diminishes vkm via ridesharing and AMs exhibit greater capacity compared to AVs—the latter prone to augmented vkm from deadheading—the observed outcomes are explicable. With private cars being the main cause of accidents, S1's improvement was limited as only buses were replaced. S3 and S4 performed slightly worse than S2 due to increased vkm.

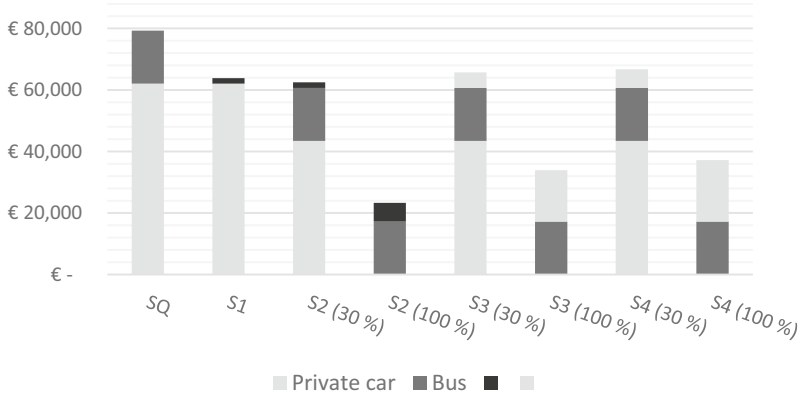


Fig. 2. External costs per vehicle category

Figure 2 shows that private cars were the largest contributors to external costs, accounting for over half of the total costs in the scenarios that included them. Replacing private cars with 100% AMs could reduce external costs by up to ten times when only considering the change from private cars to AMs. In S4 (100%), AVs caused higher costs than diesel buses due to increased vkm. S2 (100%) was the most cost-effective option.

When examining external costs by category, it was found that CCC costs accounted for 51–63% of total costs, while AP costs only made up 10–17%. S2 (100%) showed a 68% CCC reduction compared to the SQ while S3 (100%) and S4 (100%) were able to provoke reductions of 62% and 59%, respectively, others only 16–20%. S2 (100%) saw a 61% decrease in AP costs, S4 (30%) only 16%. S2 (100%) experienced an 80% decrease in accident costs, and S1 had the lowest 18% reduction. Table 4 shows costs per vkm and per pkm and changes in total external cost. Remarkably, AMs demonstrated the lowest costs per pkm. Gasoline cars showed the highest costs per pkm. All scenarios reduce external costs from the SQ, ranging from 16% (S4, 30%) to 71% (S2, 100%).

Table 4. External costs per vkm/pkm and changes in total external costs compared to SQ

	cent/vkm	cent/pkm
ICEV-G	9.43	8.32
ICEV-D	8.05	7.10
BEV	3.71	3.27
PHEV	6.34	5.59
Bus-D	56.26	7.83
Bus-E	19.20	2.67
AM	3.90	0.78
AV	1.96	1.80

	Change
SQ (Baseline)	79,305 €
S1	-15,448 €
S2 (30%)	-16,798 €
S2 (100%)	-55,997 €
S3 (30%)	-13,609 €
S3 (100%)	-45,362 €
S4 (30%)	-12,627 €
S4 (100%)	-42,091 €

Consequently, S2 (100%) is the most optimal choice since it provides the largest reduction in external costs. It combined electric AVs and reduced vkm, resulting in remarkable scores. Obviously, the "AV in MaaS" scenario is dependent on the implementation of a MaaS ecosystem, but if this is in place, automated vehicles could represent a real social and ecological benefit.

4 Discussion

This study sought to explore the potential advantages of incorporating AVs into mobility networks, specifically in the suburban Grorud Valley, to ascertain their impact on reducing external costs associated with transportation in suburban regions. All the evaluated scenarios were favourable to the status quo considering external costs. Surprisingly, non-exhaust PM_{10} emissions contributed significantly to PM_{10} emissions, indicating that vkm must be reduced. S2 (100%) showed the most favourable outcomes, with the greatest reduction in GWP, AP, accidents, and external costs. This confirms that electric AVs in suburban areas can be beneficial for the environment and help reduce external costs even if 100% market penetration is not reached yet.

4.1 Implications and Generalizability

The scenarios, rooted in international literature, are broadly applicable to developed country suburbs. However, developing country suburbs may present unique challenges,

making some scenarios impractical. Tailoring scenarios and assumptions to each suburb's specific needs, in consultation with local transportation stakeholders, is essential. Factors like a suburb's infrastructure and Norway's renewable energy advantage mean that results may vary, especially in nations with significant fossil fuel reliance. Despite this, the study's modal shift and market penetration rate assumptions provide a foundation for translating results to diverse suburbs.

The results are in line with the Lisbon studies [9–11] and the Oslo study [12], reinforcing the idea that AVs and shared mobility can improve the transportation system. It builds on existing knowledge that this is not only the case for densely populated urban areas, but also for suburban areas that are more spacious and less populated. This is essential to convince people to use new transport modes, change their behaviour and to help local authorities make informed decisions about AVs.

4.2 Limitations of This Study

Many of the positive effects can be explained by the electrification of the vehicle fleet and not necessarily by the service model, i.e. AV in MaaS. Replacing all ICEV and PHEV with BEV could reduce CCC by 72%, compared to 85% for S2 (100%). Nevertheless, the positive effect of ridesharing on vkm is still significant. Additionally, this study did not consider that the vehicle fleet of buses used for PT will become increasingly electric, according to Norway's mobility goals. However, the proportional reductions would mostly stay the same, since all scenarios used the same diesel bus share as the SQ. ICEV fading out, experiencing future technological advances (such as reduced emissions) or being replaced by electric vehicles raises the question of whether GWP and AP are still the best indicators for transportation. To obtain a clearer understanding, more indicators should be integrated, such as land use, barrier costs, and health benefits of active mobility. Apart from that, 100% market penetration is unlikely in the near future. However, AV in MaaS was also the best solution for all 30% market penetration scenarios, so the goal could be to achieve the highest market penetration rate possible.

The study employed average workdays for each transport mode. Although AMs showed potential to replace the buses in Scenario 1, it's uncertain if peak hours demand 2–3 AMs per bus for capacity reasons. Furthermore, adverse weather might prompt shifts not only from bus and car users but also from cyclists and pedestrians towards AVs/AMs for short distances. Therefore, surveys are crucial to assess mobility behaviour changes, offering insights into potential modal shifts in the future. Generally, the scenarios are relatively theoretical and will most likely rather appear in a blended form in practical application. Therefore, further development is required to fully explore their potential. Moreover, accidents are challenging to estimate. AVs may reduce accidents even more because of their effect on other vehicle categories, as pedestrians being involved in 6% of car and 22% of bus accidents [28]. For cyclists the number might be even higher, especially in areas where they share roads with motorised vehicles. Contrary, complex AV technology may lead to more accidents due to technical failures. Predicting a 93.5% decrease is therefore difficult, but it estimates potential outcomes. Van Essen et al. [15] provided external costs factors for accidents as the data was insufficient to calculate them. These factors were adapted to Norway using a country factor provided by the same study, but considering the low accident rates in Norway, the real numbers might

differ. Lastly, this study does not include rebound effects. AVs can offer convenient, affordable, and safe transportation and therefore may lead to an increased number of trips, reducing active mobility and PT use, requiring more vehicles to meet the new demand and thus affecting the environment and increasing external costs. Consequently, a regulatory framework is essential to monitor AVs' integration into the transportation system and to prevent the possible negative effects.

4.3 Potential Further Investigation

Further research could survey Grorud Valley residents' willingness to use AVs and how their mobility behaviour would change with AVs in different scenarios. Moreover, there is potential for improvement in refining and customizing the scenarios to more accurately reflect real-world situations. On the other hand, simulations of the suburb's traffic could also provide more insights into vkm changes. Other studies could investigate and develop additional indicators for a more comprehensive analysis. Interesting indicators to calculate are congestion, land use, barrier costs, energy use, number of vehicles, and health benefits. In addition, examining the need for increased electricity capacity would be worthwhile: Is the current renewable energy generation sufficient if all vehicles were electric or would Norway need more power plants? Moreover, observing the Oslo urban region, including train and metro trips, could be beneficial to understand how AVs could alter the transportation network. Finally, calculating Norway's own external cost factors may provide valuable insights for the external cost calculation.

5 Conclusion

This study aimed at assessing the advantages of integrating AVs into the mobility system within suburban areas on the basis of a case study by determining how various deployment scenarios of these vehicles influence the external costs of transportation in suburban settings. A review of literature on mobility trends and AV integration identified various deployment scenarios. These scenarios were analysed for their impacts on global warming potential, air pollution, and accidents, and then consolidated into overall external costs. The analysis indicated that AMs combined with ridesharing in MaaS and the highest market penetration rate possible results in the largest reduction of external costs and is therefore considered as the best strategy of the reviewed scenarios. Subsequently, this study recommends implementing AMs in MaaS and a high market share in Grorud Valley. The AMs should not replace PT, but rather supplement the PT network, and should focus on ridesharing. Surveys could be conducted to determine if potential users would prefer to be alone in a vehicle. This would help evaluate if a scenario with AMs together with ridesharing and AVs without ridesharing could increase acceptance and use. While the impact assessment provides valuable insights, incorporating additional indicators is imperative for a comprehensive and well-informed decision-making process. This research also questions if CO_2 emissions and exhaust air pollution such as NO_x or PM are still relevant when considering the shift to electric vehicles and renewable energy. Interesting indicators could measure health benefits from active mobility and barrier costs from highways and unsafe streets. Nonetheless, this study demonstrates

that AVs in MaaS can benefit suburban transportation networks, supports the transition and shows why a mobility paradigm shift is desirable.

6 List of Abbreviations

AM/AV	Automated Minibus/Automated Vehicle
AP	Air Pollution
BEV	Battery Electric Vehicle
CCC	Climate Change Costs
CO_2(eq)	Carbon dioxide (equivalents)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICEV(-G, -D)	Internal Combustion Engine Vehicle (gasoline, diesel)
LC	Life Cycle
MaaS	Mobility-as-a-Service
NMVOC	Non-Methane Volatile Organic Compounds.
NO_x	Nitrogen oxides
PHEV	Plug-in Hybrid Electric Vehicle
Pkm	Passenger kilometre
PM_{10}	Particulate Matter with a diameter of <10 µm
PT(A)	Public Transport (Authority)
Vkm	Vehicle kilometre

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Declarations.

Availability of Data and Material All data is publicly available excluding the mobility demand of Grorud Valley which was received by personal communication from the local PTA Ruter and published with their agreement.

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Transport Sectors' Real-World Emissions: From Gaseous Precursors to Secondary Aerosol Formation in Urban Air

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Abstract. Mobility is essential to our modern world to move people and goods. However, mobility has also its downside as transport sectors are substantial emitters of greenhouse gases and air pollutants. Increasingly energy efficient combustion engines and turbines, as well as electrification and carbon-neutral fuels, will reduce the climate impacts of transportation. When such technologies are combined with advanced exhaust after-treatment technologies, air pollution impacts will also be reduced. Many exhaust emissions are already regulated regionally or globally, while actions to prevent the formation of secondary aerosols from emitted gaseous precursors in the atmosphere are missing. To increase understanding on the role of transport sectors' exhaust emissions on the secondary aerosol formation and to identify gaps in the knowledge, we present a summary of semi-volatile compounds, secondary air pollutants, ultrafine particle and particulate matter (PM2.5) emissions. Non-exhaust emissions are also considered. The results are based on the PAREMPI project's emission database based on a literature review and new results from the projects' ongoing research activities.

Keywords: Exhaust Emissions · Particles · Secondary Aerosols · Toxicity · Health impact · Transport Sectors

1 Introduction

Mobility plays a vital role in our modern society, facilitating the movement of people and goods to meet our various needs, including those related to food, energy, and essential resources. However, it's essential to acknowledge that the transport sector comes with

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its challenges, primarily associated with greenhouse gas emissions and air pollutants. While making strides in developing more energy-efficient combustion engines, adopting electrification, and exploring carbon-neutral fuels, these advancements are crucial for mitigating the climate impacts of transportation. In addition to addressing climate concerns, we must also consider the reduction of air pollution resulting from transportation. To achieve this, advanced technologies, such as exhaust after-treatment, are integrated into the transport sector. This is increasingly important in certain segments of the industry, such as aviation and maritime transportation, that present unique challenges in achieving full decarbonization through electrification alone. Many gaseous and particle emissions are already regulated as they are known to pose significant threats to health and global ecosystems as well as causing societal costs. However, transport emissions' role in the formation of secondary aerosols (SecA) in the atmosphere has not been taken into account.

In this context, we present a comprehensive overview of emissions from the transport sectors' emissions, focusing on (semi)-volatile organic compounds ((S)VOCs), secondary air pollutants, ultrafine particles (UFP), and particulate matter. Additionally, we consider non-exhaust emissions, broadening our perspective on the issue. Our findings are based on the extensive emission database, which is the result of an exhaustive literature review and ongoing research activities within the PAREMPI project. Throughout our discussion, we highlight the knowledge gaps that persist in our understanding of these exhaust emissions and their role in the secondary aerosol formation, emphasizing the need for specialized expertise to comprehensively evaluate and address these complex challenges. The results will assist further research to find solutions and initiate actions to prevent these emissions.

2 From Precursor Emissions to Secondary Aerosols

To approach discussion of secondary aerosols, we present definitions of aerosols, particles and secondary aerosols. By definition, aerosol is a suspension of gas with solid particles or liquid droplets originating either from natural (dust, volcanic ash etc.) or human-made processes (industry, vehicle exhaust etc.). Aerosols affect human health by entering into the respiratory system and even the bloodstream, and climate by scattering and absorbing solar radiation or by influences on cloud formation. Particulate matter (PM), constituent of aerosols, is described by World Health Organisation (WHO) as "*a mixture of solid and liquid particles in the air that are small enough not to settle out to the Earth surface*". Important features of particles are their mass, size and number emissions. Ambient PM2.5 is a mass-based definition for particles having aerodynamic diameter below 2.5 μm, while combustion originated particles are small, below 1 μm or even nanometers in diameter and hence included in PM2.5, while e.g. sea salt, geological dust, biogenic PM and residual ash tend to be in the larger size range than PM2.5. Small particle sizes may have low mass, but still substantial adverse health effects caused by high number of ultrafine particles (<0.1 μm) and nanoparticles (<50 nm). Hence, particle exhaust emissions are defined also by their number and lung deposited surface area [1]. In the European emission standards, number of non-volatile particles (nvPN) are included, currently those with diameter above 23 nm [2], and smaller particles above

10 nm are proposed to be included [3]. For atmospheric and health aspects, total number of particles is considered, including also volatile particles and those below 10 nm, since these particles may carry for example harmful polyaromatic hydrocarbons (PAHs) [1, 4, 5].

Secondary aerosol form via secondary reactions of gas-phase precursors in the atmosphere under presence of H_2O, O_2, oxidants (OH, O_3) and sunlight besides aerosol emitted directly into the atmosphere from biogenic or anthropogenic sources. For secondary reactions, combustion of carbonaceous fuels contributes by emitting precursor gases, such as sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), as well as organic and inorganic aerosols (e.g. (S)VOCs, metals, salts, acids) and black carbon (BC) depending on fuel constituents, engine and aftertreatment technologies [1, 2]. SecA is further divided in secondary organic aerosol (SOA) and inorganic aerosol (SIA) [6, 7]. SOA formation involves nucleation, the partitioning of organic gases onto existing aerosol particles or reactions of primary OA and even the photosensitized chemistry is proposed leading to autocatalytic formation of SOA [8]. Aromatic compounds contribute significantly to the formation of SOA and faster than thought via molecular rearrangement of the bicyclic peroxy radicals (BPRs) leading to aerosol-forming low-volatility products [9]. SIA covers e.g. salts formed from metals, SO_2 or NH_3.

Formation of SecA is complicated in the atmosphere where exhaust species mix and react with atmospheric compounds in local meteorological conditions (Fig. 1). Firstly, composition of exhaust varies depending on transport application, secondly the compounds present in atmosphere and their concentrations vary regionally, and thirdly, variable atmospheric conditions (e.g. meteorology, oxidants, UV) affect the reactions. For example, air quality is typically worst at low winter temperatures with low mixing height, however, dependences causing this phenomenon, and particularly the role of transport sectors' emissions, are not evidenced. Overall, ambient PM2.5 accumulates from many sources, also those transported with air masses across borders, and apportionment of different sources in ambient PM2.5 levels and its harmfulness is challenging.

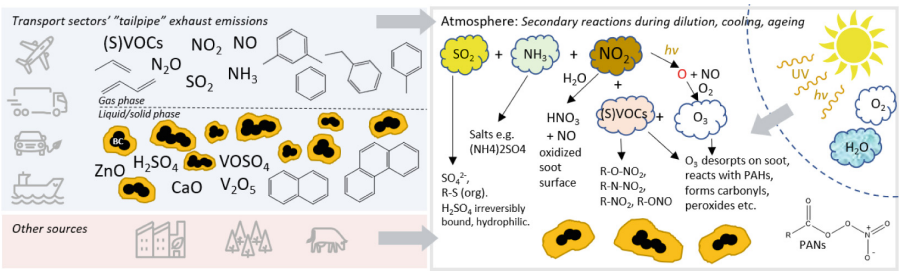


Fig. 1. Exhaust emissions from variety of transport sources form SecA in the atmospheric reactions thus contributing to ambient PM2.5 levels.

As secondary emissions form during the atmospheric aging process lasting from minutes to weeks, it is not possible to directly measure secondary aerosol formation. Therefore, SecA formation is typically characterized using oxidation flow reactors (OFRs) such as Potential Aerosol Mass (PAM; [10]) and Tampere Secondary Aerosol Reactor

(TSAR; [11]) chambers. The OFR is irradiated with UV light (of 185 and 254 nm) to form high concentrations of oxidants (O_3, OH, HO_2) that can initiate SecA formation. High oxidant concentrations (up to 1000-fold to atmosphere with the same oxidant ratios as in the atmosphere) and intensive UV lights ensure fast oxidation of compounds. The aging as the sample flows through chamber is shown to represent from minutes to weeks aging in the atmosphere, depending on used oxidant amounts. After the PAM chamber, either PN concentrations, size distributions or composition of aerosols (including SecA) are typically measured either online with e.g. ELPI or aerosol mass spectrometers or offline from filter samples. The first widely available OFR (PAM) was developed by prof. Brune at Penn state university and first publication about the PAM chamber concept was published in 2007 by Kang et al. [10]. After that the amount of OFR publications has steadily increased and currently there are over 150 publications utilizing OFR in different laboratory and field studies.

3 Existing Data for Precursor Emissions and SecA

To understand the role of transport sector's emissions on the SecA, knowledge on the precursor emissions is necessary. Emission factors are available for basic emissions, SO_x, total hydrocarbons (HC), PM and NH_3, for cars and heavy-duty vehicles [12], ships [13], and aircrafts [14] as presented in Table 1. Apparently, emission factors for ground-transport applications are low when compared with those for aircrafts and especially for ships. Less information is available for (semi-)volatile organic compounds e.g. benzene, toluene, PAHs, ultrafine particles, as well as formed SecA mass and its composition and toxicity, than for emission species presented in Table 1. In the continuation of work, a comparative analysis of emissions from different transport sectors will be refined.

Table 1. Examples of emission factors (EFs) for older cars, HDVs, ships and aircrafts.

Examples	SO_x g/kg fuel	HC/NMHC g/kg fuel	NO_x g/kg fuel	NH_3 g/kg fuel	PM g/kg fuel
Cars, petrol [12]	–	–/10.1	8.7	1.1	0.03
Cars, diesel [12]	–	–/0.7	13.0	0.065	1.1
HDVs [12]	–	–/1.9	33.4	0.013	0.9
Ships, diesel [13]	10.5	2.9/–	66.4	0	1.4
Aircrafts [14]	0.84	0.61/–	18	–	0.13

On-road: older fleets (Tier 1). Marine fuel < 0.5 wt% sulphur. Aviation: Airbus A-300B2.

Table 2 summarizes the availability of the results for the different transport sectors and shows that even for cars and heavy-duty vehicles (HDVs), relevant precursor emissions are sparsely reported in on-road real-driving (RDE) conditions. Many campaigns for measuring emissions from ships have been carried out, however, datasets are for single ships and for limited emissions species, e.g. (S)VOC data is almost non-existing. In the datasets, ships typically use residual or distillate marine fuels compliant with the

IMO's 0.5% sulphur limit (or 3.5% sulphur limit if scrubbers are used). More information is needed on the emissions for alternatives, such as LNG DF and methanol DF, or biofuels that are anticipated to enter market along with the IMO targets to cut GHG emissions of shipping to reach net-zero by 2050. For aviation sector, there are reports only on the basic emissions and limited data is available for the sustainable aviation fuels (SAF). Synthetic jet fuel (ASTM D7566) components are typically sulphur-free and low-aromatic, while final blends need to meet JET-A1 standard. More data than currently available is needed for precursor emissions from all transport sectors, and hence, new complementary measurements are needed to gather sufficient information.

The database and synthesis are needed for modelling and identifying different exhaust and SecA compositions [15]. For the database, we selected all the studies involving OFR measurements of transport emissions from different sectors (cars, HD vehicles, shipping, aviation). Altogether 21 publications with SecA emission factors for the transport exhaust emissions were identified.

Table 2. The major SecA related emission components for different transport sectors (Cars, HDVs, Shipping, Aviation) and the availability of measurement data.

Source	Existing data
Cars, HDVs	A few SecA studies. RDE data sparse for precursors and SecA
Shipping	Very few SecA studies. Measured data only for single ships
Aviation	No measured SecA data. Limited data for precursors

4 Conclusions

Analysis of the existing data showed that there are gaps in the knowledge of the transport sectors' precursor and secondary aerosol emissions, especially those measured in real-life, on-road conditions. This knowledge is essential to understand and model reactions and processes leading to formation of health impacting SecA due to atmospheric aerosol chemistry and for predicting SecA based on precursor emissions. In the continuation of the work presented here, complementary measurements will be carried out and toxicity of exhaust will be studied. With sufficient information on SecA emissions in combination with European level modelling, health impact assessment and improved quantification of externalities is possible. Scientific findings, together with tools and methodologies created, enable solid and well-justified policy considerations.

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Effects of Teleworking in Air Quality During and After the COVID-19 Pandemic: A Spanish Case-Study

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Abstract. Since the outbreak of the COVID-19 pandemic in 2020, the habits of the population have changed significantly, leading to a rapid popularization of telematic activities, especially teleworking and e-learning. Telework can be a solution to weekday rush hour congestion as commuting is a major source of air pollutant emissions in urban areas, especially nitrogen oxides such as NO_2. To test the possible effect of air quality improvement due to teleworking, the present work analyzes by weekday the concentration of pollutants between a pre-pandemic period in 2019, where teleworking was not as widespread, and the post-pandemic period in 2022, together with traffic levels for a central area of the city of Madrid. The results indicate a reduction in NO_2 concentration and urban traffic recorded in 2022, which may be due to an increase in the number of people teleworking on a regular basis. By days of the week, it has been found that pollution peaks change between the two periods, occurring in 2022 on Tuesday and Fridays, and not on Mondays. The study may be inspiring and help decision makers to propose plans and strategies that include the proposal of which days of the week could be more beneficial to telework in order to improve the air quality of urban areas.

Keywords: Teleworking · Traffic · Air Quality · COVID-19 Pandemic · Survey

1 Introduction

Since the first cases of a new coronavirus disease (later called COVID-19) were reported in late 2019, the world has changed significantly. This new disease was classified as a pandemic on March 11, 2020 by the World Health Organization (WHO) [1].

In Spain, the first COVID-19 case was reported on January 31, 2020, and the first state of emergency was declared on Spring 2020. During this time a home lockdown as enforced, among other measures. A second state of emergency was declared after the summer, enforcing a perimetral lockdown and night curfews.

During the pandemic, the habits of the population had changed greatly. Two of the most affected aspects were the education and work. During this time, the working habits of the population have shifted from an in-person type of work to a telematic type of work. Figures from the Spanish Ministry of Economy (MINECO) show before the pandemic,

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at least a 75% of the Spanish workforce had never teleworked [2]. However, this changed with the pandemic and with the approval of the telecommuting law in July 2021, allowing 35% of weekly hours to be teleworked[1].

Telework was firstly recorded in the 1970s, but was disliked, mainly due to the technological limitations of the time, which prevented a fluid communication between manager and employee. From an employee's point of view, the use of telework has a number of benefits, which can be summarize in two: family reconciliation and travel time savings, although family reconciliation seems to play a secondary role when compared to travel time savings [3]. Pérez et al. in 2004 [4] found that, in Spain, at least 50% of the employees lived within a 50 km radius from their working place. So, from the point of view of benefits to society, an increase in the number of people teleworking could lead to an improvement in air quality by reducing the number of kilometres travelled per day by workers and hence a reduction in transport externalities, such as reduction of air pollutant emissions. Air pollution have been an increasingly complicated issue in big metropolitan areas such as Madrid. Of all air pollutant sources, urban air quality is mainly influenced by the traffic that navigates the streets [5]. Additionally, being exposed to a polluted air has a negative impact on the human health, even aggravating the newly discovered COVID-19 disease [6].

The topic of telework and its relationship with air quality is not a new topic, but since the COVID-19 pandemic it has gained a lot of interest for the scientific community. As the lockdowns were imposed, the emission of air pollutants decreased greatly, signalling the cause-and-effect relationship between commuters and air pollution, specially nitrogen oxides (NO_2 and NO_x) and particulate matter [7]. Studies carried out in different environments, such as a typical medium size European city and an American city in California showed a reduction of air pollution recorded in the days telework is more prominent. The reduction of the number of workers who commute daily leads to a reduction of road traffic related air pollutants emissions, thus improving air quality [4, 8–11].

The main objective of this study is to analyse the effect that telework has had on air quality in a big urban area such as Madrid city by comparing a pre-pandemic scenario (2019) with a post-pandemic scenario (2022).

2 Materials and Method

2.1 Study Area and Data

The study area is a centrical point of Madrid city, located at the Escuelas Aguirre Air Quality Station (40.421564, −3.682311). Madrid city is located in the center of the Madrid Region and is the biggest municipality in the region. In 2022 was inhabited by 3,286,647 people, making it the most populated city in Spain. Air pollution has become one of the main challenges Madrid faces. Of all air pollutants emissions, a 42% were caused by road traffic [12] which makes Madrid one of the most polluted cities in the country. A variety of measures has been enforced to tackle this problem. Among them, the implementation of Low Emission Zones (LEZ) stands out due to the direct impact on

[1] https://www.boe.es/eli/es/l/2021/07/09/10.

the citizens they have [13]. Other measures include the renovation of the vehicle fleet and the encouragement to use the public transport. Additionally, Spanish legislation allows for employees to work from home at least 2 days per week in order to improve energy efficiency.

The data used for this study were obtained from two sources. Data of telework in Madrid city was obtained from the E.MORES-CM project survey [14]. For the teleworking data, this survey asked the subjects for their teleworking habits before, during and after the COVID-19 pandemic, sorting the answers in 6 categories: daily, 3–4 times per week, 1–2 times per week, once a month, occasionally, and never.

The air pollution and traffic gauges data were obtained from the Madrid City Council Open Data Portal [15]. For air pollution, average daily concentrations of NO_2 were collected from Escuelas Aguirre urban traffic air quality station located in the city center. Traffic gauges data consisted of daily average number of vehicles per day recorded in each of the stations selected from the stations close to the selected air quality station.

2.2 Methodology

The impact of the adopted teleworking measure on air quality in a centrical area in Madrid has been evaluated, specifically by analyzing and comparing two scenarios. The pre-pandemic scenario corresponding to 2019 and the post-pandemic scenario in 2022. Observations of NO2 average daily concentrations, and daily average of vehicles in the roads was performed together with the analysis of teleworking days per week.

3 Results and Discussion

Concerning teleworking, the number of people who teleworked saw the greatest change. From a 6% of the Madrid workforce before the pandemic, the number of people who teleworked daily increased to a 11% after the pandemic. It is noteworthy that even after the post-pandemic decrease, when life returned to the prepandemic normality, it is still the double than before the pandemic, which suggest that the telework has stayed as a viable option in the Madrid Region (Fig. 1).

Figure 2 shows an example of the first 13 weeks of both 2019 and 2022 of the evolution of the NO_2 concentration (in blue) and traffic data (in grey) by day of the week (Monday to Sunday) and by week of the year. The complete dataset consists of 4 periods of 13 weeks each, for both 2019 and 2022 years.

As can be seen in Fig. 2, on the one hand, 2022 data shows a lower concentration of both NO_2, and a lower traffic density detected than the 2019 data. Both variables are down in 2022 compared to 2019, and this tendency can be seen in all weeks of the year.

On the other hand, the decrease in vehicles may be due the changed the habits of the workers after the pandemic and teleworking policies carried out by employers. This prompted a decrease in the NO_2 concentration recorded in this period [16]. The fact that teleworking has become an option for a not insignificant number of employees (11% of the Madrid workforce after the pandemic) has meant that the number of kilometers travelled by workers are reduced significantly and with it the reduction of traffic in the city, which, consequently, reduces NO_2 emissions and improves air quality in the area.

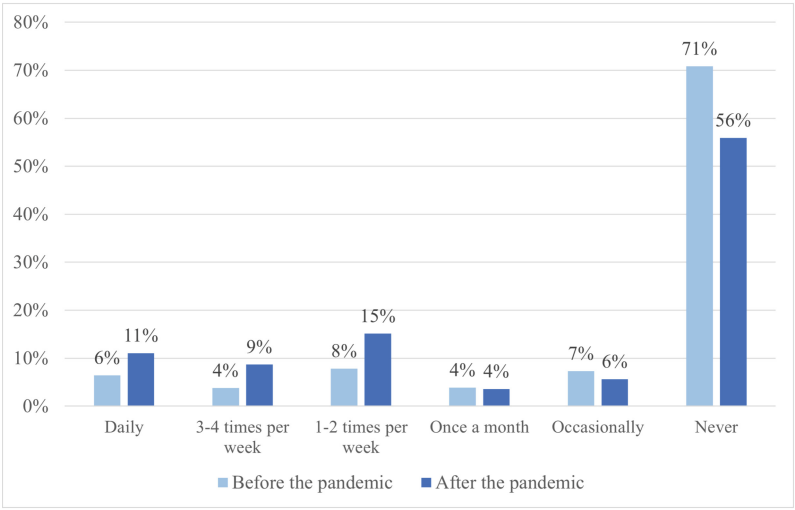


Fig. 1. Frequency of teleworkers in Madrid city before, during and after the COVID-19 pandemic. Source: EMORES-CM study project [14].

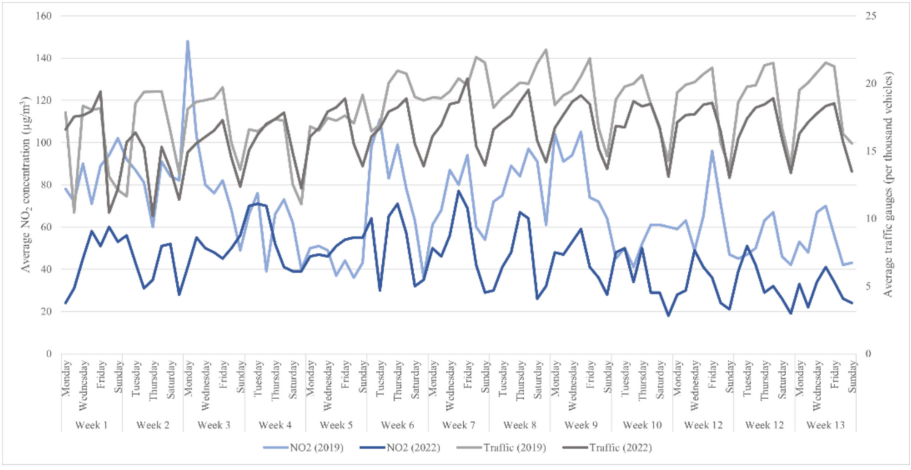


Fig. 2. Example of the NO_2 daily average concentration and traffic data recorded in the Escuelas Aguirres Air Quality Sation in the 13 first weeks of 2019 and 2022.

However, although teleworking is a factor that has improved air quality, we should not forget that the result of this improvement is augmented by other measures such as the creation of LEZ in Madrid. The LEZ does not act on the gross number of vehicles that are circulating on the streets. It acts based on the Euro emission standards of the vehicle [17]. Older vehicles are more polluting than those of recent manufacture, so by prohibiting the access to these zones to these older vehicles, a decrease of air pollutants' concentration is achieved.

By day of the week, it appears that the days were a peak in air pollution is detected are Tuesday and Friday. This matches with a recent study that said that people tend to telework more on Monday [18]. This can be explained by the desire of the workers to work from home on the first day of the week. Summer variations are also observed in the data, but to a lesser extent in 2022 than in 2019, before the COVID-19 pandemic.

4 Conclusions and Further Work

Air pollution is undoubtedly a pressing concern that must be at the forefront of government agendas, particularly in densely populated urban hubs like Madrid. Addressing this issue requires not just a superficial approach but a thorough and sustained commitment.

One promising solution that deserves careful consideration is teleworking. Apart from the social benefits such as family reconciliation and energy efficiency, air quality is also benefited as it has been analyzed in this study. Such days that the telework is more prominent air pollution decreases (Friday and Monday), only to increase again when those occasional teleworkers return to the office (Thursdays).

A more comprehensive study is needed in order to fully understand the relationship between air pollution and telework, not only for Madrid, but for the European Union. This future study will serve as a foundation for crafting new policies and plans that help to achieve the goal of a sustainable mobility.

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Walkability as a Catalyst for More Sustainable Mobility Patterns and Urban Rehabilitation in Rome

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Abstract. Walking in a pre-car, historic city center feels natural and appealing, but the same cannot be said for contemporary districts designed during the car-centric era. These modern areas often lack landmarks, social activities, and appeal, discouraging pedestrian lifestyles. Literature showcases numerous examples of district rejuvenation efforts aimed at increasing walkability, promoting non-motorized transportation, and fostering healthier, sustainable lifestyles.

Walkability serves as a catalyst for urban regeneration, but assessing and quantifying it pose methodological challenges, especially in areas lacking social functions and attractiveness. To address these issues, a methodology is presented and applied to quantify walkability across different urban environments and identify factors that promote it as the primary mode of mobility. The methodology employs a composite index, combining 12 indicators categorized into functions and use, safety, urbanity, and attractiveness. Data for these indicators are collected through direct observation, resulting in a 0 to 1 scale score, with 1 representing excellent walkability. The study tests this methodology in three distinct districts of Rome, each with varying urban characteristics and socioeconomic conditions. Notably, the paper not only quantitatively compares scores among the districts but also highlights an increase in walkability over a decade in the district where a regeneration process took place.

Keywords: Walkability · Healthier Lifestyles · Urban Mobility

1 Introduction

Historic city centers naturally encourage walking due to their premium design, while contemporary car-centric districts lack landmarks, social activities, and attractiveness, promoting car-based lifestyles. Examples of district regenerations, areas repurposing or outdoor environments redesign abound in literature [1, 2] often with the common goal to increase walking, and not just to rebalance the modal share in favor of non-motorized modes, but also to increase physical activity, in the awareness that more walkable districts create more sustainable and healthier lifestyles. Walkability is therefore a well-known catalyst for urban regeneration but a typical methodological problem is to assess the

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eligibility of an area to become more walkable, especially if the local built environment is deprived of social functions and, more in general, attractiveness. This also introduces the issue of measuring walkability associated with the quality of the built environment, which relies on three types of assessment:

- Surveys and interviews (self-reported), usually employed to gauge individuals' perceptions of their environment and explore how walkability relates to the presence of various nearby activities (e.g., commercial, educational, leisure) accessible on foot [3]. These studies also evaluate factors influencing people's choices, such as infrastructure quality, pathway accessibility, neighborhood attractiveness, perceived safety [4, 5], and the presence of green spaces and well-maintained buildings along pedestrian routes (public lighting, cleanliness) [6].
- Walkability audits, which are simple and reliable, and often dedicated to specific routes, like "home-to-school" for example [7].
- GIS-based measures derived from archived datasets. These archive-based data are used to create composite indices like the "Walkability Index" (WI) and the "Walk Opportunities Index" designed to consolidate diverse aspects of the built environment and facilitate result communication [7–9].

But, as built environments evolve, one more methodological problem is to quantitatively assess how much walkability has increased after a given regeneration intervention and in which way. Driven by these two research questions, i.e. how to assess the walkability of a given area and measure its variation after a rehabilitation program, the paper introduces a solving methodology and applies it to three districts in Rome, aiming to measure walkability in diverse urban environments and identify factors promoting it as a primary mode of daily transportation.

The methodology, duly elaborated in Sect. 2, relies on an assessment procedure based on a composite index, as a combination of a set of 12 indicators, subdivided into four evaluation categories: functions and use; safety; urbanity; and attractiveness. The methodology is tested in three different districts in Rome, with different urban features and socio-economic conditions: i) a supposedly superior quality, central historic area; ii) an apparently poorly-walkable in a recently-developed zone in northern, and eventually iii) a district conceived during the 1930s and developed after World War II. The paper describes the results by comparing scores achieved in the three test area, thanks to a new assessment occurred a decade later, and highlights the proposed index ability to measure changes in walkability especially in the districts where regeneration processes have taken place meanwhile.

2 The Adopted Methodology

The main aim in walkability assessment is to pinpoint and enhance a tool for gauging the potential of an urban area to facilitate physical activity, specifically walking, among its residents. In this case, to assess the walkability of the case study areas, the Territory's Walking Suitability Index (T-WSI) has been applied. T-WSI enables the assessment of walkability on a street-by-street basis within the environmental area under scrutiny. As already described in a previous study [10], this assessment relies on the acquisition of data from 12 distinct indicators, further categorized into four analytical groups, i.e.

- *Practicability*, in terms of the ease and practicality of walking, with a focus on the challenges posed by the current physical and mechanical conditions. This category encompasses the following factors: *sidewalk surface*, *obstacles*, and the gradient of the road, i.e. *road slope.*
- *Safety*, pertaining to the level of protection against accidents provided by the road infrastructure. This category encompasses the following factors: safeguards against vehicle-related incidents*, i.e. protection from vehicles*, adequacy of *road lighting*, and safety measures for pedestrians crossing the road, i.e. *crossing protection*
- *Urbanity*, encompassing all aspects of hospitality, comfort, attractiveness, and vibrancy that a street can offer based on the available amenities. This category comprises the following factors: the *width of sidewalks*, the quality of road infrastructure (*road equipment*), and the presence of *activities* such as shops.
- *Pleasurableness*, focusing on the well-being aspect, recognizing that even the subjective perception of the environment's pleasantness influences the choice to walk. This category includes the following factors: *traffic conditions*, the surrounding urban fabric or the *context*, and the presence of greenery (*green*).

Different weights are allocated to each category and its indicators based on their specific impact on walkability. An assigned weight is given to each indicator using a 1–0 scale that categorizes them from excellent to bad, determined according to an expert assessment described in [10].

The algorithm computes weighted sums and consolidates the indicators and categories based on percentiles and decimal coefficients. This process ultimately culminates in the determination of the Final Street Index (FSI):

$$FSI = 0,30 * C_P + 0,25 * C_S + 0,22 * C_U + 0,23 * C_G. \quad (1)$$

By summing up all the streets in a given study area as the sum of the weighted averages of FSI, where the length of each street is also considered, the final score is obtained. An average score ≥ 6 is considered sufficient for walking, therefore acceptable.

3 The Three Case Studies

In 2009, the methodology was tested in three different district in Rome, i.e. San Saba, Sacco Pastore, and Tufello, each featuring diverse infrastructure, accessibility, building stock, population density, vegetation quality, areas, but all with dominant residential functions (Fig. 1). The purpose was to quantify walkability in such diverse built environments and highlight factors needed to create pedestrian realms, including the quality of the built environment (a premium-value in historic San Saba), the residents' perception of the walkable environment (apparently poor in recently-developed Tufello) and the available walkable infrastructure supply (theoretically appropriate in Sacco Pastore).

The calculation of the indicators provided the figures presented in Fig. 2. The density of each area associated with the quality of the building stock (low-rise, pre WWI little villas at San Saba; 1940–1950s medium-to high rise apartment blocks at Sacco Pastore and high rise co-ops at Tufello) can intuitively explain some of the scores, including the markedly significant elements of weakness in the three areas: road equipment and protection from vehicles. However, these occurrences can be attributed to inadequate traffic

District	Surface (ha)	Population (units)	Density* (inh/m², avg)
San Saba	20.00	2,400	120
Sacco Pastore	20.35	9,100	447
Tufello	150.00	53,146	354

* excluding empty areas



images produced using Googlemaps and Powerpoint software

Fig. 1. The three test sites.

management in the three areas, which resulted from a failure to accurately anticipate this phenomenon. In the case of San Saba and Sacco Pastore, this can be attributed to the fact that the widespread use of passenger cars had not yet materialized, while in the case of Tufello, it was exacerbated by a transit supply, unsuitable as alternative to cars.

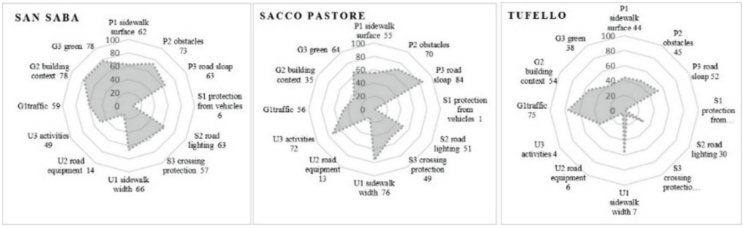
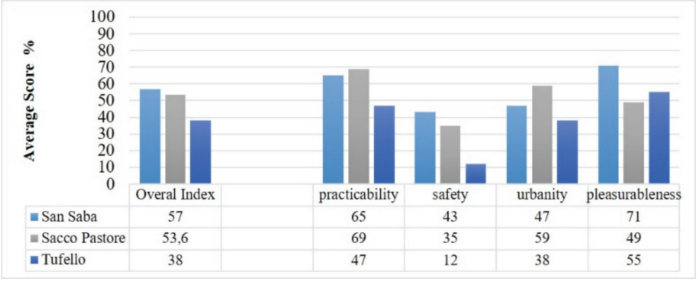


Fig. 2. Indicators scores in the three test sites.

This is also confirmed if the overall TWSI values are observed (Fig. 3), being safety the evaluation category with the lowest score in the three areas and urbanity not a top driver.



	Overal Index	practicability	safety	urbanity	pleasurableness
San Saba	57	65	43	47	71
Sacco Pastore	53,6	69	35	59	49
Tufello	38	47	12	38	55

Fig. 3. Overall assessment in the three test sites.

The comprehensive assessment was revisited a decade later, in 2019, with different researchers scoring the indicators. Although the three areas maintained their socio-demographic characteristics, they underwent distinct maintenance programs. In San Saba, an urban maintenance initiative was meticulously planned and consistently executed, albeit lacking specific regeneration or repurposing endeavors. Consequently, this translated into a modest increase (+0.51%) in the TWSI compared to a decade earlier. In stark contrast, Sacco Pastore witnessed a remarkable rejuvenation, spearheaded by both public authorities and various volunteer organizations. This renewal manifested as a substantial enhancement across all performance indicators, with a the noteworthy +14.68% increase in TWSI (from 53.6 in 2009 to 68.3 in 2019). The success can be attributed to the meticulous planning of interventions, primarily centered around traffic calming schemes (mostly sidewalks enlargement) and the creation of new bike lanes, coupled with the collaborative efforts between the local municipality and advocacy groups. This hypothesis is confirmed by the scores of each category too, showing the greatest improvements in Safety (T-WSI scores: from 35.0 to 59.3; increase of 24.3%) and Pleasurableness (T-WSI scores: from 48.5 to 61.4; increase of 12.9%).

On the other hand, Tufello experienced a notable absence of significant management program revitalization. This led to a marked deterioration in its overall conditions, resulting in a decline in TWSI values.

4 Concluding Remarks

The two-time assessment yields several key conclusions. Firstly, maintenance programs undeniably influence urban well-being, as seen in San Saba, where regular urban maintenance alone led to modest walkability improvement. However, it is evident that maintenance alone may not suffice for substantial urban enhancement. Conversely, Tufello's declining TWSI values underscore the detrimental consequences of neglected management. Secondly, Sacco Pastore's success highlights the significance of effective planning and collaboration. Here, careful coordination between public authorities and volunteer organizations played a pivotal role in improving walkability. This emphasizes the importance of well-thought-out interventions and community involvement in urban development. Additionally, Sacco Pastore's success challenges the notion that premium-value built environments inherently promote walking. The comparison with San Saba's scores stresses the importance of strategic planning, collaborative partnerships, and targeted interventions in encouraging healthier lifestyles and increased walking. Work ahead is to extend this study to more district to consolidate the methodological approach (cope with an uncertainty range for the outcome data, if need be; increase the amount of data, include additional topological features, etc.) and further advance the knowledge on walkability.

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Experiences, Valuable Activities, and Worthwhile Travel: A Comparison of E-cycling and Conventional Cycling Trips

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Abstract. E-cycling (EC) is often considered a simple 'upgrade' to conventional cycling (CC), but important differences exist between the two modes in terms of experiences, values, and worthwhileness. Using Chi2 tests, this study analyzes 8543 e-cycling and conventional cycling trips legs across eight European countries collected through the Woorti mobile app (May-December 2019) and evaluates differences in negative and positive trip experiences, valuable activities, worthwhile travel time, trip characteristics, environmental elements, and demographic characteristics. Results indicate that the appreciation of travel time by EC is linked to listening to music/podcasts, thinking, enjoyment, and irritation toward (unsatisfactory) infrastructure and congestion, implying that these trips are more solitary with higher experience expectations. CC use is linked to schedule predictability and a range of trip types, implying that these trips might be associated with trip chaining. These findings suggest important differences between EC and CC trips in terms of how they contribute to the intrinsic utility of travel, with implications for overall happiness and well-being.

Keywords: Worthwhile travel · Travel values · Travel experiences · E-cycling · Utility of travel

1 Introduction

E-cycling is often promoted as a travel alternative to conventional cycling for those with limited mobility, traveling longer distances, living in warmer climates, or living in gradient topographies. While differences between e-cycles (ECs) and conventional cycles (CCs) have been investigated in terms of trip characteristics and cyclist profiles, the distinctions in terms of experience factors, activities while traveling, and types of perceived values between ECs and CCs have not yet been researched. A normal assumption might be that EC trips are simply an 'upgrade' to CC trips because they can reach destinations faster or require less physical effort, but they may in fact fulfill different

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needs or be associated with different values for cyclists. This relates to ideas of the positive utility of travel or worthwhileness of travel, stating that there are underlying reasons other than speed and efficiency for travel, with implications for travel satisfaction or subjective well-being. Experiences, value of activities, and worthwhileness may differ fundamentally for EC users and CC users and are therefore important to investigate.

2 Literature Review

EC user profiles have become a topic of discussion alongside their rising popularity because there are clear distinctions in terms of usership and the barriers that ECs allow individuals to overcome. Research has found that EC users are more often female, though this could be changing over time [1]. They are also often older and with weaker physical conditions, as ECs require less physical exertion than CCs (though still more physical exertion than walking) [1, 2]. Subsequently, ECs are more often used by employees that are in the second or later stages of their careers, and by individuals more likely to own cars [1, 3]. Finally, EC users are more likely to live in suburban or rural areas and in areas with more elevated or diverse topographies [1].

ECs have further unique characteristics in terms of how they are used. They are more often used for the commute, and especially by those who need to cover longer commuting distances, and they are also used generally for trips with longer durations [1, 4, 5]. Another main way that ECs are used is to transport children [1], especially because the extra weight of a child is easier to overcome with a battery, or larger electric cargo bikes are easier to manage with multiple children.

In terms of the motivations for using ECs, they have been found to be related to a number of factors [1]. First, they are associated with the desire to move quickly from point A to point B, with these trips being more purposeful than leisurely. Second, they are more associated with cultural meanings such as freedom, or the ability to ride further and farther or the option to get out of the house unassisted, and status, or the perception of improved social ranking due to, for instance, improving one's environmental impact by switching away from cars or the ability to purchase a fancier, more technological bicycle. Third, ECs are associated with positive experiences, such as cycling for its own sake. Finally, EC use has been found to lead to increases in total cycling frequency [6]. On the other hand, while EC use is expected to be related to a motivation for time savings because of their speed and efficiency (relative to CCs), this has not been found to be a significant motivating factor for EC use [1].

Additionally, satisfaction with EC use has been recently researched [7], with important implications for overall well-being. EC satisfaction has been found to be higher than satisfaction with car use. This might be an important factor to consider as an argument to prompt car users toward ECs. Next, satisfaction with ECs was found to increase alongside an increase in habitual EC use, which could be a consequence of improved health alongside EC use. EC satisfaction is further improved by route attractiveness, meaning that EC users are happier when they cycle in greener or livelier conditions. Further, satisfaction with EC use is higher in less-urban areas, potentially linking to the higher satisfaction found in green areas. Finally, factors that are specific to EC use, such as the autonomy of speed choice, improve satisfaction, indicating that CCs and ECs are indeed unique in terms of satisfaction and implications on well-being.

3 Data and Methods

The Woorti mobile app was designed by the Horizon 2020 MoTiV (Mobility and Time Value) project to both automatically detect trip legs and transport modes (traveler-validated) and conduct an app-based survey based on experience factors, travel activities, and travel time worthwhileness [8]. Participants from eight European countries were recruited between May and December 2019 based on representative targets for the basic sociodemographic characteristics of gender and age and used the app for a minimum of 7 consecutive days, however citizens of other countries could also participate in the data collection, therefore in this paper data from eight countries are used. For more information on the full open source dataset [9], see Cornet et al. [8, 10].

The data for this investigation includes only the trip legs recorded by the Woorti app completed by EC (1,228) or CC (7,315), as this is the dependent variable under investigation in this analysis. Specific information about this sample, EC trip legs, and CC trip legs including key objective and subjective independent variables are discussed below. Objective variables include trip characteristics such as purpose, frequency, and distance, environmental elements such as weather, temperature, and elevation, and demographic characteristics such as gender, age, and country. Subjective variables include positive and negative trip experiences, travel activities, types of perceived value including paid work, personal tasks, fitness, and enjoyment, as well as overall worthwhileness.

Chi^2 tests were completed to identify significant differences between EC and CC trips regarding the objective variables of trip characteristics, environmental elements, and demographic characteristics for categorical variables, and ANOVA mean comparison tests were used to identify significant differences between EC and CC trips for two continuous variables, distance and elevation. Further Chi^2 tests were completed to identify significant differences between EC and CC regarding the subjective variables of positive and negative experiences of 20 trip leg factors, travel activities including accompanying, talking (including on the phone), listening to music/podcasts, thinking, and cycling for its own sake, types of perceived value including paid work, personal task, fitness, and enjoyment, and overall worthwhileness.

4 Results

4.1 Chi^2 Tests for Objective Variables

First, results of Chi^2 tests in terms of trip characteristics, environmental elements, and demographic characteristics are discussed. EC trips were associated with trips to work ($p = 0.032$) and for personal tasks ($p < 0.001$), while CC trips were associated with trips home ($p < 0.001$), to shop ($p = 0.009$), for leisure ($p < 0.001$), and to pick up others ($p = 0.002$). Next, Chi^2 tests did not show significant differences between EC and CC trips regarding trip frequency ($p = 0.404$). Further, regarding trip distance, CC trips were significantly shorter (mean = 4983.23 m) than EC trips (mean = 7799.58 m). No significant difference was seen regarding changes in elevation between EC and CC trips ($p = 0.200$). Next, EC use was more associated with cloudy ($p = 0.028$) and rainy weather ($p = 0.026$), while CC use was associated with clear weather ($p < 0.001$). Regarding temperature, EC use was more associated with warm ($p < 0.001$) and

warm/hot weather ($p < 0.001$), while CC use was more associated with cool weather ($p < 0.001$). There were no significant differences between EC and CC use when the temperature was comfortable ($p = 0.197$) or uncomfortably hot ($p = 0.598$). Being female ($p < 0.001$) and being in the older age category (50 + years old; $p < 0.001$) was associated with EC use, agreeing with previous literature [1]. In terms of country differences, participants in Belgium ($p < 0.001$), Italy ($p < 0.001$), Norway ($p = 0.027$), and Portugal ($p < 0.001$) were more likely to report EC use, while participants in France ($p = 0.004$), Finland ($p < 0.001$), Slovakia ($p < 0.001$), Croatia ($p < 0.001$), and Czechia ($p < 0.001$) were more likely to report CC use.

4.2 Chi^2 Tests for Subjective Variables

Second, results of Chi^2 tests in terms of positive and negative trip experiences, travel activities, worthwhileness elements including paid work, personal task, fitness, and enjoyment, and overall worthwhileness are discussed. EC trips were negatively associated with crowding and congestion ($p < 0.001$), path availability and safety ($p < 0.001$), traffic signals/crossings ($p < 0.001$), path quality ($p < 0.001$), other vehicles ($p = 0.004$), and information and signs ($p = 0.044$). EC trips were also positively associated with crowding/congesting ($p < 0.001$). On the other hand, CC trips were positively associated with information and signs ($p = 0.001$), other people ($p = 0.025$), accessibility (escalators, lifts, ramps, stair, etc.; $p < 0.001$), simplicity of the route ($p = 0.022$), schedule reliability ($p < 0.001$), today's weather ($p < 0.001$), path directness ($p = 0.008$), and ability to carry bags, luggage, etc. ($p < 0.001$). CC trips were negatively associated with air quality ($p < 0.001$), noise level ($p < 0.001$), and urban scenery and atmosphere ($p = 0.003$). CC trips were more sensitive both positively and negatively to the ability to take kids or pets along ($p < 0.001$; $p = 0.009$) and lighting/visibility ($p < 0.001$; $p = 0.001$). Regarding travel activities, CC trips were more associated with accompanying ($p = 0.014$), talking ($p = 0.006$), and cycling for its own sake ($p < 0.001$). On the other hand, EC trips were more associated with listening to music/podcasts ($p < 0.001$) and thinking ($p = 0.002$). CC trips were associated with three of the four types of worthwhileness: paid work ($p = 0.008$), personal productivity ($p < 0.001$), and fitness ($p < 0.001$). EC was also somewhat associated with fitness, indicating the difference in physical exertion between CC and EC trips. CC trips were also associated the most with overall worthwhileness ($p < 0.001$), while EC was associated with moderate overall worthwhileness.

5 Discussion and Conclusion

This investigation aims to identify differences between EC and CC trips in terms of negative and positive trip experiences, value of activities, types of perceived value, while also accounting for differences in trip characteristics, environmental elements, and demographic characteristics. While this is a first analysis of these aspects of cycling in this way and should be confirmed with future studies, initial findings provide evidence for important distinctions between EC and CC users and trips. First, EC use was more associated with listening to music/podcasts and thinking, with these cyclists being more

bothered by (unsatisfactory) infrastructural elements and congestion. This indicates that EC trips are a more solitary activity, that calmness might be an important element of these trips, and that EC users might have higher expectations. ECs move faster than CCs, therefore EC users might feel more substandard road quality, for instance, simply because they are riding faster.

This investigation uncovered a different profile in terms of experiences, value of activities, and worthwhileness for CC trips and users. CC use was associated with a range of different types of trips. This indicates that CCs might more often be used for multi-purpose journeys for personal tasks that require trip chaining and accessing a series of destinations. They might also be more often taken in urban areas where there are a higher density of destinations, contributing to the ease of trip chaining. CC trips could be, in turn, a more engrained occurrence than EC trips and therefore might not be as susceptible to the negative experiences found with the latter. Finally, no differences between EC and CC trips were found in regards to frequency.

Some findings in this investigation confirm what has been previously found regarding ECs and CCs. ECs were more likely to be used for longer distances [1, 4, 5], those who used ECs seemed to be less sensitive to environmental factors [2], and ECs were found to be associated with the commute [11]. However, some findings are different from what has been previously found. ECs have been previously found to be used to transport children [1], while 'pick up' trips in this study were associated with CC use. This requires a more in depth investigation of the type of trips undertaken with children.

The main limitation of this dataset was the elevation variable. As discussed, the difference in elevation was only able to capture the difference between starting and ending point of the trip. While this can provide some indication of the topography that the cycler may have endured, it is insufficient in capturing the full elevation of the trip. This means that a trip up and back down a hill, for instance, would not be captured. This is important to this paper specifically because ECs are promoted as an alternative to CCs in places with diverse topographies to overcome the additional physical effort that CCs require. Therefore, while it was important to include this variable in the analysis, further investigation into the relationship between elevation and EC use is necessary.

In sum, EC use was linked to listening to music/podcasts, thinking, and irritation toward (unsatisfactory) infrastructure and congestion, implying that they are more solitary with higher experience expectations. CC use was linked to a range of trip types, implying that they might be associated with trip chaining. These findings are important because they offer an initial suggestion of the differences between EC and CC trips in terms of trip experiences, value of activities, and worthwhileness, with implications for the intrinsic utility of travel and overall well-being and happiness.

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Estimating the Socio-economic Impacts of Cycling in the EU

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Abstract. This paper presents an update for the estimations of the European Cyclists' Federation on selected socio-economic impacts of cycling. It uses the most recent data sources, like a new EU-wide passenger mobility survey and the latest versions of the EU Handbook on the External Costs of Transport as well as the World Health Organisation's HEAT tool for walking and cycling, to calculate the impacts of cycling the fields of health, greenhouse gas emissions savings, and selected environmental impacts. In these fields, we estimate total external benefits of cycling to correspond to a monetary value of ca. €119 billion annually for the EU-27. In health, we estimate that more than 30,000 premature deaths are prevented each year in the EU. The paper also identifies data and research gaps, e.g. concerning the diversion rates from other modes caused by cycling, the levels and impacts of electric cycling in the EU, or morbidity benefits of cycling as opposed to mortality benefits in the field of health.

Keywords: Cycling · active mobility · transport economics · cost-benefit analysis · health

1 Introduction

In 2019, the European Cyclists' Federation (ECF) published its latest estimation of the socio-economic impacts of cycling in the EU [1]. The document provided evidence on the different benefits in relevant fields, and quantified them at the level of the EU-28 wherever possible. It showed that benefits of cycling appear not only in isolated fields like transport or environmental policy, but in many other areas where the EU has competences as well, like industrial policy, employment, health and social policy.

The calculation of benefits was based on an annual cycled distance of 146 billion kilometres for the EU-28, as estimated in a study on active modes data carried out for the European Commission in 2017 [2]. This was the best available EU-wide estimate that we could identify at the time. The results showed that already at these levels, cycling produced positive externalities of around € 90 billion per year in the EU-28.

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Since the publication of the document in 2019, significant amounts of new data and evidence for the impacts of cycling have emerged. This includes a comprehensive survey on the mobility patterns of Europeans, which gives much more detailed and harmonised data on the kilometres cycled in the EU and in all member states [3]. ECF has therefore decided to update its estimations on the socio-economic benefits of cycling using these new sources of data and evidence. Like its predecessor, the new report presents our estimates, as the main global pro-cycling civil society organisation, of the socio-economic impact of cycling. It should also serve as an invitation from civil society for further academic research into the impacts of cycling. To this end, in this paper, we present selected results for the areas in which we found a quantifiable impact of cycling, and try to identify gaps in data and methodologies.

2 Methodology

In this section, we describe the general methodological framework for estimating the quantifiable impacts of cycling. The different sub-chapters of part 3 detailing impacts in specific areas contain more information on the specific methodologies used in the corresponding area.

To estimate the impacts of cycling in different fields compared to a hypothetical situation without cycling, three main questions have to be answered: What is the volume of cycling in a given population? Which transport modes would replace cycling if it did not exist? And what is the impact of cycling and of these other modes, expressed on a comparable basis per volume (e.g. per passenger kilometre)?

For the first question, the data basis has improved considerably since the publication of the last ECF report on the benefits of cycling. While at that point, only a rough estimation of the kilometres cycled in the EU based on a limited number of national travel surveys with different methodologies was available, the European Commission has published the results of an EU-wide passenger mobility survey in the meanwhile, which provides comparable data on the average cycled distance per person per day as well as the total number of kilometres cycled per year for each EU member state. This data has been used to calculate the impacts of cycling in the new report.

For the second question, there is much less data available. To produce comparable figures for the modal shift from cycling to other transport modes in the hypothetical scenario of no cycling, an EU-wide mobility survey would have to include questions like “If you had not done this trip by bicycle, which other mode would you have used”? In absence of this data, we use the recommended default values of the World Health Organisation’s (WHO) Health Economic Assessment Tool for Walking and Cycling (HEAT) [4], combined with data on the share of different fuel types in car traffic in the EU in 2021 from the EU-wide mobility survey (Table 1):

For the third question, a variety of data sources is available based on local, regional and national studies. For the report, data sources that give comparable data across the EU have been given preference, namely the WHO’s HEAT tool and the EU Handbook on the External Costs of Transport [5].

Table 1. Diversion rates/modal shift from cycling to other modes in a no-cycling scenario

Transport mode (+ fuel type for passenger car)	Share (%)
Local bus	40
Car (petrol)	13
Car (diesel)	12
Car (LPG)	1
Car (hybrid)	1
Car (electric)	3
Local train/light rail/metro/tram	10
Walking	20

3 Results, Discussion and Needs for Further Research

3.1 Health Impacts of Cycling

Methodology

To calculate the health impacts of cycling in the EU, the WHO's HEAT tool was used. In brief, the tool calculates the reduced mortality in a given population due to increased physical activity linked to cycling, compared to a hypothetical scenario with no cycling. It also calculates increased mortality due to exposure of cyclists to air pollution and due to increased crash risks. The results of these calculations are then expressed in premature deaths avoided/caused, and monetised using the value of a statistical life. For the moment, the tool only calculates mortality impacts (longer lives), not morbidity impacts (healthier lives) of walking and cycling. In a study at regional level, morbidity impacts were estimated at 40% of the monetary value of mortality impacts [6]. We use this value to also give a rough estimation of morbidity impacts.

We should also note that the tool only calculates impacts for the population aged 20–64 years. In the EU-wide mobility survey, the closest age group for which figures are available is the group between 15–64 years. The average cycling levels might be slightly higher in this group than in the group between 20–64 years since one could expect teenagers between 15–19 to be among the most active cyclists. However, the overall effect of this discrepancy on the results should not be disproportionately high.

The tool was used with the assumption that all cycling would be for mobility purposes and not with the sole aim of physical activity. This can be justified with the fact that the data on cycling volumes comes from a mobility survey and not from a sports survey, where participants would have answered on cycling as a sport. Here we assume that they only reported their cycling trips for transport purposes.

Results

Running the HEAT tool with the data from the EU-wide mobility survey and using the assumptions stated above for each EU member state gives a total number of 36,646

premature deaths avoided due to increased physical activity levels linked to cycling. The number of premature deaths caused by exposure of cyclists to air pollution is 2,777, and the number of premature deaths caused by the increased crash risk is 3,631. In total, a net number of 30,272 premature deaths is avoided each year in the EU-27 through cycling. This corresponds to a monetary value of ca. €80.35 billion for 2021, the year of the EU-wide mobility survey.

The value of the impact on morbidity (healthier lives) could be roughly estimated at €32.1 billion according to the study quoted above (40% of mortality benefits). Taken together, the benefits of cycling in the EU-27 linked to reduced mortality and morbidity can be estimated at €112.45 billion per year.

Discussion

There are several assumptions used in our calculations that would benefit from better availability of data and calculation methodologies. This concerns first the assumption that all cycling is for transport and not a substitution for other physical activity. More research would be needed to verify this assumption. The second assumption is on the value of the morbidity impact of cycling, which for the moment is a rough estimation based on one regional study. The authors of the HEAT tool user guide themselves recognise that the addition of morbidity effects of walking and cycling would be an important future step for the development of the tool. Thirdly, we implicitly assume that all cycling is solely by muscle power since the data from the mobility survey does not distinguish between muscle-powered and electrically assisted cycling. Since its latest update in 2023, the HEAT tool can make the distinction between the two and calculate the impact on physical activity levels, so for future calculations new and comparable data on the modal share of electric cycling in the EU member states would be helpful.

3.2 Greenhouse Gas Emissions Impact

Methodology

To calculate the greenhouse gas emissions impact of cycling in the EU, the data from the EU-wide mobility survey was used (total kilometres cycled in the EU per year, average occupancy rate of passenger cars). For greenhouse gas emissions per passenger kilometres for different transport modes, different sources had to be used: Transport & Environment's Life-Cycle Emissions Guidance for different types of cars [7], and data from French train operator SNCF on modes of public transport [8]. For cycling itself, values from a recent study estimating the greenhouse gas emissions savings potential of cycling at an individual level were used [9].

Results

Using the source values mentioned above, the gross greenhouse gas emissions savings from cycling replacing motorised modes of transport in the EU-27 are ca. 15.58 million tons of CO2 equivalent. The additional emissions from cycling replacing walking trips are ca. 0.19 million tons of CO2 equivalent. The net emissions savings are ca. 15.4 million tons of CO2 equivalent. Using the central value for long-run climate change avoidance costs from the EU Handbook on the External Costs of Transport, we calculate a monetary value of ca. €4.14 bn for these emissions savings.

Discussion
The calculations in this field would benefit from more research on the total greenhouse gas emissions of all modes of transport, including cycling. As in the previous field, electric cycling should also be included in the future, as we have indications that while emissions are slightly higher than for conventional cycling due to the production of batteries and electricity, there might also be a higher potential for replacing car trips. For all electric modes of transport (cycling, trains, cars), emissions largely depend on the energy sources of electricity production. Finally, the large range of values given for the social cost of carbon or for climate change avoidance costs makes it complicated to give an exact monetary value for the greenhouse gas emissions savings.

3.3 Environmental Impacts

Methodology
For the calculations in this field, data from the EU-wide mobility survey (kilometres cycled, average vehicle occupancy for passenger cars) was combined with values from the EU Handbook of External Costs of Transport in the fields of air pollution, noise pollution and habitat damage.

Results
Using the data and parameters quoted above, the following results were obtained for the environmental impact linked to current cycling levels in Europe (Table 2):

Table 2. Selected environmental impacts of cycling in the EU-27

Area	Impact of cycling – monetary value (€)
Air pollution	994,960,961
Noise pollution	765,169,561
Habitat damage	552,383,912
Total	**2,312,514,434**

Discussion
The calculations above are based on average cost values for the EU as a whole. With more detailed data on when and where cycling takes place, it would be possible to also calculate marginal costs for different settings, for example in densely populated urban areas vs. rural areas. For habitat damage, the results are gross values not taking into account the habitat damage caused by cycling infrastructure. Since cycling is much more space-efficient than car traffic, we could assume that cycling infrastructure causes much less habitat damage for the same amount of people transported, but more research would be needed to corroborate this assumption.

4 Conclusions

The results of our calculations show total external benefits of cycling in the EU-27 of ca. €119 billion in the areas that we described here. This does not yet include fields like congestion reduction, where substantial quantifiable benefits could also be expected. As in the previous report, the results show that health benefits of cycling have by far the largest share in total benefits. This is an important finding, since health effects are often not taken into account in "classical" cost-benefit analysis for transport projects. In 2022, the WHO in its Global status report on physical activity estimated the cost of physical inactivity at US$ 27 billion per year [10]. Our results show that investment in active mobility can play an important role in bringing down these costs in the EU.

In our paper, we also identified several research and data gaps for estimating the impacts of cycling. First and foremost, this concerns the replacement of other modes of transport by cycling, as well as cycling habits and purposes (e.g. sport cycling vs. transport cycling). There is also a need for more data and research on electric cycling, since we know that sales of electrically assisted bicycles have grown almost exponentially over the last few years in the EU, and we expect to see an impact of this development on cycling usage. Finally, the first EU-wide mobility survey from 2021 has proven to be extremely valuable for our work, and we consider that it should be repeated over regular intervals to track changes in mobility behaviour over time across the whole EU.

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Remote Monitoring of Habitats to Support Management of Biodiversity Alongside Railways Across Britain

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Abstract. Biodiversity has been quantified for the first time in the 200-year history of the railway in Britain. We can now view habitats on our land in the context of the landscape through which the railway passes. This landscape view allows our land managers to look after these habitats working with adjacent landowners to the benefit of us all and the wildlife.

Traditional surveying methods need somebody 'out in the field' which is time consuming and can be difficult and dangerous. This remote monitoring technology has kept our surveyors safe and delivered information that can be used by our managers to target where further information may be needed.

The satellite data were converted to the UK habitat classification system. Using the area of the habitats, determined from pixel count, the biodiversity metric was used to quantify the amount of biodiversity on the railway estate. Future, higher resolution data, together with imagery from helicopters, fixed wing aircraft and drones will enable artificial intelligence techniques to improve the analysis of habitats and their condition.

It will transform the way that the railway in Britain, and others, will collect and interrogate data and plan any intervention. This new knowledge informs the better, targeted management of the habitats on the railway estate. These green corridors help the movement of isolated species and wildlife communities, improving genetic diversity and helping to build resilience against changes in climate. Our good management of the railway estate will improve the health and well-being of millions of passengers and neighbours.

Keywords: Green corridors · Linear infrastructure · Landscape-scale

1 Railway in Britain

The railway estate in Britain connects England, Scotland and Wales. It passes through every local authority and National Park. The railway boundary of 32,000 kms is bordered by seven million neighbours. One-third of the population of Britain lives within 500 m of a railway line – seven million of whom have a railway line only 12 m from the back fence. The estate itself is a long, thin slice of Britain covering an area of 52,000 hectares – the size of one and a half Isles of Wight.

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The railway infrastructure ranges in age from that managed on the original Stockton to Darlington services in 1825 to those newly constructed routes like the high-speed lines to Europe and parts of the East West Rail route. The infrastructure varies too with engineering marvels like the Glenfinnan viaduct in Scotland and the Box tunnel under Wiltshire. The construction activities of the Victorian engineers also exposed important geological formations, now protected as sites of special scientific interest (SSSIs) – over 200 SSSIs are found on the estate across Britain. These structures and the landscape features all provide a variety of biodiversity benefit.

Approximately 25,000 trains travel across the rail network every day. The management of the railway estate is key to the safe and timely passage of well over a billion passenger journeys every year. The maintenance work that takes place has often conflicted with the communities that we pass through… not only the people, but also the plants and animals that live on and in our infrastructure.

2 Habitat Management Techniques

Over the last two hundred years, variations in the approaches to vegetation management have resulted in some unique lineside habitats. This management has evolved over time, from regular cutting of the meadows during the age of steam to a more reactive management of woodland beside diesel and electric trains. The railway has not had the same cultivation or fertiliser use as the adjacent agricultural land. This has benefitted the soils and associated species that are found growing there. On parts of the network some particularly rare plants can be found, like the Deptford pink (*Dianthus armeria*) in a few locations in Devon and Leicestershire. It is also possible to find indicators of the 'wooded past' of the countryside in Britain with indicator species like dog's mercury (*Mercurialis perennis*) found growing lineside.

The different techniques and regimes of management alongside the railway has resulted in a change in the habitats that are found there. Network Rail [1] published some figures showing the changes in habitats found on the estate between the 1930s and 2015. The decline in the species-rich grassland by over 30% and increases in woodland and rank grassland were identified by Sargent [2]. They recognised the changes in management techniques stating "*prior to 1960, verge management generally took the form of annual burning, grass cutting and scrub clearance*". Varley [3] in his review of Network Rail's vegetation management illustrated the management of the lineside grasslands with an image from taken in March 1950 (Fig. 1 (left)). The extent of woodland and scrub encroachment on to the cutting slopes can be seen in the aerial image of the same location taken in May 2023 (Fig. 1 (right)).

Messenger [4] described the 'protection' of railway vegetation from agricultural practices but also pointed out that the railway management interventions created a specific 'railway habitat'. This habitat structure being lost on closure of lines (as happened frequently in the 1960s) and subsequently changes in management techniques on the rest of the operational network is a reason Messenger says that the flora found on the railway estate "*loses its character*."

The presence of certain habitat types, specifically trees, next to the railway has the potential to negatively impact both safety and performance. The vegetation can create

hazards for trackworkers, train drivers, passengers and level-crossing users. Trees can fall onto the track during extreme weather events, blocking the line and causing delays. The reduced levels of management that enabled the encroachment seen in Fig. 1 (right) led to vegetation management practices that focused on managing Network Rail's lineside woodland for safety and performance purposes, often to the detriment of valuable habitats such as species-rich grasslands. There were also challenges with managing a thin, linear asset through communities not used to a view of the rail infrastructure.

Challenges to Network Rail in 2018 resulting in widespread criticism and government ministerial intervention because of a lack of consideration of both communities and wildlife. The independent review led by John Varley recommended changes to Network Rail standards and procedures and also set a target for no net biodiversity loss by 2024 and a biodiversity net gain by 2035. Essential vegetation management for safety reasons could take place as before. However, the railway needed to take into account how to protect and nurture the habitats and species that live on the railway.

In order to consider these habitats, Network Rail had to understand what it had.



Fig. 1. (left) A Nottingham to Grantham train leaving Gonersby Tunnel in March 1950, photograph courtesy of Humphrey Platts. (right) Gonersby Tunnel in May 2023, photograph courtesy of Network Rail.

3 Data Collection

3.1 Initial Trials

Data collection alongside an operational railway is a challenging task. The presence of fast moving vehicles, overhead and ground level electrification systems and variable topography require good safe systems of work to be in place. Strong and Holt [5] describe the trialing of light detection and ranging (LiDAR) techniques to monitor vegetation alongside the railway. They describe an on-foot tree survey during the 2000s across the whole rail network that took 20 surveyors, two years to complete. The trial demonstrated that the use of fixed wing aircraft collecting LiDAR imagery could be used to plan

necessary work based upon vegetative growth and could assist with land use identification (Fig. 2). Within three years, the whole of the rail network had been surveyed using high-resolution imagery alongside LiDAR [6].

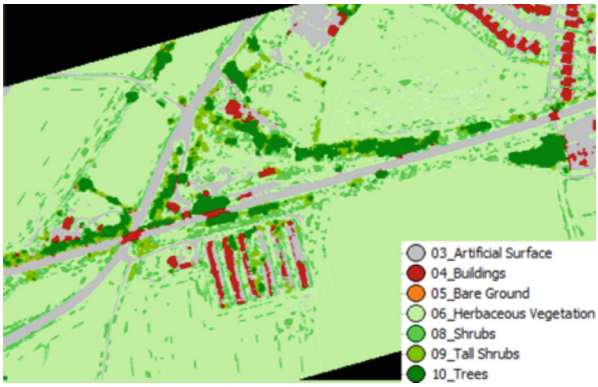


Fig. 2. Land cover classification from the 2011 Network Rail trial [5].

The recommendation from the Varley Review in 2018 to consider biodiversity during the management of the lineside estate added a further complexity to the survey requirements. The recommendation included the requirement to report annually on the management of biodiversity across the network. It is standard practice when calculating biodiversity units using the Biodiversity Metric to base the inputs on a field survey, undertaken by a competent ecologist. In order to survey all habitats across the Network Rail estate using a traditional, field survey methodology would require significant resource, both in terms of capable ecologists and funding. The access required to the railway lineside would mean that a number of surveying seasons would be required to cover the Network Rail estate. The survey of trees in the 2000s had already shown that an on-foot survey was not viable. It would not be feasible to complete this annually. Surveyors would also be required to work in the vicinity of the operational railway. Network Rail aim to minimise lineside working wherever possible for safety reasons and the use of lineside 'look out' safety staff ended in 2021. Opportunities to access the trackside environment are now much more restricted and limited to when trains are not running or lines are closed. An alternative methodology to assess the estate was required. Network Rail worked with global experts to access satellite data. This computer technology has kept the surveyors safe and delivered information that can be used by land managers to target where further information may be needed. These additional visits can be planned to take place at the safest and most suitable time collecting useful data and keeping personnel safe.

3.2 Sentinel-2 Satellite Data

In order to be able to use the satellite data to monitor and measure biodiversity, Network Rail commissioned the UK Centre for Ecology and Hydrology (UKCEH) to undertake

a remote sensing survey of the rail network in order to produce a 10m pixel land cover map showing 21 habitat types across the rail network. This exercise was undertaken during late 2019, early 2020. The Sentinel-2 data were translated to UK-Habitats Classification System. This system aligns with the Department for Environment, Food and Rural Affairs (DEFRA) and Natural England's Biodiversity Metric. This approach will enable subsequent years' datasets to be analysed consistently to determine changes.

A land cover map truncated to a one-kilometre buffer either side of the rail network was created – this is an equivalent area to 3.2 million hectares (Fig. 3). Using the Network Rail ownership boundaries, regional statistics describing habitat types across the five regions were calculated by intersecting the boundary data with habitat types and creating pixel counts for each habitat type within the railway property boundary.

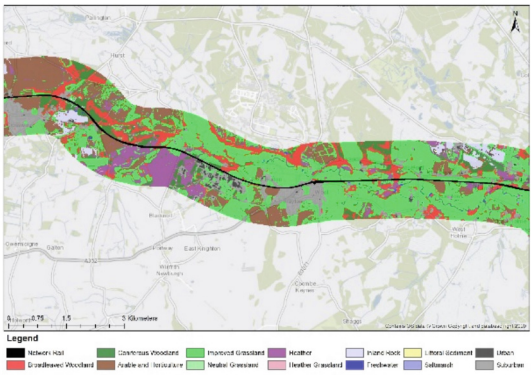


Fig. 3. Example land cover map [7]

4 Results

The use of satellite data has enabled the quantification of biodiversity on the railway in Britain to be achieved for the first time in the 200-year history of the railway. It has also been achieved safely, with no injury to surveyors.

The *circa* 250,000 units provides a baseline by which the railway is able to demonstrate the improvements of the management of its estate. Its obligations to protect and enhance biodiversity can now be monitored and managed accordingly.

This information that we now have demonstrates the opportunity for using our land for the benefit of people and nature. The railway estate may be one of the largest estates in Britain, but there are many challenges still to address if we are to make best use of this opportunity, including improving the accuracy and detail of the data collected.

The maps of the habitats cross the railway network and a swathe of British countryside have been used by external organisations. Using the knowledge and the learning from the project we have successfully bid for funding for feasibility work to develop tools for land managers to make the correct intervention decisions based on the local habitats, amongst other features. We can now use satellite imagery to pinpoint areas for additional

inspections. The improvements in the way we manage our estate will increase safety on the tracks, in turn reducing delay, enhancing customer satisfaction and increasing passengers' positive experiences. It further increases customer and stakeholder confidence in the railway.

5 The Future

The work here is applicable to any linear network and the techniques and technology are not restricted to use in Britain. This project is already improving the quality of habitat data available to the rail industry. It is already providing value for public money and contributing to the strategic goal of Network Rail becoming a leader in land management for biodiversity. This project provides data, whole life costing and carbon footprint data to facilitate future projects protecting, maintaining and enhancing biodiversity on the railway estate.

It is transformative by demonstrating how artificial intelligence may be utilised in the future to give insight and visualisation on activities in difficult-to-reach areas. It also provides an innovative solution to major operational issues associated with managing habitats and trees within a given distance of the railway (Fig. 4). It will transform the way that the railway in Britain, and others, will collect and interrogate data and plan any intervention.

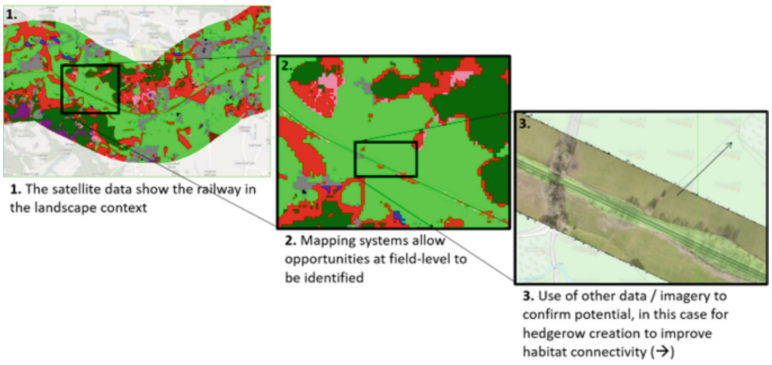


Fig. 4. Using satellite data to manage and enhance habitat connectivity along the railway's green corridor [7]

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Enhancing Biodiversity During the Development of Transport Infrastructure in Ireland

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Abstract. Transport Infrastructure Ireland (TII) provides sustainable transport infrastructure and services in Ireland, delivering a better quality of life, supporting economic growth, and respecting the environment. TII has developed a biodiversity plan and an accompanying landscape plan to ensure that biodiversity is an integral part of landscape treatments of major transport infrastructure.

The following paper will present two case studies where it will be demonstrated that driving change with the support of such plans will contribute and support the following policy areas where:

a. Biodiversity is fully integrated into all TII operations and processes,
b. TII transport corridors will promote habitat connectivity across the wider landscape and will contribute to the enhancement of wider ecosystem services,
c. New projects will be developed with no net loss of biodiversity and will strive for a net gain in biodiversity,
d. Legacy impacts to biodiversity from existing infrastructure will be identified and addressed, and finally
e. All TII activities (e.g. plans, projects and programs) comply with relevant biodiversity legislation.

Keywords: Biodiversity · landscape treatments · landscape management · habitats · no net loss · net gain in biodiversity · pollinators

1 Introduction

The world is experiencing a significant biodiversity crisis and it is estimated that global wildlife populations have fallen by as much as 60% in the last four decades [1]. Declines are attributable to a range of factors including changes in land and sea use, over exploitation, pollution, and the spread of alien invasive species. Ireland is not immune to these negative trends with 85% of European Union (EU) protected habitats and 32% of EU protected species classified as being in unfavourable status [2]. TII is committed to embedding sustainability across all its activities and has developed a sustainability Implementation Plan (SIP) which encompasses six sustainability principles to ensure it provides sustainable transport infrastructure and services which deliver a better quality of life, supports economic growth and respects the environment [3].

In its SIP, TII has committed to the following biodiversity objectives:

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a) Investigation into restoration of degraded ecosystems through sustainable management and continuing to address biodiversity loss, protecting nature and restoring habitats, and
b) Bringing nature back into our lives in accordance with the EU Biodiversity Strategy for 2030.

TII developed a biodiversity plan [4] and an accompanying landscape plan [5] to ensure that biodiversity is an integral part of landscape treatments of major transport infrastructure.

TII considers 'biodiversity', as a measure of the variety of species, habitats, and ecosystems on earth, ranging in scale from microorganisms to the amazon rainforest and it has set a clear vison for biodiversity which will contribute to the recovery of biodiversity at a local and national level while developing and maintaining a safe and reliable transport infrastructure network.

TII as a state provider of infrastructure recognises the potential for our activities to impact biodiversity. Such impacts can result from the development of new projects or legacy and ongoing impacts associated with existing infrastructure. TII also recognises that there are opportunities to enhance and restore biodiversity and has set a clear vison which will contribute to the recovery of biodiversity at a local and national level while developing and maintaining a safe and reliable transport infrastructure network [6].

2 Dedicated Biodiversity and Landscape Plans

TII**'s** Biodiversity and Landscape plans sets out TII's aims and actions regarding these aligned topics which will be applied to all TII projects along our National Road and light rail networks.

The Biodiversity Plan contains the following five overarching objectives and associated actions for biodiversity which were developed to deliver on specific policy areas**:**

1) Increase biodiversity capacity, resources, collaboration, and capability. Recognising that the successful delivery of TII Biodiversity Plan is largely dependent by the availability of suitably skilled and experienced staff.
2) Develop a biodiversity standard and related technical documents. TII plays an active role in ensuring compliance with national and international biodiversity related legislation through the development of standards and guidance documents. These documents, on subjects including biodiversity impact assessment and protected species survey methodology ensures our projects adhere to the most up to date best practice guidance.
3) Support research, monitoring and data sharing. Biodiversity related research informs the creation of new standard documents and monitoring of biodiversity interventions is vital in establishing the efficacy of these measures.
4) Embrace biodiversity accounting methodologies and strive for net gain. Biodiversity Net Gain (BNG) is an approach to development, and/or land management, which aims to leave the natural environment in a measurably better state than it was beforehand.
5) Focus on key biodiversity issues. Our biodiversity plan focuses on key areas where the greatest benefits to biodiversity can be achieved through targeted interventions.

Our Landscape Plan has its own stand-alone objectives but with a focus on incorporating biodiversity into all aspects of the landscape design of new projects and the management of our existing landscape assets. Currently, there is approximately 3,500 ha of Landscape adjacent to the National Road Network so the opportunities for biodiversity enhancement within our road networks and improving ecological connectivity in the wider Irish Landscape were a focus of the landscape plan.

Both documents are complimentary, and they will inform the future development of biodiversity standards which will define how project managers ensure the integration of biodiversity and landscape expertise at the outset of major project development.

3 Case Study – Legacy Landscapes Opportunities for Enhanced Biodiversity

A landscape trial was carried out on a section of motorway under the direct control of TII. The landscape management of this asset is through the Motorway Maintenance and Renewals contract (MMaRC). A collaborative approach to the trial was taken with the support of the TII Network managers and the MMaRC Contractors to assess how changing our grassland mowing regimes could benefit pollinators and to align with the aims and actions of the All-Ireland Pollinator Plan [7], of which TII is a member of the steering committee. The principles of the trial were to modify the times and frequency of mowing the verges alongside the motorway corridors, grass in central medians and at roundabouts. Weed spraying with herbicides was also changed from a condition-based maintenance (3 to 4 times a year) to two timed sprays. The trial regarding altered mowing resulted in a clear increase in wildflowers on the motorway with native orchids being recorded in increased numbers because of later mowing. The reduction in herbicide use resulted in a clear increase in weed growth on the network, but there was no spike in complaints received regarding weeds on the network or impact on the safety or functionality of the network. A reduction of approximately 26% of herbicide used on the network was achieved in the first year of the trial. While the trial was focussed on pollinators the enhancement of the grassland for all of biodiversity was recognised. The results of the trial will inform the upcoming landscape and biodiversity standards currently being developed.

4 Case Study – Luas Finglas No Net Loss of Biodiversity

Luas Finglas is a 3.9 km planned extension to an existing Luas Light Rail line in the suburbs of North Dublin. It is planned to run through several parks and local open spaces and crosses a river and a canal with their associated biodiversity and amenity values. The Project Team recognised that the existing use of these spaces, and opportunities for their landscape and biodiversity enhancement could be realised through the design process. In response to Biodiversity Net Gain (BNG) commitments detailed in Dublin City Councils Biodiversity Action Plan [8] a BNG approach was adopted on the Finglas Luas Project in 2022 [9]. A short-term objective in TII's Biodiversity plan is to develop a biodiversity accounting metric to implement on all new projects and track progress

on project specific biodiversity enhancements. A biodiversity metric is a standardized means of quantifying biodiversity losses and gains. A BNG approach was trialled on the Luas Finglas project to see how the project team could apply the principles of BNG to a linear infrastructure project where several different habitat types were impacted. In the absence of a biodiversity metric for the Irish landscape, the UK Department of Environment, Food and Rural Affairs (Defra) metric (BNG 3.1) [10] was used for this BNG assessment with some 'translation' of Irish Fossit habitat classification [11] for input into the calculation Tool which is based on UK habitat classifications. The incorporation of this accounting methodology from the early design stages of the project has meant that a sensitivity and appreciation of the impacts on local biodiversity has been a focus of all design disciplines. The project final design is not completed but thus far the preliminary results are showing notable biodiversity gains within the terrestrial habitats with a minor reduction in biodiversity in the linear aquatic habitats.

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Opportunities to Rehabilitate Peatlands via Transportation Projects

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Abstract. A refined approach for Transport Infrastructure Ireland (TII) projects will help in the strive for rehabilitating Ireland's peatland habitats. After rehabilitation, peatlands can act as a major asset to reduce annual carbon emissions due to their carbon sink potential. Opportunities have been identified to reduce carbon emissions as part of TII's peatland rehabilitation research project and will be published in technical guidance. Strategies to progress projects in ways that are sympathetic to degraded peatlands were assessed. Key elements include existing drainage infrastructure, flood risks and underlying hydrogeological conditions. Project earthworks are also highly influential, with solutions available to avoid excavating peat or create suitable deposition sites with arisings from degraded peatlands. These can rewet peatlands and promote long-term sphagnum growth.

Keywords: Peatlands · Rehabilitation · Ecology · Hydrology · Hydrogeology · Earthworks

1 Introduction

1.1 Background

During route appraisal and design, every effort is made to minimise earthworks and the requirements for importing or exporting material as this requires significant volumes which often must be hauled large distances. However, in areas where the substrate is predominantly peat there are additional requirements for the removal of this soft material to facilitate construction. The route selection process is designed to avoid these peat areas as these soft ground conditions are so problematic and peatlands are also areas of strong biodiversity attributes. Where this cannot be avoided, the construction phase of the road project require removal and redeposition of peat arisings. Legislative and climate change objectives will also affect project sustainability criteria. Appropriate consideration needs to be given to peatlands to inform on potential direct and indirect impacts and significant emissions.

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Peatland habitats across Ireland store an enormous amount of carbon as wet organic matter and have an essential role in carbon sequestration and biodiversity. Many of these areas have been degraded through peat extraction and agricultural drainage and have lost their essential sequestration and biodiversity functionalities. Peat covers only 3% of the world but contains 30% of its carbon (550Gt) (Parish et al. 2007). Peat soils cover 20% of Ireland's land surface (Connolly & Holden 2009) with a majority having degraded status and represent ongoing sources of Greenhouse Gases (GHG) emissions.

1.2 Research Aims

The purpose of this research project is to identify a hierarchy for consideration in the preparatory phases of projects to identify synergistic improvements for drainage, earthworks, biodiversity and carbon designs, suitable methods to dispose of excavated peat materials and for rehabilitating peatlands. Opportunities to maintain higher water levels to support better growth of key species in proximity to road or greenway developments will be sympathetic to degraded peatlands. Restoration can vary from minor works such as blocking drains, to major rehabilitation works with earthworks and acute detailing of site drainage amendments, achieving significant biodiversity enhancements.

The research will result in a detailed technical guidance document detailing all the necessary desk top studies, field surveys, site investigation techniques and sampling requirements to achieve these sustainability objectives. It will also outline legislative issues and project management aspects of the rehabilitation process.

The water table and surface runoff conditions are fundamental in rewetting peatland areas in order to nurture sphagnum growth. The focus of this paper is to outline the findings to date on optimising earthworks, materials management and drainage designs in the context of biodiversity gains, carbon storage and carbon sequestration benefits.

2 Pressures and Impacts on Organic Peat Soils

As a wetland ecosystem, peatlands are dependent on the maintenance of near waterlogged conditions. The drainage or drying out of peatlands leads to changes in the flora and fauna of the site, where specialist wetland species are replaced by species more suited to drier habitats. This typically involves the degradation of the acrotelm, a reduction and eventual absence of sphagnum species and a succession by dwarf shrubs, tussock forming species and trees such as birch, willows, conifers (Lunt et al. 2010). This degradation results in organic decomposition of the carbon when exposed to air over longer periods of time.

Historically, the main reasons for the reduction in the area of natural peatlands are habitat loss including afforestation, turbary (peat harvesting), land reclamation for agriculture, including drainage, the application of fertilisers and overgrazing, invasive alien species, nutrient pollution, and climate change also affecting status.

Impacts to near-intact peatland regimes can be significant where routes for road or rail construction have traversed such habitats. Construction near these peatlands can lead to direct and indirect effects due to the removal of compressible soils and changes in hydrological regime due to drainage via permeable fill under embankments and drainage trenches. These changes result in subsidence, followed by peat oxidation. Rewetting will not simply return it to its original volume (Regan & Johnston 2012).

2.1 Current Management and Reuse Options on TII Roads Projects

The current management and reuse options of peat/organic soils on TII road projects differ widely depending on for example local site conditions, sensitive receptors including the ecological importance of the peatland habitat features, global earthworks or geotechnical requirements, available lands and stakeholder inputs.

It is generally expected that where impacts to peatland habitats cannot be avoided, mitigation measures will be implemented such as translocation of local features to a nearby position, but leaving it in a similar environment such that it can re-establish itself. Habitat enhancements and translocations do arise on projects, particularly in the west, and have had varying success upon implementation (e.g. Leenamore, Co. Mayo).

Earthworks design restrictions and TII contractual works requirements around peat and other organic soils are also a key factor to consider. Treatment options for peat soils are restricted to either: a) excavation and replacement; or b) pile supported embankments for the majority of all such national roads. Ground improvement techniques are allowed for other mineral soils e.g. alluvial, estuarine and lacustrine deposits but rarely for organic peat soils, without departures.

TII projects with peat arisings typically encroach into adjacent lands for the purposes of material deposition close to the scheme and have suitable plant for haulage on-site anyway. Generally, the key objective is material storage rather than for biodiversity or carbon storage. At the M6 Galway East Pollboy site, peat was deposited on three raised peat disposal bunds to a maximum height of 2 m. This was designed to accommodate a native woodland including birch and willow as part of the landscaping design with benefits in both biodiversity and carbon storage. Some quantities of peat can also be used to establish topsoil over slopes inside the lands made available in many projects.

Peat can also be infilled into deep borrow pits from which rock or better soils, are 'won' for use on the site. These typically widen out areas of cuttings suited to steeper slopes or require pre-split drilling and blasting through rock. Examples of this technique can be found along the M6 motorway at Rahally, Co. Galway as shown in Fig. 1, where it is now an effective reed swamp thanks to a sympathetic drainage design. There is a significant distinction between the habitats that naturally established on the site.

A larger raised bund peat restoration area was developed near Maam Cross on the N59 which was constructed with some promising results shown in Fig. 2. Within 3 years the best areas have wet conditions, initial sphagnum growth and other positive indicators, e.g. common frog and sundew, whereas some places showed signs of drying out, presumably through underlying voids between clumps of peat.

3 Positive Environmental Impacts from Designs

There are various options to consider when optimising earthworks and assessing drainage designs in the context of biodiversity gains, carbon storage or sequestration. Local site conditions, sensitive environmental features, design objectives, available lands and whether excavation can be avoided or not are critical. Methodologies comparing Life-Cycle Accounting (LCA) of such works were derived by Duggan *et al.* (2015) and have been revisited recently to compare options utilising up-to-date emission factors.



Fig. 1. A deep material borrow pit that was exploited during construction of N6 motorway. This was backfilled with wet glacial soils and peat deposits – a reed swamp habitat was well established after 10 to 15 years.

It is important that baseline peat depth and water table are understood in the Do-Nothing scenario as degraded drained peatlands are already significant emitters. This offers synergies for all disciplines to reduce material impacts, protect against flooding and implementing designs encouraging sphagnum growth compared to alternatives.

3.1 Options Where Excavation of Peat is Required

As mentioned previously, many Irish peatlands have been converted to agricultural or afforested land and are drained. Such degraded areas are frequently encountered in road projects means that options for suitable storage areas of excavated peat can be considered. Arguably, and indeed paradoxically, removing an area of drained peatland and providing conditions suited to rehabilitation in controlled conditions could be a positive impact in terms of both biodiversity and carbon. Excavated peat is typically placed into cells surrounded by shallow berms or deep borrow pits where material mass haul requirements suit. If these can improve other degraded sites, multiple benefits are likely.

3.2 Options Where Excavation of Peat Can Be Avoided

Options for construction as alternatives to excavating peat may include ground improvements, providing surcharge construction, lightweight fill, piled embankments/load transfer platforms or deep soil mixing. For greenways, floating construction is adequate. The main benefit of keeping the peat in the ground is additional lands are not required for peat disposal areas. Covering the peat with embankments is also likely to reduce the process of degradation however there is an interaction if permeable fill leads to drainage of adjacent peat. While options that leave peat in place minimise peat disturbance, further research is needed on dry soil-mixing, surcharging and piling options. A potential



Fig. 2. Variability in surface vegetation at a bermed peat restoration area on N59. Aerial image of the area during construction (top), comparisons of established sphagnum growth (bottom-left) and poor areas that have dried out (bottom-right)

change to using small clay bunds to coral roadside run-off instead of excavating ditches into peat could also be positive, providing drainage at a higher level.

3.3 Options for Restoring (Rewetting) and Rehabilitating Peatlands

Road drainage must be kept entirely separate to avoid excess nutrient loadings as colonisation by various macrophytes can replace peat-forming sphagnum. Discharge to peat drainage networks should be avoided. Agricultural runoff also carry excess nutrients.

Drain blocking with the aim of restoring existing bogs by local co-operative groups, Bord na Móna and National Parks & Wildlife Service (NPWS) are numerous, including the Liffey Head Rewetting (Co. Wicklow). Further measures are outlined in Bord na Móna's methodology paper (Bord na Móna 2022). UK research projects by MoorLife 2020 and Yorkshire Peatland Partnership provide standard detailing and strategies for managing risks of erosion and piping (Allot et al. 2022). European projects like Care-Peat (2023) also assess carbon flows. The blocking of drains slows flow rates and increases water levels in the adjacent peat. Slowing water movement reduces carbon losses, silt and ammonia contents. Perimeter and cell forming berms also impound surface waters.

Large perimeter bunds are placed on the downslope edge periphery of degraded peatlands to control excess runoff but must avoid excessive hydraulic gradients.

Without rewetting, Ireland's drained peatlands will continue to emit significant CO_2. If rehabilitated/restored, GHG emissions will reduce, protecting biodiversity and water quality. Despite initial CH_4 emissions upon rewetting (Renou-Wilson et al. 2019), the cost of inaction is greater.

4 Conclusions

This research project is addressing how the management of peatlands during the planning, construction and aftercare of TII projects can yield net biodiversity gains and positive carbon impacts. This will consider how peat is characterised, assessed, valued and monitored over the full life-cycle of a project. The guidelines will highlight best practice in peatland management using sustainable synergistic designs.

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Logistics and Sustainable Transport

A Multi-objective Approach to Flight Scheduling and Fleet Assignment in Hub Network

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Abstract. The hub-and-spoke (HS) network is a widely used business strategy by airlines to optimize their operations and increase their reach by connecting multiple destinations through a central hub, and the majority of the passengers are transit passengers. The airline schedule planning process starts with the flight scheduling problem (FSP) to generate a timetable in advance of six months. Then, the fleet assignment problem (FAP) is examined to determine aircraft types. This sequential solution approach causes suboptimal solutions, and the schedule must be adjusted to increased demand. Due to the complexity of this problem, this study focuses specifically on incremental schedule design with one hub two-flight leg network. This study presents a Multi-Objective Mixed Integer Programming Model for integrated FSP and FAP to adjust the generated timetable with launching new flights. Two solution approaches are proposed to decide the new proposed flight's time, aircraft type, and passenger assignment: the Weighted Goal Programming Model (WGPM) and the Lexicographic Goal Programming Model (LGPM). This study shows that there is a conflicting relationship between cost and $C0_2$ emissions in the flight scheduling process. If carbon dioxide emissions are prioritized, airlines need to schedule more flights with small-capacity aircraft.

Keyword: Hub-and-Spoke Network · Schedule Design · Fleet Assignment · Integrated Airline Scheduling

1 Introduction

The hub-and-spoke (HS) network, a complex system central to airline strategies, optimizes operations and extends reach by connecting multiple destinations through a central hub, emphasizing careful airline schedule planning to efficiently transport transit passengers and maintain competitiveness. The airline scheduling planning initiates with the flight scheduling problem (FSP), determining serviced markets, frequencies, and flight strategies [1]. FSP's goal is a schedule integrating route, departure, and arrival times, considering passenger demand and ticket prices [2]. Schedules, typically planned six

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months ahead using projected block time, prioritize profit maximization [1, 3]. Subsequently, the fleet assignment problem (FAP) allocates suitably sized aircraft to flights [1]. Most practitioners address only one stage of airline scheduling such as [4]; however, a few focus on FSP among other problems in airline schedule planning [3]. Since the sequential solution approach causes suboptimal solutions [3], integrated models gain attraction as they overcome suboptimal sequential solutions such as [5, 6]. Majority of the integrated problems' main goal is cost reduction or profit maximization [7].

This study addresses integrating flight schedule design and fleet assignment in airlines, focusing on one hub, two-flight leg network. It aims to create a timetable accommodating excess demand without disrupting the existing flight schedule by introducing new flights. Since the transit passenger demand for a flight will change till the realization of the schedule, the schedule must be adjusted to increased demand. The models explicitly capture interactions between transit passenger demand, flight seat availability, and newly introduced flight departure times. They address passenger assignment for scheduled and new flights, along with newly introduced flights' timing and aircraft type. This research contributes by minimizing transit passenger waiting times, reducing newly launched flights, and minimizing total CO_2 emissions per passenger while maintaining the existing schedule in the HS network. It also develops an efficient decision support system for airlines, presenting diverse scenarios based on newly introduced flight capacities and departure times under varying transit passenger demand. Notably, WGPM demonstrates superior total cost value over LGPM when total CO_2 values are equal. Moreover, in cases where total CO_2 is more important than total cost, models tend to open to many small-capacitated aircraft in the schedule. This paper is organized as mathematical modeling, computational experiment, and conclusion, respectively.

2 Mathematical Modeling

The objective is to adjust a daily timetable, including aircraft type, period, and passenger assignment for respective aircraft when demand exceeds scheduled seat capacity, necessitating new flights. Figure 1 indicates the conceptual model graphically to represent inputs and outputs of the problem in abstract level:

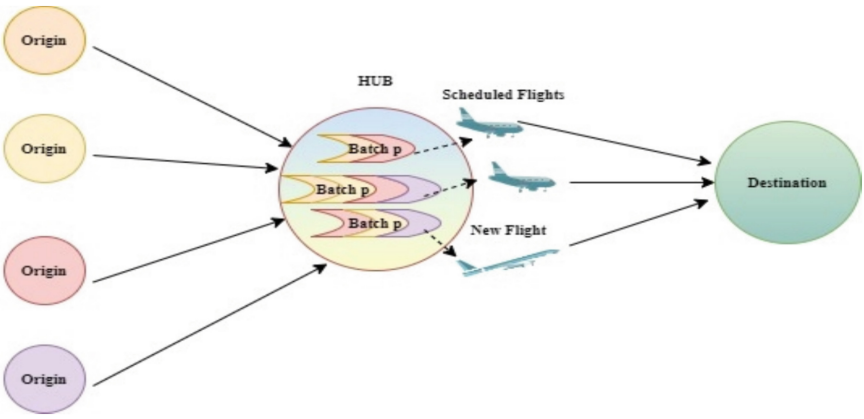


Fig. 1. Conceptual Model

A flight encompasses an aircraft, schedule (arrival and departure times), and route. Each aircraft-time combination represents a flight, whether scheduled or new. To manage high demand efficiently, passengers are grouped based on aircraft capacity and time eligibility, streamlining the assignment process. Grouped passengers are then assigned to a flight batch, reducing computational complexity. Moreover, the scheduling problem pertains to a single day. In this study, the problem is formulated as a multi-objective MILP, and then LGPM and WGPM are proposed to find promising solutions with conflicting objectives, respectively. Sets, indices, parameters, and decision variables are given in the following:

Sets and Indices

t: Transit passenger index, t = 1, …,T
p: Batch index, p= 1, ...,P
G: Set of time periods, G={1,2, …, |B|}
g, j: time period indices, where g, j ∈ G
K: Set of aircraft types, K={1,2,…, |Z|}
k, q: aircraft type indices, where k, q ∈ K
G_t: Set of eligible periods for passenger t
T_g:Set of eligible passengers for period g

Parameters

M_t: Maximum time without cost applied
e_g: Expected time period g
r_t: Ready time of the transit passenger t
N_{gk}: Cost of opening aircraft k at g
D_k: $C0_2$ emission/passenger for aircraft k
M: A very large number
O_{kg}: Occupied seats of scheduled flights
A_k: Capacity of aircraft k
L_{kg}: Capacity of aircraft k at period g, $L_{kg} = A_k - O_{kg}$,
w_{gt}:Waiting time of passenger t, $w_{gt} = e_g - r_t$, $g \in G_t$, $t \in T_g$

$$h_{gt} = \begin{cases} 1, \text{ if } w_{tg} \le M_t \\ C_1, \text{ if } M_t < w_{tg} \le S_1 \text{ where } C_1 > 1 \\ C_2, \text{ if } S_1 < w_{tg} \le S_2 \text{ where } C_2 > C_1 \\ C_3, \text{ otherwise where } C_3 > C_2 \end{cases}$$

h_{gt} parameter is the cost coefficient (C_1, C_2, *and* C_3) based on the waiting time of transit passenger t for the specified time periods (S_1, S_2 *and* S_3).

C_{gt}: The weighted cost of assigning transit passenger t to at period g, $C_{gt} = h_{gt}\, w_{gt}$.

The waiting time of the transit passenger t at period g is multiplied by incremental fixed costs (C_1, C_2, C_3 *and* C_4) for the specified time intervals if its waiting time exceeds the maximum allowable time; otherwise, the transit passenger is multiplied by 1.

Decision Variables

Y_{gpk} = total number of transit passengers in each batch p in aircraft k at time g

TC_{pk} = total waiting cost in each batch p in aircraft k

$$X_{gpkt} = \begin{cases} 1, \text{ if transit passeneger i is assigned to batch p of aircraft k at time g} \\ 0, \text{ otherwise} \end{cases}$$

$$U_{gpk} = \begin{cases} 1, \text{ if any transit passeneger is assigned to batch p of aircraft k at time g} \\ 0, \text{ otherwise} \end{cases}$$

$$AU_{kg} = \begin{cases} 1, \text{ if aircraft k is used at time g} \\ 0, \text{ otherwise} \end{cases}.$$

TD_{gp} = total $C0_2$ emissions for transit passengers that are assigned batch p at time g

Multi-Objective Mixed Integer Linear Programming Model (MILPM) is as follows:

$$Min \sum_{k\in K,\ g\in G|(k\neq q \vee g\neq j)\&(k=q \wedge g\neq j)} N_{gk} AU_{kg} + \sum_p \sum_k TC_{pk} \quad (1)$$

$$Min \sum_g \sum_p TD_{gp} \quad (2)$$

Subject to:

$$\sum_p \sum_k \sum_{g\in G_t} X_{gpkt} = 1 \quad \forall t \quad (3)$$

$$\sum_{t\in T_g} X_{gpkt} \leq M\ U_{gpk} \quad \forall g, \forall p, \forall k \quad (4)$$

$$\sum_p U_{gpk} \leq AU_{kg} \quad \forall g, \forall k \quad (5)$$

$$U_{gp+1k} \leq U_{gpk} \quad \forall g, \forall p, \forall k | p < |P| \quad (6)$$

$$\sum_{t\in T_g} X_{gpkt} = Y_{gpk} \quad \forall g, \forall p, \forall k \quad (7)$$

$$\sum_p Y_{gpk} \leq L_{kg} \quad \forall g, \forall k \quad (8)$$

$$\sum_g \sum_{t\in T_g} X_{gpkt}\ C_{gt} = TC_{pk} \quad \forall p, \forall k \quad (9)$$

$$TD_{gp} = \sum_k D_k Y_{gpk} \quad \forall g, \forall p \quad (10)$$

$$AU_{kg|(k=q\ \vee g=j)} = 1 \quad \forall g, \forall k \quad (11)$$

$$X_{gpkt} \in \{0,1\} \quad \forall g, \forall p, \forall k, \forall t \quad (12)$$

$$U_{gpkt} \in \{0,1\} \quad \forall g, \forall p, \forall k, \forall t \quad (13)$$

$$AU_{kg} \in \{0,1\} \quad \forall g, \forall k \quad (14)$$

$$Y_{gpk} \geq 0 \quad \forall g, \forall p, \forall k \quad (15)$$

$$TC_{pk} \geq 0 \quad \forall p, \forall k \quad (16)$$

$$TD_{gp} \geq 0 \quad \forall g, \forall p \quad (17)$$

The model has two objectives. The first objective is the minimization of the total cost as shown in Eq. 1. Total cost is composed of total waiting time at the airport for the transit passenger and opening a new aircraft k at time g. First summation in the objective function calculates the summation of the new flights opening cost at time g ($\forall g \in G$) with aircraft k ($\forall k \in K$) excluding already scheduled flights at time j ($j \in G$) with aircraft q ($\forall q \in K$). q and j indices are used to define scheduled flights. The second summation in objective 1 calculates the total waiting cost for batch p in aircraft k. The second objective is the minimization of the total $C0_2$ emissions for each batch p at each time g shown in Eq. 2. Equation 3 ensures that each passenger t has to assign to exactly one of the batches ($\forall p \in P$) of an aircraft k ($\forall k \in K$) at time g ($g \in G_t$). Equation 4 ensures that if at least one passenger is assigned to a batch ($\forall p \in P$) of an aircraft k ($\forall k \in K$) at any time ($g \in G_t$), then aircraft k is marked as used. Equation 5 ensures that at most one batch ($\forall p \in P$) is assigned each time (g ∈ G) for each aircraft k ($\forall k \in K$).

Equation 6 guarantees that a passenger can be assigned to a successor batch p + 1 if and only if the batch p is also used. Equation 7 returns the total number of passengers of each batch p ($\forall p \in P$) of each aircraft k ($\forall k \in K$) for each time period (g ∈ G). Equation 8 ensures that total number of passengers in all batches does not exceed the available seat capacity of aircraft k at time g. Equation 9 returns the total cost of each batch p ($\forall p \in P$) of each aircraft k ($\forall k \in K$). Equation 10 gives the value of total C02 emissions of each time period ($\forall g \in G$) of each aircraft g ($\forall g \in G$). Equation 11 ensures that scheduled flights have already opened ($\forall g, \forall k | \mathrm{k} = \mathrm{q} \vee \mathrm{g} = \mathrm{j}$). Equations 12 to 17 are domain constraints.

The WGPM requires additional variables, so the deviational variables are added to the model (d_v^-, d_v^+, v = 1,2). This problem aims to minimize positive deviations from both objective functions (total cost and total $C0_2$ emissions) from their target values T_o, o = 1,2. $\alpha(\alpha \in (0,1))$ is the weight of the d_1^+ while $\beta(\beta \in (0,1))$ is the weight of the d_2^+. The WGPM is given as follows:

$$Min\ \alpha d_1^+ + \beta d_2^+ \tag{18}$$

Subject to

$$\sum\nolimits_{\mathrm{k}\in\mathrm{K},\ \mathrm{g}\in\mathrm{G}|(\mathrm{k}\neq\mathrm{q}\vee\mathrm{g}\neq\mathrm{j})\&(\mathrm{k}=\mathrm{q}\wedge\mathrm{g}\neq\mathrm{j})} N_{gk} AU_{kg} + \sum\nolimits_p \sum\nolimits_k TC_{pk} - d_1^+ + d_1^- = T_1 \tag{19}$$

$$\sum\nolimits_g \sum\nolimits_p TD_{gp} - d_2^+ + d_2^- = T_2 \tag{20}$$

$$d_{\mathrm{v}}^+, d_{\mathrm{v}}^- \geq 0 \qquad \forall v \tag{21}$$

Equations between (3) and (17).

The LGPM proposes two levels of priority between their target values To, o = 1,2. It is assumed that total cost is more important than total $C0_2$ emissions. The model to be solved in the first level with the objective of minimization of d_1^+ with the following constraints: Eqs. between (3) and (17) and between (19), and (21). Optimal solution of the problem equals to d_1^{+*}. The model to be solved in the second level with the objective of minimization of d_2^+ with the same constraints in the first stage in addition to $d_1^+ = d_1^{+*}$.

3 Computational Experiment

300 passengers (t), 24 time periods (g), 3 aircraft types (k) and 7 batches (p) are used in the computational experiment. Parameter values are as follows: $r_t = 1$, $M_t = 4$, $S_1 = 6$, $S_2 = 10$, $C_1 = 4$, $C_2 = 24$, $C_3 = 50$, $D_1 = 46$, $D_2 = 150$, $D_3 = 251$, $M = 150$, $A_1 = 50$, $A_2 = 168$, $A_3 = 251$, $N_{g1} = 10000(\forall g \in G)$, $N_{g2} = 10500$ ($\forall g \in G$), $N_{g3} = 11000$ ($\forall g \in G$), $O_{2,11} = 118$, $O_{3,17} = 201$, and $O_{kg} = 0$ ($\forall g \in G, \forall k \in K | (k = 2 \wedge g = 11) \& (k = 3 \wedge g = 17)$). One day is planned 24 h (g = 24). Aircraft capacity and C02 emissions data is obtained RDC [8]. Additionally, all models are developed using ILOG IBM CPLEX Optimization studio 12.6.

Table 1. Weighted Goal Programming Model Results

β	α	d_1^+	d_2^+	d_1^-	d_2^-	Cost	$C0_2$	New Flights (k,g)
0.1	0.9	28	29.632	0	0	23.835	43.432	(2,12),(1,19)
0.2	0.8	300	27.312	0	0	24.107	37.907	(2.12),(1,19)
0.3	0.7	300	27.312	0	0	24.107	37.907	(2.12),(1,19)
0.4	0.6	300	27.312	0	0	24.107	37.907	(2,12),(1,19)
0.5	0.5	300	27.312	0	0	24.107	37.907	(2,12),(1,19)
0.6	0.4	26.969	5.200	0	0	50.776	19.000	(1,19),(1,14),(1,12),(1,9),(1,7)
0.7	0.3	36.969	0	0	0	60.776	13.800	(1,19),(1,14),(1,12),(1,9),(1,7),(1,11)
0.8	0.2	36.969	0	0	0	60.776	13.800	(1,19),(1,14),(1,12),(1,9),(1,7),(1,11)
0.9	0.1	36.969	0	0	0	60.776	13.800	(1,19),(1,14),(1,12),(1,9),(1,7),(1,11)

In LGPM, d_1^{+*} is found 29.922 at the end of the first level. By setting $d_1^{+*} = 29.922$ s level is solved with the aim of minimizing d_2^+. Following results are obtained: $d_1^- = 49$, $d_2^+ = 5200$, $d_2^- = 0$, Cost = 53.680 and $C0_2 = 19.000$. This solution is achieved by launching 5 new flights: (1,20), (1,17), (1,13), (1,9) and (1,8).

MILP model is solved considering only the cost objective shown in Eq. 1 and 23.807 is obtained by launching 2 new flights with aircraft types 1 and 2 at periods 19 and 12, respectively; whereas, the model is solved considering only C02 emissions shown in Eq. 2 and 13,800 is achieved by launching 6 flights with all capacities 50. Therefore, target values of the objective functions are as follows: $T_1 = 23.807$, $T_2 = 13.807$. Based on these parameters, WGPM results are given in Table 1. The closest value based on LGPM is achieved when β equals to 0.6 and α equals to 0.4 with opening 5 new flights.

4 Conclusion

Integrated FSP and FAS is a complex problem for airlines, especially in the HS network. MILP model is proposed for the problem with two solution approaches: WGPM and LGMP. According to computational experiments that concern the case with one hub two-flight leg network for a 24-h day schedule for transit passengers, models frequently open to a large number of small-capacitated aircraft in the schedule when total CO_2 is higher than total cost. When total CO_2 values are precisely the same, WGPM generates a superior overall cost value than LGPM. This study differs from other studies by considering cost and CO_2 emissions objectives at the same time in the HS network for solely transit passengers with scheduled flights. The future direction could solve the proposed model with data taken from one of the airline companies.

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The Single European Sky and Aviation Sustainability

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Abstract. Despite the regulatory efforts, fragmentation of European Union Airspace is still a matter along with the increase of traffic and emerging necessities like environmental sustainability, innovation.

In 2020, the Commission proposed an upgrade of the Single European Sky (SES) regulatory frameworkin the light of recent developments.

The proposal no longer contained provisions on the use of FABs and among other things it introduced the possibility of common unit rate for en route services across the SES airspace.

On the same time and in 2021 as part of the 'Fit for 55 package', the Commission proposed amendments to the EU ETS Directive 2003/87/EC as regards aviation's contribution to the EU emission reduction target.

All these proposals are on discussion before the EU Parliament and Council but beyond this, the forecast related to air traffic growth, innovation and digitalization, strikes, war crisis and meteorological events will put pressure to the current European airspace management.

The aim of this paper is to analyze the current legal framework and proposals related to SES and Aviation Sustainability in the lights of evolutions, highlighting strengths and weakness in consideration of goals and on-going negotiations aiming to support the reaching of the Green Single European Sky.

Keywords: Single European Sky · Aviation Sustainability · Airspace Route Charges · Fit for 55

1 Introduction

European Union aviation is a history of success. Since the end of the Second World War, aviation is a key transport mode and a strategic sector that makes a vital contribution to the EU's overall economy and employment. Aviation supports 5.1 million jobs and contributes more than €365 billion, or 2.4% to European GDP. This remains a growth area where the expansion is estimated to be 5% annually until 2030.

In practical terms as a result of a current legislation at international and national level as well as in terms of legacy grounded in the history of aviation, aircraft make a patchwork route when flying across the EU and this because airspace boundaries have remained although the land frontiers have ceased to exist among EU Member States.

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In few words, this means that flights do not take the shortest straight-line route as they are obliged to undertake a complex (and often longer) route due to airspace boundaries and consequential fragmentation. Without these kinds of "legal" restriction (territorial boundaries) and airspace fragmentation, aircraft would be able to make a more efficient use of airspace and in the light of environmentally friendly principle, a huge amount of million tonnes of CO_2 per year would be saved.

Since 2004 European Union is struggling to reach the ambitious goal of the Single European Sky (SES I) or, in straight terms, overcoming the national airspace fragmentation. The first regulatory package dealt with several aspects to reach these goals such as the set-up of national supervisory authorities which are independent from air navigation service providers, general minimum standards for carrying out air navigation services were established, a common system of certification for air navigation service providers is introduced and principles for imposing air navigation fees on airspace users are established. At that time there was another relevant innovation – in both technical and regulatory aspects – and it was the set-up of Functional airspace blocks (FABs) that were not based on national boundaries but on the optimisation of traffic flow.

A regulatory framework had been created already also in 2009 (SES II) to monitor performance of the air navigation service providers in terms of safety, capacity, cost efficiency and environment through a performance scheme for air navigation service providers with binding performance targets as well as free market access for air navigation service providers and detailed provision for the creation of functional airspace blocks (FABs).

Despite the efforts started in 2004, supported in 2009, in 2013 the European Commission presented a revision of the Single European Sky consolidated regulatory framework (the SES 2+ package) by the strengthened of independence of national supervisory authorities and separation of air traffic services will be separate from support services in order to facilitate competition for support services.

The goals highlighted decades ago are not yet reached.

2 The Pending Proposal on Single European Sky and Aviation ETS

Whitin this regulatory environment the European aviation industry has gained a lot of experience and despite failing to deal with issues such as the European Union airspace fragmentation, those principles and approaches highlighted almost twenty years ago are still valid.

In this sense and indeed, issues like high costs of air traffic management, delays arising from limited capacity, as well as inefficiencies in air traffic management causing congestion leading to delays that are detrimental to the environment, are still out of the window and they call to be addressed and solved.

At the same time and in these latter twenty years aviation has changed showing a constant growth in terms of airspace and airports users and passengers as well, increasing of congestion in the airspace, capacity reduction and new emerging paradigms such as digitalization and environmental sustainability able to scale up the magnitude of the problems.

This enlargement of the picture has been approached by regulators and policymakers through two different ways.

For the first side, in September 2020 also in consideration of the Covid-19 effects on air transport, the European Commission unlocked the situation by proposing an upgrade of the SES regulatory framework, to consider recent developments and compromises already achieved.

The 2020 proposal no longer contained provisions on the mandatory use of FABs and it also provides the integration of a separate EU body – Performance Review Body (PRB) – into the EASA that would oversee the assessment and approval of the performance plans and performance targets for *en route* air navigation services. This proposal also introduced the possibility of introducing common unit rate for *en route* services across the SES airspace that is one of the elements that contribute to the fragmentation solution.

For the specific purposes of this paper the proposal also introduces the concept of "environmental optimization" in relation to airspace use, airspace trajectories as well as operation of aircraft.

For the European Commission, air traffic management network functions should indeed contribute to the sustainable development of the air transport system and support the achievement of Union-wide performance targets. They should ensure the sustainable, efficient and environmentally optimal use of airspace and of scarce resources, reflect operational needs in the deployment of the European air traffic management network infrastructure and should provide support in case of network crises.

On the other hand, the proposal provides the necessity to set up a mechanism for modulation of charges to improve environmental performance and service quality, notably through increased use of sustainable alternative fuels, increased capacity, and reduced delays, while maintaining an optimum safety level. Having learned the lesson of almost twenty years of difficulties for the development and deployment of functional air blocks – in other words: difficulties to reach the Single European Sky according the first regulation – the European Commission has provided that this mechanism of modulation of charges should be set up at Union-wide level given the cross-border nature of aviation, leaving at National supervisory authorities the possibility to establish mechanisms at local level regarding terminal services.

The proposal of Single European Sky regulatory framework is on discussion before the EU Parliament and Council within the so-called trialogue negotiations that started in 2021.

While the technical negotiations are pending and are more focused on the role of the network manager (EUROCONTROL) as well as the creation of separate EU body (performance review body) within EASA, it is important to note that in the Commission 2023 Work Programme, the Commission said that this proposal is a priority pending proposal and moreover that (in 2021), the Commission placed it under the priority 'A European Green Deal' but previously it was under a priority 'A Europe Fit for the Digital.

This latter consideration is of paramount relevance as it shows the shift – from political view – of the approach on the Single European Sky topic.

In this sense and from a second side, in 2021 the European Commission as part of the 'Fit for 55 package', proposed amendments to the EU ETS Directive 2003/87/EC as regards aviation's contribution to the EU emission reduction target. Among these

amendments there is one related to the measures to ensure equal treatment of airlines on the same routes regarding their obligations with economic impacts.

The same package also contains the proposal on ensuring a level playing field for sustainable air transport, sets minimum obligations for all fuel suppliers to gradually increase the share of sustainable aviation fuel (SAF) in the fuel supplied to operators at EU airports (ReFuel EU). The draft regulation also establishes the obligation for aircraft operators to ensure that the yearly quantity of aviation fuel uplifted at a given EU airport is at least 90% of the yearly aviation fuel required, with the aim of preventing fuel tankering practices.

In detail, the "Fit for 55" package provides amendments to the EU ETS Directive regarding aviation establishing a progressive phasing-out of the free allocation of allowances for airlines, with a progressive reduction in the number of aviation allowances auctioned by a certain percentage per year from 2023, to reach full auctioning by 2027.

Currently airlines balance costs of free allowance through the transfer of the cost to the consumer (pricing) and the benefit of a jet fuel tax exemption. Also, the system requires a monitoring activity by all airlines operating in Europe: they have to verify and report their emissions and surrender allowances against those emissions annually. From this framework, are excluded flights going beyond the EU's in order to not overlap interfere with the ICAO's development of an international offsetting scheme (CORSIA). The Regulation 2017/2392 ha extended this exemption up to 2023.

Under CORSIA, the international airline sector is obliged (with some exceptions) to offset any emissions exceeding 2019 (baseline) levels of CO2 emissions on international routes from 2021 onwards. More specifically, offsetting under CORSIA is possible on a voluntary basis since 2021 and will become mandatory in the year 2027.

According to "Fit for 55" package, the EU ETS Aviation system should be aligned with implementation of CORSIA for extra-EU flights and emissions pricing. The proposal requires the application of CORSIA to flights outside the EU ETS that depart from/arrive in countries that apply CORSIA.

In 2021 EUROCONTROL and EASA made a joint no-paper put on the light issues that avoided the reaching of the European Green Single European Sky.

For both entities advantages of digitalization and automation are not fully exploited due to the fragmented grounded infrastructure of air traffic management as well as fragmentation is also in governance as there is not a uniform approach to manage the path towards sustainable aviation. What both public entities suggested is also the necessity to elaborate new indicators that from a regulatory point of view, they will be able to allow the tracking of the environment and climate performance targets.

In order to deal with old and new emerging issues (and goals) especially under a climate-neutrality principle, EUROCONTROL and EASA have provided some ways such as i) the necessity to enlarge the effects of SES updates to other domains (noise pollution); ii) providing of "green trajectories" to airspace users; iii) provide incentives to encourage efficient flight trajectories.

3 Conclusions

There is no doubt that the forecast related to air traffic growth, innovation, and digitalization, strikes, war crisis and meteorological events will put pressure to the current European airspace management. The necessity to align the air transport to environmental goals as well as to ensure the EU aviation industry to continue to be competitive with non-EU ones, also recalls the attention to be given to the future evolution.

In this sense, after twenty years the regulatory framework on SES should be revised taking into account the lessons learned (e.g., the difficulties on FABs, fragmentation, technological evolution, and innovation etc.) and that along with safety, cost-efficiency, increase of capacity, scalability we also add the environmental sustainability as global emerging issue.

At the same time, the introduction of concept like "*the sustainable, efficient and environmentally optimal use of airspace*" together with already applicable concepts could create a "chokepoint" in consideration of the parallel legislation and regulation that, for example affects ground infrastructures (e.g., airports and their roles in the game of sustainable aviation fuel practice implementation) as well as the legacy of national boundaries and related restrictions that the State could impose on air navigation.

Speeding up some specific field of aviation industry, like the air traffic management, through the key concept of sustainability could bring with it the other risk to create conflicts with others branches of aviation regulation that do not run ahead in parallel or that are not able to align all stakeholders.

In this sense, the deployment of the principle of sustainability in aviation will impact on other areas already regulated by aviation law other than those related to air traffic management.

In this sense we may consider (not at all):

a. Commission Regulation (EU) No 139/2014 on aerodromes;
b.1. Commission Regulation (EU) No 748/2012 of 3 August 2012 - Airworthiness and Environmental;
b.2. Commission Regulation (EU) 2015/640 of 23 April 2015 - Additional Airworthiness Specifications;
b.3. Commission Regulation (EU) No 1321/2014 of 26 November 2014 - Continuing Airworthiness;
c. Commission Regulation (EU) No 965/2012 of 5 October 2012 - Air Operations;
d. Regulation 1008/2008 on common rules for the operation of air services in the Community;
e. Council Regulation (EEC) No 95/93 of 18 January 1993 on common rules for the allocation of slots at Community airports;
f. Regulation n. 261/2004 on passenger rights in order to study the key enabler of the EASA Environmental Label Programme
g. All those regulations related to intermodality and urban air mobility that are able to be considered as a leverage for aviation decarbonization;
h. TEN-T Regulations related to airport and aviation that the European Commission has started to review.
i. All those regulations related to aviation and airport noise and quality of the air.

So, the necessity to develop a holistic approach to the subject matter as from many parties has been highlighted, calls for an establishment of a regulatory Roadmap that based on shared and clear definitions such some provided in the European Commission proposals on SES (2020) and on ETS for Aviation (2021) could be able to contaminate other regulations and trying to reach the goal of European Green Single European Sky.

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Enabling Automated Zero-Emissions Air Mobility Trough U-Space Infrastructure

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Abstract. EALU-AER is a scalable U-Space technology infrastructure integration and demonstration project to establish Ireland's first Digital Sky Demonstrator (DSD), enabling the smooth transition towards smart cities and is located at Future Mobility Campus Ireland's (FMCI) recently established vertiport site, in the vicinity of Shannon Airport, Ireland. This project focuses to demonstrate the proposed U-Space architecture operations and enable U1 and U2 services integrated with AirNavIE Air Traffic Management (ATM) systems, allowing the safe integration into the airspace of zero-emission drones that will perform different Urban Air Mobility (UAM) missions. This project will leverage world-class integrated Unmanned Traffic Management (UTM) technology solution that encompasses an Unmanned Aircraft System (UAS) platform (Collins Airspace Services), a backhaul network (ARINC Ground Network) that will ensure the secure data exchange, Control and Non-payload Communications (CNPC) Command and Control (C2) link equipment, and advanced three-dimensional phased array radar (Skyler®). To demonstrate a range of UAM operations, across the range of U-Space services projected through the Single European Sky ATM Research (SESAR) U-Space Concept of Operations (ConOps), several use cases are proposed that capture the technology demonstrations associated with the projected near-term UAM services market. The project will collaborate with EUROCONTROL and other DSD projects to harmonize requirements, ConOps and recommendations for standardization and regulations and derive measures for public acceptance. It is expected that this technology driven by eVTOLs (electrical vertical take-off and landing) vehicles will improve the connectivity on the Ireland island both internally and internationally, which is of vital importance for the continued development of the country.

Keywords: ECO-FRIENDLY · UAM · SUSTAINABILITY · UAS · ELECTROMOBILITY · DIGITIZATION

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1 Introduction

The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. The transition to a climate-neutral society is both an urgent challenge and an opportunity to build a better future for all[1]. This requires accelerating the change to smarter and more sustainable mobility, compelling the aviation sector to intensify its endeavours in emissions reduction. In pursuit of this objective, a comprehensive set of operational measures and strategies is essential to tackle these emissions, moving to new zero emissions air vehicles. Simultaneously, in pursuit of sustainable growth in air traffic, expediting the modernization of infrastructure becomes imperative. This endeavour aims to enhance both capability and capacity, rendering it more robust in the face of future traffic demands. Additionally, the incorporation of flexible and seamless procedures between UTM-ATM is essential for adaptability. In this context, the U-Space architecture offered by EALU-AER assumes a central and pivotal role.

The project builds on TRL7-9 technologies matured world-wide in other UTM programs, such as CNPC5000, which is a prototype implementation of DO362A Minimum Operational Performance Standards (MOPS)[2]. In EALU-AER, Beyond Visual Line of Sight (BVLOS) flights will be achieved through deployment of terrestrial CNPC ground network and switchover capabilities to safely transition link from one ground station to the other. It innovates delivering integrated and interoperable U-Space solutions that can enable higher automation for future U3/U4 services that will allow an enhanced fleet management efficiency optimizing the power consumption.

These eVTOLs provide solutions for addressing supply chain emissions and facilitating the transition to zero-emissions logistics. They promote efficient freight transport by connecting long-distance and "first and last mile" connections. eVTOLs navigate congested urban areas, minimizing delays and reducing carbon emissions compared to traditional vehicles and enhancing freight intermodality by facilitating the seamless transfer of goods between different transportation modes. At same time, the load optimization processes ensure efficient use of resources by precisely calculating weights and volumes, reducing the need for unnecessary trips, therefore leading to decreased emissions.

2 EALU-AER U-Space Architecture

To harness the full potential of the drone economy and facilitate widespread UAM, it is imperative to establish a novel air traffic management framework tailored for low-altitude operations. Referred to as U-space, this framework envisions a comprehensive array of novel services underpinned by a high degree of digitalization and automation of functions. It incorporates specific procedures meticulously designed to ensure the safe, efficient, and secure integration of a substantial number of eVTOLs into the

[1] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en [Access: Sep 2023].

[2] https://my.rtca.org/productdetails?id=a1B1R00000LoYFeUAN [Access: Sep 2023].

airspace. U-space, therefore, serves as an enabling framework crafted to streamline routine missions across all categories of airspace and diverse environments, even in highly congested areas. It accomplishes this while maintaining a harmonious interface with manned aviation and air traffic control, ensuring the seamless coexistence of aerial operations.

The deployment of such U-Space is being produced in blocks of digital services that depend on the evolution of drone automation and connectivity, as can be shown in the Fig. 1 below, from the U-Space Blueprint[3].

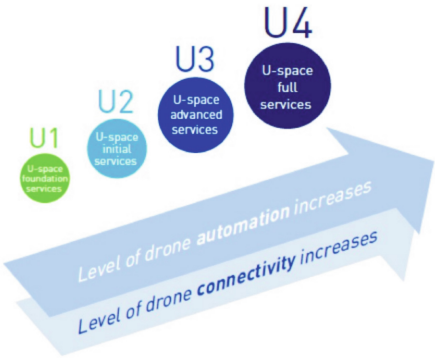


Fig. 1. U-Space Blueprint: Progressive deployment of U-Space

Within the scope of the EALU-AER project, the deployment of U1 and U2 services is planned, with reference to the ConOps outlined in the CORUS-XUAM SESAR[4] project as a foundational framework. The scope includes a comprehensive exploration of advancements in digitalization and automation of these services, thereby laying the groundwork for the evolution towards U3 and U4 services.

3 Impact on the Interconnectivity at Ireland

Ireland is the western most nation in the EU, shares a land border with a non-EU country, and is one of only two island nations within the EU. The country's current population of approximately 5 million is projected to grow by up to an additional 1.5 million by 2040 but despite this growth is still anticipated to be one of the least densely populated nations in Europe. It is for these reasons that connectivity, both internally on the Island of Ireland and internationally, is of vital importance for the continued development of the country.

An illustration of the all-island transport interconnections is included in Fig. 2[5]. Connectivity on the Island has been primarily driven by the expansion of the country's motor way network in the past 30 years, with planned continuation of expansion of this

[3] https://www.sesarju.eu/u-space-blueprint [Access: Sep 2023].

[4] https://www.sesarju.eu/node/4544 [Access: Sep 2023].

[5] https://commons.wikimedia.org/wiki/file:ireland_transport_map.svg [Access: Sep 2023].

network to a total proposed 1100 km by 2035 being now put under increased scrutiny due to Ireland's commitments to the EU's green deal and new environmental legislative targets set out. A shift to sustainable transport is seen as key to meeting these objectives. Irish road freight accounts for approximately 75% of all deliveries and will be another sector that will need to confront the challenges of decarbonization.

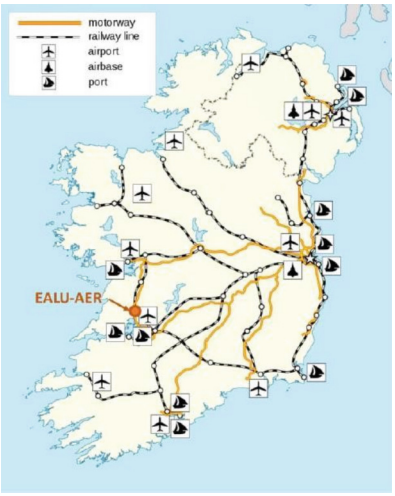


Fig. 2. Transport connectivity across Ireland, source: Wikimedia, reprinted with permission of the copyright owner.

The rail Network in Ireland has become a focal point for potential investments aimed at fostering environmentally sustainable connectivity between cities. However, historical decommissioning efforts have resulted in a concentration of these investments towards interconnecting the two largest cities, Dublin and Cork. These investments primarily revolve around modernizing commuter rail systems, electrification initiatives, enhancing the overall passenger experience, and facilitating seamless journeys.

The utilization of rail freight has been in decline, largely due to the dominance of road freight and a decrease in the presence of heavy industries in close proximity to the rail network. This disconnect in interconnection is also evident in the transportation options available between Northern Ireland and the Republic of Ireland. Currently, there is limited motorway connectivity, and the primary rail interconnection between Belfast and Dublin is constrained by online accessibility. This disparity in connectivity is particularly pronounced when examining the more remote regions in the northern, western, and southern areas of the island.

For the EALU-AER project, the strategic location adjacent to Shannon Airport and Foynes Port, give the project an interface to the Trans-European Transport Network (TEN-T) Atlantic/North-Sea – Alpine corridors, as illustrated in Fig. 3[6]. As referenced

[6] https://transport.ec.europa.eu/document/download/41528897-a27b-4768-ab61-c98df2681f41_en?filename=Annex3_alignment_EuropeanTransportCorridors.pdf [Access: Sep 2023].

above, the reliance on Ireland's continued connectivity to mainland Europe is now of even higher importance with the impact of Brexit. Air and maritime traffic will require continued and expanded investment in Ireland to ensure this position on the periphery of Europe is strengthened in the coming years. The role of future air-transport is likely to play an outsized role for supporting Ireland in this regard, and to ensure the sustainable and automated Advanced Air Mobility (AAM), projects such as those being undertaken through European Climate, Infrastructure and Environment Executive Agency (CINEA) and technologically aligned with SESAR and as proposed by EALUAER will be vital to allow industrial and societal stakeholders to engage and understand the impact and potential operations for UAM.

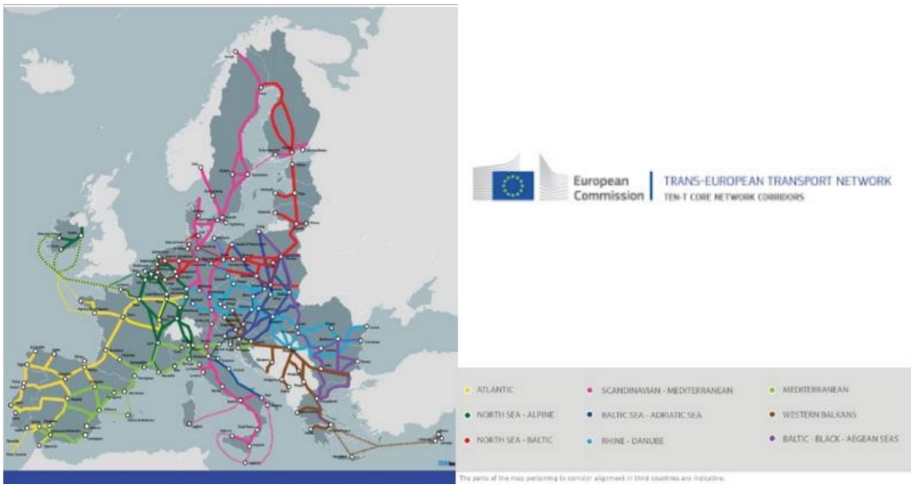


Fig. 3. TEN-T European Map as in the last European Commission proposal December 2021. Source: European Union Commission, reprinted with permission of the copyright owner.

The EALU-AER project is aimed at the demonstration of cutting-edge integrated systems and services that can illuminate the operational realities of U1 and U2 services as envisioned under the U-Space architecture proposed through the EU ATM Masterplan[7] and SESAR3 Strategic Research and Innovation Agenda (SRIA). These actions will also support elements such as the Intelligent Transport System directive, which envisions more effective and sustainable traffic management through digitalization of services. The UAM economy cannot function without enhanced and automated traffic management and EALU-AER will demonstrate aspects of how the deployment of such U-Space Architecture can solve issues for basic U-Space services and enable advanced automation required for U3 services and beyond.

[7] https://www.sesarju.eu/masterplan [Access: Sep 2023].

4 Conclusions

The latest revision of the TEN-T regulations highlights[8] synergies with the EALU-AER program that can enhance the connectivity of Shannon-Limerick region, at the western edge of the TEN-T Network, with a scalable U-Space infrastructure than can be extended through the rest of Ireland, fostering cohesion and improving the island connectivity trough zero-emissions vehicles and systems. These include the followings:

- Use of innovative technologies to enhance the digitalization of transport infrastructure, as EALU-AER will facilitate the integration of ARINC backhaul network to support the connectivity requirements for the U-Space demonstration platform. New radar technologies such as the Collins Aerospace Skyler radar will be able to demonstrate enhanced tracking and detection for complex airspace envisioned by UAM operations and support the digital airspace management through UTM platforms such as the Collins Airspace Services system being integrated here, and CNPC500 C2 link, providing an interoperable deployment.
- Transhipment hubs and multimodal passenger terminals to facilitate multimodality in particular for last mile passenger or freight journeys is addressed as well, as AAM is designed to operate across multiple modes of transportation. The EALU-AER project aims to showcase the potential of international airport and UAM integration for air-shuttle services. A public transport hub at Limerick City Bus/Train Station could facilitate seamless connections between the airport and other forms of public transit. This approach will enable scalable operations in urban areas, such as last-mile delivery. Electric AAM is expected to play a pivotal role in future urban mobility strategies, contributing to sustainability goals, assessing energy consumption and being essential for efficiently managing fleets, promoting system-wide efficiencies, and seamlessly integrating unmanned aviation with manned operations.
- EALU-AER addressed the environmental impact of transport infrastructure and operations, by the overall decarbonization in accelerating the transition from Internal Combustion Engines (ICE) power trains to fully electrified architectures. This architecture allows the integration with powerful visual sensors (camera, LiDAR, Radar) coupled with machine learning enhancements to monitor, identify, and process environmental impacts (e.g., accurate identification and counting of wildlife species, etc.).
- EALU-AER provides a test bed and demonstration of a variety of use cases to aid in the leverage and proliferation of UTM technologies and standards across EU jurisdictions enabling the cohesion in transport networks.
- EALU-AER satisfies the desire for decreased traffic congestion while ensuring efficient mobility options across the EU, which accelerates the development and deployment of electrified, software-defined vehicles and aircraft that dramatically decrease the operating costs and lend themselves to overall shared mobility business models for service providers.

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[8] https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en [Access: Oct 2023].

and innovation program EALU-AER (grant agreement No. 101079674). The content of the paper does not necessarily reflect the position or the policy of the funding parties.

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A New Typology for Classifying European Container Terminals, Considering Their Ability to Green Their Operations

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Abstract. The current container terminal market is facing challenging and uncertain times. The growth in container vessel size and high competition are pushing terminals to increase their storage capacity and productivity. In addition, environmental regulations and local governments are pushing terminals to reduce their environmental impact during terminal operations. Consequently, it is impossible for terminals to increase their productivity and terminal capacity without considering the environmental impact of container handling operations. This is the first paper of a two-part study that researches the readiness of certain clusters of container terminals to innovate their container handling operations. This paper identifies the variables that are essential for classifying European container terminals. By conducting a literature review, nine characteristics have been identified: equipment, level of terminal automation, spatial dimensions (yard layout, terminal size, terminal capacity, quay length), geographical location, port and terminal governance structure, throughput, available energy sources, and labor and union organization. The terminal clusters that come out of the classification, depend on the research goal. For this reason, the actual clustering of terminals will be performed in the second part of this research, as the actual clustering of terminals depends on the goal of that research as some clusters are better suited for certain research goals. In the second paper of this research, terminals will be clustered according to their readiness to implement specific container terminal innovations.

Keywords: Container terminal · Typology · Greening · Innovation

1 Introduction

The container terminal industry faces increasing pressure to innovate and green their container handling operations (Acciaro et al. [2018]; Gharehgozli et al.

F. Claudio and V. Thierry—These authors contributed equally to this work.

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[2020]). This pressure stems from evolving technologies, requiring terminals to innovate to remain competitive (Carlo [2014]; Gharehgozli et al. [2016]). Secondly, container shipping companies have steadily gained market power, and their vessel size has significantly increased. Consequently, terminals must handle more containers in a shorter timeframe, pushing them to increase productivity and efficiency (Böse [2020]; Lian et al. [2019]). Additionally, regulatory organizations, like the European Union (EU), European Seaports Organisation (ESPO), United Nations Conference on Trade and Development (UNCTAD) enforce regulations and publish environmental reports to steer ports and terminals to reduce their environmental impact (Commission et al. [2021]; ESPO [2022a]; UNCTAD [2022]). The focus on sustainable development and innovation is further emphasized by the Sustainable Development Goals (SDGs), introduced by the United Nations (UN).

However, the sector approaches innovation cautiously due to the long-term commitment, high investment costs, and operational uncertainties associated with new technologies and energy sources. When investing in new technologies, it is in the best interest of all stakeholders to comprehend both the technology's requirements and gain a thorough understanding of the specific terminal where the technology will be deployed. Considering the complexity between (European) container terminal environments, it is difficult to transfer the sucess of one innovation without considering the terminal-specific conditions that might differ between terminals.

This paper proposes a set of terminal characteristics, hereafter referred to as variables, that impact container terminals' innovating and greening potential. Utilizing this set of variables, terminals can be clustered according to similar variables and as a result, similar greening and innovating potential. Operators and other stakeholders can use this classification typology to address their readiness to implement green innovations in their container handling operations.

For the scope of this paper, the environmental impact of the terminals' operations encompasses air-, water-, and noise pollution that happens during container handling operations in the terminal. The container handling operations include the (un)loading of containers at the quay, the quay-to-yard transport, and the interstack transport. European container terminals were chosen because of the EU's commitment to becoming climate neutral by 2050 and their focus on the SDGs (Alamoush et al. [2021]; Caliskan [2022]; Commission et al. [2021]).

2 Methodology

This paper aims to identify the terminal variables that best define the categorization of a container terminal in terms of its greening and innovating potential. Each variable is further divided into different classes to achieve an accurate classification. Both variables and their corresponding subclasses are identified through a literature review. Because there is limited research regarding terminal classification, port classification literature is also reviewed. Academic search engines like Google Scholar are employed, utilizing keywords like *container terminal,*

port, innovation, green, variables, typology, cluster, terminology, and greening. Lastly, reports like the "Port City Atlas", developed by TU Delft, are consulted to determine relevant variables. With regard to these indicators, it is vital that each indicator can be identified in each of the terminals.

3 Previous Research

It seems that academic literature on terminal innovation often excludes the stage before implementing it. Javahernia et al. [2017] has studied the pre-implementation phase of innovations in the manufacturing sector. The study emphasizes that to remain competitive, manufacturing companies must be prepared to innovate their operations at all times, requiring flexibility in operations, labor organization, etc. An organization's readiness to innovate can be seen as a function of the readiness estimates of the individual influencing factors (Javahernia et al. [2017]). When studying this readiness, the first step is to identify these factors. As a result, this paper aims to identify these variables that influence the potential of a container terminal to innovate and green its operations.

There has been a scarcity of research concerning the classification of container terminals beyond conventional methods based solely on size or throughput. Voß et al. [2004] classified terminals according to their equipment used operations. Adenso-Díaz et al. [2020] studied container terminal management and included more variables. This scope included variables referring to the yard equipment, level of automation, and the operations and installations of the terminal. Pallis and Vaggelas [2015] studied the different types of terminals, terminal operations, and their influence on terminal efficiency. These two characteristics are further divided into subclasses, resulting in a more precise classification method.

The classification of seaports has been addressed more thoroughly, and valuable insights can be gathered to classify container terminals accordingly. Bichou and Gray [2005] mentioned that the clustering of seaports enables managers to benchmark the ports' performance and compare these results with competing and non-competing ports. However, the same study warns that the classifying process of seaports is complex due to operational, organizational, physical, and regulatory differences between seaports. With the classification of container terminals, the operational differences are less relevant due to the similarities of terminal operations (Voß et al. [2004]). Nevertheless, the other factors will have to be considered.

4 Results: Terminal Variables

This section discusses the results of the exhaustive literature review. The result hereof is a collection of variables that enable the classification of terminals according to similar characteristics linked to their greening and innovating potential. The classification is performed by subdividing each category into a number of subcategories, similar to the work of (Pallis and Vaggelas [2015]). Finally, the link to greening and innovating a terminal environment is also briefly discussed for each variable.

4.1 Terminal Equipment

Terminal equipment is classified into horizontal and vertical transport equipment (Stahlbock and Voß [2007]). The horizontal equipment usually performs quay-to-yard transport, and includes the Ship-to-Shore crane (STS-crane) and yard cranes. Three types of yard cranes are included in the classification: the Rail-Mounted Gantry Crane (RMG), Rubber-Tired Gantry Crane (RTG), and the Overhead Bridge Crane (OBC) the Tractor Trailer Unit (TTU) and the Multi-trailer System (MTS). This type of equipment cannot lift containers from the ground (Jörg et al. [2009]; Stahlbock and Voß [2007]; Thoresen [2018]; Vis [2006]).

This paper proposes a third class, namely, the combined transport equipment. This class performs both horizontal and vertical transport operations and includes the Straddle Carrier (SC), reach stacker. Other types of combined transport equipment exist but are not often used in container terminals.

The potential of the terminal to introduce green operational innovations is directly linked to the equipment utilized on the terminal. The equipment determines whether a terminal can easily retrofit their equipment or has to replace it entirely. Many terminal variables influence the equipment: the available energy sources, the available space and layout of the terminal, the labor- and union organization, the level of automation of the terminal, and, depending on the terminal- or port governance structure, the terminal- or port governance structure (Voß et al. [2004]). A practical example is the automation of RMGs. because they are fixed on rails, their movement is more predictable and easier to electrify and automate (Ding et al. [2021]; Jörg et al. [2009]; Park and An [2020]; Rijsenbrij and Wieschemann [2020]).

4.2 Level of Automation

Research of (Adenso-Díaz et al. [2020]) considered this variable significant when classifying container terminals. While automation mostly refers to yard equipment, the quay area also shows potential, with STS-crane cranes being partly automated already (Martín-Soberón et al. [2014]). This paper distinguishes three types of automation: manual, semi-automated, and fully automated. Manual container terminals are solely human-operated. Semi-automated have automated vertical or horizontal transport operations, and fully automated terminals have automated horizontal and vertical operations Knatz et al. [2022a]. As mentioned in the methodology, the scope of this research includes container handling operations; automation at the gate or further inland is not included.

Though the impact of automation varies between terminals, most studies conclude that automation reduces labor expenses and increases productivity (Knatz et al. [2022a]; Martín-Soberón et al. [2014]; Park and An [2020]). However, these results are not transferrable to every container terminal, and automation's effect on productivity can differ between terminals. Additionally, automation could reduce the environmental impact due to the predominant use of batteries or electricity and having a smaller spatial footprint during operations, resulting in fuel savings (Forum [2021]).

Automation is influenced by the equipment that is currently operating at the terminal, the available space and terminal layout, the port or terminal governance, and the labor and union organizations.

4.3 Spatial Dimensions

Variables discussed in this section include terminal size, quay length, and terminal layout. The container terminal size, expressed in hectares, is closely related to the geographical location of the terminal. For the scope of this paper, the terminal size includes all zones from the berth to the gates. Based on previous research by Knatz et al. [2022b], the terminals are classified into three size categories: 0–50 hectares, 50–99 hectares, and 100 hectares or more. Utilizing alternative energy sources can potentially influence the spatial dimensions of the terminal due to the additional space necessary to accommodate the new infrastructure safely and stringent operational safety regulations. Freeing up the necessary space in smaller terminals might complicate implementing certain technologies (Notteboom and Haralambides [2023]). The lenght of quay, expressed in meters, is closeley related to the size of the terminal as it determines how many ships can be serviced simultaneousley (Adenso-Díaz et al. [2020]; CHU and HUANG [2005]). Additionally, the length of the quay will determine the size of the vessel that can berth the container terminals and the number of STS-cranes that can operate on a single vessel (Thoresen [2018]). This indicator is also based on research performed by Knatz et al. [2022b], which identified three classes: 0–1000 m, 1000–2000 m, and 2000 m or more.

Finally the layout refers to the orientation of the containers that are stored in the yard against the quay and can be categorized as either perpendicular or parallel (Gupta et al. [2017]; Lee et al. [2018]; Wiese et al. [2008]). When comparing the two classes, both perpendicular and parallel layouts can attain high productivity levels, and one has no inherent superiority. A well-organized layout can improve terminal productivity and capacity, which is crucial, considering that many terminals have limited space, and expansion is a complex and expensive process (Felício et al. [2015]; Gharehgozli et al. [2020]). Additionally, optimal yard operations can reduce the operational emissions of yard equipment due to lower travel times (CHU and HUANG [2005]; Gupta et al. [2017])

4.4 Throughput

Terminal throughput results from all terminal assets working together as efficiently as possible and indicates how many containers go through a terminal yearly. This indicator is usually expressed in Twenty Foot Equivalent Unit (TEU) per year and is often used to rank terminals according to the number of containers a terminal handles yearly (Statista [2022]). Regarding the classification of specific container terminals by their throughput, limited research can be found. On the port level, some authors classify container ports into small, medium, and large ports, handling 0–5 million, 5–10 million, and 10 or more million TEUs yearly, respectively (Othman et al. [2019]; Sohn and Jung [2009]). However,

because port throughput is an accumulation of all terminals insde a port area, it does not represent the throughput of a single container terminal environment. For this reason, this paper proposes a new clasification, identifying three classes. The terminals are categorized into three classes based on their annual handling capacity of TEUs. The first class includes terminals that handle less than 0.5 million TEUs annually. The second class encompasses those handling between 0.5 million and 4 million TEUs, and the third class encompasses terminals with an annual handling capacity exceeding 4 million TEUs.

Despite its value as a classification variable, its impact on the greening potential is ambiguous. One could argue that high throughput terminals are more ready to innovate, have a larger cash flow, and are bigger in size. However, when addressing terminal automation, for example, Knatz et al. [2022a] illustrated that both high and low-throughput terminals benefit from automation. Nevertheless, categorizing terminals based on higher and lower throughput could prove advantageous to address distinct opportunities for greening and innovation within each category.

4.5 Terminal Yard Capacity

The terminal yard capacity, hereafter called terminal capacity, refers to the number TEUs that can be stored in a container terminal at a certain point in time (CHU and HUANG [2005]). This variable enables a classification of terminals beyond merely considering their total size and yearly throughput. Having adequate yard capacity is crucial for terminals to cope with the constant increase in container traffic and vessel size (CHU and HUANG [2005]). Multiple variables, including the equipment, available terminal area, geographical location, etc., determine the yard's capacity. (CHU and HUANG [2005]; Chuanyu et al. [2003]). Additionally, terminal capacity differs between a transshipment hub or a gateway terminal (Notteboom et al. [2021]). On an operational level, the yard capacity greatly influences productivity and emissions. For example, storing more containers without expanding the terminal itself increases the tiers of the blocks, which increases the likelihood of reshuffling. This, in turn, raises handling time, costs, and emissions (Kim et al. [2008]). Due to the lack of previous literature on the classification of terminals by their capacity, this research distinguishes three classes, namely, 0–30000, 30000–60000, and 60000 or more.

4.6 Geographical Location

In this paper, the term "geographical location" refers to the sea where the terminal is situated. This classification technique was used by the Port City A, developed by Hein et al. [2022]. Five European seas were used to classify the ports(i.e. the Baltic Sea, Black Sea, North Sea, Mediterranean Sea, and the Atlantic Ocean. The geographical location influences many other variables, including labor and union regulations, port and terminal governance, etc. (ESPO [2022a,b]). Additionally, the port's location in the global trade routes determines its importance in the global supply chain, affecting its throughput.

It also influences the availability of alternative energy sources that can be utilized in the terminal environment. Some terminals near petrochemical industry clusters provide direct access to (green) energy. In Europe, many ports plan to invest in infrastructure to produce alternative energy sources, enabling a direct green energy supply for ports and terminals. Concerning wind and solar energy, the port's location influences their options significantly. The ports' exposure to wind and sunshine affects the effectiveness of solar panels and wind turbines (Ballini et al. [2022]; Gharehgozli et al. [2020]; Sadiq et al. [2021]; Salem and Seddiek [2016]; Seddiek [2020]).

4.7 Available Alternative Energy Sources

The availability of green energy sources is directly related to the geographical location of the terminal discussed in 4.6. To remain competitive and support their sustainable development, ports should embrace the fuel choice uncertainty and investigate multiple alternative fuels (Cullinane and Yang [2022]). This uncertainty also spills over to the terminals, pushing them to remain flexible and investigate different innovation routes, utilizing a wide range of alternative fuels. For the classification, the following energy sources are included: natural gasses, biofuels, hydrogen, ammonia, wind, and solar.

4.8 Port Governance

Following (Bichou and Gray [2005]), port governance refers to the ownership of infrastructure, superstructure, and labor management (Notteboom et al. [2021]). There is no clear distinction between port- and terminal governance models in the literature, resulting in different interpretations and classifications of both governance structures (BICHOU [2008]). However, concerning European seaports, four types of governance structures are often used: public-, private-, landlord-, and tool ports. In Europe, the most common port governance structure is the landlord port model, where the public port authority issues concessions to private companies to operate the container terminal and invest in the terminals' superstructures (ESPO [2022b]). This model allows the private Terminal Operator (TO) to organize its operations while the port authority keeps control of the infrastructure and port management. A public port is governed and operated by the state. Both superstructures and infrastructure are owned by the public port authority (Bichou and Gray [2005]). A private port is in the hands of one or more private companies that operate both the port and the terminal (Chen et al. [2019]). Lastly, a toolport is owned by the state, which owns the infrastructure and superstructures but leases out the equipment utilized in the port to private companies. This governance structure is less often used and is considered to be a transitional phase between a public and private port governance structure (Notteboom et al. [2021]). When operating under a landlord port, the infrastructure remains in the hands of the port authority, while the superstructures, like office buildings, terminal equipment, gates, etc., must be provided by the TO. This gives the TO considerable freedom to determine the

operational direction of the terminal and opt for green, alternative technologies. Additionally, this cooperation between the public and private sectors is beneficial for co-investing in new infrastructure (Baird [2000]). The TO controls its specialized labor pool to operate the terminal equipment, ensuring that terminals control the readiness of their workforce to operate new technologies. Under a public port governance model, this freedom is limited. The port authority owns all port assets and performs all operational and regulatory functions. Because all terminal aspects are controlled by one entity, there is a streamlined approach to growth. However, because there is no internal competition, this might lead to inefficient port administration, services that are not user- or market-oriented, and a lack of innovation (Brooks [2004]). Additionally, Brooks [2004] indicates that the dependency on public funding might lead to wasteful money management or under-investments.

Lastly, a private company performs the regulatory and operational functions when a port is privately owned, like some ports in the United Kingdom. The port has less political influence, and theoretically, higher terminal efficiency can be gained. The products of these ports, like container terminal services, are also considered to be more market-oriented. Nevertheless, monopolistic behavior and a loss of long-term economic strategy are pitfalls for this governance structure (Brooks [2004]).

4.9 Terminal Governance

Authors have proposed different classifications of terminal governance Bichou and Bell [2007]; Knatz et al. [2022a]; Notteboom and Rodrigue [2012]. This paper follows the classification of Knatz et al., identifying three types of terminal governance, but also adds another fourth type of governance structure. Carrier-linked terminals, financial holdings, and purely stevedores terminals (Knatz et al. [2022a]). In addition, a terminal can also be governed by a public port authority. Each type of ownership has a different core business, pursuing different objectives. Consequently, their view on green management practices might also differ.

Firstly, a carrier-owned terminal is (partly) owned by a (global) shipping line to support its core business. This class also includes terminals that are terminals governed by a daughter company of the shipping line due to their shared strategies and company goals. This governance operates according to dedicated berth models, providing container handling services to their own ships and ships from shipping lines from the same strategic alliance (Notteboom and Rodrigue [2012]; SLACK and FRÉMONT [2005]).

Stevedoring terminals are governed by a (global) TO, meaning that handling containers is their main activity. Between TOs, the main form of competition is found in customer satisfaction. This is due to the homogeneous character of container handling operations. Compared to a carrier terminal, this type does not give preferential service to certain shipping lines but pursues a multi-user business model where they do not provide dedicated container handling services to certain shipping lines. Additionally, stevedoring terminals pursue horizontal integration to increase market power, while shipping lines focus on vertical

integration to increase their reach into the supply chain. Lastly, global terminal operators often have centralized purchasing divisions, providing significant negotiating power in purchasing agreements for terminal equipment and IT systems, reducing acquisition expenses (Medda and Liu [2013]; Notteboom and Rodrigue [2012]). According to ?, most of the European container terminals are in the hands of global terminal operators. However, the shipping lines also own a significant share of the container handling market.

The third class of terminals is (partly) owned by financial holdings looking for steady revenue over a long period, leaving the container handling operations to the operator. These terminals are not involved in the container handling operations and day-to-day terminal management. However, they are more inclined to maximize the cash flow. Financial holdings' main objective is to generate a return on investment (Notteboom and Rodrigue [2012]).

Lastly, the public port authority controls the container handling operations under a public container terminal governance structure. Given that the operations and management of the port fall under a public entity, this governance class exhibits similar characteristics and potential pitfalls as previously discussed in the section on port governance.

4.10 Variables Interrelationships

In this final section, all variables and their interrelationships are visualized under three port governance structures: the landlord-, private-, and public port (BICHOU [2008]; Petit and Beresford [2018]; Song [2021]). This section aims to better understand the variables and the way they are interlinked with one another. Figure 1 shows the landlord port governance structure, while 2 illustrates the relationships under a public or private port governance structure. Altering any of these variables will inevitably affect their related variables. In both figures, the dotted lines visualize a two-sided relationship between two variables where one influences the other and vice versa. These relationships are critical to consider when greening a terminal. Terminal throughput stands apart from the other variables as it serves as a key performance indicator for terminal operations, representing the culmination of all these variables working together. 2 combines both private and public governance models in the same figure because the relationships remain consistent regardless of whether the port is privately or publicly owned. However, it's important to note that the degree of influence of certain variables can differ between port governance structures. Under private port governance, a private company manages all port operations and labor; in a public port, these roles are reversed. This alters each variable's influence in the terminal's greening potential.

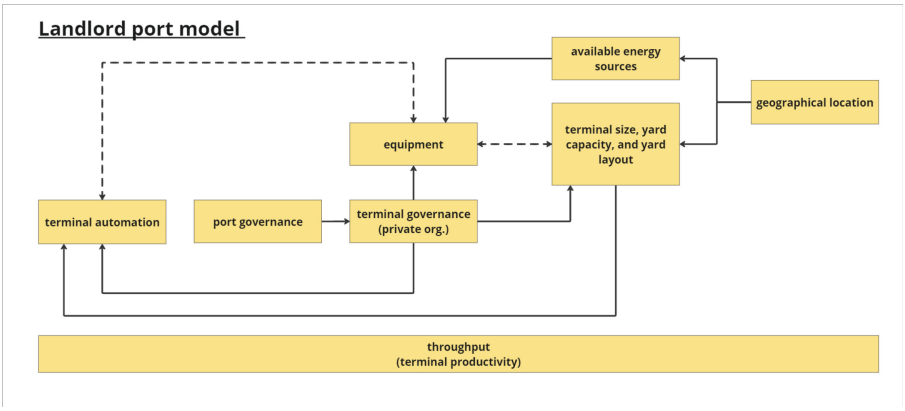


Fig. 1. Relationships between variables under Landlord port governance

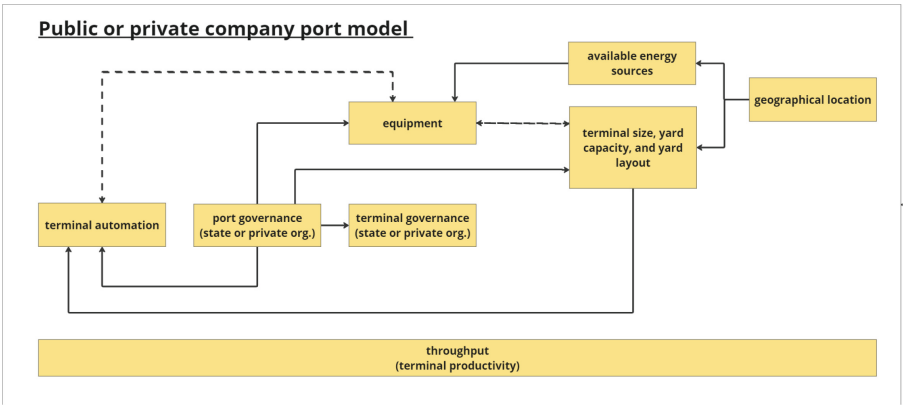


Fig. 2. Relationships between variables under public or private port governance

5 Discussion and Conclusion

This paper identified the terminal variables influencing a container terminal's potential to innovate green its container handling operations. Additionally, the interrelationships between these variables are also determined and illustrated. An exhaustive literature review identifies the following variables: equipment, level of terminal automation, spatial dimensions, geographical location, port- and terminal governance structure, throughput, and yard capacity.

Future research can utilize these characteristics to classify terminals by their ability to green their operations. It might also be interesting to study the other side of the spectrum and determine the requirements of certain terminal technologies that must be met for a successful implementation. Utilizing the output of this paper, it will be possible to determine whether a technology with a cer-

tain set of requirements can be implemented successfully in a certain cluster of container terminals.

6 List of Abbreviations

- ESPO European Seaports Organisation
- EU European Union
- IMO International Maritime Organization
- MTS Multi-trailer System
- OBC Overhead Bridge Crane
- RMG Rail-Mounted Gantry Crane
- RTG Rubber-Tired Gantry Crane
- SC Straddle Carrier
- SDGs Sustainable Development Goals
- STS-crane Ship-to-Shore crane
- TEU Twenty-Foot Equivalent Unit
- TTU Tractor Trailer Unit
- UK United Kingdom
- UN United Nations
- TO Terminal Operator

Declarations

Availability of Data and Material

Most data was available through the use of free academic libraries and handbooks accessed through the University of Antwerp and Genova.

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Resilience of Inland Waterway Transport: Towards a Practice-Oriented Repository of Common Threats and Hazards

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Abstract. Exploitation of the potential of inland waterway transportation (IWT) is seen as a crucial step in reducing carbon emissions in the logistics sector and meeting future transportation needs in alignment with the goals of the European Commission's Green Deal. In this context, establishing resilience within the IWT landscape is considered a key element for sustainable market development. As part of the EU-funded project "Resilience-centric Smart, Green, Networked EU Inland Waterways" (ReNEW), various threats and hazards in IWT have been identified and classified into five event categories: Labor oriented, natural phenomenon disruption events, crime and cyber-attacks, operational disruption events, and other disruption events. Although the repository contains over 50 identified threats and hazards in total, this paper will concentrate on the ones considered highly relevant by practitioners. According to the results, responses vary depending on the geographic regions and business models, and only a small number of events were identified as relevant to the entire sector. The repository of common threats and hazards may be beneficial not only for the ReNEW living labs but also for other stakeholders engaged in IWT, as it enables them to implement suitable resilience strategies.

Keywords: Resilience · IWT · Threats · Hazards · RENEW · Horizon Europe

1 Introduction

Inland waterway transportation (IWT) is considered to play an important role in the decarbonization of the logistics sector [1], and its further exploitation is seen vital to sustainably meet future transportation demands while staying in line with the European Commission's Green Deal objectives [2]. However, recent events such as market disturbances due to the COVID-19 pandemic or the Russo-Ukrainian War as well as the impacts of heat and drought on navigability conditions on major waterway corridors have shown vulnerabilities of the IWT system. For this reason, increased attention is being paid to assessing and strengthening the resilience of IWT.

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Resilience in the context of IWT may be defined as the ability of the transport system to absorb or to face disturbances in a way so that permanent breakdown can be avoided or recovered from in reasonable time [3]. However, to be able to implement strategic and operational resilience measures, it is necessary to have a clear mapping of possible threats and hazards that may disturb the IWT sector. As part of the EU-funded project "Resilience-centric Smart, Green, Networked EU Inland Waterways" (ReNEW), we identified various threats and hazards in IWT which can be classified into five event categories: labor-oriented, natural phenomenon disruption events, crime and cyber-attacks, operational disruption events, and other disruption events.

The project covers a wide spectrum of IWT applications in Europe, with predefined goals: improved navigability capacity, enhanced land/sea/ infrastructure resilience, increase in modal shift, smooth functioning of passenger mobility and reduced environmental impact. Although it is important to achieve resilience of IWT, all three aspects of sustainability (economic, environmental and social) must be taken into account.

Geographic and practical scope of the investigations have been set by four living labs (LL). A "living lab" represents a real-world environment or setting where new technologies, products, and services are tested, developed, and evaluated in collaboration with users and stakeholders to gather practical insights and refine innovations [4].

In this respect, the first LL covers an urban waterway network in Ghent (Belgium), with the goal of creating a flexible and resilient logistic system for multi-user and multifunctional purposes, considering also impact of events caused by climate change [5]. The second LL covers a free-flowing natural river (sensitive ecological habitat), i.e., Douro River in northern Portugal. The goal is to prevent illegal waste water dumping (waste water management). Additionally, river behavior simulation for extreme weather conditions [6] will be carried out. In contrast, a canal network has been the main focus of the third LL (the East and South Corridor in the Netherlands). The goal is further development and demonstration of a planning mitigation application to boost modal shift [7]. The fourth LL is focused on promoting autonomous zero-emissions barges and covers canal network, one of the most important corridors (being the Lower Rhine and Rhine Delta) [8].

2 Methodology

One of the expected project results is to establish a repository of common threats and hazards for the IWT sector. To achieve this goal, a mixed-methods approach was used. First, in order to get an initial set of potentially disruptive events, various sources such as scientific papers, reports and white papers, news articles and historical datasets were analyzed and mapped to the respective categories within an exploratory desk research phase. Sources that analyze threats through practical examples were also taken into account.

The search for scientific papers and other types of sources was carried out using several databases such as Web of Science, Science Direct, iwd (the information service of the German Economic Institute), JRC Publications Repository, etc.

In the research, we were focused on the following keywords:

- Inland Waterway Transport AND Environmental Impacts

- Inland Waterway Transport AND Threats
- Inland Waterway Transport AND Hazards
- Inland Waterway Transport AND Climate Change
- Inland Waterway Transport AND Labour
- Inland Waterway Transport AND Crime and Cyber Attacks
- Inland Waterway Transport AND Operational Disruption

A search was performed in order to determine whether the publications contained at least one of the search terms in the title, abstract, or the entire manuscript, reports and other types of sources.

Next, consultations were held with industry experts, to add, delete or modify the initial draft of identified threats and hazards. A special focus was placed on organizations within the ReNEW project living labs. Consultations with LLs were hold to carry out an assessment on the relevance for each hazard and threat. Relevance has been assessed using a four-point ordinal scale: high, medium, low and none. The answers have been coded numerically such that the arithmetic mean (mean rating) of the perceived responses could be calculated. Only the most relevant threats and hazards (mean rating above or equal to 3) were taken into account.

3 Results

3.1 Description of Initial List

The total repository contains 56 identified threats and hazards in total, which are divided into five groups: labor-oriented (6 threats/hazards), natural phenomenon disruption events (22), crime and cyber-attacks (10), operational disruption events (15), and other disruption events (3). Regarding the first group, the interrupted operation of IWT relies significantly on the availability of skilled labour [9] required for the operation and maintenance of vessels, infrastructures, and other essential elements. However, employees in IWT might face challenging working conditions. In order to avoid negative consequences (e.g. a shortage of employees, work-related injuries, possible strikes), which ultimately results in uninterrupted business processes, it is necessary to guarantee proper working conditions, regular education, and decent salaries [10].

Furthermore, in the past, inland waterway transport has been vulnerable to the impact of natural disruptive events, i.e., storms/tornados, hailstorms, high and low waters, resulting in direct and indirect consequences such as damage to property and vessels, loss of life or injuries, increased transportation costs [11], and may affect occupancy, and arrivals at the origin or destination [12], etc.

Crime and cyber-attacks have also been considered, as inland waterway transport is vulnerable to the aforementioned attacks, which may result in financial losses, damage to infrastructure, and other detrimental outcomes. Cyber-attacks, for instance, can compromise the integrity of sensitive data [13], highlighting the importance of defining and implementing appropriate mitigation measures [14].

Operational disruption events can also significantly impact IWT and may include breakdown of energy supply, IT breakdown, infrastructural bottlenecks, etc. These disruptions can also lead to negative consequences such as delays, damage to the infrastructure and vessels, increased costs, etc. In addition to the aforementioned events,

it is possible to single out a few that are for example related to bureaucracy and economical/regulatory events.

3.2 Final List

In order to achieve a resilient system, it is necessary to develop resilience strategies to address vulnerabilities and mitigate the impact of possible threats and hazards. Vulnerability refers to the circumstances resulting from various factors (e.g., environmental, physical) that make communities, assets, or systems more vulnerable to hazard impacts [15]. In this respect, Table 1 presents the 19 most important threats and hazards as rated by the interviewed experts and practitioners.

Table 1. Most important threats and hazards in inland waterway transport.

Type of Event	Risks/Relevance	None (1)	Low (2)	Medium (3)	High (4)	Mean Rating
Natural Phenomenon Disruption Events	Flood/Storm surge	0	0	2	2	3,5
	High waters	0	0	1	3	3,75
	Heavy rain	0	1	2	1	3
	Low waters	0	0	0	4	4
	Dry warm periods	0	2	0	2	3
Crime and Cyber Attacks	Data theft	1	0	1	2	3
	Sabotage	1	0	0	3	3,25
	Corruption and insider crime	1	0	1	2	3
	Hybrid attacks	1	0	1	2	3
Operational Disruption Events	Breakdown of energy supply	0	0	1	3	3,75
	IT breakdown	0	0	1	3	3,75
	Technical breakdown	0	0	1	3	3,75
	Accident	1	0	0	3	3,25
	Infrastructural bottlenecks	1	0	1	2	3
	Infrastructural defaults	1	0	1	2	3
	Restriction to international access by hostile country	1	0	0	3	3,25
Other Disruption Events	Change of law/regulations	0	0	0	4	4
	Protectionism	0	1	1	2	3,25
	Economical condition	0	1	1	2	3,25

Low waters and change of law/regulations are assessed as most relevant threats by all living labs. Vulnerabilities that can lead to negative (logistical) consequences during low waters periods may be inadequate maintenance of barges and infrastructure, insufficient training, limited collaboration with other carriers/ stakeholders, etc. Direct consequences encompass reduced or restricted navigability [16] which may become visible in terms of missing under keel clearance and thus decreased speeds and lower capacity utilization. Furthermore, the implementation of new laws or alterations to existing regulations has the potential to impact processes and/or can lead to higher bureaucracy [17].

In addition to the aforementioned threats and hazards, there are some threats and hazards that may further be considered as highly important: high waters, breakdown of energy supply, IT and technical breakdown. In case of the energy breakdown, it is assessed as relevant since it may lead to unanticipated outcomes, for example, insufficient power to operate locks. In the event of an energy breakdown, bunkering or electrical power supply services become unavailable, which may lead to constrained or missing navigational capabilities. IT breakdowns can cause, among others, failure of dependent systems in the network (e.g., traffic control). Furthermore, other technical breakdowns, as another highly relevant threat, may lead to accidents due to defective equipment and delays in the transport of good.

Regarding the operational disruption events, one of the living labs responsible for autonomous vessel has added "faulty or unavailability of AIS", as another, relevant threat, since it can cause, among others, accidents.

4 Conclusion

In order to minimize negative consequences of disruption events, the development of back-up solutions and alternative plans is seen a key determinant for the resilience of a logistics system. After the analysis of various sources, the authors have concluded that the majority of existing works on threats in inland waterway transport focus on detailed analyses of one or several specific threats. The repository described within this paper may be used as a first step to raise awareness and prioritize the areas of action and thus strengthen the resilience of the IWT.

While in total a repository of more than 50 threats and hazards was created, this paper narrows its focus to those being evaluated as the most relevant by the experts. Preliminary results show, that answers differ along the different geographic areas and business models, while few events were found to be relevant to the sector as a whole. The repository of disturbance factors may be not only applicable to the ReNEW living labs but may help other stakeholders involved in IWT to develop and implement appropriate resilience strategies.

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Modal Shift Potential for Danube Shipping: The Market for Containerized Transport of Dry Bulk

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Abstract. In the field of inland waterway transportation (IWT), Europe faces substantial shortcomings when it comes to integrating this mode of transport into the broader transportation network. Transportation of containers is a promising market segment for Danube waterway transport. Containerization of goods potentially reduces handling time, risks and therefore costs since goods can be transported from origin to destination without having to change the cargo unit when changing modes of transport. Moreover, several types of goods could be consolidated on one vessel, addressing the decreasing average shipment size. The competitiveness of multimodal transports by inland navigation thus potentially increases. This study uncovers the potential for a shift from road transport to inland vessels in the EU Danube riparian states, particularly within the dry bulk goods market. The extracted substantial quantity transported by road which bears potential for a shift to Danube navigation amounts up to 140 Mio. tons and 75 billion TKM in 2021.

Keywords: Modal Shift · Inland Waterway Transport · Containerization

1 Introduction

Although a substantive shift to more sustainable modes of transport, such as inland waterways, is demanded by the EU [1] the share of IWT has decreased from 7.4% in 2012 to 5.6% in 2021 [2]. In general, the IWT network in the EU still has available capacities [3]. Hence, a modal shift to the Danube waterway is desired and possible [4]. The present study elaborates on the market potential that the increase of containerization on the Danube would have and what proportion of road transport could be shifted to multimodal transport using the Danube waterway. The study area includes the Danube riparian states which belong to the EU, namely Germany, Austria, Slovakia, Hungary, Croatia, Bulgaria and Romania. This paper answers the research questions (RQ1) *"Which dry bulk goods are potentially suitable to be shifted to containerized Danube shipping?"*, and (RQ2) *"What proportion of the current road transport volumes of the dry bulk goods in the Danube countries could potentially shifted to Danube shipping?"*. The remainder of the paper gives a brief theoretical background on potentials of containerization of Danube shipping, introduces the applied methodological steps to determine a potential modal shift volume and discusses the results.

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2 Containerization of IWT and Its Potential

Known for its high payload and low cost per ton, IWT is a cost-effective transport mode [5]. As a result of globalization and the demand for greater flexibility in production and distribution, freight flows are more likely to be smaller in volume, more frequent and cover longer distances [6], resulting in reduced competitiveness in terms of cost-effectiveness of traditional IWT of bulk cargo. Containerization of goods is a promising way to overcome barriers towards modal shift to IWT as it potentially improves IWT in terms of mode choice criteria. The most important criteria are costs, transit time, reliability and flexibility [7].

Containers offer the possibility of bundling different types of goods on one barge to achieve cost advantages [5] and improved capacity utilization. In addition, as a container is a standardized load type used worldwide for transport [4], it opens up the possibility of improved links with pre- and post-haulage by road to improve multimodal transport. Bundling could also improve the flexibility of IWT, as the cargo would be less dependent on one particular vessel and could be loaded on an earlier/later liner. The transit time can be reduced as there is no need to transship the goods onto other transport units while changing the mode of transport for the pre- and post-carriage. Finally, if container handling equipment is installed in all Danube ports, overall reliability can be improved with coping mechanisms for low or high water: Cooperating truck and barge carriers would allow switching between road and water to meet customer delivery times.

While containers are well-established along the Rhine waterway, accounting for 99.95% of the EU's container transport performance, this concept is hardly used on the Danube (0.05%). In the EU, container transport has a share of 9.6% in the total performance of IWT (136 billion TKM in 2021) [8]. Containerization is a promising market segment for Danube shipping due to its wide range of advantages on the one hand and the low market penetration on the Danube on the other hand. It offers the opportunity to gain market shares from road transport and the possibility to shift them to the Danube. The aim of the present study is to assess the current market situation of dry bulk transported by road and to estimate the share that can potentially be replaced by multimodal container transport with barges on the Danube.

3 Methodology

The methodological steps to determine a potential modal shift volume from road to the Danube waterway are summarized in Fig. 1. First, a comprehensive desk research was conducted to identify suitable dry bulk product groups. Main sources for the identification of well-suited goods for Danube shipping were market observations by the CCNR [8] and the Danube Commission [9] as well as outcomes of EU research projects [10–12]. The identified goods are assigned to the "Standard Goods Classification for Transport Statistics (NST 2007)" which is a uniform list of goods specifically developed for the compilation of transport statistics [13]. In the second step, the EUROSTAT transport database [14] was screened for available datasets about road, inland waterways and rail. Suitable data were collected where transports are classified according to NST 2007, by country and the transport distances. The following datasets are used: *road_go_ta_dctg*,

iww_go_atygo. At the time of evaluation, the most recent year with data available was 2021 and used for the analysis. To identify a quantity of the selected product groups, an approach based on secondary data proposed by [15] was chosen. It considers *type of goods*, *transport distance* and *supply quality*. Types of goods are defined in step 1. Transport distances of ≥ 300 km are proposed in [15, 16] to be suitable for a modal shift. The supply quality of IWT is anticipated to be satisfied due to the containerized transport (see Sect. 2). In the last step, the collected data was evaluated regarding transport volume (t) and transport performance (TKM).

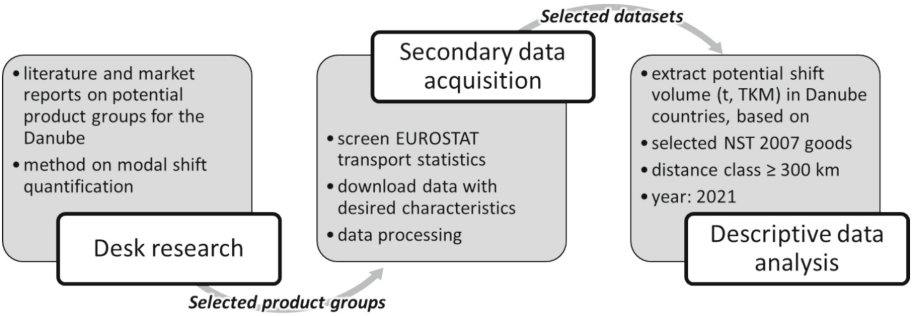


Fig. 1. Methodological approach to determine a modal shift potential of suitable bulk product groups from road to multimodal transport using IWT.

4 Results

The desk research revealed that inland navigation has a significant role in the transport of dry bulk cargo in the Danube region. It emerges that this type of cargo has a high but underutilized potential for IWT in the Danube countries [10]. The potential can be justified by the fact that these materials can be transported and stored in large quantities due to their characteristics [17] and are typically not time-critical [10]. Eleven potential dry bulk commodities for inland navigation were identified from the main literature source [10] and assigned to the appropriate seven divisions according to NST 2007 shown in Table 1. The NST 2007 divisions 01, 03, 07 and 08 already have an affinity with IWT, as these are product groups of which high volumes (T and TKM) were transported by inland waterways in the Danube riparian states in 2021 (*iww_go_atygo*). Finished metal items (NST 2007 division 10) are also confirmed by historical transport data to be related to IWT [9]. Group 09 "Other non-metallic mineral products" has lower transport volumes in tons in the Danube countries but contains the bulk goods cement and used glass, hence is added to the list of potential products for containerization. These divisions are considered to determine a modal shift potential from road to IWT. The first research question (RQ1) regarding potentially suitable product groups for containerized Danube shipping is answered by the products and NST 2007 divisions included in Table 1. Research question RQ2 asked for the quantities that could potentially be shifted from road transport in the Danube countries to IWT on the Danube. The answer is that

the maximum modal shift potential of the identified dry bulk goods to IWT results in approximately 140 Mio. tons and 75 billion TKM for the year 2021, as depicted in Table 2. This corresponds to about 3% of the total road transport volume and 15% of the performance of the countries examined (*road_go_ta_dctg*).

Table 1. Identified potential goods and assignment to NST 2007 divisions [13]

Identified products	NST 2007	
Wheat, maize, soybeans	GT 01	Products of agriculture, hunting, and forestry; fish and other fishing products
Coal	GT 02	Coal and lignite; crude petroleum and natural gas
Industrial salts	GT 03	Metal ores and other mining and quarrying products; peat; uranium and thorium
Pellets, Coke	GT 07	Coke and refined petroleum products
Urea	GT 08	Chemicals, chemical products, and synthetic fibers; rubber and plastic products; nuclear fuel
Cement, used glass	GT 09	Other non-metallic mineral products
Metal scrap	GT 10	Basic metals; fabricated metal products, except machinery and equipment

Table 2. Road transport of NST-2007 divisions (01, 02, 03, 07, 08, 09, 10) and potential shift in total and percentages, 2021 (*road_go_ta_dctg*)

	Transport volume in thousand tons			Transport performance in million TKM		
Country	Total	$\geq$ 300 km	%	Total	$\geq$ 300 km	%
Germany	1 790 646	83 258	4.6	121 375	38 949	32.1
Austria	283 465	7 193	2.5	13 820	3 784	27.4
Slovakia	101 082	11 611	11.5	13 228	8 721	65.9
Hungary	79 513	8 243	10.4	10 065	5 029	50.0
Croatia	56 743	5 682	10.0	6 235	3 664	58.8
Romania	199 716	11 159	5.6	15 583	8 070	51.8
Bulgaria	112 138	10 370	9.2	12 075	6 970	57.7
Total	**2 623 303**	**137 516**	**5.2**	**192 381**	**75 187**	**39.1**

To understand to what extent the maximum potential volume of the selected NST 2007 divisions would enlarge the volume of transported goods via IWT on the Danube, the sum of all countries per NST 2007 class is presented in Table 3 and compared to the cargo handling volume at the Danube ports of the year 2021. The classes with the highest shiftable volumes are GT10 (finished metal items) and GT08 (chemicals) which

account for almost half of the total shiftable road volume. In 2021, a small amount of these product groups was handled at Danube ports (GT10: 6%, GT08: 7.4%). If the full potential of all product groups could be utilized, the total amount of handled cargo would double with an increase factor of 2.1.

Table 3. Potential shift from road volume (=SV, tsd. t) to IWT in 2021 per NST 2007 division (*road_go_ta_dctg*) & comparison with handled cargo (=DV, tsd. t) at Danube ports in 2021 [9].

	GT 01	GT 02	GT 03	GT 07	GT 08	GT 09	GT 10	**Total**
SV	26 303	1 011	10 644	6 452	31 303	27 205	34 598	**137 516**
% of total SV	*19.1*	*0.7*	*7.7*	*4.7*	*22.8*	*19.8*	*25.2*	***100***
DV	44 785	14 202	32 585	13 067	9 192	2 325	7 465	**123 621**
% of total DV	*36.2*	*11.5*	*26.4*	*10.6*	*7.4*	*1.9*	*6.0*	***100***
SV + DV	71 088	15 213	43 229	19 519	40 495	29 530	42 063	**261 137**
% of total SV + DV	*27.2*	*5.8*	*16.6*	*7.5*	*15.5*	*11.3*	*16.1*	***100***
Increase factor	*1.6*	*1.1*	*1.3*	*1.5*	*4.4*	*12.7*	*5.6*	***2.1***

5 Conclusion and Outlook

This study identified promising dry bulk product groups suitable for containerization to leverage a modal shift from road to the Danube waterway. Unimodal road volumes suitable for shifting to multimodal transport using barges and trucks have been identified. IWT already has a traditional share of bulk cargo transport. Nevertheless, the analysis of road data reveals that there exist higher volumes that have potential for a shift to Danube shipping. In order to overcome the barriers to IWT, the criteria for mode choice must be addressed. Containerization favors a modal shift through improved costs, transit time, flexibility and reliability. The use of containers will make existing IWT more efficient. We propose that IWT affine commodity groups should be focused for shifting first to provide positive examples. On the long run, Danube IWT shall seek to gain shares in other commodity groups as well. Our method delivered the maximum theoretical modal shift potential from road to IWT and revealed quantities that should be shifted from road in the Danube states to other modes due to the transport distances. The analysis could be extended to other commodities, as containers can be used across many industries [4]. Although we have outlined the advantages and potential of containerized transport on the Danube, market take-up in the Danube region still needs to be promoted, together with the continuous development of port and waterway infrastructure and the development of optimized vessel types for container transport. Cooperation between barge and truck operators is strongly recommended to realize the full potential of multimodal transport in the Danube region.

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Development of an Intelligent System for Urban Logistics to Facilitate Sustainable Optimization

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Abstract. One of the major rising factors nowadays is, the use of automobiles for daily commute and usage of big trucks for shipping goods are rapidly and incredibly increasing in all major and important cities all around the world, which indeed leads to a problem of traffic jam. Indeed, for road users, whether they are residents or professionals, there is an unbalance in the circulation, increased congestion and road traffic affects all types of users from industry to office people on their day-to-day run. This congestion leads to many problems like air and noise pollution, parking problems, affecting quality of life for habitants, traffic problems on the road. This paper aims to develop an intelligent tool exploiting the concepts industry 4.0 as a support for the definition of alternative solutions to road transportation to increase companies' sustainable performance. The article is organized as follow. After a literature review on artificial intelligence and urban logistics, the intelligent tool being developed for the sustainable optimization will be presented. An illustration case will be exposed.

Keywords: Urban logistics · sustainable transportation optimization · artificial intelligence · big data and analytics · digital twin

1 Introduction

The continuously increasing share of the population living in urban areas, the pollution and safety in cities, the issues of traffic and congestion, have led to various issues like Greenhouse emission, air pollution, noise pollution and parking problems etc., in the urban areas. Focusing on freight transport, several problems must be addressed, such as the increasingly fragmented demand due to the spread of e-commerce and the lack of synchronization and harmonization between different flows of goods. Consequently, this paper focuses on urban logistics, frequently referred to as city logistics [1] or urban freight transport, whose solutions aim, on the one hand, to reduce all of the aforementioned negative impacts and, on the other hand, to offer a better sustainable solution, by developing a decision aided tool for defining and optimizing an alternative solution to road transportation in a city. After a literature review on concepts artificial intelligence and urban logistics the concepts and methodology supported by the tool will be explained. Finally, a user case based on "Grand Paris Sud" conurbation will be exposed.

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2 Literature Review

The elaboration of concepts, methodology and the development of a decision aided tool to optimizing sustainable solutions alternatives to road transportation requires the exploitation of existing theories and concepts on artificial intelligence and sustainable optimization.

2.1 Artificial Intelligence

Artificial Intelligence (AI) is widely used in the automotive industry, logistics, Medical Industry, robotics, finance, transportation, education, etc. [2]. The urban logistics optimization tools that exploit AI are generally based on concepts such as expert systems, multi-agent systems, machine learning, or deep learning. Knowledge-Based Expert Systems (KBES) are popular AI-based tools that have been successfully applied to planning, diagnostic, classification, monitoring and issues in design [3]. An expert system simulates the human reasoning process by applying specific knowledge and interfaces [4, 5]. It can be used to define and exploit rules to optimize urban logistics. A multi-agent system is a set of agents. Agents have objectives which give them autonomy in their decision-making regarding the messages they receive. On the other hand, they establish complex interactions involving high-level communications [6]. A BDI (Belief, Desire, Intention) [7] architecture could be combined with the expert system structure. They are exploited in digital twin tools for simulating urban logistics flows but also through the training agent's performance modules development [8, 9]. Machine Learning and deep learning systems are actually the most used AI concepts. Machine Learning addresses the question of how to build computers that improve automatically through experience [10]. The essential aspect of deep learning is that these feature layers are not designed by human engineers: they are learned from data using a general learning procedure [11, 12]. Deep learning could be used for making an automatic classification of user requests [13]. For instance, deep learning could contribute to define GHG emission prediction on road networks [14] or on train and river transportation networks. These AI concepts will be exploited for the sustainable optimization of the urban logistics.

2.2 Urban Logistics Sustainable Performance Improvements

Urban logistics is defined in [15] as the system integrating the urban traffic environment, congestion, energy conservation and labor cost reduction. Its optimization involves logistics stakeholders' expectations improvement. AI and new technologies are used to elaborated urban logistics tools that will increase the urban logistics traffic quality by taking into account stakeholders' opinion. For instance, Co-creation [16] is defined as "an active creative and social process based, collaboration between producers and users, initiated by the firm to generate value for consumers". As explained in [17] all stakeholders including consumers are engaged at all stages of the product life cycle development. New technologies and communication tools such as internet and other applications are an advantage for succeeding in the co-creation process. The idea is to apply this concept for defining the best sustainable city transportation solution, by integrating opinions of citizens, companies, and other local authorities in the solution elaboration. Indeed, digital

twin applications are largely exploited in this case to define and to test scenarios of optimization [18]. And AI applications are combined to classical optimization tools to define in a software the optimum required as explained in [19]. Urban logistics plays an important role in the sustainable development of cities, which must be integrated into urban development strategies [20]. Sustainable urban logistics corresponds to the reduction of transport-related impacts, the reduction of nuisances linked to logistics buildings, the reduction of energy and material consumption, and the development of logistics activities as a tool for economic growth. Big data analytics (BDA), lean and green manufacturing are required for measuring actual city performance and future changes impacts [21]. These concepts are combined with AI tools in the following section for developing a software tool to propose alternative solutions to road transportation in a city.

3 Concepts and Methodology

The aim of the research is to improve the city logistics flows through the definition of adapted alternative solution to road transportation. The general idea is to use simulation systems associated with other processes to achieve this objective. In [22], a conceptual scheme for elaborating sustainable city transportation solutions has been presented. A global approach and a generic framework have been defined as shown in [23]. A software tool (Fig. 1) is being developed to support the concepts, approach and framework introduced above. Indeed, the software tool capitalizes different organizations proposed by stakeholders and optimize them for defining a sustainable alternative solution for the city. The principal process is as follows: a stakeholder (user, company, or local authority) connects on the platform to simulate his traffic organization in the digital twin of his city. The software tool helps him to elaborate an efficient alternative solution to road transportation in his city. Data related to his proposition are recorded and reused the simulation. The tool records all data according to the proposition. These data are compared to a reference model contained in the tool (previously elaborated). The results (simulation, performance, analysis proposition of improvement) are presented to the user. This new proposition coupled with old data from other users, are combined for improving the reference model (Case-based reasoning and training agent system). This paper focuses on the elaboration of alternative solutions and their performance measurement. For a city, the digital twin is elaborated representing the existing organization and by exploiting the software to acquire data related to this city. Three possibilities of transportation have been integrated: road, fluvial and rail transportations. Sustainable performance indicators have been defined such as economic, social and environmental aspects. The user can select the type of transport, percentage of goods extra to have an idea of cost, carbon emission and transportation time. The setting of the tool started by selecting an ISO certified container dimension that is used all over the world by trucks, cargo ships and trains. The classical information about type of trucks, fuel consumption, average distance and speed of the trucks, likewise for trains, boats and price for shipping the product have been collected and integrated in the tool. Then, the comparison with the existing data is done by the tool for deducing the performance.

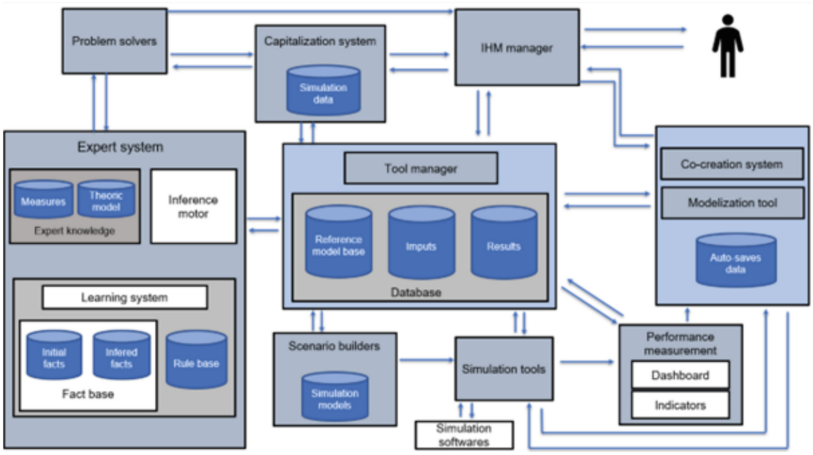


Fig. 1. Structure of the software tool

4 Illustration

"Grand Paris Sud" conurbation is composed of 23 cities and contains a lot of logistics and e-business platforms for providing products to Paris city. The digital model of "Grand Paris Sud" has been elaborated on Anylogic by trucks, electric vans, ships and trains with a warehouse located near RER railway station. An example of "Grand Paris Sud" area simulation is presented in Fig. 2. The basic idea and thought behind designing and creating this simulation are to develop alternative solutions to road transportation and to compare them to road for showing their positive impact in terms of sustainability. If a distribution consolidation center is developed in the city near RER railway station, this distribution center will reduce the flow of trucks inside the city center. Then, products will be dispatched (or collected) in the city by cargo bikes and electric vans. Products could also be transported to "Grand Paris Sud" area by boat, stored into a small distribution center near the port before being dispatched by electric vans or cargo bike in the city. The implementation of this concept in the conurbation will increase the quality of life in the cities, improve carbon footprint, decrease congestion and traffic related to big trucks. The performance measurement module of the tool allows to measure the existing organization and the alternative solutions performances. The performance indicators have been defined in the tool and validated on the case of "Grand Paris Sud" conurbation through three criteria: social, environmental and economic. Then, cases concerning logistics companies have been tested to define for them the best alternative sustainable transportation solution. The use of fluvial solution to transport goods from this area to Paris and from the Havre port to Grand Paris Sud has also been tested. But the best solution according to this case was to use the railway solution because of the delivery time and environmental optimization without cost increasing.

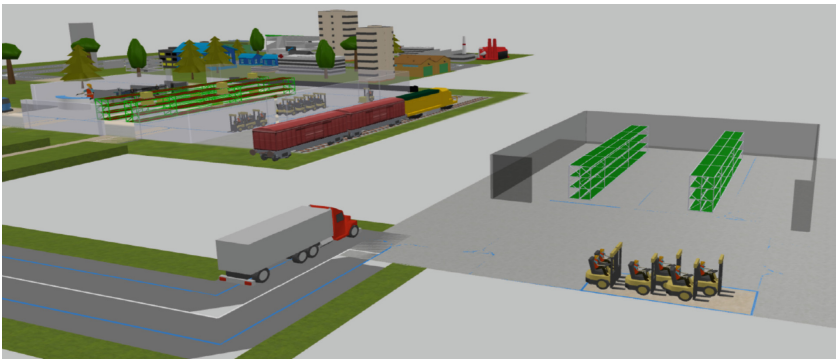


Fig. 2. 3D view of the simulation model

5 Discussion and Conclusion

This paper presents the elaboration and development of a co-creation decision aided tool for simulating and optimizing sustainable solutions alternative to road transportation. The main difficulty for the alternative solutions validation is the real performance measurement. Indeed, companies are interested by economic performance, but city authorities and citizens are focused on the environmental and social aspects. Then, fluvial and railway solutions are less economic, but the low ecological impact makes them interested alternatives. The global architecture of the tool has been shown to support the concepts and methodology developed in this frame. The software tool is being validated on the "Grand Paris Sud" conurbation through the use of use cases proposed by companies, citizens and local authorities. The results will allow to adjust the performance indicators and to integrate recommendation of the stakeholders.

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Inefficiency Assessment for Agricultural Commodities in Urban Areas

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Abstract. Agricultural commodities make up a significant portion of India's freight transportation. They pass through urban areas during various supply chain stages, making urban freight essential. However, importance of urban freight often goes unnoticed, impacting efficiency, society, and the environment. In towns with agricultural hubs, issues intensify as freight vehicles block entrances and exits due to inadequate management and infrastructure. This leads to higher expenses in urban areas. The study attempts to identify certain challenges that plague the transportation of agricultural commodities in urban areas. The study is conducted in the city of Kanpur, Uttar Pradesh due to its unique character of production, processing, storage, consumption of agricultural commodities. The primary data was collected by the OD survey, establishment survey, interviews and questionnaires. The study identifies inefficiencies like empty return trips, increase in the trip lengths, along with congestion, overloading, etc. These identified issues coupled with the informality of the sector, lack of education and enforcement lead to other implications in terms of cost, emissions, and opportunity cost.

Keywords: Urban freight · inefficiencies · supply chain

1 Introduction

Agriculture is said to be the backbone of the Indian economy. India clocked a record production of food grains in 2021–22 at 315 million tonnes (Ministry of Finance 2023) while the world was struggling with the pandemic. A NITI Aayog report states that out of the total goods movement of 4.6 billion tonnes in the country approximately 22% are agricultural commodities (RMI India and NITI Aayog 2021). These goods are mainly transported via road and rail throughout the country. But in terms of urban areas, the road is the major mode of transport.

Urban freight vehicles occupy around 20–40% of the road space and they account for 10–15% of the vehicle kilometers travelled (Shakti Sustainable Energy Foundation and The Energy and Resources Institute 2020). Road Transport Yearbook 2016–17 by the Ministry of Road Transport and Highways suggests that Light Commercial Vehicles (LCVs) and Trucks account for 30.6% and 19.3% registrations respectively (Ministry of Road Transport and Highways 2017). A study indicates that 23% of the total CO_2 is emitted by road transport vehicles in which freight transport vehicles account for

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45%(ICCT 2020). Urban freight is an extremely important sector to investigate since it is involved with the transportation of the necessary (agricultural) commodities. The logistics cost as estimated in the NITI Aayog report stands at approximately 14% which is comparatively higher than other major economies (RMI India and NITI Aayog 2021).

In the urban domain the inefficiencies are due to freight being mostly an unorganized sector. It has many adverse impacts on the environment, social life as well as the cost.

2 Literature Review

An extensive review of various research articles, reports, and news articles was conducted. The articles were obtained via keyword searches on google scholar using city logistics, urban freight, city freight, urban logistics as keywords. It was clearly seen that there is very limited literature available in the field of urban freight concerning agricultural commodities in case of India. Which clearly indicates the research gap this study intends to address.

Holguin- Veras and Thomson in 2003 have defined urban freight activities to be the most complex and impacting activities within a supply chain since logistics service providers and carriers need to be more responsive to the needs of the business and consumers (Zenezini and De Marco 2016). Urban freight transport systems consist of different stakeholders which have their own vision and specific goals which is why they tend to act accordingly to achieve their goals (Ioannis Karakikes and Eftihia Nathanail 2020). This leads to improper coordination, causing inefficiencies in the supply chain. The stakeholders which are generally involved in it are shippers, freight carriers, administrators, manufacturers, storage companies, authorities, retailers and consumers (Ioannis Karakikes and Eftihia Nathanail 2020). In the case of agricultural supply chains farmers and traders are an integral part. Last mile logistics as a part of urban supply chains is considered to be the costliest, least efficient and most polluting (Guerrero and Díaz-Ramírez 2017). City of Cartagena in Spain is an example of the same. Centre of the city has been an extremely important commercial hotspot for centuries and have never experienced such high demands in the history (Lorenzo Ros-McDonnell et al. 2018). The study indicates that the area lacks parking and that freight vehicles occupy pedestrian spaces on the streets. Prolonged parking due to loading/unloading along with non-logistical tasks aggravates the issue. Use of unsuitably sized vehicles, high freight volumes add to the woes faced by pedestrians. Logistics Sprawl is another issue that challenges efficient freight transportation. It is a term that is used to define the spread of goods transport facilities in the urban areas (Sanjay Gupta and Garima 2017). Laetita Dablanc defines it spatial deconcentration of logistics facilities and distribution centers (Laetita Dablanc 2014). Logistics sprawl is the outcome of high land prices, and lack of land in the city centre (Sanjay Gupta and Garima 2017), which forces the logistics facilities to be set up on the outer periphery. This leads to longer more trips, empty return trips, trips with high freight volumes, and increased CO_2 emissions shunning the urban road network (Prasanta K Sahu et al. 2022).

Globally many practices have emerged to solve the issues faced in urban areas. They include vehicle route planning, establishing consolidation and deconsolidation centers, freight quality partnerships, use of freight trams and many more. But the best solution

for one city might be difficult to replicate in the other city. Which is why we need a systematic approach to tackle the issues case by case.

3 Methodology

The site selected to conduct the study is Kanpur, because of its unique character. The city is situated on the banks of river Ganga in the heart of Uttar Pradesh, India. It has a flourishing food processing industry, which has been there for many years. Since the major focus is on agricultural commodities, the Agricultural Produce Marketing Committee (APMC) is the major node where all the trade happens, it was studied, and the operations were analyzed. Various surveys were conducted which included Origin- Destination; Establishment; Logistics operators in the city to understand the costs, farmers survey to understand the farming pattern. The cost of transportation was also analyzed along with the GHGs emitted. This was paired with identification of loopholes in the system. The study then culminated various suggestions to reduce the cost and overall emissions and other recommendations which could be implemented to improve the system.

4 Analysis

In India in the Agri-produce market Agricultural Produce Marketing Committee plays a significant role. It is the nodal centre for trade of all the agricultural commodities. No agricultural produce in the country can be sold without being through an APMC in any part of the country. This gives the government a legitimate source of data and formalizes the country's agricultural market. A general supply chain gives a better understanding of the stature and place of APMC in the supply chain in Fig. 1.

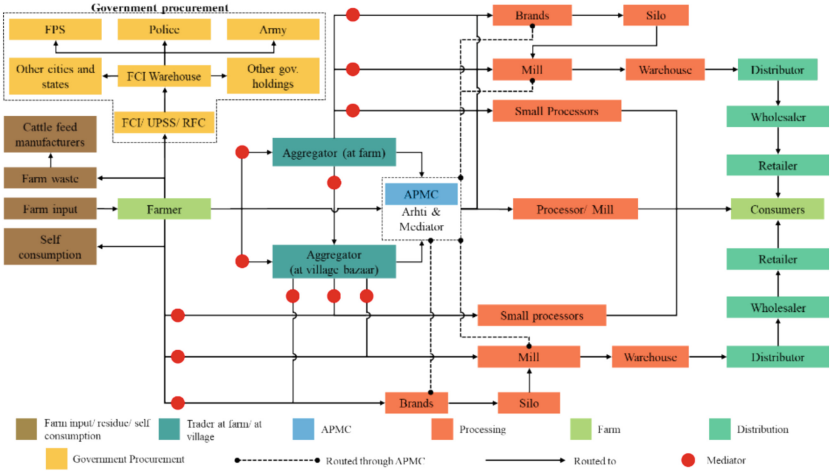


Fig. 1. General agricultural supply chain

The city of Kanpur has 2 APMCs, one deals in fruits and vegetables, and the other deals in food grains, spices, oil seeds, etc. For this study the one that deals with food grains is considered. To understand the freight flows, modal share, trips, and cost of different types of freight vehicles is analyzed.

4.1 Modes

The data collected shows that the LCVs were the prominent mode for intracity trade followed by SCVs and tractors whereas for the intercity trade HCVs followed by MAVs.

For the commodities being transported into and out from the APMC within the city overloading was seen to be prevalent, where the vehicles carried 1.5–2 times the weight, they were registered for. This phenomenon is directly related to increased fuel consumption as well as reduced vehicle life, thus indirectly leads to greater emissions. The SCVs which were used for freight transportation were mostly passenger three wheelers.

4.2 Cost and Operations

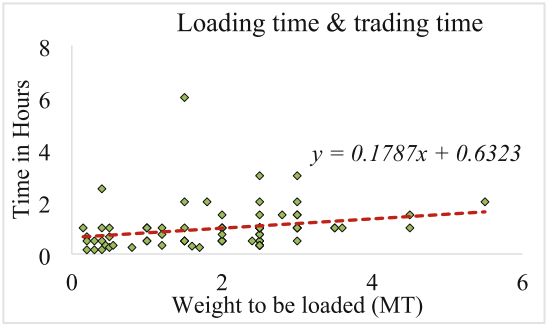


Fig. 2. Loading/ unloading & trading time.

The loading and unloading operations at the APMC are generally expected to be optimized. Figure 2 shows the loading/unloading time along with order processing and documentation time segregated by payload capacity of vehicles. The equation achieved when solved indicates that it takes approximately 38 min. to load/unload a vehicle irrespective of the payload capacity. The slope of the line in the graph is mild which means that other factors are also responsible for high trading time. This lost time translates into opportunity cost affecting the freight vehicle operator's turnover, this opportunity cost would then lead to the increase of freight transportation cost of the commodities into and out from the APMC.Cost of operating vehicles is an important factor that can be used to determine the choice of vehicle along with other factors like road network, restrictions, volume to be transported, etc. The cost of operating vehicles is generally divided into operating costs and fixed costs (calculated yearly).

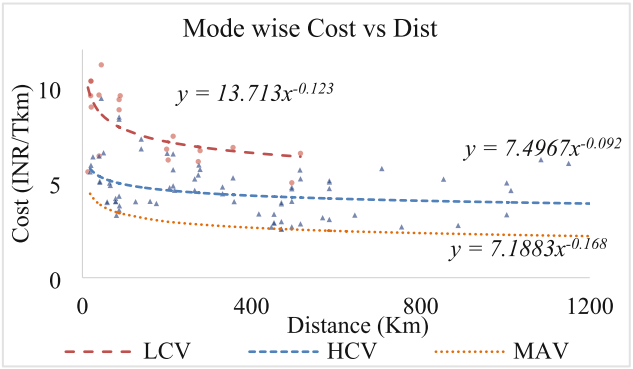


Fig. 3. Operations cost of LCV, HCV, MAV

Here the cost is calculated in INR/tkm which gives us the operating cost of a specific kind of vehicle carrying one ton of commodity for a km in Fig. 3. Here it must be noted that the LCV is assumed to carry <= 2.5 MT, HCV <= 18 MT and MAV > 18 MT based on the axel load characteristics and operator's survey. The lesser the payload capacity, greater is the operations cost. Even for shorter distances heavier vehicles prove to be more cost efficient.

Emissions are one of the factors which govern access and restrictions of freight vehicles in the city even for vehicles carrying necessary commodities like food grains, vegetables, etc. Emissions must also be evaluated based on the mode/ weight category of the vehicles that is separately for LCVs, HCVs, MAVs. To assess this parameter and calculate the emissions, emission factor method is used for which the factor to calculate per km emission of CO_2 for a specific category of vehicle is taken from a study that was conducted by World Resource Institute in India along with pollutant emission proportions (Reif 2014). The Table 1 shows the pollutant emissions for different vehicle categories assuming the total distance to be 10 km for each vehicle and volume be 30 MT.

This clearly indicates LCVs contribute more to pollution when the volume of the commodity to be carried and the distance to be travelled are same. This is because of the lesser payload capacity which results in them making a greater number of trips.

Table 1. Mode-Wise Emissions

Mode	Weight cat	Distance (km)	Volume (MT)	CO2	CO	NOx	HCs	PM (including sulphates)
LCV	<= 2.5 MT	10	30	36.84	0.22	0.18	0.03	0.04
HCV	<= 12 MT	10	30	17.78	0.11	0.09	0.01	0.02
MAV	>12 MT	10	30	14.75	0.09	0.07	0.01	0.02

*All the pollutant values are in Kg

4.3 Trips

The city of Kanpur is a nodal hub for trade of agricultural commodities for the entire district of Kanpur Nagar (Urban), Kanpur Dehat (Rural) and other rural and urban centers

within 50–60 km from the city. This leads to commodities being shipped to places outside of the city boundary as well. Almost all of the major processing and packaging units consuming these agricultural are within the city boundary. On the other hand, the city has 4 major wholesale hubs which not only trade within the city, but also in the areas mentioned above. This leads to transportation of commodities for trade to these major processing units, and wholesale markets.

Certain commodities which come from different parts of the country were traded online via government of India's portal E-NAM and were destined to the processor or the wholesaler. But the commodities had to pass through the APMC for weighing and documentation. This leads to an increase in lead time, trip length, as well as emissions and cost. Because certain processing units are located outside the city, the vehicle must detour to the APMC first and then to the processing plant or the wholesaler. This led to the trip's lengths increasing by an average of 19.42 km on the roads falling within the urban boundary.

This increase in the trip length and detour also causes congestion, especially during the early morning and late-night hours when the trucks are parked outside the APMC. Empty return trips are the other issue arising due to vehicle originating from APMC. 95.8% of vehicles carrying agricultural commodities return empty to the APMC. The Table 2 shows the total dead milage trips along with the emissions due to empty trips.

Table 2. Dead Milage Trips

Mode	ATL (km)	Empty return trip length	CO2	CO	NOx	HCs	PM (including sulphates)
SCV	18.87	198.74	647.36	1.20	0.95	0.14	0.22
LCV	23.58	836.62	2725.14	5.07	4.01	0.59	0.94
Tractor	33.46	151.14	151.14	0.92	0.72	0.11	0.17

*All the pollutant values are in Kg

5 Conclusion and Recommendation

Agricultural commodities and their transportation in and out of urban areas are facing certain challenges, which have been discussed. Most of these challenges have a trickling down effect on the prices of these commodities. One way to keep them under control is to optimize their supply chain, especially transportation and storage.

LCVs which are costlier to operate and contribute more to pollution, these vehicles can be replaced with ones with more payload capacity to reduce the number of trips and emissions, optimize on cost. Use of heavier vehicles would require making suitable infrastructural provisions on certain corridors. Since heavy vehicles are restricted in urban areas, provision can be made of certain corridors leading to main markets and industrial areas on which these vehicles can ply.

The issue of increased trip lengths can be solved by decentralizing certain operations of the APMC to the major entry points of the city. This would help reduce congestion in areas near the main APMC where the major trade happens, along with emissions and costs. This can be taken up with establishing new wholesale markets and industrial areas near the periphery of the city, distant from the residential areas. This would further lead to reduction of trip lengths, emissions, and cost. Route planning and stakeholder integration are other two initiatives that can be taken up to improve the load factor of the freight vehicles. This can be done by introducing a common data exchange portal for the traders, buyers and, sellers and vehicle operators to exchange information and collaborate in terms of vehicle sharing. This might result in a reduction of empty trips, and even reduction of number of trips for LTL volumes.

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Mobile-Depots and Cargo Bikes Towards a Sustainable Last-Mile Future

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Abstract. E-commerce growth is driving the need for novel, more sustainable last-mile delivery strategies. One potential strategy is based on setting up a mobile-depot from where last-mile deliveries are conducted using cargo bikes. This research explores the impacts of this strategy through a microscopic traffic simulation based on a medium-sized European city. The strategy was evaluated at three levels: operational (route length and duration), energy consumption, and emissions. The results showed that adopting a last-mile delivery strategy based on a mobile-depot and cargo bikes leads to significant benefits in terms of energy consumption and emission, which decrease by more than 80 %, but imply lengthier (+49 %) and more time-consuming (+14 %) routes compared to a traditional parcel delivery strategy.

Keywords: Last-mile logistics · Sustainability · Parcel delivery · Simulation · Mobile-depot · Cargo bike

1 Introduction

The rapid popularization of e-commerce has revolutionized the way consumers and businesses interact. This popularization has put the entire supply chain under pressure, especially the last-mile. This last part of the supply chain accounts for around 40 % of the overall supply chain costs [1], therefore, organizations need innovative strategies for more efficient logistics operations.

New strategies are even more urgent considering the fact that the last-mile is a source of negative externalities such as road congestion, noise, or emissions of pollutants like nitrogen oxides (NO_X) and particulate matter (PM_X).

One strategy that emerged as a potential alternative to the problematic traditional strategy is the mobile-depot. This strategy is based on a large vehicle that includes loading and storage capabilities and acts as a mobile warehouse from where last-mile deliveries are conducted using vehicles like cargo bikes.

This concept, also known as mobile-hub, has been discussed for over a decade and pilot-tested in countries like Belgium [7], Ireland [6] or Germany [2]. However, the mobile-depot is usually designed as a 'static' mobile-depot i.e., its location is always the same within a given day. In this context, this study aims

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to explore the impacts of a mobile-depot system for last-mile deliveries that changes locations within a city during the day through a microscopic road traffic simulation model based on a medium-sized European city.

2 Methodology

The first step was defining the case study, modeling the network and traffic conditions and estimating the e-commerce demand. Secondly, the scenarios were defined by parameterizing the delivery strategies. Then, the model was simulated using a microscopic road traffic simulation model. Lastly, the model's results were evaluated at three levels: operational performance, energy consumption, and emissions.

2.1 Case Study

The case study is based on a 1 km^2 residential area located in the metropolitan area of Porto, Portugal. This area comprises essential services including schools, shops, gas stations, and public transportation infrastructure and houses more than 15 000 people [5]. This area's main roads connect key Porto locations such as Aliados or the historic center.

This area was carefully modeled using the microscopic road traffic simulation package Simulation of Urban MObility (SUMO) (Fig. 1). The simulation included factors like road slopes, location of traffic lights or mobility patterns.

The simulation model included the movement of pedestrians and different types of vehicles including passenger vehicles; motorcycles; bicycles; trucks; vans; and buses. The frequency of each was defined based on vehicle counts performed on one of the main roads of the study's area. In the simulation, these elements traveled randomly through the zone, except the buses, which traveled according to the actual schedules and routes. Other factors like rush-hour periods or the most common routes were also taken into consideration.

The e-commerce demand modeled was based on data sourced from official reports issued by the key Iberian logistics player CTT. In 2022, this company delivered 33.1 million parcels in Portugal, of which 20 % are estimated to be made in Porto's metropolitan area [3,4]. Therefore, considering how many people live in the case study area, it is estimated that 59 380 parcels were delivered in the studied area in 2022, equating to 163 parcels each day, on average.

These parcels have different weights and volumes: 74 are small parcels (●) and 89 are larger parcels (▲). These will be delivered to 100 stops. Each one has a different delivery time according to the type of parcel: the 74 small parcels need 2 min, while the remaining 89 larger parcels require 4 min to deliver the first package and an extra 2 min per additional one. These times are reduced by 30 s for deliveries made with cargo bikes as they are easier to park. Moreover, the bikes need around 10 min in each mobile-depot's location for loading purposes.

2.2 Scenarios

Two scenarios were considered in this study:

- The **baseline scenario (BASE)** refers to the traditional last-mile strategy where the parcel delivery operation is done using one Internal Combustion Engine (ICE) van.
- The **alternative scenario (ALT)** involves using one ICE van as a mobile-depot. This mobile-depot – loaded with all 163 parcels – moves between four different strategic locations, chosen according to population density; the number of parcels; and real-life space adequacy. From each, one electric cargo bike carries out the last-mile deliveries for the associated zone (colored in Fig. 1), before returning to the mobile-depot.

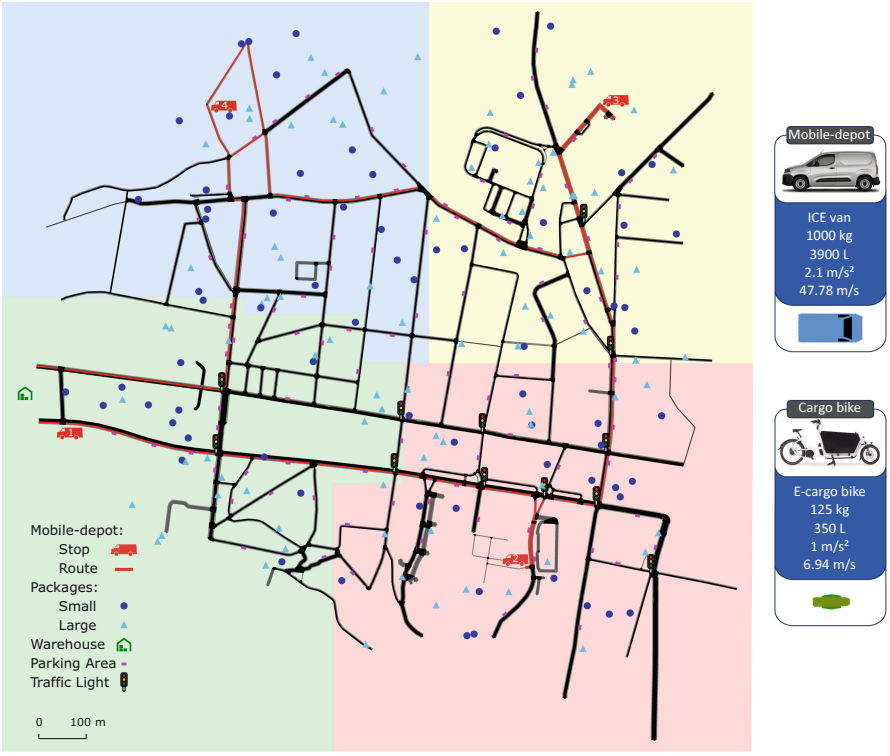


Fig. 1. Simulation area depicting the network, traffic, and e-commerce settings.

3 Results

The simulation's results and their analyses are divided into three main categories: Operational performance; Energy consumption; and Emissions. The results listed

are the outcomes of 10 simulation runs with random seeds. The warm-up period of the simulations was 5 min.

3.1 Operational Performance

The results present in Fig. 2 show that, in the baseline scenario, the van traveled around 24 km to complete the delivery service, while the mobile-depot-based scenario implied a total route length of more than 35 km (cargo bikes: 30 km; mobile-depot: 5 km). Similarly, the time needed to complete the delivery operation in ALT is also around one hour longer than in the baseline scenario (BASE: 07:23:45; ALT: 08:26:05, on average). These 49 % and 14 % increases in length and duration, respectively, could be attributed to the fact that in a mobile-depot-based strategy, contrary to a traditional service, the delivery operation is not continuous. The mobile-depot needs to change locations, and the cargo bikes that depart from them need to return to them later. Additionally, the cargo bikes spend around 10 min loading in each mobile-depot's location.

The tasks conducted at each delivery stop, namely, parking the bike; finding the package; delivering the package; and returning to the bike, are responsible for 64 % of the entire duration of the ALT scenario. The cargo bikes driving from the mobile-depot to these stops; driving between each stop; and returning to the mobile-depot is the second most time-consuming stage, accounting for 26 % of the total duration. The remaining time is spent loading the parcels into the bikes (8 %) and driving the mobile-depot to each location (2 %).

3.2 Energy Consumption

Figure 3 maps the strategies' energy performance in terms of the fuel/electricity consumed during the delivery round. The baseline scenario's ICE van consumes on average 111 MJ (2.43 kg) of diesel fuel while the ALT consumes 21 MJ, which includes the 0.42 kg of diesel consumed by the ICE van used as a mobile-depot and the 563 Wh consumed by the electric cargo bikes that deliver the parcels. This 81 % decrease in energy consumption suggests economic savings and environmental benefits when adopting a delivery strategy based on a mobile-depot with cargo bikes.

3.3 Emissions

In line with the energy consumption outcomes, Fig. 4 shows that the emissions are also much lower when using a strategy based on mobile-depot and cargo bikes. There are 84 % less hydrocarbons (HC); 83 % less carbon monoxide (CO), carbon dioxide (CO_2), and PM_X emissions; and 82 % less NO_X emissions. These results also further confirm the benefits of such an alternative strategy. In fact, producing fewer emissions not only benefits the environmental and social sustainability of the strategy but can also play a key factor in its operational performance, since more cities are implementing low-emission zones (LEZs) to restrict the movement of polluting vehicles.

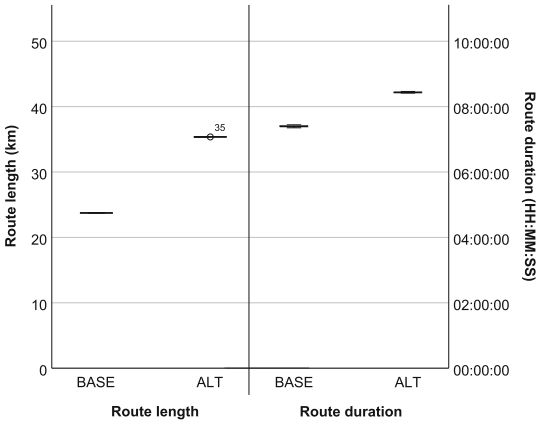


Fig. 2. Operational performance.

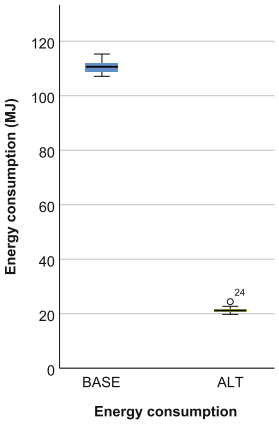


Fig. 3. Energy consumption.

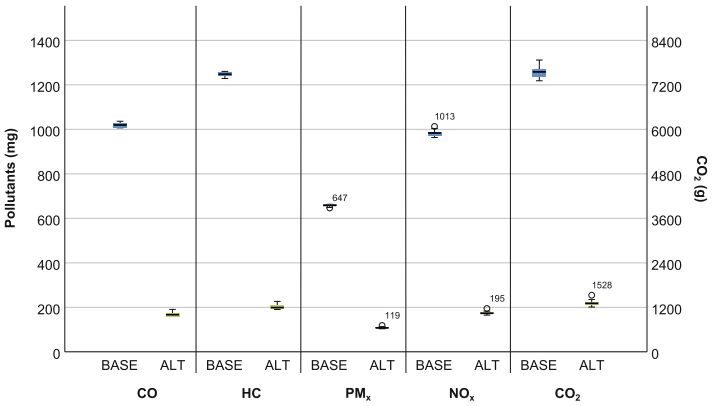


Fig. 4. Emissions of two delivery strategies.

4 Conclusion

When adopting a strategy based on mobile-depot and cargo bikes, there are significant benefits in terms of energy consumption (−81 %) and emissions (−83 %) when compared to a traditional delivery strategy. Nonetheless, this strategy implies lengthier (+49 %) and more time-consuming (+14 %) routes.

These results demonstrate a common problem that hampers the design of truly three-dimensional sustainable solutions for last-mile logistics: the trade-off between sustainable practices and maintaining a good operational service level. However, the results present strong positive arguments for implementing such an alternative delivery strategy beyond environmental and social factors. The results suggest that there are potential cost-savings due to the decrease in energy consumption, and operational advantages in some cities that limit pollutant vehicles.

Furthermore, the mobile-depot and cargo bikes' operational viability could be immensely improved if the political and industry stakeholders made real efforts to collaborate toward common goals like improving infrastructure dedicated to cycles or planning optimal locations for stopping a mobile-depot. Additionally, the efficiency of a strategy based on mobile-depot and cargo bikes could potentially be enhanced if the delivery is performed by more than one bike at the same time, or if the mobile-depot's locations are optimally adjusted in accordance with the demand.

Although elements like the number of parcels or the delivery times were defined through estimations based on official reports, it is necessary to acknowledge that they should be considered approximations. Moreover, the obtained results are dependent on the parameters and assumptions followed for this case study. Nonetheless, the authors believe that the results and insights are generalizable to other contexts.

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Assessing the Potential for a European Modal Shift Towards Rail

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Abstract. Purpose: The aim of this paper is to present a computational method for identifying bottlenecks in the rail transportation network under the assumption that a modal shift from road to train should be emphasised.

Methods: From a methodological point of view, the contribution is twofold: First, an estimation of the overall freight transport in Europe is done. Basic statics, as available from countries and the European Union, are utilised to estimate the actual freight transport demand between NUTS3 areas in Europe. Second, the (theoretically) needed train transports are computed by finding the shortest route between two NUTS3 regions. If the capacity of the train network is reached on a specific strech, alternatives are searched.

Results: To assess, where bottlenecks are, we used the European rail network (from OpenStreetMap) as well as intermodal terminals (provided by a project partner) for our computations. The results show that our approach is working.

Conclusion: The method presented within this paper is easy to use (only a few input data are needed) and fast (with respect to computational effort) such that it can be easily used for infrastructural planning tasks and assessing whether envisaged extensions of the rail network contribute to the higly desired modal shift.

Keywords: modal shift · intermodal transport · freight and logistics · computational method

1 Introduction

The international and national goals are to decrease our carbon footprint (United Nations, 2015). Different ideas have been developed to achieve this goal. The transport sector is one of the main CO_2 contributors (Umweltbundesamt Österreich, 2023b) and therefore decarbonisation (in this sector) is urgent. Increase in intermodal transportation (Economic Commission for Europe, 2001) is one of the pursued goals (United Nations, 2016) and taken over in various national strategies, cf. (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology 2022a; 2022b).

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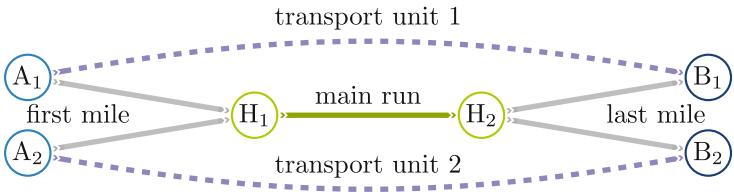


Fig. 1. A sketch of a general intermodal transport. First/last mile are usually realised via truck and independent of each other. At some hub (H_1) the transport units are transshipped onto a train (or barge) and transported to a second hub (H_2). The transport units are forwarded to their final location independent of each other again.

Intermodal transport (in freight transportation) is defined as follows (Economic Commission for Europe, 2001): Along one transport (chain) at least two different modes of transport are incorporated. The freight is transported using a transport unit (e.g. container) which is switched among the involved modes of transport. I.e., the cargo is not transshipped piece by piece. A general intermodal transport can be summarised as shown in Fig. 1: The transport is split into three segments, with the first (referred to as *first mile*) is typically realised using a road-bound vehicle. The second segment (referred to as *main run*) is realised via mass transportation (e.g. train or barge). The third (and last) segment (referred to as *last mile*) is again covered with road-bound vehicles. On the main run, multiple transport units are transported on the same vehicle.

The main advantages of intermodal transports can be summarised as follows:

- Breaking up the transport into multiple smaller distances (using different modes of transport) provide the possibility that for the large distances more environmentally friendly transport modes can be utilised as bundling can take place. I.e., multiple transport demands going into the same direction are united on one train (or e.g. barge).
- Due to increased volumes (in the long run), it is possible to be not only more environmentally friendly but also more sustainable from an economic point of view. E.g., instead of needing 40 truck drivers only one train driver is sufficient.
- Trains and barges are more energy efficient than trucks (Fastenbauer et al., 2023b; Umweltbundesamt Österreich, 2019) leading to less energy consumption which obviously also leads to less energy costs.
- By using transport units, only one transshipment operation is necessary instead of transshipping thousands of pieces one by one.
- For certain relations, the main run can be used to overcome driving time restriction. E.g., a transport along the Danube on Saturday and Sunday might be faster than a parallel truck transport.
- The number of trucks on the road is significantly reduced. This leads to decreased abrasion of the roads. Furthermore, road safety is increased. Both lead to reduced costs for the society.

However, there are also some disadvantages, among others:

- In most cases, an intermodal transport takes longer than a (unimodal) direct one incorporating only truck. Among others, because bundling has to take place, which means that some load units will most probably wait for others.
- In addition, a graphical representation on a map might look cumbersome with, e.g., the first mile starting in the "wrong" direction. This is the case, when the closest intermodal hub is located opposite to the destination.
- The organisation of intermodal transports can be time-consuming and complex as multiple transports (including intermediate transshipments) need to be coordinated.

That said, one can summarise that intermodal transports have some disadvantages. The advantages are, however, predominant, especially with respect to road safety and environmental impacts. Therefore, the main goal of us as a society has to be to foster intermodal transportation. The remaining question is, however, how much of the freight transport can actually be shifted towards the rail network. And obviously, if not all can be shifted, where do we have to invest for achieving this complete shift.

Contribution of this Paper. Within this paper, we are trying to answer the question, how much of the actual freight transport (in Europe) can be shifted towards the rail network. I.e., how much of the freight transport can be realised using intermodal transportation. To the best of our knowledge, there is no work focusing on this specific European-wide topic. Works presented in the literature focus on the organisational processes and/or decision making related processes, cf. (Jonkeren, Francke, and Visser 2019; Sallnäs, Rogerson, and Santen 2022).

We introduce a general algorithm operating with publicly available data, i.e., transport statistics as reported by the national statistics agencies and (rail) infrastructure data, e.g., available in OpenStreetMap (OpenStreetMap contributors, 2023). In addition, we propose a first version of an algorithm that tries to distribute the European freight transport on the rail network (under consideration of passenger transport). Finally, this paper lists a number of future works in order to achieve the desired decarbonisation via intermodalisation.

2 Algorithmic Approach

In order to answer both questions (namely how much of freight transport can be shifted towards rail and where to invest to achieve 100%), we propose an algorithmic approach that is a) independent of personal interpretations and b) easily repeatable.

The general outline is as follows:

1. The general freight transport demand is estimated based on publicly available statistics.
2. For the rail transport network, capacities (for freight trains) are estimated.
3. For each transport demand, the shortest route from source to destination incorporating an intermodal route is searched based on the capacities in the rail network.

4. For each transport route, it is determined how much of the freight cannot be transported.
5. The results are visualised.

2.1 Estimation of the Freight Transport Demand

Transport quantities are available through an online database (EuroStat, 2023a) which is published by the statistical office of the European Union (EuroStat). Furthermore, data is available with respect to amounts of goods transported between different NUTS3 (European Commission, 2003) regions. (Widhalm, Buchegger, and Hu 2024) describe a method, how these two data sources can be merged using additional input data from, e.g., toll data and traffic counts. In this work, we use the outcome of that paper as input meaning that we can assume an OD-matrix (origin-destination-matrix) providing information how much freight is transported from each NUTS3 region to each other NUTS3 region (in Europe).

2.2 Estimation of Rail Network Capacities

The second main input for our proposed method is the rail network and the capacities (for freight transport) on the rail network. The capacities on the rail network are determined by various parameter. The most important ones are:

Number of Tracks. The number of tracks build the main factor with respect to the capacity of the rail network. Typical numbers on segments are:

- Just one single track that is used in both directions. At strategically important locations a passing siding might be available. This type of track is typically used in rural areas with low frequent traffic on the rail network.
- Two unidirectional tracks (one in each direction) is the typical layout in regions with medium traffic and mainly for regional connections. Suburbs are normally connected with this layout.
- Four tracks (two in each direction) are used for highly frequented segments. Typically, two tracks (one in each direction) are reserved for high-speed trains while the other two are used for regional trains.

Speed of Trains. The speed of the trains is a critical input parameter as the faster a train is, the more safety space before and behind the train is needed. This is mainly reasoned by the fact that in most regions still the "old" block system is applied with analogue signals. When a train breaks down (or any other incident occurs on the tracks) all preceding signals are switched to red in order to make sure that no train collides with the barrier. That means, however, that a full speed train needs to come to a full stop. Basic physics tells us that this emergency stop distance is proportional to the square of the speed of the train. Therefore, the faster trains are on specific segments the more safety distance between the trains is needed. This leads to a (significant) reduction of capacities.

Length of Blocks in the Rail System. As mainly analogue signals are still used in the railway sector, the tracks are segmented (also referred to as blocks). The length of these blocks is (more or less) indirectly proportional to the number of signals along the tracks. As explained before, the track ahead of a train needs to be clear. However, to ease system operations, not the actual distance before a train is calculated as a minimum safety distance but a fixed number of blocks (e.g. 3) is defined. Therefore, longer blocks lead to decreased capacities.

Speed Differences. Beside the actual speed of one train, the differences in the speeds of two consecutive trains are essential as well. If a faster train is closing up to a slower train, a takeover at some location is needed. This implies due to the block rule explained above that extra waiting times are necessary leading to a further decrease of capacities.

Freight and Passenger Trains on the Same Tracks. The mixture of passenger trains with freight trains has an additional impact. First, each passenger train reduces the capacities for freight trains. Second, passenger and freight trains normally operate on different speeds. Third, passenger trains have intermediate stops while freight trains could ride without stops.

More details on the influences of these parameters (and many others) can be studied in detail in (Pirkopf, 2012). In that work, the authors also give an introduction into "typical" train settings (e.g., 1 high-speed train, 1 medium-speed train, 1 regional train, 4 suburb trains, 2 freight trains). Based on our own estimations, and in line with the numbers presented in (Pirkopf, 2012), we assume a total of three freight trains per hour for our further calculations. Further, we assume a train to transport 1000 t cargo. This leads to 72 000 t cargo per day on a double track segment. This value is then assigned to each track/segment in the rail network obtained from OpenStreetMap (OpenStreetMap contributors, 2023).

For a discussion on the limitations with this estimation method, we refer to Sect. 3. Further, we want to highlight, that the main purpose of this paper is to introduce the computational method.

2.3 Shortest Intermodal Route

The third step in our approach is to compute for each OD-pair of the OD-matrix obtained via the method described in Sect. 2.1 an intermodal route. For this purpose, we apply an intermodal version of the well-known shortest path algorithm (Dijkstra, 1959; Prandtstetter et al., 2018; Prandtstetter, Straub, & Puchinger, 2013). The necessary transshipment points, i.e., terminals and hubs, have been provided by one of our project partners. The transport network has been extracted from OpenStreetMap (OpenStreetMap contributors, 2023). If the main run of the intermodal route is shorter than 300 km we neglect this route as intermodal transportation is not meaningful for these short distances (European Commission, 2011; Rodrigue, Comtois, & Slack, 2013).

Algorithm 1: CapacityComputations

Input: set $\mathbb{O}$ of OD-pairs (incl. tonnage to be transported)
transport network G
begin
  while $\mathbb{O} \neq \emptyset$ **do**
    select one random OD-pair p;
    $\mathbb{O} \leftarrow \mathbb{O} \setminus \{p\}$;
    compute shortest intermodal route in transport network G for p;
    set the transported capacity for p to the minimum residual capacity along the chosen route;
    compute for each link $l \in G$ a new residual capacity r_l;
    remove all links from G with $r_l = 0$;

2.4 Determination of Residual Capacities

As described in Sect. 2.2, a capacity for each segment in the rail network can be computed. To compute how much of the actual demand can be (theoretically) shifted onto the rail network, the following procedure is applied. We randomly select one OD-pair and compute the shortest intermodal route for this transport demand. Now, there are three possibilities:

- The capacity of all segments along the shortest route is high enough to handle the actual demand. In that case, the residual capacities of each used link are computed by subtracting the actual demand from the available capacity.
- If the capacity of one (or more segments) is not enough, then we identify the most limiting segment. The available capacity on that link will be used for intermodal transportation. Therefore, we subtract this (remaining) capacity from all used links. Those links with remaining capacity of 0 are removed from the rail network for further iterations.
- No intermodal route between the origin and the destination could be found. In that case, we proceed with the next iteration.

This process of selecting one randomly OD-pair, finding the shortest route for it, and updating the (capacities in) the rail network is repeated until all OD-pairs have been processed. The overall procedure is also shown in Algorithm 1.

As this algorithm is randomised and the actual sequence of processing the OD-pairs has an impact on the output, the overall procedure is repeated at least 50 times in order to minimise statistical outliers. The then received maximum modal shift is assumed to be the best available estimation on the shift potential.

Table 1. Summary of the usage of the European rail network.

	>95%	80%–95%	0%–80%	unused
average usage	6.15%	2.24%	14.93%	76.68%

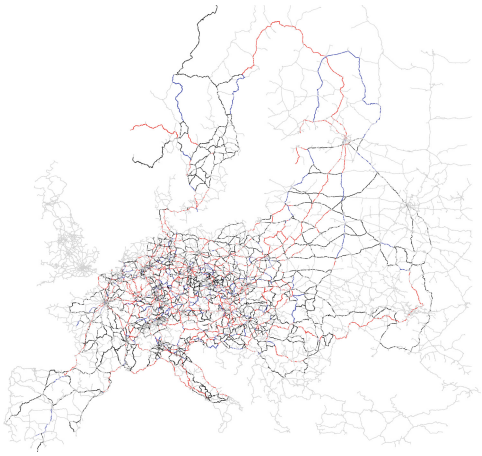


Fig. 2. Visual representation of the used rail network. Grey lines represent unused tracks. Black lines correspond to tracks used up to 80%. Blue lines are tracks with usage between 80% and 95% of their capacity. While red lines are those tracks with >95% utilisation.

Please be aware, that with the current version of the algorithm, it is not tried to reroute transport demand if no route of high-enough capacity is found. For further discussion on this and other limitations, we refer to Sect. 3.

2.5 Result Processing

Algorithm 1 provides us with the information for each OD-pair how much of the actual demand can be transported on a specific (intermodal) route. This output can now be used for further processing. Two main insights can be generated:

- It is possible to estimate the potential for a modal shift towards the rail sector.
- As we know, how much can be transported via an intermodal option, we also know, how much cannot be transported. In addition, we have the information, which segments in the rail network are fully used. It can be assumed that these segments need to be extended with respect to capacity.

In Table 1 some statistics with respect to our showcase are presented. The values are averages of 50 runs of the above mentioned randomised algorithm. We refer to Fig. 2 for a graphical representation of the results obtained so far. The lines shown correspond to the European rail network. Grey ones are completely unused and make up of approx. 76% of the overall rail network. Black lines are tracks which are used with up to 80% of their capacity. These are about 15% of the network. Blue lines make up of about 2% and represent tracks of usage values between 80% and 95%. Red lines, finally, represent tracks which are basically

fully occupied with a contribution of about 6%. That is, about 24% of the rail network is used whereby only 38% of the overall tonnage is transported on the rail network. The remaining 62% have to be transported via other modes of transport.

3 Conclusions and Future Work

Within this work, we presented a method on how to assess the modal shift potential in the European transport network. First, we estimate the actual freight transport demand based on statistics provided by the individual states towards the European Union. Further, we calculate the shortest intermodal routes in the European transport network to cover that transport demand. Based on a capacity estimation, it is then assessed how much of the actual demand can be shifted. A visual representation of the results, highlights the bottlenecks and potential for expansion.

Based on this first approach, he results obtained so far show that about 38% of the overall freight transport demand could be handled by the European rail network. This indicates, however, that the set goals of significantly increasing intermodal freight transport is rather hard as already 16.9% of inner-European freight transport are already on the railway sector (EuroStat, 2023b). It can be expected that future, more detailed computations reveal severe bottlenecks and major investments in the rail infrastructure will be necessary.

The algorithm presented within this work, gives a first rough estimation on how the potential for a modal shift actually is. However, there are many points that need to be improved for a more detailed assessment:

- First of all, the algorithm assumes that only a direct (intermodal) route is feasible. However, future versions of this algorithm need to compute alternatives as well. E.g., if the direct connection is already fully occupied but a slight detour is possible (and there is still capacity left), this option should be chosen.
  In addition, the algorithm is randomised (and therefore executed several times) but does not try to improve during one iteration. Further developments are therefore necessary to integrate additional mechanism to improve the output of one single iteration. One can think of a procedure similar to a classical destroy and repair operator in, e.g., adaptive large neighbourhood search (Pisinger & Ropke, 2007).
- With the current shortest route computation different track widths and electricity systems are not considered. Future data processing should include that information too.
- Currently, the overall transport volume reported to EuroStat is used. However, some of these goods might have more potential for a modal shift than others. Therefore, we suggest to further investigate the input data and try to figure out more precise transport demand for goods flows that are predestined for intermodal transportation.

- Furthermore, the values used are yearly values. That is, we assume (based on the available statistics) that freight transport demand is evenly distributed over the year. Unfortunately, this is not true—especially for seasonal goods like agricultural products or in the construction industry.
- With respect to the rail network and especially the estimation of capacities on the rail network, we think that the current approach is too shallow. It is well-known that not all tracks are equally used. Furthermore, some are reserved for passenger trains only while others are reserved for freight trains only. Currently, this is not included in our computations as this detailed information is not publicly available. And even if it is available for one country, this is not enough as intermodal transport is a European task.
- Furthermore, a modal shift in freight transportation is the main goal. However, at the same time, a modal shift in passenger transportation is a goal too. This implies that the number of passenger trains will (hopefully) increase in the future as well. This increase needs to be incorporated into the method as well.

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Availability of Data and Material. All data used within this research is publicly available. Sources are given in the appropriate sections.

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Comparing the Environmental and Economic Impact of the CargoTube System with Road-Based Transport

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Abstract. CargoTube is a low-pressure tube transport (LPTT) solution aimed at zero-emission high-speed transport. In order to prove the feasibility of the solution a use case is investigated which should connect a LSP with an automotive plant. The Horizon 2020 project ePIcenter has defined the demonstrator in a cooperation project of multiple partners with different expertise in terms of hyperloop technology, simulation and analysis of the impact. To support an investment decision, an analysis is planned that will investigate the environmental and economic impact of the CargoTube system in comparison to the current truck-based connection.

In order to evaluate the impact of the LPTT CargoTube connection, a Life Cycle Performance Assessment (LCPA) is carried out. It compares one or more future scenarios against a baseline scenario representing common practice. In the context of the CargoTube demonstrator, the analysis concentrates on a subset of available KPIs. The financial aspects are mainly covered by CAPEX, OPEX and NPV, while the environmental impact is represented by the GWP (Global Warming Potential) measured as CO_2 equivalent.

The paper will show the results of the analysis and the conclusions to be drawn for the demonstrator implementation.

Keywords: Hyperloop · CargoTube · Sustainable Logistics Transport · Energy Efficient Transport · Environmental Impact · Life Cycle Performance Assessment

1 ePIcenter and the CargoTube System

1.1 Introduction to the ePIcenter Project

The ePIcenter project aims at developing and testing AI driven logistic software solutions, new transport technologies and supporting methodologies to increase the efficiency of global supply chains and reduce their environmental impact.

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Main aspects are visibility and collaboration, making the supply chains or logistic processes more transparent through cyber secure data exchange and sharing, and optimisation, using new data and emerging technologies in a smart way, that can optimise the real life logistics and synchromodal planning processes end users are facing daily.

In combination, the work on these two themes will take a major step towards the Physical Internet concept and seamless sustainable global freight flows. The project delivers relevant applications, that can easily be transferred to other end-users. Taking into account emerging technologies (e.g. hyperloop, automated vehicles) and trade routes (Silk route, Arctic route) in the simulation modules, the project also prepares for the future and challenges ahead.

1.2 CargoTube in the ePIcenter Context

The use case scenario is the implementation of hyperloop as a reliable transport system to deliver cargo to one of the major logistics hubs of the Wolfsburg. VW plant design criteria are set according to the needs that have been identified during a visit of the logistics hub inside of the manufacturing plant.

The transport of incoming material from a possible Logistic Service Park (LSP) in the WOB-Heinenkamp-area to the VW plant could happen e.g., via hyperloop to reduce road traffic in an already congested area, while the logistics centre itself is perfectly connected via the A39 to the road network. The hyperloop system would supply the "Logistics Hall 55" in time with necessary items while the complete offloading, storage and sorting is handled at the "LSP-Heinenkamp" site. A detailed description of the envisaged prototype is given in [2]. This paper concentrates on evaluating the environmental and economic impact of the demonstrator.

2 Assessing the Performance of the CargoTube Demonstrator

2.1 The LCPA Method

The Lifecycle Performance Assessment (LCPA) method can be used to analyse the environmental and economic performance of a product or system. The method typically compares one or more innovative solutions against a reference system (typically the commonly used solution that should be replaced by an innovative development. The LCPA tool implementing the method covers all lifecycle phases starting with the design and finishing with the recycling. The energy consumption is not only measured for system construction and operation but also for the fuel production.

Depending on the availability of information the LCPA model might be created with brief information first and can then be refined when detailed information becomes available during detail design and especially during operation. Therefore, an overview of the expected results may be generated with limited input while in later stages the expectations might be compared with the actual performance of the final product.

The Key Performance Indicators with respect to the economic performance are Net Present Value (NPV), Operational Expenditures (OPEX) and Capital Expenditures (CAPEX). For the environmental performance, Acidification Potential (AP), Eutrophication Potential (EP), Aerosol Formation Potential (AFP) and Global Warming Potential (GWP). A detailed description of the method is given in [1].

2.2 Software Tool to Carry Out LCPA

The LCPA software tools implements the method and supports the entire LCPA process starting from model preparation over running the calculations to the presentation of results. It has a built-in database for predefined elements (e.g. materials, energy converters fuels, and financial data) while the project related input data either will be imported from external applications such as LCA databases or simulation systems or will be entered manually. Once the scenarios have been defined, the LCPA calculation will be run, resulting in the KPI values for the entire life cycle determined by the model. The results will then either be visualized as development over time or as bar chart showing the total values. By analysing these charts, it can be determined which scenario performs best for the different KPIs. To get an overview of all KPIs, a spider web chart is provided that supports the decision of which scenario will overall the most promising one.

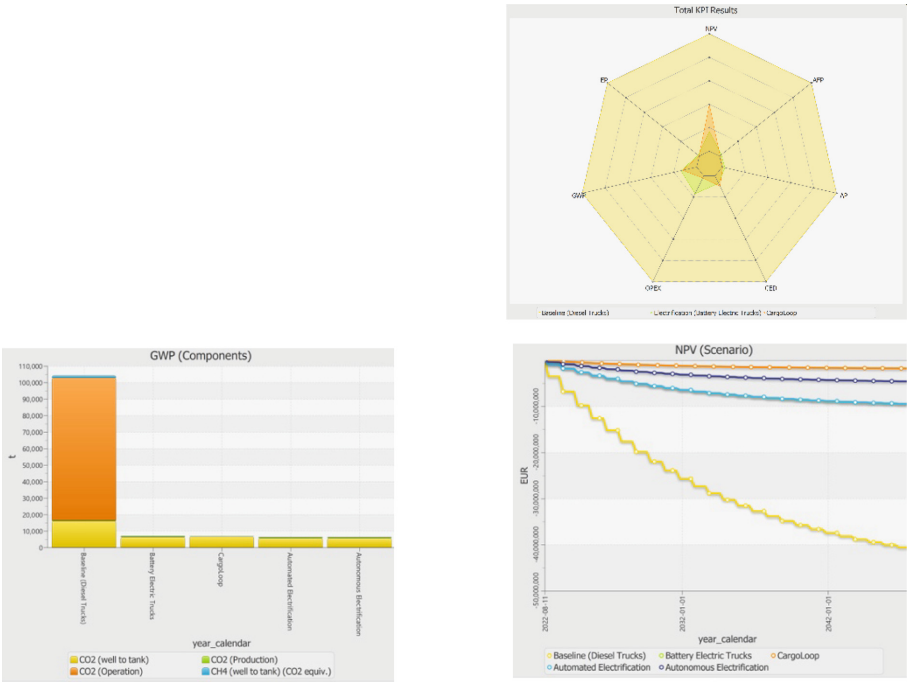


Fig. 1. Visualisations of LCPA results

3 Comparison of CargoTube and Truck-Based Solutions

3.1 Scenarios to be Considered

The hyperloop demonstrator will be compared against two alternative scenarios: The reference scenario is the transport by diesel trucks (as used today). A second scenario will be the transport by electric trucks. Although this scenario has not been realised

yet it is likely that it will materialize itself in the next few years and will therefore be the actual competition of the hyperloop. Actually, the transition has already started by ordering the first battery-electric vehicles. To extend the look into the future even further, automatized and autonomous trucks have been considered as well.

In the first step the LCPA model template has been implemented, containing the three scenarios and the input variables required to run the calculations. An example of the hyperloop scenario is shown in the following figure (Fig. 2).

All scenarios consist of two main phases, construction and operation. The construction phase will mainly cover the investment effort needed to set up the different solutions while the operation phase comprises the transport, loading, unloading and maintenance activities and the financial effort and energy consumption to perform the transportation tasks. To reduce calculation time, the different activities are bundled per year which will result in an output that will be accurate on a yearly granularity. If more detailed results will be needed, the phase durations and repetition could be adjusted. As the demonstrator evolves, the model will be refined in order to cover all necessary values. Input values for the hyperloop will be taken from the simulation module for the variables used in both models. The data for the truck scenarios will be either retrieved from the Wolfsburg GVZ or, in case it is not available or incomplete, from comparable logistics enterprises.

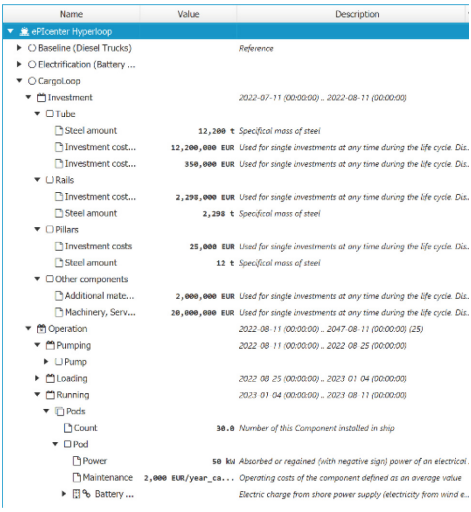


Fig. 2. LCPA model template

3.2 The LCPA Model and the Input Data

In autumn 2022 around 1,000 trucks/day delivered goods to the VW plant, a number still oppressed by the parts shortage. There are approx. 130 unloading points in the VW factory, with Hall 55 having the most incoming units. Therefore, the LCPA model is based on the assumption that the transport is carried out as a 1:1 connection between the logistics center and Hall 55. The following basic data characterize the current logistics processes in Hall 55:

- An average of 78 loading units (LU) per truck across all load carrier units
- Capacity/utilization of Hall 55 about truck deliveries: peak 140–150 trucks per day. An average of around 100 trucks/day in recent years.
- Further, the ePIcenter team was able to examine various location options for a possible logistics service park (LSP) in the "Wolfsburg-Heinenkamp" urban area. The LSP could be the starting point for supply chains using a hyperloop tube.
- Around 12,600 boxes must be transported each day.

- The CargoTube system is expected to have two tubes of a length of 12 km, one tube for each direction. The minimal inner diameter of the tube needs to be 1.65 m resulting in around 14,000 t of steel and 12,000 t of concrete for the floor inside the tube. Further steel and concrete are needed for the rail system and the pillars.
- The total volume within the two tubes is around 45,000 m3. The time for tube evacuation down to 10 mbar is around 3 days.
- Assuming a repressure time and automated unloading/loading time of one minute each result in a handling time of 4.2 min including the evacuation.
- The total travel time for a pod is 5.5 min including acceleration and braking.
- In full operation, this CargoTube system can handle 36 pods simultaneously.

The compared truck scenarios assume that an amount of 15 diesel or battery electric trucks are needed to fulfil the transport requirements. These trucks are typically leased and therefore frequently replaced, thus reducing degradation and maintenance costs.

For each scenario, the investment and the operational phase were modelled. The LCPA tool supports the enabling and disabling of model parts. It therefore allows consideration of either the full lifecycle (including the investment phase) or the operation phase only. This aspect was used to compare different variations, including or excluding certain cost types such as the initial investment for the tube as well as maintenance costs for public roads used by the trucks.

Each of the three scenarios consist of two major parts, the investment phase and the operation profile. In each of these elements the determining components and their attributes are defined (costs as well as environmental parameters). In order to run selected calculations (in- or excluding the investment phase, comparing two or all three scenarios) elements might be disabled before the actual calculation is started. The current approach assumes a duration of 6 months for the investment phase followed by 25 years of operation. These values can be adapted but for comparability of results the phase lengths should be synchronised between scenarios.

3.3 Preliminary Results

First comparisons have been run based on a preliminary data set which is subject to refinements in the coming months. This first analysis already shows that the hyperloop saves cost and has less environmental impact in operation compared to the trucks that are performing these transports today. The NPV will become better after approx. 10 years while the GWP will reach the break-even after two years. Depending on the energy mix, the electric truck will be a serious competition to the CargoLoop, especially because this approach is realizable in the coming months and can be realized by successively exchanging the existing trucks. It will therefore perform better in both economic as well as environmental terms in the operational phase. This means that the comparison of the different scenarios is heavily influenced by the concept of considering the investment costs. The infrastructure for the trucks is already existent and has to a large extent realized by public investments which makes it difficult to justify the CargoLoop under solely private economic aspects. Therefore, all analyses have been carried out twice, considering the investment costs and leaving them out.

The current status of the model is that the structure for each of the three scenarios has been defined (extended by the two additional automatised/autonomous scenarios) and input data is available that is based on actual experiences (for the diesel truck) and on designs or expert assumptions.

The sample charts in Fig. 1 provide an overview of the results based on the current state of data collection.

4 Conclusion and Outlook

4.1 Status of the Project

The current status half a year before the project ends is that the LCPA model structure has been prepared and assessments with preliminary data sets have been performed. Whenever new and more detailed data can be obtained, the analysis will be updated. This is especially required when the prototype definition evolves leading to changed circumstances with respect to the amount of cargo, the realisation of the demonstrator or the current economic situation which might require fundamental changes to the planned prototype site. Therefore, final results will not become available before the end of the project in May 2024.

4.2 Next Steps Within and Beyond ePIcenter

Despite the aforementioned refinements, the LCPA model will be adjusted if necessary before the final analysis will be carried out close to the end of the ePIcenter project. These calculations will lead to a conclusion whether the CargoTube solution will provide economic or environmental advantages over the solutions using trucks.

In parallel, discussions are already ongoing with car manufacturers to identify the final location for a real-life demonstrator. Depending on the decision and the success in convincing investors or funding authorities, the realization of the demonstrator might be realistic within three to five years after the end of the ePIcenter project. Once this happens, the system will again undergo and LCPA analysis to evaluate the current system compared to the predecessor solution but to also get additional information about the precision of the LCPA models which will result in further improvements of the application.

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Full-Scale CargoTube Demonstrator Based on Hyperloop Technologies

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Abstract. CargoTube is a technological solution for transporting goods in a low-pressure tube with significantly reduced frictional resistance and minimal energy input. CargoTube is based on hyperloop technology and focuses not only on the development of the system technology, consisting of tube, guiding system and transport vehicle, but also on intermodality with other modes of transport. Freight handling plays an essential role in the efficiency and cost-effectiveness of the CargoTube system [1].

To investigate this innovative transport system, a full-scale demonstration facility with a steel tube 26 m long and 1.7 m in diameter and adapted vacuum technology is being built. The demonstrator will be used to compare different drive concepts such as linear motors or an integrated drive system within a low-pressure tube. Airlock technologies are to be developed and evaluated to enable a high throughput of the cargo. Possible technology solutions are the discharge of the pods in a segmented unloading chamber or the docking to the vehicle inside the tube via lateral pressure locks. In a further research step, concepts are developed that enable highly automated loading processes in logistics hubs.

The determined test data of all subsystems will be compared with simulation and modelling results to refine existing models and increase the accuracy of the simulations. This paves the way for extrapolation to a larger network with existing local supply chains as well as regional or national networks leading to an outlook for a European Hyperloop research infrastructure that enables research, development and certification processes.

Keywords: Hyperloop · CargoTube · transportation · infrastructure · demonstrator

1 Introduction

New transport systems such as Hyperloop or CargoTube are track-guided systems that travel in a low-pressure environment inside a tube with low energy consumption and zero emissions [2]. The technical development of tube systems, vehicles, drives and operating

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procedures is currently being worked on worldwide. Individual components have already been built in the form of prototypes and must now be used in real test environments for the next stage of development. Knowledge gained in different test systems must be evaluated in order to transfer the innovative concept for passenger and freight transport based on Hyperloop technologies into a long-term coordinated transport system. The CargoTube concept transports goods in the size of standardized Euro pallets and Euro boxes, for which a tube diameter of slightly more than 1.6 m is sufficient. A full-scale demonstrator for CargoTube is currently under construction and can generate relevant test results so that further development steps for this mode of transport are possible.

2 CargoTube Concept

Today's freight transport volume in Europe is largely carried out on standardized Euro pallets or Euro boxes and had a volume of more than 13 million tons in 2020 [3]. The CargoTube concept focuses on the transport of goods in this magnitude in order to achieve a significant reduction of transport-initiated emissions. At the same time, the substitution of road or rail transports by in a relatively small tube up to diameters of 2 m is easily realizable. This tube diameter allows a pod size to accommodate goods in pallet width with a flexible number of boxes lined up in the direction of travel. The number of boxes per pod must be determined by optimization and depends largely on the application of the system. In the case of an exclusive point-to-point connection, larger units (10 pallets) make sense; within a widespread network, smaller units (3–5 pallets) can also be bundled to enable order-related individual delivery. This size of tube requires little space and can be installed on stilts, at ground level or underground. In the case of above-ground installation, the required energy can be largely generated by the installation of solar modules. The speed is planned to be up to 300 km/h to realize simple vehicle guidance systems. Wheel/rail combinations are currently the most cost-effective solution. The drive of the pods can be installed inside the vehicle or as a linear motor in the track.

3 Design of the CargoTube Demonstrator

To validate the CargoTube concept, a demonstrator is being developed and realize at Emden/Leer University of Applied Sciences. The aim is to create a test infrastructure that enables the implementation of CargoTube in a technology-neutral way. Technical solutions from other development teams can also be examined and validated. All test results are needed for further development stages up to the realization of a commercial transport system. The focus of the investigations is on the drive concept, the vacuum technology, the airlock system and the intra-logistics for loading and unloading the pods.

3.1 Overall Design

The tube size of the demonstrator is based on the standardized delivery sizes of the steel tube industry in order to keep costs to a minimum, even for commercial applications

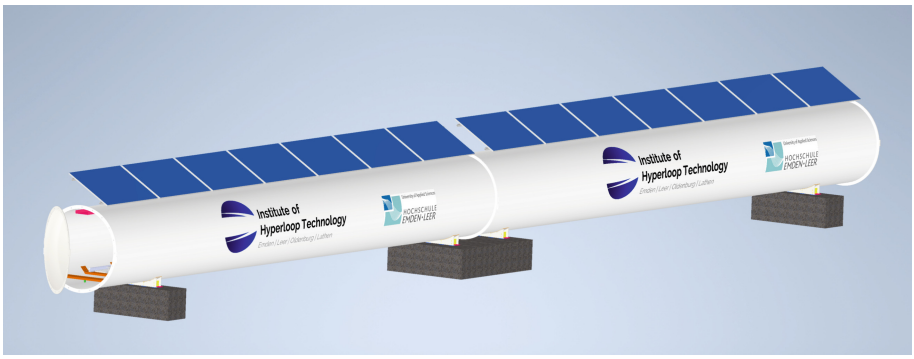


Fig. 1. Demonstrator with support structure and solar panels

[4]. Suppliers currently supply standard tubes up to 1676 mm (66 inch) in diameter with wall thicknesses up to 25 mm, which are sufficient for transporting standard pallets on a transport capsule. Since the pressure difference is a maximum of 0.1 MPa, a standard wall thickness of 14.5 mm is chosen. These tubes are sufficiently stiff to realize spans of 12 m. The demonstrator is composed of 2 tube segments, each 13 m long over flanges, and supported on three foundations as shown in Fig. 1. The middle foundation point is designed in such a way that a slide valve or experimental structural components can be inserted between the pipes at a later stage. With that two individual chambers can be created, among other things. This can then be used to test the entry and exit transfer from the main tube under different pressure situations. Relevant factors here include ventilation and evacuation times, taking into account noise emissions and the formation of condensation.

Inside the tube, a track is realized by support beams in order to place and test different drive and guide systems, see Fig. 2 left. A wheel/rail system and a linear motor will be installed in order to carry out driving tests with the experimental vehicles for operational stability, see Fig. 2 right. These include acceleration and braking tests as well as investigations on the behaviour of system components under low-pressure conditions. This also includes monitoring the operating conditions of the vehicle and the tube.

For the operation of the demonstrator, a vacuum system is used which can reach pressure ranges of down to 0.1 kPa. In particular, the operating behaviour of vacuum chambers or networks of this magnitude is of scientific and economic interest for future CargoTube applications. Furthermore, the operating procedure is being developed to optimize the logistical processes inside and outside the tube and to prepare them for commercial applications.

3.2 Motion Concept

The full-scale CargoTube demonstrator investigates different drive systems for transporting goods while minimizing energy consumption. As CargoTube is designed for low speeds and the demonstrator initially only has a length of 26 m, a vehicle concept for the wheel/rail system with its own drive is being built. The drive is provided by

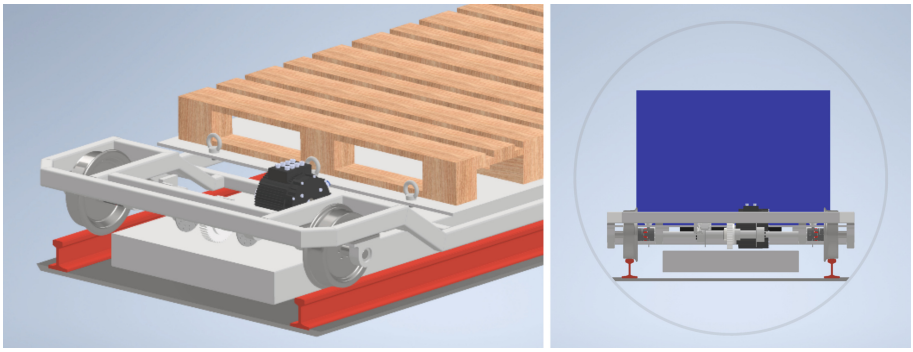


Fig. 2. Left: Self-propelled Pod platform (shell not shown) with electric engine and linear motor (schematic) between the tracks. Right: Cross section.

an axle-coupled electric motor with battery, see Fig. 2 on the left. With this, relevant characteristic data for the operation of a self-propelled pod can be determined.

In a further equipment stage, a linear motor is installed in the track, whereby the guidance of the vehicles is still provided by the wheel/rail system, see Fig. 2 right. With this system, higher acceleration values and shorter braking distances can be achieved, so that the resulting loads can also be examined in relation to the goods. For both drive systems, the problem of limited heat transfer during operation in low pressure is also being investigated and possible solutions are evaluated.

3.3 Air Locks and Handling

The fast and automated handling of goods is an argument for CargoTube. At the ends of the demonstrator tube, a locking door is initially provided, which is swung out to the side or automatically moved upwards. This allows the first handling data to be determined, which describes the loading and unloading. After the chamber has been ventilated, the pod can be moved out of the system and the load exchange is automated. The logistics processes then take place behind the tube, which corresponds to a approach for a point-to-point connection, for example to supply an industrial site through a logistics hub.

In order to minimize lock times, the pod is to be loaded and unloaded inside the vacuum tube in a further expansion stage. In this case, the pod is in the position of a docking lock without having to be ventilated. The docking lock encloses the loading hatch so that the automated loading processes can be carried out under normal pressure without ventilating the tube [5].

Handling and picking of the goods is to be automated. A Digital Twin is to be set up as part of development projects. With regard to the achievable cycle times of the lock technology used, an optimized solution can be generated by varying system elements from known automation elements (including robotics, autonomous vehicles and AI-supported pick-and-place solutions).

3.4 Vacuum System

The operation of the demonstrator and the subsequent economic operation of the transport network according to the CargoTube principle is also influenced by the vacuum system used. A system providing high volumetric gas flows leads to shorter cycle times. First of all, a vacuum must be created in the tube so that the movement of the vehicles can take place with minimal air friction resistance.

With the vacuum system installed, the pumping costs to generate the pressure level as well as to compensate for pressure losses during the locking process and for the expected leakage rates can be determined. An initial configuration is equipped with a rotary vane pump, which can realize the normal operation of a CargoTube system via a pipe system with different valves and flexible arrangement of various other components. The evacuation time and the aeration time of the 40 m^3 tube are set at 8 min each. Control and monitoring by means of a large number of sensors so that operating data is available for future system configurations.

4 Hyperloop Research and Certification Infrastructure

Due to its technical equipment and dimensions, the full-scale CargoTube demonstrator is able to determine essential parameters for the design of a transport system based on the Hyperloop principle in a scientifically proven way. The data can be used for validation in simulation software, among other things, in order to carry out economic feasibility studies. Furthermore, the demonstrator is very flexible in its design, so that system components from other developers can also be examined in the test facility. Since the Emden/Leer University of Applied Sciences operates independently of manufacturers, the test facility can also be regarded as a certification facility.

Technical testing and also the approval of system components are essential for the later operation of CargoTube/Hyperloop systems. The first draft standards are already being prepared by the European Joint Technical Committee [6]. The experience gained with the full-scale demonstrator can form the basis for a large-scale test and certification facility.

5 Conclusion

In the full-scale CargoTube demonstrator, various investigations into the operating behaviour can be carried out with experimental vehicles for the transport of goods on Euro pallets and Euro boxes. In addition, the low-pressure test environment can be used to determine the system behaviour of all components, including those from external developers, for later commercial use. Data is obtained for use in simulations and set up of a Digital Twin.

The experience gained from this test environment can serve as the basis for a future international certification centre for Hyperloop applications, where continuous operation, driving in a loop and testing of various system components should be possible. After a homologation phase on this large-scale facility, commercial operation for CargoTube and Hyperloop systems could take place, thus making a significant contribution to the low-emission and sustainable transport of goods and people.

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Benefits, Challenges, and Opportunities of the Digital Automatic Coupling

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Abstract. To combat climate change and to improve and diversify transportation across Europe, the EU has started initiatives to assist the railway industry in meeting its intended role in the modal split. The Shift2Rail and the European Rail Joint Undertaking initiatives both aim to drive innovation in the rail sector and to make transportation by train a more attractive alternative to trucks. One major innovation in the rail cargo sector is the Digital Automatic Coupling (DAC). It is set to replace the obsolete screw-couplers, which are currently used to connect freight wagons to each other, in order to improve the overall efficiency of cargo transportation by rail and to act as an enabler towards automation and digitalization.

However, while there are certainly benefits brought about with the DAC, there are challenges associated with it as well. The switch to an automatic coupling was attempted twice before in Europe, and it failed both times. Thus, a comprehensive strategy is necessary for this transition to be successful.

This paper aims to lay out the obvious benefits, the possible opportunities, and the upcoming challenges of updating European rail cargo transport to the 21st century.

Keywords: Rail · Cargo · Digitalization · DAC · Coupling

1 Introduction

In order to combat climate change and to improve and diversify transportation across Europe, the EU has started immense initiatives to help the railway industry catch up to other modes of transportation. The Shift2Rail and the Europe's Rail Joint Undertaking initiatives both aim to drive innovation in the rail sector and to make transportation by train a more attractive alternative to trucks or planes. One of these new inventions is the so-called Digital Automatic Coupler (DAC), which is set to replace the obsolete screw couplers in rail cargo transportation, to reduce freight train turnaround times and

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to reduce the risk of accidents for railroad employees, as well as to act as an enabler for new technologies. Preliminary work necessary for such a monumental task, such as first studies, tests and requirements engineering, was performed by the DAC4EU project and is being continued by Europe's Rail Joint Undertaking.

With the switch to a new coupler, it makes sense not only to upgrade wagons and make them smarter, but also to optimize parts of marshalling yards and the shunting processes. For this purpose, the Austrian national project "Digital Automated Coupling in Infrastructure Operations (DACIO)" was started in 2021, to support the efforts of the European DAC projects, to make the switch to the DAC in Austria as smooth as possible and to create new innovations to improve the shunting processes.

2 Benefits and Opportunities

2.1 Train Run

During the train run the rolling stock is moved between destinations on open tracks. Although a coupler has limited impact on this part of the operation, certain benefits can be gained even here. The FR8RAIL project of the SHIFT2RAIL project has performed and released a preliminary cost-benefit-analysis regarding the DAC. The benefits regarding the train run are in theory considerable, but their impact in practical operation seems limited. While the DAC would allow for heavier and longer trains, the infrastructure in most European countries is not capable of accommodating longer trains, and heavier trains are rarely needed. The construction of the DAC improves the force transmission between wagons, allowing for higher brake forces and reducing the risk of derailments. These are of limited relevance, however, as derailments due to the force transmission are rare. The brake forces can be improved in many countries even with the screw couplers by just adapting the current rules to more "ambitious" brake settings, which are still demonstrably safe. Furthermore, the construction of the DAC would allow for a simpler and lighter design of the frame, which would only apply to newly built wagons, and not the around 400.000 wagons currently in use across Europe [1].

Lastly, as the DAC is an enabler for new technologies, more benefits can be gained indirectly with other inventions or systems. Regarding the train run, examples for such technologies are an electric on-board power supply, an on-board integrity control and real-time monitoring of wagons and their condition [1]. Furthermore, the implementation of EP-brakes and advanced on-board controllers are currently being considered. A significant added value of DAC technology is its ability to ensure continuous train integrity control. By facilitating real-time monitoring and management of wagon connections, the DAC enhances the overall reliability and safety of rail freight operations. This can be seen as a possibility to reduce physical signaling along the train infrastructure and to get closer to a moving block system, an important element necessary for improving network capacity.

2.2 Shunting

General Description. While the exact definition of what constitutes shunting is sometimes debated, for the purposes of this work it can be described as the sorting of rolling

stock to form trains. This involves things such as coupling, decoupling, train preparation and inspection, sorting out broken or damaged wagons, etc. This is mostly done in shunting yards, which are commonly classified as either hump yards or flat yards.

DAC as an Enabler and to Ease Shunting Work. Shunting is hard, manual labor, which is performed open air, under all weather conditions and at all times of the day. It is an unattractive profession, despite things such as hazard pay, which is why there are efforts to improve the working conditions for the employees and to reduce the required manual effort. The DAC is an enormous step towards this goal, as it greatly reduces the effort and time required to decouple and completely eliminates the need for someone to recouple wagons, as it is done automatically, leading to significant time savings, as shown in [2].

Furthermore, the true potential of the DAC lies in its role as an enabler for the automation of various rail freight operations. One of the key advantages of automation is the elimination of the need for workers to physically access the wagons, thereby reducing potential safety hazards and using the capabilities of the workers in other necessary working operations. One of the main opportunities for new technologies is the automation of the brake tests, as it is currently extremely time intensive [1]. The Swiss rail freight operators have developed and tested a system for automatic brake tests in cooperation with the company PJM, which has shown great promise already [3]. The use of the DAC would allow for this system to directly communicate to the drivers cab reliably using the data line, as an example. Other functions, both wagon based and infrastructure based, are now easily feasible, as the DAC provides a standardized physical and electrical interface to the outside. The impact of automation elements, such as the automatic brake test, centralized electrical control of braking devices in wagons, and streamlined train and shunting preparation procedures on the overall operation of a marshalling yard was considered in [4].

Rail Vehicle Based Improvements. As already mentioned, one important improvement expected from a train equipped with a DAC would be automatically coupled electrical and bus systems, thereby enabling the use of electropneumatic brakes even in Single Wagon Load operations, where the train configuration changes very frequently. Depending on the route and weight of the train, this may yield measurable gains in average travel speed which in turn could help to gain capacity, critical if European transport modal shift objectives are to be met.

Currently, shunting in yards has to be done by driving on sight, which is not possible for the locomotive driver when pushing a train, therefore requiring a head shunter at the front communicating with the driver via radio. Since the reduction of manual effort during shunting operations is an overarching objective, a type of perception system at the front of the train, integrated into or attached to the DAC, could allow the driver to work in a single person operation while maintaining the driving on sight principle.

Another time-consuming task of vehicle sorting and preparation is securing consists without locomotives, which requires staff to either manually operate parking brakes or to place a requisite number of brake shoes to prevent wagons from unintentionally rolling away. A remote or locomotive initialized parking brake, able to provide the necessary braking force even with empty brake air pressure lines and reservoirs, would drastically reduce the required time and manual effort during shunting.

The automatic brake test is another element of on-board technology that can yield not only significant improvements in safety, but will contribute to less time being spent doing this preparatory step as it may be performed from a single location.

Infrastructure Based Improvements. Although an automatic decoupler for screw couplers was already developed in [5], the DAC provides the opportunity for a simpler infrastructure system to autonomously decouple. Braking the first wagon of a new train to a standstill and filling the brake reservoirs after the hump are two more tasks that are done manually nowadays. A system installed in the tracks, which can perform both of these tasks autonomously, is now feasible with the automatic coupling of the brake lines with the DAC, as is establishing a connection to the wagon controller for e.g. an automatic brake test. It can also act as a parking brake, eliminating the need for staff to secure wagons with braking shoes or hand brakes.

3 Challenges

3.1 Previous Attempts of Introducing an Automatic Coupler

Introducing an automatic coupler to Europe was attempted twice before, first starting in the 1950s and again in the 1990s. Both attempts failed as the operational benefits and cost savings ultimately did not outweigh the costs of the new couplers for the operators. Issues that increased the costs, such as lacking winter capabilities and tensile strength of the coupler, kept appearing during field tests, of which there have not been enough with the DAC so far [6, 7]. Today, as there is a more urgent need to improve our railways, the EU seems willing to provide subsidies to help with the financing. Field tests are also underway, albeit slowly, with many issues, such as the currently lacking reliability of the couplers, still partly outstanding.

3.2 Migration

In summary, the challenge in migrating from the prevailing screw coupler to the DAC configuration is characterized by a fundamental incompatibility, underscoring the need for a dual-focused strategy aimed at cost-efficiency and the acceleration of migration. These strategies can be delineated into simultaneous migration, characterized by synchronized vehicle modifications, and progressive migration, which unfolds over an extended temporal horizon. [8, 9].

Historical Examples. Other countries which have already made the switch to automatic coupler systems offer diverse examples for migration strategies, with the USA opting for progressive migration amidst a proliferation of coupler designs, Japan implementing a simultaneous migration with meticulous preparation, and the USSR employing a progressive approach coupled with the concurrent use of different coupling mechanisms to facilitate the transition [8].

Plan in Europe. A case study by the University of Technology of Dresden found that neither a mixed migration strategy, where trains would comprise of both DAC-

and Screw Coupler (SC)-wagons, nor a single-mode migration, where trains would consist exclusively of wagons of a single coupler type, could allow the marshalling yard to accommodate the transition effectively. This emphasizes the imperative need for a meticulously coordinated management strategy [10].

Building upon the insights garnered from the aforementioned study, the European project DACcelerate introduced a more nuanced approach to wagon fleet migration. They delineated the wagon fleet into two distinct categories: the "Core Wagonload System" (CWS) and the non-CWS. The non-CWS primarily consists of wagons transported via unit trains, which typically entail minimal or no coupling procedures during transportation. As a result, migrating this subset on a case-by-case basis, contingent on factors such as the type of goods being transported, was found to pose relatively minor planning and operational challenges. Conversely, the migration of the CWS was structured as a hybrid approach combining elements of progressive and simultaneous migration. About 55% of the wagons would be prepared over years and then converted in a "Big Bang" operation, while 35% of the wagons would be converted in pairs, with one side of each wagon maintaining a SC and the other receiving a DAC, facilitating coupling compatibility with other wagons, and being fully migrated slowly over time. The remaining 10% of the wagons would be exchanged with already migrated wagons from the non-CWS category [11].

In conclusion, the migration strategies elucidated in this scientific context encompass a nuanced and comprehensive approach to facilitate the transition to DAC, drawing upon extensive research and operational considerations.

3.3 Others

Other issues, such as financing, different stakeholders and interests, the politics of a European wide solution, certification of wagons and locomotives, and others, are still partly open as well. However, we leave these to their respective experts.

4 Conclusion

In conclusion, DAC technology's application in the rail freight industry offers a promising avenue for optimizing safety, efficiency, and employee well-being. Its enabler function, by minimizing manual interventions and enabling advanced control and monitoring, positions the DAC as a transformative force in modern rail freight transport. Further research and implementation efforts in this field hold great potential for revolutionizing the industry and ensuring its sustained growth and safety. While some issues are still left unresolved, there are many reputable institutions and talented individuals currently working on those. If we want to keep the rail competitive, however, new innovations are simply necessary, and the DAC is not only one of those, but allows many others to be developed.

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Comparative Analysis of City-Specific Light Freight EV Applications in Asia, Africa and Latin America

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Abstract. The paper compares selected financial, environmental and social aspects pertaining to eight light freight electric vehicles that the SOLUTIONplus project designed and tested in developing countries. They range from e-3W & 4W in Kathmandu, e-quadricycles in Pasig, e-cargo bikes in Quito and Montevideo, and e-bikes in Dar es Salaam. All prototypes are co-developed by local manufacturers and aim to replace traditional vehicles powered by fossil fuels, while considering local conditions and priorities. They have proven a good solution for last-mile urban deliveries, due to their flexibility, small dimensions and low investment requirements. All vehicles tested exhibit a healthy return on investment. However, the lighter vehicles such as the e-bikes and e-cargo bikes appear very sensitive to demand forecasts requiring a well-functioning distribution network and integration services leading towards collaborative business models. Conversions of existing vehicles are generally profitable albeit at lower return rates. In general, the old fossil-fuel-driven solutions are also profitable depriving operators of running vehicles from sufficient motivation to convert. As such, conversions at scale can be expected only at the end of the useful lives of existing vehicles. Cities need proper infrastructure planning, supporting regulations and policies for manufacturing, and awareness raising among drivers.

Keywords: e-Mobility · Urban Freight · Developing Countries

1 Introduction

Despite its vital role in meeting the daily needs of more than 55% of the global population that lives in cities today [1], urban freight transportation is associated with significant externalities, such as adding to the traffic congestion, conflicting with other road users (often due to limited parking and (un-) loading facilities) and significant air quality, noise

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and road safety issues [2, 3]. The frequent land use conflicts and inadequate regulation, maintenance and management of the vehicle stock and road infrastructure in developing countries aggravate these problems. Light-duty electric freight vehicles (LEFVs) offer a potential solution to these challenges, particularly those concerning the environmental implications of last-mile urban delivery services [4, 5].

The EU-funded SOLUTIONSplus project [6], which aims at kick starting urban e-mobility in developing countries, has included eight LEFV demonstration activities in Asia, Africa and Latin America. All these prototypes, which consider local conditions and priorities and are co-developed by local manufacturers, will be examined here:

- *Remodeled Safa tempo for cargo (Kathmandu).* Safa tempos are electric 3Ws built in late 1990s for passenger transport. A remodeled Safa tempo demonstrates the possibility of expanding the vehicle's utility to freight transport while replacing a conventional ICE petrol-powered truck, such as the popular Tata Ace pickup.
- *New e-3W cargo design (Kathmandu).* Designed as an alternative to the petrol-powered pickup truck, provides access to the secondary and tertiary narrow streets of the city in a carbon-free manner.
- *New e-4W design for waste collection (Kathmandu).* Currently, Lalitpur Municipality uses petrol-powered 3Ws with open trunks to collect waste, subsequently transferring it to larger containers for disposal. The new e-4W prototype is a closed design that will offer improved hygiene and environment-friendly services.
- *Converted pickup truck (Kathmandu).* Aims to replace the widely used petrol-powered pickup truck, while enhancing the efficiency of cargo services.
- *E-quadricycle (Pasig).* Powered by high quality electric motors and second-life batteries from Europe, this novel shared multi-purpose EV aims to replace existing ICE-powered all-purpose vehicles.
- *E-bike (Dar es Salaam).* Pedal-assist electric bicycles aimed at replacing ICE-powered motorcycles for the delivery of medical supplies to a local hospital among other uses.
- *E-cargo bike (Quito).* Aligned with the vision of a pedestrian-friendly low-emission zone in the historic center of Quito, e-cargo bikes were tested as replacements for motorcycles (courier services), cars (restaurant) and manual carts (recycling associations and stevedores from a local market).
- *E-cargo bike (Montevideo).* E-cargo bikes of two different configurations (a 2W and a 3W option) were tested through a platform (mobile app) as replacements of common bicycles without pedal assistance.

The project has developed an impact assessment methodology that combines the classic financial cost-benefit analysis (CBA) with multi-criteria decision analysis (MCDA) techniques to investigate potential effects on all sustainability pillars.

The 34 Level-3 key performance indicators (KPIs) of the project's assessment methodology form 20 Level-2 families and 6 Level-1 categories. The weights assigned by the stakeholders to the Level-1 KPIs in the five demo cities of interest in this paper appear in Table 1. They resulted from a 2-round Delphi method application involving 10–20 knowledgeable individuals from all stakeholder groups in each city, thus, reflecting the corresponding stakeholder priorities.

On average, project finances hold the top position with a share of 18.87%. This is more profound in Kathmandu, where the financial performance of the project attracts

the highest stakeholder interest among all demo cities (23.44%). Hence, the financial assessment of the project LEFVs will be given the highest attention in this analysis.

Table 1. KPI weights for the demo cities (stakeholders' input)

	Kath	Pasig	Dar	Quito	Mont	*Avg.*
Project finances	23.44	17.75	16.00	18.35	18.82	*18.87*
Institutional framework	17.65	15.09	14.30	15.21	16.43	*15.74*
GHG emissions	13.19	17.25	16.20	16.65	16.40	*15.94*
Environment	15.46	19.88	16.90	18.63	16.55	*17.49*
Society	13.81	14.15	18.30	17.32	18.03	*16.32*
Wider economy	16.44	15.87	18.30	13.84	13.77	*15.64*
Total	*100.00*	*100.00*	*100.00*	*100.00*	*100.00*	*100.00*

Preliminary results of the project focusing on the financial assessment of the solutions examined are presented in the next section. Section 3 discusses specific environmental and social attributes of interest to the local communities. Identified conditions enabling the vehicles' effective operation are discussed in Sect. 4, which also concludes.

2 Financial Analysis

The financial performance of the project vehicles is assessed either through the Net Present Value (NPV), Internal Rate of Return (IRR), and payback period for revenue-earning operations, or the Cost Effectiveness Ratio (CER) otherwise. Due to the size limitations of this paper, it was decided to restrict the analysis to IRR. Furthermore, and in order to exclude tax-related effects, the discussion is based on before-tax returns. The expected IRRs for six project vehicles are shown in Fig. 1. They denote returns on investment associated with the acquisition of the demo vehicle exclusively through own funds, and its operation according to an operational profile typical for the vehicle type examined in the corresponding demo city. Two more vehicles will be assessed through the CER approach.

Due to the iterative design process followed, all vehicles exhibit a healthy financial performance, reaching the extraordinary rate of 181.9% for the Dar e-bike. It is worth noting, however, that the very high returns of the African and Latin American vehicles are associated with 2W and 3W pedal-assist e-bikes of very low capital expenditures, which tend to be very sensitive to demand projections.

The Dar e-bike costs about € 770 ($ 820) and its Fig. 1 performance assumes an average of 9.7 daily deliveries, which is the current production of an ICE motorcycle used by the targeted hospital. This can only be achieved if the customer base is expanded, a digital order/fleet management system is introduced, and the e-bikes are equipped with a second battery to be swapped during the day. In the absence of this second battery, only 6 daily deliveries are possible, and the IRR drops dramatically to -1.1%.

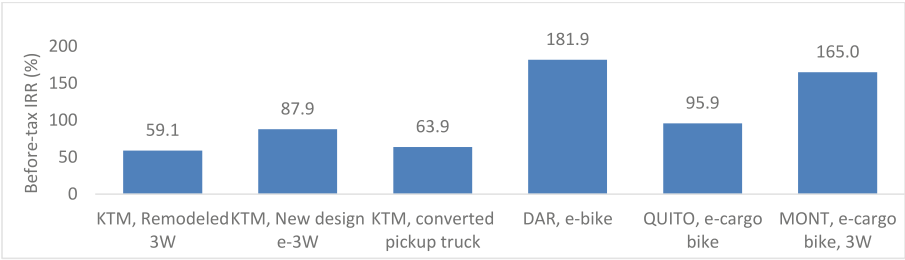


Fig. 1. Before-tax IRR (%) – Investor's perspective

At a cost of € 3,090 ($ 3,300), the performance of the 3W e-cargo bike of Montevideo is equally impressive. Furthermore, it is characterized by lower uncertainty, as it is based on an average of 9.5 trips per day, a figure supported by the trial period results, achieved through an existing delivery platform using traditional bicycles. Under a similar operational profile, the 2W version can be even more profitable due to a lower capital cost (€ 2,400). It is worth noting, however, that the productivity of the e-cargo bikes lagged 18% behind that of common bicycles due to maneuverability problems, while the cargo consolidation possibility they offer was not exploited during the trials.

With a € 2,630 ($2,800) investment, the Quito Long John e-cargo bike generates a return of 95.9% when performing 8 short trips within the historic center of the city. Other configurations tested in Quito proved much more cost effective than a petrol-run car serving a local restaurant, and also more effective than manual carts used for recycling waste due to significant increases in productivity (the project's impact assessment survey showed that the recyclers increased their monthly income by 25%).

The Kathmandu vehicles are larger. With a 10kWh LiFePO4 battery, the € 9,920 newly designed 3W offers a return of 87.9% when performing 3.5 trips/day on average. For comparison purposes, a new petrol-driven pickup truck, costing € 13,900, generates a return of 44.9% under identical operations.

A cargo 3W was also produced through remodeling an existing 'safa tempo.' Safa tempos are electric passenger 3Ws that were constructed in late 1990's and are approaching the end of their useful life. In addition to replacing the passenger cabin with a cargo platform, the remodeling included replacing the old lead-acid battery with a li-ion 23 kWh set. Over the useful life of 6 years, the required investment of € 13.720 is expected to produce a return of 59.1%. Seen from a safa tempo operator's viewpoint, however, the picture differs. Until the expiration of its license, an existing safa tempo is expected to make a pre-tax profit of NPR 1.280.000. This constitutes earnings foregone for the operator who decides to remodel their vehicle. After accounting for this additional cost, the IRR of the remodeling drops to 41.3%, which is still quite attractive.

The conversion of a 15-year old petrol-driven pickup truck, worth about € 3,170, to electric was also tested in Kathmandu. The € 13,560 total investment leads to an IRR of 63.9%. However, during the remaining 6 years of its life, this vehicle is expected to produce a NPV of about NPR 3.5 million (at a discount rate of 10%). After considering this foregone profit, the pickup operator is expected to make a further profit of NPR 737,000 before-tax on the conversion, equivalent to a 14.9% return.

In relation to non-revenue-earning operations, the design of the new e-4W waste collector in Kathmandu has been optimized to achieve 495 NPR/cu.m. of waste collected, 13.5% lower than the CER of the petrol-powered 3W currently used by the Lalitpur municipality. At 70.30 PHP/ton-km, the cost savings achieved by the Pasig e-quad against the existing ICE vehicles that move primarily medicines to/from public health facilities for the City Health Department are even more impressive (43.8%).

3 Environmental and Social Attributes

In Kathmandu, no major environmental impact is expected from the remodeled 3W, as it replaces an older e-vehicle. This is not the case, though, for the newly designed 3W and the converted truck, both of which will typically replace a petrol-driven pickup. The yearly CO_2 emissions of this vehicle for similar mileage are estimated at 5.8 tonnes on a well-to-wheel basis. The corresponding NOx and $PM_{2.5}$ emissions (on a tank-to-wheel basis) are 24.9 and 36.9 kg/year respectively. The annual emissions of the petrol-powered 3W waste collector are estimated at 2.8 tonnes of CO_2, 12.1 kg of NOx and 18.0 kg of $PM_{2.5}$. Given that almost all electricity production in Nepal is hydro-based, it can be safely assumed that the above figures constitute the emissions abated by each unit of the two vehicles under examination. In relation to societal impacts, figures have been compiled only for the remodeled safa tempo, the prototype of which has already been tested. The drivers interviewed found significant improvement in comparison to an ICE-run pickup in terms of noise and drivability, and slight improvement in accessibility, comfort and safety. The old solution was found easier to charge/refuel though. No impact on road safety was foreseen by the experts interviewed. In relation to institutional issues, the lack of technical standards for electric vehicles and the frequent rotation of public servants in Nepal hinder the promotion of e-mobility in the country.

In Pasig, the commercial ICE vehicle to be replaced by the project e-quad emits over the same mileage 0.5 tonnes of CO_2 (WtW), 1.0 kg of NOx (TtW), and less than 0.1 kg of $PM_{2.5}$ (TtW) per year. The e-quad was favored for its ease of driving and compatibility for first-/last-mile operations due to its capability to travel narrow roads. However, the e-quad scored unfavorably in terms of suitability of adverse weather conditions (battery is prone to get wet during flooding), travel comfort (lack of air-conditioning), security (parts can easily be stolen), and continuity of journey chains. In relation to institutional issues, uncertainties in alignment of the regulatory framework at the national and city levels (e.g., regarding the extent to which EV types are allowed on certain roads) hinder the promotion of e-mobility in the demo city.

The e-cargo bikes of Montevideo are tested against traditional bicycles, leading to a higher carbon footprint that depends on the carbon intensity of the grid electricity. In general, their carbon emissions are much lower than those of an ICE van (23.6 vs. 389.0 gCO_2e/km), which also applies on NOx emissions (0.066 vs. 1.794 gNO_x/km) [7]. In Quito and Dar, the project LEFVs aim to replace gasoline motorcycles, which emit 59.9 gCO_2, 0.26 gNOx and 0.1 $gPM_{2.5}$ per km [8]. The corresponding emissions of the e-bikes depend on the source of electricity generation but can be much lower, ranging from 1:5 for CO_2 to 1:40 for $PM_{2.5}$ emissions [8]. The lack of proper parking areas and bike lanes is a challenge for these lighter vehicles, particularly for e-cargo bikes

that have difficulties moving to/from the sidewalks. Security is an additional concern for these vehicles, as cargo can remain unattended while the driver delivers a package. Safety has been identified as a major concern for all electric bikes tested.

4 Conclusions

LEFVs prove a popular solution for last-mile urban deliveries, particularly in developing countries such as those of the SOLUTIONSplus project, due to their flexibility, small dimensions and low investment requirements. All vehicles tested exhibit a healthy return on investment, meaning that no financial support is required for their promotion. However, the lighter vehicles such as the e-bikes of Dar es Salaam and the e-cargo bikes of the Latin American cities appear very sensitive to demand forecasts. A well-functioning distribution network (probably supported by a digital management scheme) and integration services (exploiting the consolidation possibilities of e-cargo bikes) are necessary for the efficient operation of LEFVs, leading towards collaborative business models according to the 'broader EV uptake' approach [4]. Furthermore and in order to deploy them effectively, cities need proper planning for infrastructure (both for accommodating the rather bulky e-cargo bikes and for charging), supporting regulatory framework and policies for manufacturing (e.g., technical standards, licensing, etc.), and awareness raising among drivers.

Conversions of existing vehicles are generally profitable albeit at lower return rates. In general, however, the old fossil-fuel-driven solutions are also profitable depriving operators of running vehicles from sufficient motivation to convert. As such, conversions at scale can be expected only at the end of the useful lives of existing vehicles.

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Towards Sustainable Urban Freight Transport: Insights from Data Analysis of Receiving and Shipping Behavior in a Technological Development Area in Berlin

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Abstract. The development of sustainable urban logistics is a pressing challenge in the face of increasing freight transport and environmental impacts. In this context, the research question arises as to how freight transport in urban development areas can be made more sustainable. Data on the receiving and shipping behavior of companies can make an important contribution to the development of sustainable freight transport concepts by providing insights into the actual requirements and patterns of companies. For this purpose, a primary data collection was conducted focusing on the delivery and shipping behavior of companies in Berlin-Adlershof, a technological development area. The data analysis indicates that the receiving and shipping behavior in the area is very heterogeneous, but parcel deliveries dominate. These findings serve as a basis for analyzing potential measures to reduce the local environmental impact of freight transport. The data provide an initial overview and hold the potential for further studies to collect additional significant determinants. This can drive holistic planning and the implementation of environment-friendly measures to increase the efficiency of freight transport in urban areas.

Keywords: urban freight demand · sustainable freight transport · primary data collection

1 Motivation

Sustainable urban logistics is an urgent concern due to rising freight transport and associated environmental impacts like carbon emissions, air pollution, and noise in cities [1]. Urban and interurban freight contribute to 29% of all CO_2 emissions in transport [2]. Nonetheless, freight transport is crucial for the functioning of a city, even though it constitutes only 20–30% of urban transport [3]. As freight volumes are expected to grow, we need effective measures to manage urban freight transport sustainably. The research question here is how to make freight transport in urban areas more sustainable and reduce negative externalities of logistics activities while ensuring area-wide coverage. This should consider the unique characteristics of each city. In the presented research

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project, we focused on the shipping and receiving behavior of companies in a specific area of Berlin to derive and develop a sustainable logistics concept based on the requirements of the local businesses. For this reason, we carried out a primary data collection to collect these requirements as well as sustainable challenges and environmental strategies of companies. The study was commissioned by WISTA Management GmbH (WISTA), the site developer of the study area, which intends to develop the area sustainably and implement CO2-reducing measures.

2 State of the Art

Numerous national and international studies have explored urban freight demand and parcel delivery to private customers. However, only a limited number of studies focus on corporate shipping and receiving patterns, despite the substantial share of total parcel volumes attributed to B2B transactions. For example, Thaller et al. [4] investigated the delivery and shipping behavior of companies which are mainly delivered by courier, express and parcel (CEP) service providers (e.g. small retailers, gastronomy, services, administration and research) in a representative empirical study for Berlin, Germany. They discovered a correlation between storage area size and delivery frequency, with most companies preferring parcel carriers. In a further study of Hettich et al. [5], companies from other economic sectors (e.g. wholesale, gastronomy, manufacturing sector) were interviewed in Berlin. They found that retailers generate the majority of deliveries, primarily using smaller vehicles for transporting many smaller consignments. Barthelmes et al. [6] also provided an overview of the in- and outgoing parcel volumes of urban companies delivered by CEP services in the framework of the case study Karlsruhe, Germany. Sanchez-Diaz [7] quantified freight transport trips and ordering behavior across sectors, highlighting the retail sector's dominance in generating freight trips for non-perishable goods. A study in Melbourne, Australia, employed semi-structured interviews and online surveys to examine the delivery trips and vehicle types of carriers delivering light parcels to inner-city businesses [8]. Tozzi et al. [9] and Aljohani et al. [10] revealed among others, that a significant volume of parcels delivered by freight carriers consists of parcels below 30 kg, emphasizing their commonality. In a literature review, Silva et al. [11] categorized sustainable last-mile urban logistics solutions into three types: vehicle, operational, and organizational solutions.

3 Research Design of the Empirical Study

In close cooperation with the WISTA, a primary data collection was prepared to investigate the shipping and receiving behavior of companies in the investigation area Berlin-Adlershof, Germany. In this area, small- to medium-sized companies of the sectors service companies, research and development (R&D), and IT & telecommunications are located. The total population considered is 1,045 companies in this study area. 628 contact addresses of these companies were available, which were contacted directly via email. As we focused on goods, companies that only receive mail were identified through a filter question and not considered further. An online survey was conducted in autumn 2022. In total, 84 fully completed responses were collected from companies. Based on

the direct contacts, this corresponds to a response rate of 13.5% (net of companies contacted) or 7.9% if the entire area is considered. The developed questionnaire consists of three sections. Part 1 dealt with freight demand behavior differentiated according to receiving and shipping, while part 2 focused on company and site-specific questions, and part 3 addressed company requirements and expectations for site development. The questionnaire contained hinge questions to the empirical studies of Thaller et al. [4] as well as Hettich et al. [5] so that results can be easily compared.

4 Empirical Findings

In the following chapter, selected results of the primary data collection will be presented and discussed in detail. According to the structure of the local companies, the majority of the participating companies (25%) could be assigned to the sector R&D, while the remaining were from manufacturing (23%), other industries (17%) (e.g., services, construction, transportation, warehousing) and IT & communications (9%). Science & education and media & film were represented with 5% each. The remaining companies can be associated as wholesale, retail, and health sectors were the least represented with 3–4% each. The majority of the companies are small- and medium-sized, with the local representatives usually having no more than 1–9 employees at the location.

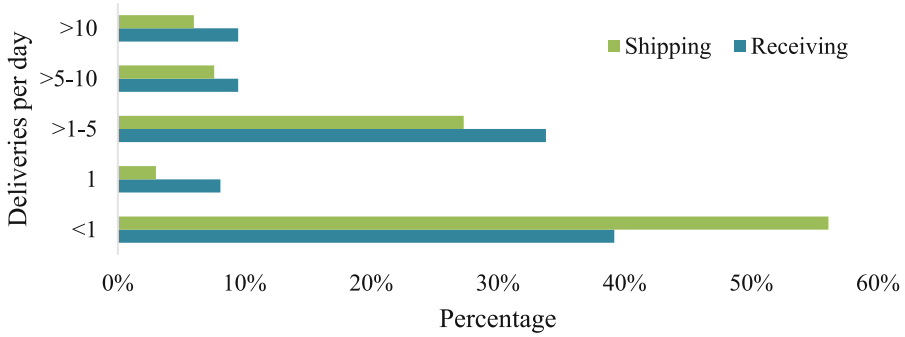


Fig. 1. Number of deliveries per day, n = 80 (own diagram)

Fifty percent of the companies possess on-site storage space, with an average size between 1 to 50 m^2. The evaluation of the data shows that the majority of the companies surveyed receive daily deliveries (61%), whereby approximately 54% receive more than one delivery per day. In terms of outgoing shipments, more than half of companies ship less than once a day. Almost 41% of the companies ship more than one delivery per day. (see Fig. 1). About half of the companies expect a rise in the number of consignments in the next 10 years. In the survey, we asked about the different types of consignments which are delivered to and shipped from the companies. Parcels are the most common type of consignment, both in terms of receiving and shipping, followed by pallets with a lower proportion. Other types of consignments, such as containers, roll containers, general cargo, or truck loads, are in lower demand. Larger companies typically demand

larger types of consignments. Parcel service providers are responsible for the majority of incoming and outgoing parcels, while for other consignment types such as pallets or larger consignment sizes, freight carriers take over the transport.

The majority of consignments, both received (74.1%) and shipped consignments (65.3%) in Berlin-Adlershof are delivered by means of delivery vans up to 3.5 tons permissible total weight (ptw). 22% of the received consignments are delivered to and 15% of the shipped consignments are shipped from the companies' sites by trucks larger than 3.5 tons ptw. Figure 2 illustrates the time window for in- and outgoing deliveries of the companies of an average business day. The graph reveals that the majority of received deliveries occur between 9 am and 3 pm, whereas for outgoing shipments, a significant proportion takes place from 12 am to 4 pm.

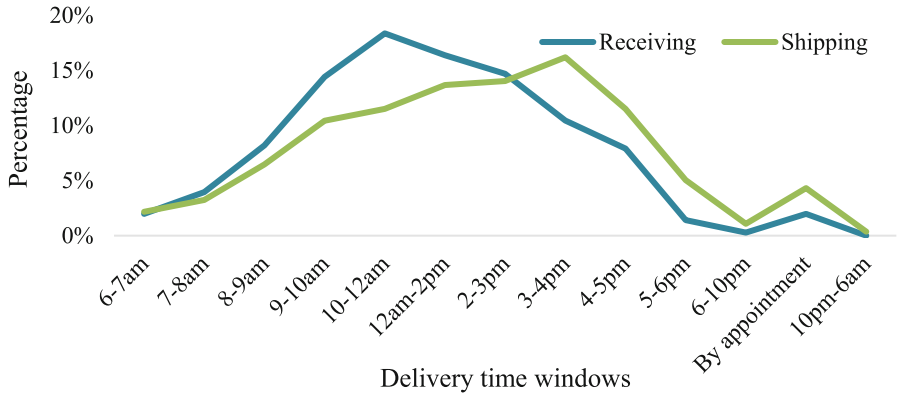


Fig. 2. Selected time window for deliveries and shipments, n = 80 (own diagram)

5 Discussion and Recommendations

Urban logistics is complex, and solutions cannot be universally applied due to the unique characteristics of each city or area. Our study aimed to identify key determinants that can be applied to other research efforts by involving a systemic approach. Thereby the first step is to clearly define the research objective. In a next step, a literature review forms the basis for understanding what is already known about the topic and which parameters can be consulted in order to specifically analyze the emergence and characteristics of freight transport in an area. Parameters such as shipment type, frequency, delivery time windows, type of business, company size and store size were identified to explain freight demand of companies. Data collection and analysis form the next steps. The diverse composition of participating companies, including those in research and development, highlights the need to consider specific industry requirements in urban settings. Our survey of companies provided valuable insights into urban commercial freight demand. The cityscape is predominantly composed of small- and medium-sized businesses, resulting in a diverse shipment volume, with parcels weighing less than 30 kg being the most

common. Companies receive multiple daily deliveries using vehicles under 3.5 tons ptw, primarily relying on internal combustion engines. This presents an opportunity for shipment bundling, optimizing delivery routes and times to alleviate congestion during peak hours. Additionally, adopting alternative propulsion technologies like electric vehicles or cargo bikes offers the potential to reduce environmental impacts. Considering the growing e-commerce trend, an increase is also expected among the respondents over the next ten years.

6 Conclusion and Outlook

In conclusion, this study examined the intricate relationship between urban development and sustainable freight transport. It underscored the crucial need to address the complexities of freight transport as cities worldwide strive for sustainability. Tailored solutions are essential, considering each urban area's unique characteristics. The research objective was to ascertain the local characteristics that underpin efficient and sustainable freight transport in the investigation area Berlin-Adlershof. By conducting a primary data collection, we gained valuable insights into the shipping and receiving behavior of companies for this urban development zone, forming the foundation for a sustainable freight transport strategy for this area. These results not only offer local solutions but also contribute to the broader urban sustainability discourse. Specific recommendations for action in the study area include bundling shipments and optimizing delivery routes with a focus on shifting deliveries and shipments to and from customers to other time windows to reduce congestion during peak hours. Further logistics measure would be to integrate loading zones for specific time windows to avoid parking freight transport in second row. In addition, the logistics service providers should use climate-neutral vehicle technologies for their transports. Identifying key parameters and recognizing size-dependent transport trends provides transferable knowledge for other cities facing similar challenges. We acknowledge the diversity of urban landscapes; wherein smaller companies may prefer smaller consignments while industrial hubs demand larger deliveries facilitated by larger vehicles. This understanding informs decision-making and targeted policies to mitigate environmental and traffic impacts. In essence, this study emphasizes the pivotal role of data-driven research in shaping sustainable urban development. It provides valuable insights for tailored solutions that enhance the environmental and economic well-being of urban communities. By involving local companies, we promote collaboration and ensure that sustainable urban freight transport is a shared and inclusive endeavor.

To gain more in-depth insights and draw precise conclusions, further information is needed. In-depth interviews or workshops with local stakeholders would be valuable to understand shipment flows and business needs. These conversations could also address challenges with large, less bundleable shipments, exploring organizational possibilities and alternative delivery concepts. Survey results already indicate an openness to new approaches. The willingness for new approaches was already evident in the results of the survey section, which asked about conceivable alternative concepts. With the help of the results, suitable measures that have the potential to reduce traffic-related problems in urban areas will be identified and discussed with the local companies and other relevant stakeholders involved (e.g. policy, logistics service providers) in a next step. Based

on these findings, measures to mitigate urban traffic issues like peak-hour congestion, limited parking, noise pollution, and GHG emissions will be identified. The goal is to reclaim public space for cycling, walking, public transport, and the environment.

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The Opportunities of Using a Logistics Service Marketplace to Decrease Emissions of Transport and Logistics Industry

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Abstract. Currently transportation is responsible for 25% of total greenhouse gas emissions in Europe. This share is set to rise, as many other industries have larger incentives to reduce emissions. Thus far, a majority of companies have concentrated on their primary emissions (Scope 1) and the emissions caused by their energy use (Scope 2). Beginning in 2024, incoming EU regulations will demand that large companies report their indirect Scope 3 emissions, and they will gradually expand to include all companies operating within the EU by 2028. The fundamental aim of the regulations is to drive emissions reductions in supply chains. To tackle the challenges posed by this new legislation, this paper takes a closer look at decision-making in transport and logistics service purchasing and considers how the use of a digital marketplace that trades transport and logistics services could improve the emissions transparency in supply chains and steer companies to select less polluting service alternatives. Finally, the paper determines the characteristics for such a marketplace.

Keywords: Marketplace · Logistics service provider · Scope 3 emissions · Sustainable supply chain management · Sustainable transport

1 Introduction and Objectives

Currently transportation is responsible for 25% of total greenhouse gas emissions in Europe. This share is set to rise, as many other industries have larger incentives to reduce emissions. Thus far, a majority of companies have concentrated on their primary emissions (Scope 1) and the emissions caused by their energy use (Scope 2). These are the emissions that companies are currently required to report, and due to public attention, many companies aim to decrease these emissions. However, emissions produced by the supply chain (Scope 3) have rarely been focused on by companies, because there has been no incentive to report these emissions, and many companies are not even aware of them. While firms are more focused on sustainability today, the reality in the logistics industry in general is that most purchasing decisions on transport and logistics services are primarily based on costs. Low energy and low polluting alternatives are only chosen if they do not significantly raise costs.

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Beginning in 2024, incoming EU regulations will demand that large companies report their indirect Scope 3 emissions, and they will gradually expand to include all companies operating within the EU by 2028. This will require companies to measure these emissions. Further public and regulatory pressure to motivate their reduction can also be expected. This progress should change the mindset in the logistics industry from price-driven to emissions-driven. However, the first challenge in this progress is companies' poor awareness of their Scope 3 emissions. Additionally, even if this emissions data is available, it might be too general to make well-informed decisions on emissions reduction efforts. The second challenge is that even if the responsible companies are aware of emissions in their supply chain, they have limited influence on them. IEA (2020) Third, providing sustainable logistics services might be more expensive than doing business as usual, at least in the short term. To create successful business with sustainable logistics services, those sustainable service providers should be easily available, and they should be able to reliably show the emissions produced and the energy used.

To tackle these challenges, this paper takes a closer look at decision-making in transport and logistics service purchasing and considers how the use of a digital marketplace that trades transport and logistics services could improve the emissions transparency in supply chains and steer companies to select less polluting service alternatives. Finally, the paper determines the characteristics for such a marketplace.

2 Theoretical Background

The CDP's Global Supply Chain Report (2023) indicates that upstream Scope 3 emissions are on average 11.4 times greater than Scope 1 and/or 2 emissions. In industries that mainly produce end products for the market, Scope 3 emissions can account for up to 90% of all emissions. Addressing Scope 3 emissions is therefore essential for companies to credibly commit to combating climate change (World Economic Forum (WEF) 2021).

Companies have historically been more interested in the direct environmental impacts of their own operations, paying less attention to the broader effects of their entire supply chain (CDP 2023). It is argued that decarbonizing supply chains could be a crucial factor in the fight against climate change, but this would necessitate a significant structural transformation, involving systematic emissions reduction through controlled transitions (WEF2021).

Major reasons preventing companies from committing to emissions reductions include costs and inadequate regulation. Challenges such as limited sharing of high-quality data, ambiguity surrounding Scope 3 boundaries, and conflicting procurement priorities are viewed as barriers to addressing supply chain emissions (WEF 2021). Scope 3 emissions are often approximations because their calculation relies on various methods, ranging from supplier- or site-specific approaches to average-data or spend-based calculations (Kojo 2023). Limited data transparency, low data quality, and a lack of automated data extraction tools are identified as additional barriers (Kojo 2023).

The complexity and interdependence of numerous factors within supply chains and transportation make it a formidable challenge for researchers to identify innovative

points of intervention that could accelerate a comprehensive shift toward significant decarbonization (Meadows 1997). To address this challenge, there is a growing trend in transportation research that adopts a more holistic perspective, viewing the issue through the lens of socio-technical systems change. Siren (2021) this approach recognizes the need for fundamental changes in both the social and technical structures that currently dominate transportation to align with the evolving environmental requirements (Shankar et al. 2019). Achieving substantial change in such a complex system through top-down policy interventions necessitates a robust bottom-up response (Grin et al. 2010).

From a technical perspective, digital platforms have been one growing solution to engage more closely with different kinds of stakeholders in value chains, business networks, and ecosystems (Shree et al. 2021). A digital platform is an infrastructure supporting interactions and defining governance conditions for the digital ecosystem stakeholders (Hein et al. 2020). Platform ecosystems have been studied extensively, but the understanding of their emergence has received less attention (Pussinen et al. 2023; Valkokari et al. 2022). Our research aims to take the longitudinal approach by observing and understanding the emergence of the ADMIRAL marketplace ecosystem.

3 Methodology

The empirical research design is based on a qualitative case study of a software company, Awake.AI, that is developing a digital marketplace for emissions-aware logistics services in the EU co-funded project ADMIRAL. Awake.AI was founded in 2018 to develop a software platform for digitizing ports and enabling Smart Ports to process remote controlled and autonomous maritime traffic. The project is still in its early phases, having begun in May 2023 and continuing until 2026. Thus, the findings and conclusions presented should be considered as preliminary.

The collaboration between the researchers and Awake.AI on developing the ADMIRAL marketplace has just begun. The aim of the research activities so far has been: 1) to understand the development history and current state of the company and its platform solution, and 2) to start depicting the future functionalities of the marketplace and the overall objectives and approaches for its development. The researchers (3–5 researchers, one acting as the main interviewer and the others supplementing with questions and documenting the interview) have had three focused 1-1,5-h semi-structured interviews with the Vice President of Product from Awake.AI that were documented through video recordings and meeting notes. Furthermore, there have been two project meetings where Awake.AI has presented its development plan to the whole project consortium. The interviewee has also provided researchers with some earlier platform development-related documents. A specific platform canvas was derived from several platform business model canvases to develop a framework to support the depiction of the ADMIRAL business model and analysis of the various factors affecting it.

4 Preliminary Findings - Platform Development

Initially the Awake.AI data platform with Smart Port UI (Smart Port as a Service) focused on enhancing and optimizing the ship-port-land transport part of the logistics chain, e.g., predicting of estimated time of arrival (ETA) and departure (ETD) of a vessel (Fig. 1).

In the beginning, the focus was on ports, which as core actors enable contacts with the most important stakeholders (port authorities, shipping companies, terminal operators, etc.) in terms of port operations, and other ports. The data platform solution contains a web-application and native applications for Android and iOS. In addition, multiple APIs are commercially available. The benefits of the data platform can be seen in the efficiency of operations, the elimination of surprises and delays, as well as the real-time transparency of information. For example, fuel savings are achieved by adjusting the vessel's speed according to optimal port arrival time. In terms of platform development, it has been important to produce functionalities that are easy to deploy and from which users immediately gain personal value.

Recently, Awake.AI has started to build the Awake.AI marketplace on top of the existing data platform. The business logic and scaling of the marketplace is different from that of the data platform. The marketplace facilitates interaction between the stakeholders by enabling service buyers to find and buy items from service providers (physical and digital services and products) via one channel in the context of port and vessel. Furthermore, it enables advertising in the marketplace. Awake.AI as an operator of the marketplace provides rules and guidance to participate in the marketplace. The marketplace has a step-by-step onboarding process and user guidelines as well as an onboarding approval procedure. The Awake.AI marketplace uses Awake.AI's data platform, which provides transparency into data, such as vessel positions and ETA predictions to be utilised in the marketplace. The data platform enriches external data (e.g., weather data, vessel position data, port call data, etc.) with the help of artificial intelligence to create estimates such as vessel ETAs for the marketplace.

In the ADMIRAL project, the multimodal marketplace is built on top of the Awake.AI data platform and marketplace (Fig. 1). The goal of the ADMIRAL project is to expand the current version of the marketplace for multimodality, emissions awareness and optimizing logistics efficiency as well as scale the AI driven trading and routing to multiple logistics chains globally.

From a collaboration point of view, the ADMIRAL marketplace enables a reliable cooperation platform for emissions transparency in logistics. The marketplace connects logistics sellers and buyers, allowing them to easily find, compare, and buy emission-aware multimodal logistics - from door-to-door. The marketplace aims to provide listings of optimal logistics service chains based on a customer's transportation needs as well as facilitate emission-based decision making by providing multimodal logistics emission calculations and comparisons of different logistics chains. Furthermore, the project is also creating the capability for application developers to build their own applications on top of the marketplace platform. Developers can also take a role in where their application(s) feed in data for the marketplace. This is related to, e.g., the launch of the developer portal and other technical and cooperative practices to support participation in the marketplace.

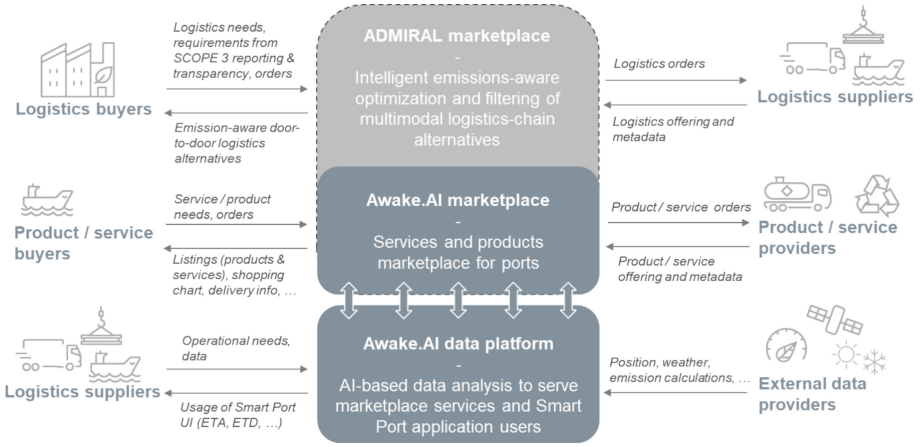


Fig. 1. ADMIRAL marketplace.

5 Conclusions

The importance of emissions reduction in business decision making is increasing, with stricter regulations being one key driver. Meeting the new landscape requirements necessitates the adaptation of technologies such as data platforms to increase transparency on emissions, in addition to social changes in current mindsets and business models. As transportation and logistics services operate in a very dispersed and interconnected business environment, driving change in the industry will be challenging. Platform-based business concepts are potential solutions to connect the stakeholders in this complex environment. The broad scope and complexity of global logistics chains means that there is a slim chance of providing a total solution for emissions-aware logistics information sharing and planning. Rather, the solution should be modular with easy to connect interfaces (APIs) to existing systems as well as new and upcoming systems. This enables the provision of good quality software solutions that are easy to deploy for different customers and can meet their varying needs.

Furthermore, from the point of view of platform ecosystems, longitudinal research on the development and emergence of new platform solutions is needed. Our case study is in its early phase and therefore the findings can only be considered as preliminary. However, the project will continue for two more years providing a unique opportunity to closely follow the development path of an emerging digital logistics platform. Moreover, it provides an opportunity to gain important insights into the complex challenges and solutions of sharing emissions data between a wide variety of logistics sector stakeholders.

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Curbside Management: A Digital Solution Space Optimisation

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Abstract. Curbside management has become a point of contention for municipalities as multiple road users, including transit, bicyclists, micromobility, shared vehicles, personal cars, city logistics and others, compete for access.

Logistics service providers (LSPs) have difficulty finding safe and legal loading and unloading spaces near delivery receivers. With tight schedules, demanding customers, congestion, heavy cargo and few delivery zones, delivery drivers tend to double park in travel lanes, making it unsafe for them and other road users and contributing to congestion and an increase in emissions. To combat this problem, EIT Urban Mobility invested in FlexCurb, a two-part digital solution to help municipalities better visualise critical curb usage data (FlexCurb Planning Platform) and to help delivery drivers find available loading zones (FlexCurb Driver App). Four cities: Funchal, Portugal, Leuven, Belgium, Strasbourg, France and Toulouse, France were chosen to pilot the FlexCurb platform, evaluating curb regulations, viewing activity patterns, and identifying allocation imbalances. The pro-cess helped cities pinpoint which data they need to gather and how to use existing data to answer complex questions about the curb. Testing and further development of the tools will continue as EIT Urban Mobility has included FlexCurb in its innovation project portfolio for a second year.

Keywords: Curbside · Urban logistics · Loading zones · Parking · Public space

List of Abbreviations

AI Artificial Intelligence
APP Application
LSP Logistics Service Providers
EIT The European Institute of Innovation and Technology.

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1 Introduction: Curb Management: A Tool to Improve Urban Logistics

The concept of curb management pertains to the urban space along the road adjacent to the sidewalk and the sidewalk itself. It serves as both the point of departure and arrival for a wide set of mobility services, constituting an intricate urban network and thus, a vital urban resource. Disruptive shifts in consumer behaviours, the exponential growth of e-commerce, emerging mobility models (including sharing mobility), instant deliveries, and the long-terms effects of the COVID-19 pandemic [1], coupled with the already substantial impact of traditional freight transport, have led to a significant surge in last-mile deliveries on one hand and increased pressure on the entire urban mobility and accessibility system on the other. This has further constrained the already limited availability of dedicated areas for delivery and pickup operations. For many years, the curb had primarily been reserved for private vehicle parking, with competition in this area mainly revolving around taxi stands and bus stops, representing the traditional mobility demand. The proliferation of the above-mentioned emerging trends, have generated new demand for curb usage, introducing new forms of competition among city users and delineating a preferential lane for the development of proximity-based delivery and pickup concepts. Thus, a shift in the management of public spaces (and even private spaces, considering temporary or shared usage for urban logistics platforms) and urban access has become urgent. Conventional users of the curb now find themselves managing conflicts with new competitors, facing the risks of operational inefficiencies and externalities. In addition to the scarcity of available urban spaces to efficiently meet all city users' mobility needs, there is the exponential growth in demand for curb usage [2, 3], whose real value, in terms of potential revenue assets (like real estate), is often inadequately recognized, significantly underestimated, or underutilised.

To address this significant challenge, tools are needed to enable public authorities to engage in a constructive dialogue with city users, based on principles of shared space, tariff hypotheses, rules, and reward criteria, while managing potential conflicts among the various parties that use the same spaces during the same hours daily. The new competition within the "curbside community" is not solely driven by the increasing urbanisation trend but also by the increasingly pressing need to create sustainable urban areas to address climate change, elevating liveability, accessibility, social equity, economic growth, and embracing the proximity principle to manage citizens' and economic operators' ever-pressing and specific mobility and supply needs. A digital and integrated vision of a city or metropolitan area would enable planners to address critical questions by adopting virtual models capable of proposing sustainable and desired "what-if" scenarios with predictive decisions based on real data. This holistic view must consider the needs of city users to make informed decisions, design governance aligned with reality, and reduce costs to mitigate real world impacts such as car crashes and air pollution.

2 Methods: The FlexCurb Solution

The FlexCurb product portfolio is aimed at addressing the needs of the most prevalent actors involved in the use of the curb. The first product, FlexCurb Planning (the "Platform"), is aimed at local authorities who need to best decide how to allocate and regulate

curb spaces to better respond to local user needs and to execute strategic mobility and logistics plans. The second product, the FlexCurb Driver App (the "App"), is aimed at urban logistics companies and drivers, who need to find the most convenient parking spaces for loading and unloading operations, while ensuring they comply with local parking regulations. The focus on urban logistics arises from the prevalent absence of digital parking solutions that cater specifically to the needs of commercial and professional drivers.

FlexCurb Planning

This Platform has been developed as a web-based tool for visual exploration and analysis of the curb. It is mainly targeted at municipal officials involved in the management and regulation of these spaces, such as mobility managers, economic development managers, curbside regulators, or active and accessible mobility managers (Fig. 1).

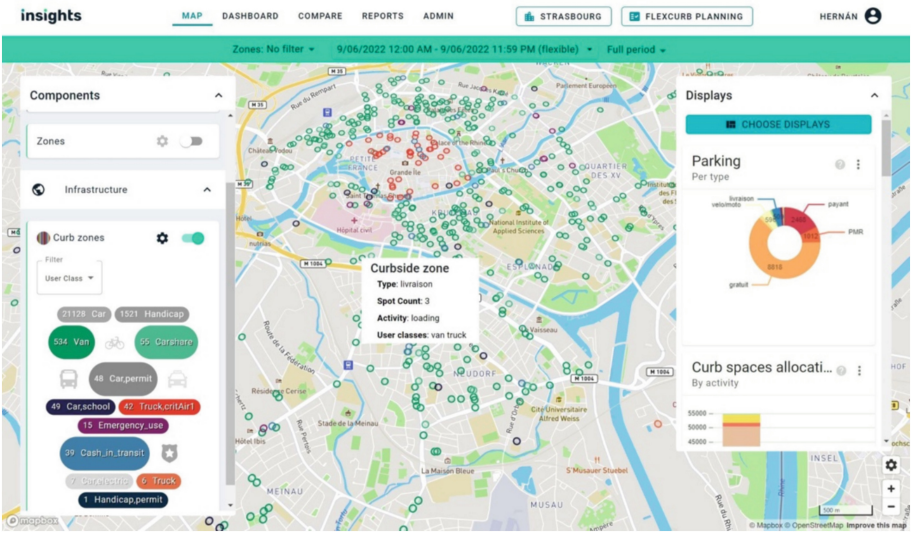


Fig. 1. Flexcurb web-based platform. Image produced upon open source content by OpenStreetMap

The Platform aggregates multiple data sources related to curbside supply and demand. On the supply side, data sources include official definitions of all parking spaces and the applicable regulations of these parking spaces. Parking regulations across testing cities were standardised using the Curb Data Specification [4] which provided a complete framework to integrate analytic outputs and compare otherwise disparate curbside regulations. The Platform offers a set of intuitive tools to perform geospatial descriptive analysis of the curb supply and its regulations. The outputs are aimed at revealing local imbalances in curb space allocation, such as excessive supply of unpaid private car parking at the expense of more efficient curb uses.

On the demand side, the Platform collects multiple data sources related to curb use. The main source being vehicle telematics data from a sample of commercial fleets which reveal historical trip and parking patterns citywide.

Overall, the FlexCurb Planning Platform has become a data-oriented tool for local government officials to better inform, prioritise, and communicate the curb allocation actions required to execute their strategic planning. By becoming a central source of curb data, cities free up analytical resources to answer common questions on how well the curb responds to users, and how different policies and regulations impact the use of this public space. Moreover, a more accessible management of complex curbside regulations opens the door to defining more nuanced regulations, catering to different needs and users by time of day and location, and defining better incentives to a more sustainable use of the curb.

FlexCurb Driver App

The App has been developed as a tool to support daily urban freight operations, mostly to help drivers more efficiently navigate and access designated spaces such as commercial loading and unloading zones. The App provides drivers with access to information about the curbside spaces they are intended to use, including their regulations and their availability. As a result, drivers spend less time cruising to find legal and available parking, reducing congestion and emissions and improving their operations (Fig. 2).

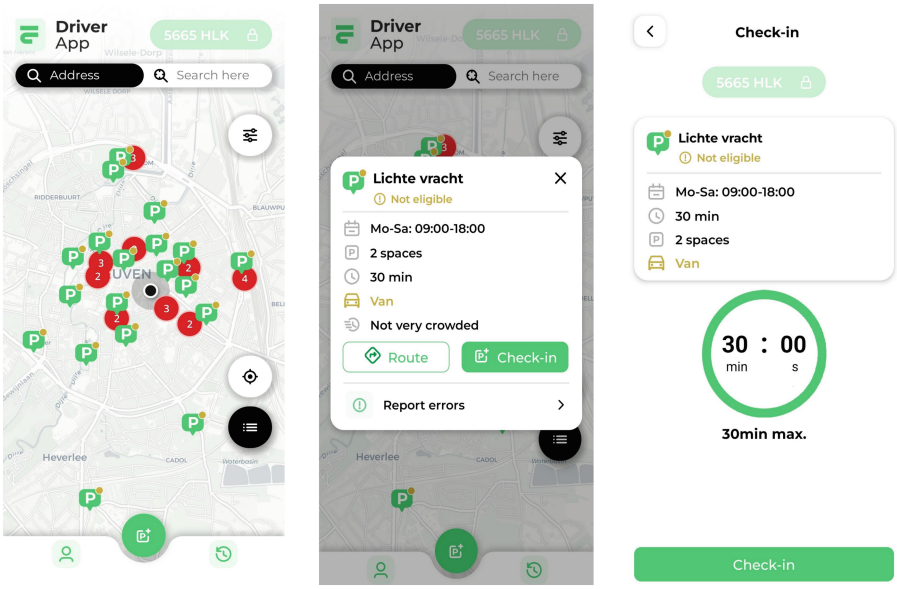


Fig. 2. Flexcurb driver app. Image produced upon open source content by OpenStreetMap

Additionally, the App is intended to be used as a method to report legal parking for logistics companies, and therefore incentivize the use of properly designated curb spaces, collect detailed activity data for cities, and if needed, enforce regulations from

the data collected through the App. By sending parking events collected from the App to a city's data portals, officials can inform policy making and regulations by learning in near real time the use of curb spaces for urban freight, as well as apply enforcement on-demand.

Specific features available on the App include search for legal parking closest to destination, parking time control according to regulations, company-based payment of parking fees, and parking selection based on spot availability. Since providing precise parking availability would require unavailable parking sensors (depending on the city), an alternative approach has been used, developing a local parking availability model from historical telematics data. Using this model, it is possible to estimate the likelihood of finding an available parking space at a given location, time of day, or day of the week. Sensor data has been used to fine tune the model, yet sensor data was limited in geographical extent during this project and more ground truth data is desirable to improve model accuracy. The model is intended to be updated regularly according to changes in parking patterns at least every season.

3 Results: Initial Piloting: Tests and Evaluations

POLIS led the relationship building with the four Living Lab pilot cities during the pilot. POLIS is the leading network of European cities and regions working together to develop innovative technologies and policies for local transport. Leuven and Toulouse are members.

Strasbourg, FR has a population of 280.000 people. Air pollution is a major concern in the city as there is a consistent flow of trucks to and from its port (the second largest river port in France). Recognizing the negative impacts of last-mile goods movement, the city is devoting employees specifically to planning for urban logistics.

Toulouse, FR has a population of approximately 1.000.000 people (in the metropolitan area). The city of Toulouse is implementing a Low Emission Zone and dedicating staff to planning for urban logistics.

Funchal, PT has a population of about 100.000. One of the biggest transport concerns is illegal parking (of both personal and commercial vehicles) at the curb. The city faces challenges with efficient enforcement measures, though a plan is currently being put into place.

Leuven, BL has a population of approximately 102.000. The city has committed to establishing a zero-emission zone for freight by 2025. An in-person meeting with the city, FlexCurb team and EIT rep was held in the fall of 2022 and included a walking tour to see where the biggest challenges are located.

FlexCurb supported a robust stakeholder engagement process for the cities to better connect with the logistics industry and provide feedback for the Platform and Driver App. This included working with Chambers of Commerce and conducting surveys and ride-alongs. Surveys asked delivery managers about their fleets, routes, goods delivered and their biggest challenges at the curb. Ride-alongs offered city employees an opportunity to sit in delivery vehicles with drivers throughout their shifts, making note of the biggest barriers for efficient and safe loading and unloading in their municipality. Because of these two feedback opportunities, the cities better understand the needs of delivery drivers and now have a closer relationship with LSPs.

Common themes in survey responses and ride-alongs included: a lack of sufficient loading/unloading zones for commercial vehicles, insufficient time to deliver to areas before limited zone rules begin for the day (i.e., pedestrianisation for a particular street), and illegal parking by non-compliant vehicles in commercial spaces.

Some cities have additional tools already in use that can be integrated into the Platform such as in ground sensors, cameras, etc., so parking sensor data was collected in limited locations. While sensor data provides high accuracy measurements of parking occupancy, their geographic extent was extremely limited, restricting occupancy analysis to a few individual parking locations. Telematics data on the other hand presented its own benefits and challenges, representing only a fraction of parking activity for commercial vehicles, but at a much wider geographical extent. Therefore, any inferences made with telematics data focused solely on the impact of commercial vehicles in public space.

4 Discussion: User Acceptance and Future Challenges

The deployment of the FlexCurb Planning Platform in the four living labs revealed product improvement opportunities including enhancements to the usability, flexibility, and overall value offered. The following insights were identified as the basis for improving the solution:

- The exploration of the curb inventory needs greater flexibility to analyse inventory subsets given user defined criteria, such as regulations details, or user defined areas.
- Curb management activities would greatly benefit from improving understanding patterns of curb usage, not just the curb regulations currently included. Therefore, adding a data layer to reveal curb activity in detail is a high priority feature to add to the FlexCurb Planning Platform.
- The Platform has limited capabilities to analyse and visualise complex curb regulations, such as those defining regulation exceptions, multiple rules, or multiple users per regulation. Nevertheless, these regulations are only a small portion of all the regulations in the living labs.
- The process of curb regulations standardisation and aggregation in the Platform currently requires the intervention of Urban Radar's data specialists, which can be inconvenient for users when regulations are updated frequently, especially since this process can imply frictions or delays.
- Some cities might prefer to use a proprietary basemap layer with updated content.

While all stakeholders involved in the design and testing of the FlexCurb Driver App agreed that this kind of technology helps for a better understanding of curb use and makes deliveries more efficient, they also agree that is only part of the solution. The LSP's are looking for more integration and links between existing systems or platforms to be developed. The more information that can be integrated in the Transport Management Systems, the more realistic the delivery rounds will be and the more they can be optimised. While in some living labs initiatives are in place to improve this understanding through on site sensors, this approach remains hard to scale. Regardless, the Driver App will be used as the main method to collect loading zones activity data, favouring this approach against sensors due to its high potential for scalability.

5 Conclusions and Next Steps

While many cities recognize the importance of urban logistics and the interest and need to advance in the topic, the approach they follow to do so is not efficient. In general terms, there is a lack of expertise in urban logistics transport within local city governments around the world. This is also the case for the living labs within this project. Each city has a different level of knowledge in the field and that expertise is often split across multiple departments, furthering the larger issue of competency siloes within a municipality.

Recognizing the importance of the curb space in cities is an ongoing process. Even though strongly related to freight issues, this importance is not limited to such. The curb is crucial in transforming the public space and in the shifts that many cities aim for in environmental, social, and economic terms. Therefore, efficiently managing the curb with reduced conflicts is essential. However, understanding all the stakeholders and the broader aspects that can impact the curb is still a challenge for cities, especially as it relates to logistics as there is limited expertise in this area.

In Addition to the lack of a curb inventory, cities have flagged their insufficient understanding of the use of the curb, including who uses it, where and when it is used. The Platform solves this problem, and the App helps delivery drivers find available loading and unloading zones (which then in turn feeds real time usage data back into the Platform).

Overall, while cities currently lack operational capacity to advance concepts of flexible curb management, the tools being tested in the FlexCurb project should become a first step to overcome the barriers precluding a more rational and dynamic use of the curb.

Disclaimer: FlexCurb is supported by EIT Urban Mobility, an initiative of the European Institute of Innovation and Technology (EIT), a body of the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Institute of Innovation and Technology. Neither the European nor the granting authority can be held responsible for them.

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Impacts of Regional Electrified Logistics on Drivers' and Transport Planners' Work Environments

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Abstract. The REEL project aims to accelerate the large-scale transition to REgional Electrified Logistics – thereby reducing freight transport emissions and noise pollution – by testing Battery Electric Trucks (BETs) for regional distribution. Over 60 regional electrified logistics flows in varying driving assignments across Sweden provide the empirical basis for the project. This paper presents initial results from an interview study with two BET stakeholder groups – drivers and transport planners at participating logistics companies. Based on employees' reflections on how the BETs affect their daily work (or not), or likely will once scaled up, findings include: ways to improve employee support in the transition to BETs (from improved planning tools to networking), varied health benefits, yet-entrenched gendered views of EVs, feelings ranging from skepticism to appreciation, and anticipation or trepidation for "the future". This study contributes empirical evidence to the very limited knowledge on and experience with BETs and, in particular, the perspectives of 'front-line workers' with BETs.

Keywords: Logistics · Electrification · Regional Transport · Battery Electric Trucks (BETs) · Drivers · Transport Planners

1 Introduction and Background

Decarbonizing the transport sector is not only important for ecological sustainability, but also for improving health impacts. One approach to tackling this challenge is electric vehicles (EVs). Although having existed for over 100 years, support for and adoption of EV technologies is gaining momentum (again) [1]. Related to battery and charging limitations, gains have, thus far, largely been achieved via personal cars, light EVs, and smaller trucks for urban logistics. However, with continued advances in vehicle and battery technologies, it is becoming possible to electrify longer-distance, heavy road transport. Accordingly, the accelerator project Regional Electrified Logistics (REEL) [2] aims to reduce freight transport emissions and noise pollution by testing Battery Electric Trucks (BETs) for regional distribution. A collaboration between the public, private, and academic sectors, the project seeks to overcome the barriers to a large-scale transition to regional electrified logistics – vehicles and charging solutions, business and financing models, work culture and skills gap, and policy, rules, and regulations. By establishing

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and driving over 60 regional electrified logistics flows in varying driving assignments across Sweden, REEL enables the empirical evaluation of real and perceived barriers to electrifying regional logistics from the perspectives of a broad range of societal and commercial stakeholders.

This paper presents results from the work package "Work Culture and Skills Gap", specifically an interview study with two different BET stakeholder groups – drivers and transport planners at participating logistics companies – to capture the 'employees' perspective'. Thus, this study contributes empirical evidence to the understandably limited knowledge on and experience with BETs and, in particular, the perspectives of 'front-line workers' with BETs. Previous existing research on 'user experiences' with BETs has typically considered the user in a broader sense, i.e. an organization, rather than the 'end-users' of BETs. Two Norwegian reports interviewed firms operating BETs and E-buses, OEMs, policy-related institutes, and government administrations, but *not* drivers or planners [3, 4]. A 2023 industry-commissioned report interviewed *two* drivers of zero-emissions trucks, one of whom was a test driver at an OEM rather than a 'typical' driver of a logistics chain out in the field [5].

2 Method

A semi-structured interview was conducted with bet drivers and transport planners from logistics companies participating in REEL. The interview guide covered themes such as: changes to a typical workday due to the use of BETs including practicalities, stress factors, perceived risks and benefits; trust for the BET and charging technologies and changes over time; new knowledge, education, skills, tools needed; and the potential effects of scaling up on one's job. In order to find interviewees, the list of participating companies was first narrowed down (with the project managers) based on a range of factors for which electrification may entail a greater effect on operations – such as transport type (restricted, temperature-controlled), route type (variable/fixed), number of shifts, utilized charging stations (own, customers', and/or public), and region of Sweden – in an attempt to ensure i) a spread across the country and ii) that all the interviewees would not work with only the 'easiest' flows to electrify. official company contacts for the REEL project were approached and, when possible, at least one driver and one transport planner per company were interviewed (see Table 1). The transport planners typically had previous experience as drivers.

3 Results and Discussion

Both employee groups, but drivers even more so, described a general trend of initial skepticism (on their own part) followed by increasing levels of conviction for the BETs. This initial skepticism was, however, not necessarily a lack of trust for the technology per se, but rather based on a pure lack of knowledge regarding the BETs' capabilities – e.g., vehicle handling and performance, battery range and the factors influencing this (weather and temperature, terrain, driving style, load, etc.), how, when, and where to charge – and how one's driving style might need to change. Several interviewees commented that humans dislike change and attributed much of the BET skepticism they had witnessed (and continue to witness within the trucking sector) to human nature.

Table 1. Overview of interviewees and the BET logistics chains and contexts

Interviewee (Org.Person-Role)	BET Logistics Chain and Context
1.1-Driver 1.2-Planner	Container, varying weight; mainly warehouse-intermodal terminal during the day; charging at warehouse
2.1-Driver 2.2-Planner	Temperature-controlled; mainly urban and periphery, day & night shifts (quiet delivery); charging at warehouse & public charging if necessary
3.1&2-Driver 3.3-Planner	Building materials; mainly urban and periphery, day; charging at home depot
4.1-Driver 4.2-Planner	Line-haul between logistics terminals; night shift; mainly motorway with hilly topography; charging at terminal at one end and public charging next to terminal at other end
5.1-Driver 5.2 Planner	Temperature-controlled; terminal to stores, day, urban-suburban; charging at terminal
6.1-Driver 6.2-Planner	Temperature-controlled; warehouse to stores, day, urban-suburban; charging at warehouse
7.1-Planner	Temperature-controlled; multiple BETs, some with fixed routes A-B, some with flexible routes based on customers' varying daily needs; charging at home depot (preferred) plus at some customers, also public charging if necessary (must charge during shifts due to longer routes)
8.1-Planner	Restricted goods (terminal-customer); two shifts; charging at home depot plus a portable charger; would like customers to install charging

This introduction of new technologies (BETs and charging infrastructure) into the workplace (also 'involuntarily' on the employees' part), particularly technologies central to one's daily work, understandably leads to many uncertainties and questions by those most directly and immediately affected. The interviewee group had experienced varying levels of formal support in this transition, from an OEM representative visiting, explaining, and riding along, to an internal 'course' offered to employees, to a general vehicle briefing (often for individual drivers), to merely being handed the keys. Although drivers who had experienced minimal support tended to 'look on the bright side' and felt that this had forced them to learn about the BET in a way they might not have with more formal support, they also reflected that it might have been beneficial with more support, e.g. to better understand, at least in theory, how the truck and battery should work. Driver 4.1 felt that it required at least three to four months of practical experience with the BET to start to 'understand' it at a level approaching one's understanding of the diesel truck (traditionally via engine noise, which was now missing). Planners often learned about the practicalities of using BETs via the drivers, although some had even tested the BET themselves and/or ridden along.

Support can also come informally, and particularly drivers expressed the usefulness of being able to bounce thoughts and questions off others, and how this opportunity

was currently limited due to the general lack of experience with BETs. In (often larger) companies with multiple employees experienced with BETs, co-workers could discuss amongst each other, but in (often smaller) companies with few or only one driver experienced with BETs, the lack of co-workers with whom to discuss became even more tangible. In some such cases, drivers had created informal networks with other BET drivers in similar situations. Multiple interviewees mentioned talking to their local authorized workshop, although it was perceived that those persons also were on the same steep learning curve. However, even if the workshop could not necessarily answer all questions, it was still good to have that opportunity to talk to them. Particular to REEL, as some trucks are prototypes, drivers sometimes had 24/7 direct access to an OEM contact, which could be viewed as a form of formal support, although informal in that this is not generally offered to all new BET drivers. Additionally, two drivers had decided to keep an informal logbook, noting various trip-related indicators, in order to build their understanding of the truck and battery performance. Driver 1.1, him/herself responsible for charging between trips and also driving variable weight loads (see Table 1), used their logbook plus feedback from another BET driver to try to understand the required charge for individual trips, particularly to be on the safe side when the weight load was unknown in advance. This driver would have appreciated more formal support in this decision making – e.g. if one could refer to a database with historic data to estimate the required charge for a trip – particularly as there are plans to utilize this BET for longer trips once charging infrastructure at the intermodal terminal is in place.

Planners considered themselves more or less affected by the introduction of BETs depending on the complexity of the BET logistics chain. These logistics companies need their business to work, so often utilized the BETs under generally opportunistic circumstances where the BETs should be able to perform well. In contexts where the BETs could drive an entire shift on one charge; trip scheduling and routing was largely fixed; and/or electricity pricing was not being taken into consideration, planners (and even drivers to some extent) felt their job had not *yet* been affected by the introduction of BETs. However, once the scheduling and routing became more variable, the trucks needed recharging during shifts, and/or differentiated pricing was considered, planners (and drivers) became more affected. The planners also utilized a wide variety of planning tools – from dynamic optimization tools with real-time truck information to analogue tools with no optimization – and these tools largely did not consider BET-related factors, e.g. charging locations and times. Submitting 'fake orders' to factor in charging time was one work-around mentioned. One planner whose BET utilized a range of charging stations lamented the fact that one could not input the geo-locations of charging stations into their planning system. Several mentioned that their organizations were looking to procure and/or develop new, updated tools which could handle EV-related factors, while others reflected that such updated tools would ultimately be needed as the use of BETs scales up – although a certain amount of manual effort would always be required to deal with last-minute changes, problems, and customers' preferences. For example, Planner 8.1 discussed how certain customers, particularly smaller ones, did not utilize digitized systems, let alone systems compatible with their own, and how some customers still preferred to telephone in their orders, both of which necessitate a greater amount of manual effort on the planners' part.

Likely the most promoted general benefits of EVs are reduced noise and emissions, (although the reduced engine noise is mainly beneficial at low speeds). Some drivers did mention the benefit of quiet engines, although some did not until probed; they attributed this to the quietness becoming a background factor over time, i.e. something one gets used to and forgets. However, at the beginning, the quiet engine was something strange and even disturbing, as this was the main way one had previously 'understood' the truck. With a BET, one heard all the *other* noises instead, which took getting used to, although this also meant that one could listen to music or have a conversation with a passenger at lower volumes. This more short-term perspective of personal benefit was typical, i.e. only the minority reflected further on the long-term consequences of the quiet engine unless probed. Those who did (without probing) mentioned driving more calmly and feeling less tired after a shift; they had previously not understood how much the background engine noise affected their mood and energy levels. Also, that their hearing would not become damaged over time, or would not have had they been driving a BET over the years. Similarly, only one reflected upon the personal, long-term health consequences of lower exposure to emissions, while the majority, when bringing up emissions, discussed it in terms of general societal benefit. The one driver who did reflect upon this lower personal exposure to emissions (without probing) was perhaps not coincidentally the only female driver to be interviewed, as females are considered more risk averse as well as more proactive regarding their health (cf. [6, 7]). When probed on this point of lower exposure to emissions, other drivers did consider this a personal benefit and appreciated the BET even more upon this insight.

Multiple interviewees, mainly drivers, associated noisy, smelly diesels with 'manliness'. (The interviewee group included one female driver and one female planner.) One (male) driver went so far as to specifically identify the diesel truck as "masculine" and the electric truck as "feminine". This driver, although satisfied with the BET and not wanting to drive a diesel again, talked about still missing the noise and smell of the diesel truck, despite also acknowledging the short- and long-term health benefits of the BET. Clearly the gendered associations of internal combustion engines (ICEs) and electric vehicles remain engrained, as over a century ago, personal EVs were originally considered feminine and even marketed for women due to their shorter range (staying close to the home/private sphere), cleanliness, quietness, and even safety (compared to dealing with horses) [8, 9]. As the modern wave of EVs has largely been framed as a technological innovation, personal EVs have resultingly become more attractive to men [9, 10], but this tentative attitudinal shift has perhaps not yet found foothold within the trucking industry, where prospective female drivers still face various hurdles to labor force participation, including organizational hurdles [11].

Many interviewees referred to BETs and electrification as "the future", but with differing meanings. Some viewed this in a positive and exciting manner – associating "the future" with innovation, with themselves (and/or their organizations) being 'front-runners' in testing these new technologies in practice, and/or with transitioning away from fossil-fueled vehicles. Some discussed "the future" with a sense of resignation, inevitability, or even trepidation. Upon probing, one driver, despite viewing BETs as positive for him/herself, reflected on the introduction and scaling up of BETs as part of a 'slippery slope' entailing fast-paced, unavoidable technological change which would,

sooner or later, entail automation and eliminate his/her job. Anxiety related to technology is not new [12], but should be taken seriously. Even if there exist aggregate benefits for society, this does not necessarily translate to personal benefit for specific individuals or groups, and such anxiety may underlie the skepticism described by many of the interviewed drivers (both their own and of others in the trucking sector).

4 Concluding Remarks and Recommendations

Both logistics chains and electrification are complex with many pieces needing to fall into place to function, from complex business ecosystems and last-minute changes from customers, to a society still organized around ICEs. As such, it is useful to keep the various complexities in mind in attempting to understand these employees' perceptions of BETs; for example, distinguishing between concerns regarding BETs per se such as learning the ins and outs of a new vehicle/engine type, concerns regarding charging infrastructure such as (lack of) availability, and concerns regarding electricity as an energy source such as differentiated pricing. Furthermore, although the hope is that BETs will attract drivers (as well as younger and female drivers as these groups are perceived to have a greater demand for a more environmentally and socially sustainable work environment) and help alleviate the heavy-weight-class driver shortage, BETs, as a mainly technological innovation, will not be a so-called 'silver bullet' which will necessarily reduce stress and risk in a stressful and risky job. Although no driver wanted to go back to driving a diesel truck, as one Driver 1.1 expressed it: "[Truck driving] is a stressful job and always will be. [BETs] may reduce some types of stress [e.g. background noise], but they increase other types of stress [e.g. charging during complex logistics chains]". As such, logistics companies still have a major role to play in finding ways to improve employees' general working conditions as well as better tailor electrification-transition support for employees, particularly those new to BETs.

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Regional Electrified Logistics System Demonstrator in Sweden - Economic Comparison of Electric - and Diesel-Powered Solutions

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Abstract. Opportunities and challenges in regional electrified logistics have been demonstrated by an innovative collaborative project with 45 Swedish stakeholders. The system demonstration includes more than 70 battery electric heavy-duty vehicles, and associated charging infrastructure, operating in various types of commercial goods flows. These operations have been analysed from a haulier Total Cost of Ownership (TCO) perspective, whereof four are detailed in this paper; Local distribution, Regional distribution, Line-haul operation, and Drayage operation. The electric options are compared with corresponding diesel driven transports. The results show that the difference in TCO, based on data from year 2023, for the electric and diesel-powered solutions varies from + 6 to –16% when public co-funding of both trucks and charging infrastructure can be obtained. The analysis indicates that the TCO for the diesel-powered solutions are lower than for the corresponding electric solutions in both Local and Regional distribution but with increased mileage the TCO for the electric option can be lower than for the diesel option for the analysed cases.

Keywords: Battery-electric · truck · TCO · demonstration

1 Introduction

In order to prevent the most drastic effects of climate change, the world needs to severely reduce greenhouse gas (GHG) emissions already this decade. The road transport sector represents about 20% of the European Union's GHG emissions and is a main cause of air pollution in cities [1]. Heavy-duty vehicles (HDVs) are responsible for more than 25% of GHG emissions from road transport in the EU and account for over 6% of total EU GHG emissions. The latter years these emissions have continued to increase, especially in freight transport. This upward curve is mainly driven by growing road transport demand, which is expected to keep increasing in the future. The current fleet of HDVs in EU is run almost entirely on internal combustion engines which are predominantly fuelled by fossil fuels. Zero-emission battery electric trucks have the potential to offer

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many benefits including lower life cycle costs, zero tail-pipe emissions, reduced total energy need, and assuming that electricity could be produced from renewable energy sources also drastically reduced GHG emissions [2]. However, the degree to which all these benefits can be realised still needs to be proven and quantified through real-world deployments. To study how battery electric HDVs operate in practice, within real fleet operations, Swedish actors have had demonstration projects in progress for a few years. In autumn 2020 the Regional Electrified Logistics (REEL) project was initiated. REEL is a national initiative where leading Swedish players have joined forces to accelerate the transition to electrified emission-free regional heavy road freight transport. Within the REEL initiative, the parties establish, operate, and evaluate around 70 different regional logistics flows for various types of goods transport including transportation of ash, building material, chemicals, concrete, containers, excavated material, food, iron ore, parcels, textiles, timber, and waste. The trucks in the project operate in urban, sub-urban, and regional assignments, with a daily mileage per vehicle ranging from 120 kms to 820 kms. REEL gathers 45 organisations such as transport buyers, freight forwarders, distributors, hauliers, terminal operators, charging point operators, grid network companies as well as suppliers of trucks, charging equipment, and management systems. In addition, regions, national authorities, and universities participate. The initiative is led by a Swedish national collaboration platform for innovation of freight transports; CLOSER at Lindholmen Science Park. REEL is centred upon performing demonstrations of regional electrified heavy road freight transports. By developing and operating these demonstrations, insights are obtained on how different transport concepts and system solutions perform, how they need to be dimensioned considering the electric truck performance, requirement on charging, and iteratively need to be revised, to meet the logistics needs in a cost effective and energy efficient way. This paper investigates the economic consequences of a haulage company replacing its diesel trucks with battery-electric ones by comparing the total cost of ownership (TCO) for four different types of operation.

Previous literature has demonstrated that under appropriate conditions, battery-electric trucks can be competitive with diesel trucks [3–6]. However, most studies examining the total cost of electric trucks are theoretical studies of possible cases and are not based on empirical data of actual costs [7]. In addition, they often focus on what the cost might be in the future, including technological development and cost reductions for, e.g., batteries [8]. Two prevailing findings from existing literature are, firstly, the economic viability of battery-electric vehicles significantly correlates with driving behaviours [3, 9] and secondly, the primary constituent of the incremental capital cost for an electric truck is attributed to the battery's expense [8]. One study evaluated the cost-effectiveness and performance of electric tractors in the Tangshan region, in China, in comparison to diesel tractors. In total, real-world data from 117 tractor-trailers operating in 2022 were tracked and collected. The findings indicated that, while electric tractors run for more hours daily compared to their diesel counterparts, they cover a shorter distance each day. This is attributed to the fleet operator's more cautious scheduling for electric vehicles. Moreover, maintenance expenditures and energy expenses were lower for the electric tractors compared to their diesel counterparts. From a cost perspective, electric tractors prove to be competitively priced when compared to diesel models. Over a five-year span, however, electric tractors come with a 10% higher cost of operation than diesel tractors

[10]. It is, however, one of the few studies that have a lot of empirical data on costs in real traffic. Therefore, more studies like the one described in this article with empirical real costs of numerous cases of truck driving are needed.

2 Methods/Experimental

REEL is a collaborative innovation project and, thus, offers a unique access to the logistics companies participating in the initiative. A common project agreement exists and provides a source of confidence among the project participants to share their insights and experiences regarding various topics in electrification of heavy-duty vehicles. Moreover, a trustee function, through a neutral stakeholder ensuring a neutral filtering function, has been set up as part of the project structure to accomplish data sharing. Data from individual project partners are thus gathered and thereafter anonymised before it is shared to internal or external partners through common project activities. In addition, the project consists of both common and separate workflows to avoid prohibited cooperation between market competitors such as truck manufacturers and logistics companies present in REEL.

To provide additional insights regarding the economic prerequisites for battery electric trucks, and to compare it with their diesel counterparts, a total cost of ownership (TCO) analysis is chosen as the primary method in this study. The TCO method allows for calculating the costs of owning and operating a vehicle over a period of time, and comparing the cost between different types of vehicles in terms of power-train options, and is applied in several other studies examining the economics of battery-electric trucks [11]. It is also a common financial evaluation method used in the Swedish trucking industry. The TCO analysis accounts for different cost components including investment and purchasing costs for e.g., vehicles and charging infrastructure, fixed annual costs, and operation costs. Several factors influencing and defining costs of logistics operations for electric, and diesel driven transport have been identified, see Table 1.

To gather empiric data from logistics companies regarding the various costs and factors forming the base to the TCO analysis, an interview study was chosen as an adequate method. It is important to note that although acquiring cost related data was one of the motives to perform the interview study, the overall goal was to obtain insights regarding all the research topics in the REEL project. An interview guide was thus constructed consisting of 140 questions regarding following topics in relation to electrification of heavy-duty trucks in the project: general info of the logistics company, particular logistics case in the REEL project, hardware and software in the electrified logistics case, policy, business models, working environment and knowledge gaps, system architecture & interoperability, and future fleet electrification projections. The questions were constructed and revised in dialogue with researchers participating in the REEL project, as well as with the Swedish association of road transport companies (Sveriges Åkeriföretag).

The interviews with logistics companies participating in the project were performed by the project's trustee representatives over a course of more than 12 months, spanning from April 2022 to May 2023. The length of the period is motivated by the desire of obtaining relevant answers based on at least one year of electric truck operation by the interviewed company. The interviews were of semi-structured type, encouraging

Table 1. Identified items for cost analysis from a haulier perspective

Category		Item
Utilisation	Yearly utilisation	Hours
		Mileage
		Days of operation
Investment	1.1 Truck incl. Superstructure (SS)	1.1a Chassis and residual value
		1.1b Superstructure (incl. e.g., tail-lift) and residual value
		1.1d Lifespan of investments (years or mileage)
		1.1e Public subsidies
	1.2 Charging infrastructure	1.2a Charging infrastructure (incl. Installation) and residual value
		1.2b Power grid upgrade and residual value
		1.2c Other (incl. e.g., IT tools)
		1.2d Lifespan of investments
		1.2e Public subsidies
	1.3 Interest	1.3a Total yearly interest for investments
Fixed annual costs	2.1 Road tax and tolls	2.1a Vehicle (and trailer) tax
		2.1b Road tax
		2.1c Other (e.g. road tolls)
	2.2 Insurance and damages	2.2a Vehicle and trailer insurance
		2.2b Charging infrastructure insurance
		2.2c Average yearly deductible
	2.3 Other costs	2.3a Parking
		2.3b Wash
		2.3c IT equipment operation and service
		2.3d Other
Operating cost	3.1 Tyres and maintenance	3.1a Tyre cost
		3.1b Vehicle and trailer maintenance/service

(*continued*)

Table 1. (*continued*)

Category		Item
		3.1c Charging infrastructure maintenance
		3.1d Consumables
		3.1e Refinishing
		3.1f Other
	3.2 Energy	3.2a Average energy consumption per km
		3.2b Energy cost (electricity or diesel)
	3.3 Grid transmission, electricity tax and power tariff	3.3a Grid transmission
		3.3b Power tariff
		3.3c Energy tax
	3.4 Staff	3.4a Driver
		3.4b Transport management
		3.4c Other staff
		3.4d Over-head -

the interviewees to elaborate on the specific question to allow for capturing several perspectives rather than obtaining a short definitive answer. In total 26 organisations have been interviewed in the study, covering more than 60 logistic flows. Interviewees were representatives of the participating logistics companies in REEL possessing roles such as fleet manager, logistics manager, sustainability manager, transport manager. The interviews were recorded with permission from the participants and were often divided in two or three sessions lasting for one to two hours at a time depending on the interviewees level of engagement and knowledge. Questions in the interview guide were slightly revised between interviews to ensure better capturing of data. In addition to the interviews, complementary questions regarding specific cost for TCO-calculations were addressed to the interviewees after the main interviews in some cases since the interviewers preferred an iterative approach. Elements of the cost structure of present TCO-calculations for diesel powered trucks were acquired from Sveriges Åkeriföretag as the organisation regularly collects these data to provide updated indexes to transport companies to simplify transport service contracting.

In the TCO analysis, four different types of logistic cases have been developed and calculated based on data from the different flows with electric trucks performed in the REEL project. The cases cover various truck applications, logistics setup and geographical location. The geographic location is of specific relevance for the electrified cases, as opposed to their diesel counterparts, considering the presence of different electricity price areas in Sweden. In the comparison all cost were defined on a yearly basis.

Investment costs are calculated by accounting for the purchasing price of the vehicle and charging infrastructure, respectively, while also considering a potential residual value of the equipment. The average annual investment cost, as used in the comparison, is estimated based on the economic lifetime or the number of years the truck and charging infrastructure is operated by the haulier. For interest cost the annual average interest cost for the analysed period is used. Elements such as insurance, vehicle and road tax, parking, wash and IT are assumed fixed over the year and not dependent of the usage of the truck. Operation costs include: costs for tyres, services and maintenance, which mainly depends on the annual mileage of the vehicle; costs of staff which are associated to the annual use of the vehicle; and costs for energy which depends on annual driving distance and specific fuel consumption of the vehicle.

As the fuel (energy) cost varies over time, both for electricity and diesel, an average over the period between June and August 2023 was applied, to reflect current price levels. While the diesel case only includes costs for the diesel fuel, the cost of fuel for the electric truck, in addition to the electricity market price, also includes electricity transmission and grid cost. The size and distribution of these cost elements have a strong geographic dependency attributed to the local electricity grid company. To account for these cost elements, discussions with grid companies were conducted to understand what power subscription model is the most common among logistic companies to use. The performed TCO calculations allowed for a further comparison between electrified and diesel-based logistics cases. The electrified cases were further divided into subsidised and non-subsidised cases, i.e., indicating presence of governmental incentives partially covering additional costs for electric trucks and charging infrastructure. The outcome of the TCO calculations as well as the method were also presented to all participating organisations in the project to acquire feedback. However, no significant feedback affecting the outcome were obtained.

3 Results and Discussion

Four different transport cases performed with battery electric HDVs have been constructed based on aggregated data and analysis from the transport cases within the REEL project. These cases; Local distribution, Regional distribution, Line-haul operation, and Drayage operation, are detailed in Table 2 and further described below.

In the following TCO calculations interest rate is set to 7.2%. The salary for drivers is set to 33,600 Swedish kronor (SEK) per month and Swedish collective agreement conditions apply. In the presented cost comparison calculations, the average fuel price for the period July to September 2023 are used both for MK1 Diesel and electricity. Sweden is divided into four geographical electricity price areas; SE1, SE2, SE3, and SE4. Due to physical limitations in the national grid these areas often display different electricity prices, see Table 3.

Costs for grid transmission and power outtake varies depending on geography, time, and subscription model. In the presented calculations, Vattenfall's subscription model for companies with 80 A or higher with low voltage connection is applied [12, 13]. Moreover, electricity energy tax varies depending on geography and type of business sector, which is also accounted for in the calculations. The current incentive schemes

Table 2. Description of the four transport cases analysed

	Local distribution (C1)	Regional distribution (C2)	Line-haul operation (C3)	Drayage operation (C4)
Mileage per year (km)	30,000	50,000	180,000	150,000
Operating hours per year (h)	2,000	2,200	4,032	3,600
Operating days per year (days)	240	220	250	250
Truck	Rigid, 6 x 2	Rigid, 6 x 2	Rigid, 6 x 2 & trailer	Tractor, 4 x 2 & trailer
Maximum Gross Combination Weight	27 tonnes	44 tonnes	64 tonnes	44 tonnes
Battery size (kWh)	300	600	600	600
Average energy consumption (kWh/km)	1.2	1.5	2.0	1.6

Table 3. Electricity prices (SE1-4) and diesel prices (MK1) in Sweden June-Aug 2023. [13, 16]

	SE1 (SEK/kWh)	**SE2** (SEK/kWh)	**SE3** (SEK/kWh)	**SE4** (SEK/kWh)	**MK1** (SEK/l)
June 2023	0.5942	0.5929	0.6332	1.1402	17.77
July 2023	0.4793	0.4795	0.4866	0.5278	18.14
August 2023	0.3466	0.3466	0.5049	0.6276	19.68
Average Jul-Sep	0.4734	0.4730	0.5416	0.7652	18.53

in Sweden for battery electric trucks allow for a maximum of 20% investment support of total cost although it cannot exceed 40% of the additional cost compared to a similar conventional truck [14]. For non-public charging infrastructure, a maximum of 20% investment support of total installation cost can be obtained for large enterprises [15].

The Local distribution case C1, see Table 4, is based on a battery-electric rigid truck with a total weight of 27 tonnes. The vehicle operates in urban areas delivering chilled and frozen food. It operates from 07:00–16:00 on weekdays, 240 days a year. The truck and its batteries are depreciated by 85% in eight years. Installed battery capacity is 300 kWh and the total vehicle on average consumes 1.2 kWh/km, while the equivalent diesel vehicle consumes 0.28 l/km. The truck operates approximately 30,000 kms per year. In this case, the extra weight of the batteries has no impact on the operation, as the goods are rather limited on volume. The truck is charged during night and sometimes during

Table 4. Economic comparison of Local distribution case, C1 (SEK/year)

Cost category	Electric	Electric incl. Public co-funding	Diesel
Truck (incl. Superstructure)	415,969	332,775	203,469
Charging infrastructure	11,250	9,000	-
Interest	143,379	114,703	68,557
Insurance, vehicle & road tax, parking, wash, and IT	103,051	103,051	102,892
Tyres, service, and maintenance	102,410	102,410	102,410
Energy	27,547	27,547	155,652
Grid transmission, electricity tax, and power tariff	24,778	24,778	-
Staff	679,791	679,791	679,791
Total	1,508,175	1,394,055	1,312,771
% from Diesel option	+ 15%	+ 6%	

lunch break if needed, using a 25-kW charger that is fully depreciated in eight years. The truck operates within electricity area SE4.

The Regional distribution case, C2, see Table 5, is based on a battery-electric rigid truck that operates in sub-urban and rural areas transporting palleted goods to industries and warehouses. The volume of goods is the limiting factor; thus, the increased weight of batteries has not affected the operation. The vehicle operates in 1-shift on weekdays 220 days a year. The truck and its batteries are depreciated by 85% in eight years. Installed battery capacity is 600 kWh and the total vehicle on average consumes 1.5 kWh/km, while the equivalent diesel vehicle consumes 0.38 l/km. The truck operates approximately 50,000 kms per year within electricity area SE1. The vehicle is charged during breaks, between shifts and at nights with 40 kW. The charger is fully depreciated after eight years.

The Line-haul operation case, C3, see Table 6, is based on a battery-electric rigid truck and trailer that operates in a volume limited operation between two major terminals in electricity area SE3. The vehicle operates in 2-shift (06:00 – 15:00 and 18:00 – 03:00), 250 days per year. The two shifts result in a daily driving distance of ~720 km. The truck and its batteries are depreciated by 85% in six years, while the trailer is depreciated by 50% in six years. Installed battery capacity is 600 kWh and maximum total weight is 64 tonnes. The total vehicle consumes 2 kWh/km, the equivalent diesel vehicle consumes 0.43 l/km. The vehicle is charged during breaks and between shifts with a maximum of 300 kW at the operator's terminal. The charging infrastructure is fully depreciated in eight years and is shared between various transport operations where this operation accounts for 40% of the total use of the infrastructure.

Table 5. Economic comparison of Regional distribution case, C2 (SEK/year)

Cost category	Electric	Electric incl. Public co-funding	Diesel
Truck (incl. Superstructure)	527,531	422,025	214,094
Charging infrastructure	25,000	20,000	-
Interest	184,907	147,926	72,137
Insurance, vehicle & road tax, parking, wash, and IT	105,264	105,264	97,228
Tyres, service, and maintenance	108,350	108,350	103,350
Energy	35,505	35,505	352,070
Grid transmission, electricity tax, and power tariff	40,240	40,240	-
Staff	747,770	747,770	747,770
Total	1,774,567	1,627,079	1,586,648
% from Diesel option	+ 12%	+ 3%	

Table 6. Economic comparison of Line-haul operation case, C3 (SEK/year)

Cost category	Electric	Electric incl. Public co-funding	Diesel
Truck (incl. Superstructure)	812,542	671,867	394,625
Charging infrastructure	80,000	64,000	-
Interest	247,557	207,425	119,035
Insurance, vehicle & road tax, parking, wash, and IT	168,357	168,357	151,765
Tyres, service, and maintenance	377,660	377,660	371,260
Energy	194,976	194,976	1,417,545
Grid transmission, electricity tax, and power tariff	208,848	208,848	-
Staff	1,482,226	1,482,226	1,482,226
Total	3,572,165	3,375,359	3,936,456
% from Diesel option	–9%	–14%	

The Drayage operation case, C4, see Table 7, is based on a battery-electric tractor that operates in a fixed hub-to-hub flow transporting semi-trailers with consumer goods in electricity area SE2. The volume is the limiting factor; thus, the increased weight

Table 7. Economic comparison of Drayage operation case, C4 (SEK/year)

Cost category	Electric	Electric incl. Public co-funding	Diesel
Truck (incl. Superstructure)	479,643	383,714	145,714
Charging infrastructure	80,000	64,0001	-
Interest	164,322	131,458	42,960
Insurance, vehicle & road tax, parking, wash, and IT	98,550	98,550	76,902
Tyres, service, and maintenance	207,700	207,700	201,300
Energy	113,520	113,520	1,111,800
Grid transmission, electricity tax, and power tariff	128,016	128,016	-
Staff	1,323,416	1,323,416	1,323,416
Total	2,595,167	2,450,374	2,902,092
% from Diesel option	–11%	–16%	

of batteries has not affected the availability to transport goods. The vehicle operates in 2-shift, 250 days a year. The distance between the hubs is approximately 60 km, and the loop is repeated five times a day resulting in a total mileage of 600 kms per day. The truck and its batteries are depreciated by 85% in seven years. Installed battery capacity is 600 kWh and the total vehicle consumes 1.6 kWh/km, while the equivalent diesel vehicle consumes 0.40 l/km. The vehicle is charged during breaks, between shifts, and at nights with a maximum of 300 kW. The charging infrastructure is fully depreciated in eight years and is shared between various transport operations where this operation accounts for 40% of the total use of the infrastructure.

The economic comparison shows that the difference between the electric and diesel-powered solutions varies from + 6 to –16% when public co-funding of both charging infrastructure (20% co-funding) and trucks (20% co-funding) can be obtained. As noted, the TCO for the diesel-powered solutions are lower than for the corresponding electric solutions in local and regional distribution but with increased mileage the TCO for the electric option can with presented conditions be lower than for the diesel option.

With introduction of electric operation, the cost type distribution changes compared to conventional diesel-powered operation, see Table 8 for the case of Regional distribution, C2. For electric operation, costs related to investments in trucks and charging infrastructure, including depreciation and interest, account for around 41%, while for the diesel operation those make up 18%. Energy related cost however only accounts for 4% for the electric operation and 22% for the diesel operation.

To cope with the higher investment costs and uncertainties with regard to residual value of the battery electric vehicles, participating transport companies in REEL experience a need for increasing the length of the transport contracts to ensure the utilisation

Table 8. Economic comparison of Drayage operation case, C4 (SEK/year)

Cost category	Electric	Diesel
Truck (incl. Superstructure)	30%	13%
Charging infrastructure	1%	-
Interest	10%	5%
Insurance, vehicle & road tax, parking, wash, and IT	6%	6%
Tyres, service, and maintenance	7%	7%
Energy	2%	22%
Grid transmission, electricity tax, and power tariff	2%	-
Staff	42%	47%
Total	100%	100%

of their electric trucks in advance. It is difficult to calculate residual value of electric trucks as a second-hand market does not yet exist and potential degradation of the batteries remains uncertain as well. Historically, when using diesel trucks, the participating companies have applied contract lengths for transport services spanning mostly from 12 to 36 months. For electric transports, most companies consider it necessary to increase the contract length to an interval between 36 to 60 months to reduce the risk due to high investment cost. Increase contract lengths have been applied for REEL transport flows. For some transport segments even longer contracts lengths are desired.

In contrast to when acquiring diesel trucks, most of the transport companies in the REEL project have chosen to use operational leasing as the financing model for their battery electric trucks, see Fig. 1.

Transport companies are unsure of the performance of the first-generation trucks, for example, considering battery degradation. They also believe that specifications of these trucks will be outdated in a few years' time due to the rapid technological development. Thus, operational leasing is used to minimise risk of potentially low residual value. The actors who forecast that they will continue to use operational leasing in five years from now, believe that these arguments will still be valid at that point in time. Multiple actors state that the financing of trucks will be a hurdle for small hauliers. A solution to this, as some of the larger actors and the haulier network organisations believe, is that to take ownership of trucks themselves and thereafter lease the vehicles to the smaller hauliers. In addition, a shift from operational leasing to cash payment is anticipated by the logistics companies in five years' time. Actors that prefer cash payment state that they benefit economically through either cash payment and/or financial leasing. They expect that the performance of vehicles will improve in the coming years and that battery electric trucks will have a longer useful life than conventional trucks. Therefore, actors would like to keep the vehicles as long as possible in their own operation, with some of the actors mentioning a period of up to 12 years. These actors see a potential to keep trucks in operation by moving it to other transport assignments as the battery degrades. When the battery is no longer sufficient for vehicle propulsion it is expected to have a

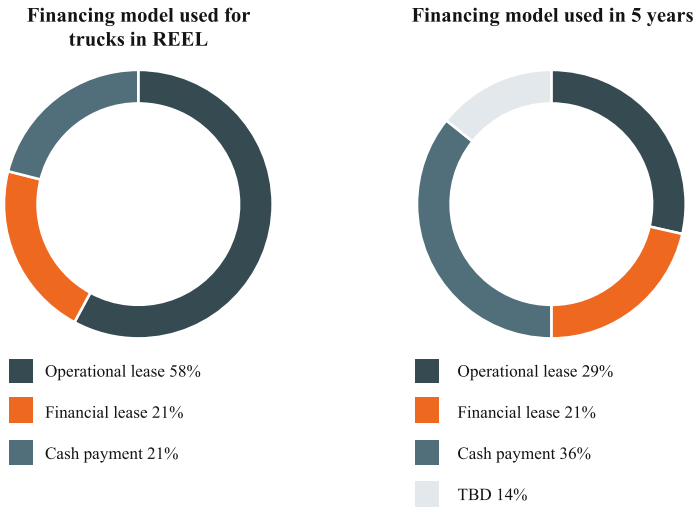


Fig. 1. Preferred financing models for trucks according to logistic companies interviewed in REEL

second life in grid frequency up and down regulation services to optimise battery value generation for the logistics companies.

For the applied period, June to August 2023, the average weighted electricity spot price of the four Swedish electricity areas (SE1-4) ranged between 0.47 and 0.77 SEK/kWh, while the diesel price averaged at 18.5 SEK/litre. As seen in Fig. 2, there have been a substantial fluctuation in electricity spot prices in all electricity areas during the last couple of years.

However, the fluctuations as well as the price have been more significant in the two southern electricity areas; SE3 and SE4, due to transmission bottlenecks in the national high-voltage grid. In addition, the electricity energy tax is reduced for most locations in two northern electricity areas, SE1 and SE2. From an energy cost perspective, it has therefore been more beneficial for actors located in SE1 and SE2 to introduce electric solutions than for actors located in SE3 and SE4. Previous studies point out that the maintenance cost for electric trucks will be lower compared to conventional trucks, however this has not yet been observed for the transport flows analysed in this study. Currently the OEMs charge truck buyers similar costs for full-service contracts for electric trucks as for diesel trucks. Interviewees state that although the service cost is reduced the repair cost is increased due to labour intensive activities that require personnel with added skills in electronics. Increased cost for truck insurance has not been noted despite the higher investment cost.

Actors in REEL currently operate between one to nine electric trucks at the same geographic location. In future, the cost effects attributed to system scale up need to be examined as additional costs might arise related to grid upgrade as well as planning and management of the operation, and potentially loss of production due to time for charging. Further on, as mentioned previously there is currently limited data on battery electric truck life expectancy operating in commercial operation. In the calculations an

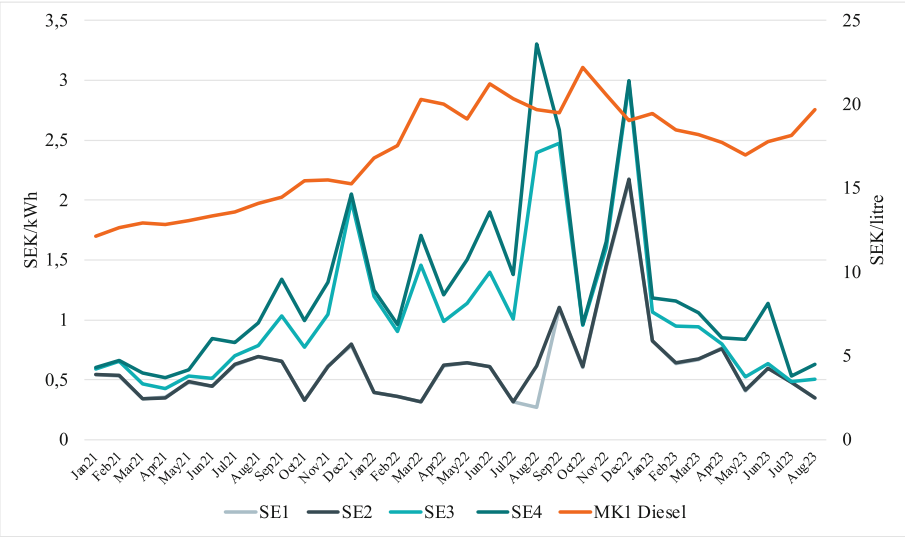


Fig. 2. Development of monthly average for diesel prices and electricity prices (based on a weighted monthly average of spot prices on the Nordic power market, NordPool) in Sweden Jan 2021–Aug 2023 [12, 16]

economic life ranging from 6–8 years, or 240,000 to 1,080,000 kms with a residual value of 15% has been used. These projections are in line with warrantee agreements offered by the truck OEMs. Currently, there is no data on maintenance cost from the end of the service life, also how battery degradation potentially will affect the operation is to be examined. However, multiple battery electric trucks in REEL each runs more than 300,000 kms per year and have in total operated more than 500,000 kms each since the project was initiated and continue to run in the same logistic operation without major impacts on charging time and range.

4 Conclusions

The REEL project with its 70 regional logistics flows makes it one of Europe's largest initiatives where battery electric trucks are operated in commercial freight transport flows simultaneously as data is collected on e.g., TCO. In contrast to previous theoretical studies of possible cases this study is instead based on empirical data of actual costs. Four transport cases have been detailed in this paper. The electric options are compared with diesel driven transports and the results shows that the difference in TCO for the electric and diesel-powered solutions varies from + 6 to –16% when public co-funding of both trucks and charging infrastructure can be obtained, see Fig. 3. The TCO for the diesel-powered solutions are lower than for the corresponding electric solutions in local and regional distribution but with increased mileage the TCO for the electric option can be lower than for the diesel option.

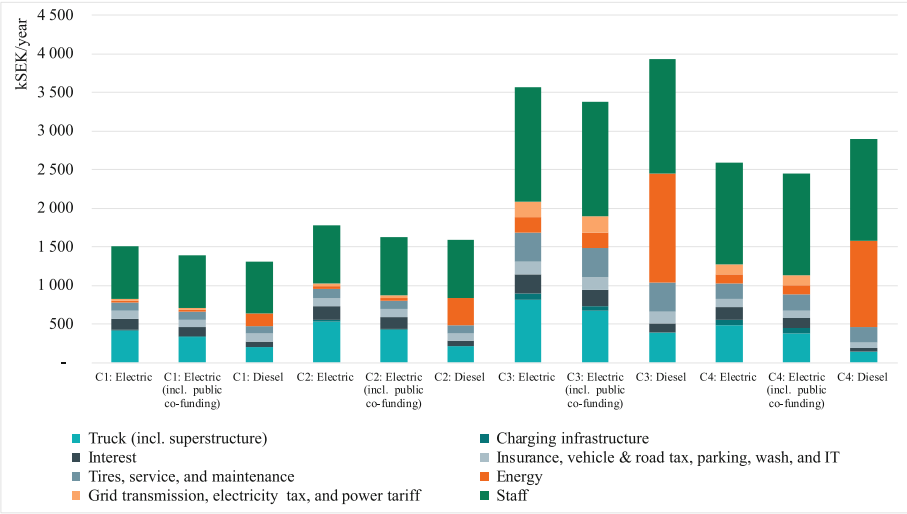


Fig. 3. Economic comparison of four freight transport cases; C1: Local distribution, C2: Regional distribution, C3: Line-haul operation, C4: Drayage operation.

With electric operation the cost type distribution is affected, for example depreciation and interest becomes more prominent while energy cost significance is decreased. For the first generation of electric trucks, truck buyers have favoured leasing as financing model to reduce risk related to residual value. Maintenance and insurance cost have been similar for battery electric trucks as for diesel-powered trucks.

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A Digital Twin-Based Framework for Evaluating Last-Mile Collaboration Schemes with Electric Modular Vehicles

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Abstract. This paper examines the distribution structure of a nationwide HoReCa company, appraising several distribution process modifications in line with the physical internet concept. Primarily, the study considers the service of electric vehicles with flexible cargo space and the utilization of a shared consolidation center within urban areas. The research leverages real-world operation data to evaluate the impact at the city and company level, and assess the effectiveness of these business models across four distinct scenarios. A digital twin incorporating customer behavior, operational choices, and stochastic events replication provides a fresh framework for evaluating shared last-mile logistics business models. Key contributions encompass results and managerial insights for implementing modular vehicles in HoReCa distribution systems, design elements for digital twins in shared urban consolidation and delivery systems, and a unified perspective for decision-making blending public and private sector needs.

Keywords: Urban Logistics · Physical Internet · Digital Twins

1 First Section

Last-mile logistics refers to the final product delivery step from sorting centers to consumers, encompassing transport to businesses and residences. This stage in urban freight transportation is particularly complex due to the diverse demands, distribution systems, traffic dynamics, and city regulations. Analyzing these intertwined factors is challenging, with added complications from environmental concerns and limited storage infrastructure. This makes innovative urban transport designs vital. Rising urban populations and regulatory constraints getting, further complicated by growing e-commerce and expanding cities. Addressing these logistics challenges requires collaboration between governments, private sectors, and research entities. The Physical Internet paradigm offers solutions benefiting businesses, consumers, and cities. However, coordinating divergent stakeholder interests can lead to conflicts. A holistic approach is crucial for effective urban logistics solutions.

This study aims to demonstrate how digital twins, which can map complex processes, can be used to examine such challenging topics. The study focuses on a nationwide

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company in the Hospitality, Restaurant, and Cafe (HoReCa) sector that offers takeaway coffee and food services. The specific contributions of this study include:

- An exploration of how digital twin solutions can be applied to address problems in urban logistics.
- A case study examining the impact of urban consolidation centers on the overall process of replenishing local shops.
- Analysis of the effects of collaborative urban consolidation on both the city and companies.
- Examination of the use of light commercial vehicles with modular cargo bodies for urban logistics.
- An integrated vehicle routing problem solution for electric vehicles and modular cargo bodies in the simulation environment.
- A comprehensive assessment analysis to evaluate the impact of such business solutions from multiple perspectives.

2 Literature Review

As it noticed by (Kaspi, Tal, & Ulmer, 2022) the urban micro-consolidation centers is an emerging solution that attracts a lot of attention both in practice and in research. The focus is both on operational and tactical level. Past studies have examined the strategic decision on urban environment considering cost aware analysis for both private companies and community gains for micromobility infrastructure development (Salanova, et al., 2022). At the same fashion the (Lyu & Teo, 2022) presented a complete methodology for the design of locker alliance network for urban logistics. These initiatives face a lot of potential on the physical internet context (Crainic & Montreuil, 2016) which supports the use of interconnected shared logistics infrastructure. The narrative is that due to space limitations and resource waste that is significant on urban logistics, the sharing economy prevails as fertile ground for new schemes. At most of these studies a principal assumption is that the last mile performed by clean and sustainable means like electric light commercial vehicles or cargo-bikes with a lot of studies focus on the operational aspect (Caggiani, Colovic, Prencipe, & Ottomanelli, 2021). Parallel studies create analytical models to examine if the collaborative schemas are effective and will increase the efficiency of last-mile operations and profits for each player (Jagan, 2020), but the study limits on two companies as its difficult to scale the models. Lastly, a last part of these are using agent-based simulation to scale the results into complex sophisticated evidence based insights under various service scenarios (Heeswijk, Mes, Schutten, & Zijm, 2020).

3 Urban Logistics Digital Twin

This study delves into urban logistics within nationwide HoReCa businesses, aiming for a deeper comprehension and practical solutions. Digital twins are generally split into:

1. **Development Digital Twins:** Used mainly in preparatory stages, they support model training, scenario testing, and decision-making processes. They enable comprehensive virtual testing and optimization before real-world application.

2. **Operational Digital Twins:** Acting as real-time reflections of physical systems, these twins adapt to environmental changes, powered by continuous data from interconnected sensors. This allows precise system behavior representation and forecasting, boosting efficiency and preemptive issue management.

In essence, digital twins are pivotal in comprehending and refining complex systems, from urban logistics to industrial production.

3.1 Urban Logistics Elements

In this study, our focus is on the application of digital twins for urban logistics. Specifically, we establish a simulation environment characterized by discrete events and multiple interacting agents, each behaving according to optimized strategies. The initial step is to identify the key stakeholders in the urban environment whose actions significantly influence the overall performance of operations and the city as a whole. These stakeholders include:

(1) **Customers:** The end users who consume the products, driving both the demand and direction of services.
(2) **Logistics Providers:** Entities involved in warehousing, consolidation, sorting, transportation, and management of goods.
(3) **Service Providers:** These could include retail outlets, and businesses in the Hospitality, Restaurant, and Cafe (HoReCa) sector, among others.
(4) **City:** The city itself is an active, dynamic environment subject to variations in traffic, parking availability, loading/unloading zones, regulations, objectives, and spatial limitations.
(5) **Market Dynamics:** These are the competitors engaged in similar, identical, or complementary activities within the city.

The primary aim is to understand the interactions among these stakeholders, their influence on urban logistics, and the potential optimizations that could be achieved using a digital twin approach.

4 Methodology

To evaluate the pros and cons of integrating urban consolidation centers, light commercial electric vehicles (LCVs), and stakeholder collaboration, we've devised four scenarios. These gauge the effects of urban consolidation and Physical Internet (PI)-inspired operations. Figure 1 depicts the baseline scenario where a large 3PL vehicle serves each city center shop with an order. Concurrently, each wholesaler uses their own vehicles for individual shop orders. The first alternative emphasizes a consolidation center exclusively for 3PL-delivered goods using e-LCVs, aiming to cut traffic, environmental impact, and last-mile costs. The second scenario includes wholesaler products in this consolidation, further enhancing delivery efficiency. The third suggests a communal consolidation center shared by multiple users, which, while optimizing space, necessitates intricate management due to varying user needs. These scenarios elucidate urban logistics' diverse complexities and optimization avenues, shedding light on prospective effective strategies.

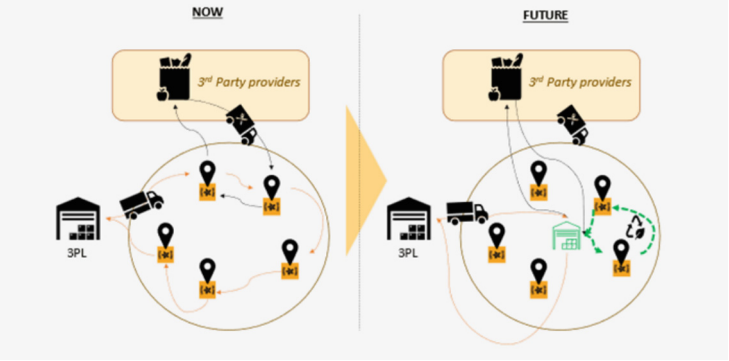


Fig. 1. The as-is and to-be distribution and fulfillment paradigm shift of the use case

4.1 The Integration Framework

The ANYLOGIC simulation software serves as the foundation for designing the urban logistics digital twin in this study. The software enables the design of an explicit representation of the complete process, incorporating discrete events and agent-based features. Its extensive customizability facilitates the integration of customized Java routines, and the inclusion of a Python connector (referred to as a pipeline) allows for the addition of intelligent algorithms that enhance the actions of the agents in the simulation.

Moreover, the software allows for the testing of realistic and optimal strategies under varying uncertainties, such as traffic variations and travel times across different hours of the day. The digital twin for urban logistics in this case study comprises four core elements, integrated into a unified environment:

(1) Created using tools provided by the ANYLOGIC software, this component includes all the logic concerning information flow and the total lifecycle of the company's products.
(2) Fleet Management and Routing Optimization Module: This module addresses all tasks related to fleet management and routing optimization. It employs vehicle routing problem (VRP) models for electric modular vehicles with capacity constraints and an emissions optimization objective.
(3) Charging Optimization Routine: This integrated routine manages all decisions relating to charging planning and operation, which is particularly relevant for fleets of electric vehicles.
(4) Traffic Layer: This component allows travel times to change depending on the time of day, weather conditions, and other external factors.

In this way, the digital twin provides a comprehensive and flexible tool for examining and optimizing urban logistics in a realistic and dynamic simulation environment.

4.2 Dataset

The dataset for this study includes information on a number of local stores, detailing the weekly demand for coffee and supplementary materials in terms of weight and number

of boxes. The case study specifically focuses on the urban areas of Thessaloniki, a region densely populated and potentially benefiting from the implementation of urban consolidation centers. An additional dataset, enriched with GPS data, provides information on the loading and unloading dwell time required for each shop (Table 1).

Table 1. Data format of the orders

Name	Description	Unit
Weight	The total weight of the order	Kg
Boxes	The total number of boxes on the palette	-
Date	The date the order placed	Year-Month-Day
Shop id	The local shop that made the order	string

4.3 Simulation Architecture

The simulation utilizes several modules of the ANYLOGIC software, including the process modeling library, material handling library, pipeline python connector library, and agent-based modules. It offers a comprehensive view of the urban logistics process by simulating both the external/urban and the intra-logistics aspects of the process. This means the simulation takes into account not only the logistics infrastructure, such as the efficiency and capacity of consolidation, but also the routing and fleet management side of operations.

This rich combination of data and simulation capabilities enables a thorough analysis of potential optimizations in the urban logistics process, considering both operational constraints and real-world uncertainties (Fig. 2).

The optimization process in this study is implemented in multiple stages, aiming to harmonize the optimization of both route scheduling and charging scheduling. The route optimization aims to discover a route that serves as many shops as possible within a day while respecting constraints related to battery life and capacity and considering recharging times. The objective is to accomplish these goals while simultaneously minimizing total energy consumption, considering factors like distance and speed. Conversely, the charging optimization algorithm attempts to optimize the long-term degradation of the vehicle's battery. It aims to charge the vehicle at a lower voltage, which, while extending the vehicle's release time, may lead to slower battery degradation. However, a longer charging time implies the vehicle remains unutilized for extended periods, potentially increasing the number of unserved deliveries per day. A synchronization master controller is utilized to strike the best balance in this trade-off. It conducts experiments and tests multiple parameters such as the number of vehicles, the size of the consolidation center, and the business model of the consolidation center. Through this process, it seeks to identify the optimal balance between operational efficiency and battery life expectancy in the urban logistics system.

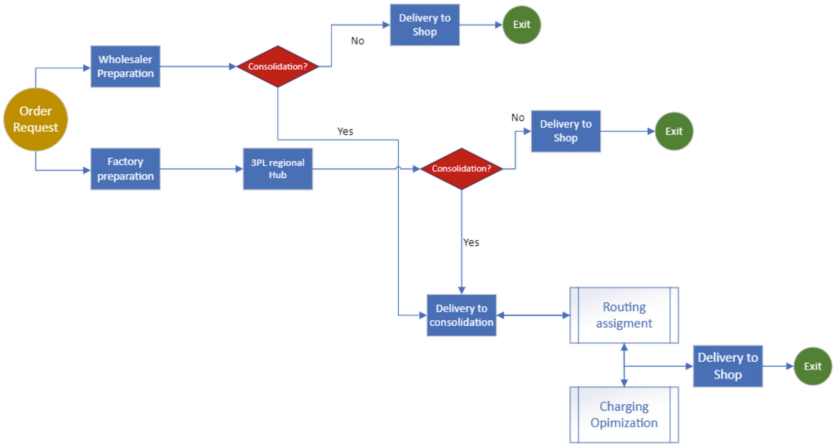


Fig. 2. Process flow diagram applicable to all use cases

5 Evaluation Framework

This study uses stochastic demand arrival at local shops for experimentation, with demand data sourced from the company's weekly logs, prompting specific replenishment actions at the factory and wholesalers. Four urban consolidation business model scenarios are simulated. Each scenario undergoes testing for variables like vehicle count and consolidation center capacity (considering elements like forklifts and rack numbers). Shop and distribution center counts and locations remain unchanged. Data for parking, loading, and unloading is analyzed to determine time distributions. Vehicle count, consolidation center capacity, recharging, and routing strategies are the primary adjustable parameters in the experiments.

The evaluation criteria are divided into seven general categories to provide a comprehensive view of the total system performance under different scenarios:

- **Total CO2 Emissions:** This measures the total carbon footprint of the logistics operations.
- **Distance Traveled/Empty Miles/On Route Time:** This assesses the efficiency of vehicle usage.
- **Third-Party Logistics (3PL) Costs:** This evaluates the costs associated with using external logistics providers.
- **Lead Time:** This measures the time between the initiation and completion of a logistics process.
- **Number of Vehicles/Cargo Bodies:** This assesses the size and scalability of the logistics operations.
- **Transportation Cost:**This quantifies the direct costs associated with moving goods from one place to another.
- **Consolidation Cost:** This measures the costs related to gathering multiple smaller shipments into a larger one for more efficient transportation.

In this way, the evaluation offers a multi-faceted perspective on the performance and efficiency of different urban logistics strategies.

6 Results

The results are under production as some of the data to complete the study and retrieve reliable results are under collection by the time this paper is written. The results will be ready until January.

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Integrating Logistics Requirements in City District Planning

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Abstract. Growing urbanisation, increasing freight volumes and freight trips as well as the requirement to mitigate climate change put pressure especially on urban areas to better address these challenges. However, planners often lack knowledge about logistics requirements. Therefore, the objective of the LOGI-TOOLKIT project is to develop an open-access and web-based toolkit which provides urban planners with decision support for better integrating effective logistics measures into the planning processes. The LOGI-TOOLKIT was developed by combining in-depth research with a survey and data analyses. It is continuously improved using feedback from urban planners. The initial results show that the toolkit is helpful for integrating logistics requirements in urban district planning and several stakeholders are interested in extending the toolkit.

Keywords: urban freight transport · city district planning · toolkit

1 Introduction

The amount of freight traffic in European cities is increasing by about 4–5% annually. Increasingly, smaller vehicles are being used due to the 'atomisation' of deliveries in the courier, express and parcel (CEP) sector caused by growing e-commerce volumes and the associated home deliveries. Using smaller vehicles further increases the amount of traffic on roadways [1]. Double parking and the heavy utilisation of loading zones by delivery vehicles show that many European cities are poorly prepared for the growth of goods delivery. Furthermore, in addition to generating more traffic, increasing goods traffic reduces the ability of cities to implement measures for addressing climate change and to re-purpose street space for urban liveability (in other words, inadequate logistics planning is an additional driver in the competition for urban space).

Given the increasing impact of goods traffic, an interdisciplinary look at logistics requirements in the context of planning urban districts is needed to give city planners,

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real estate developers and other stakeholders decision support regarding appropriate urban logistics measures to implement. The LOGI-TOOLKIT meets these needs and is designed as a web-based, open-access urban logistics information platform developed based on in-depth research combined with data analyses which uses feedback from urban planners to continuously improve its functionality.

Section 2 of the paper deals with data requirements. Section 3 describes the LOGI-TOOLKIT concept. Section 4 presents initial results and conclusions.

2 Data Requirements for Improved Logistics Planning in Urban Districts

Urban transport planning for new or redevelopment districts often focuses on individual mobility measures while goods transport plays a subordinate role. One reason is a lack of knowledge of the highly disproportionate effects of urban freight delivery on liveability, traffic load and urban space. The problem is compounded by a lack of easy-to-access data for the estimation of freight (trip) generation. This lack of information and knowledge means stakeholders who want to boost sustainability by implementing urban logistics solutions miss decision-making support especially in early project stages. More specifically logistics measures such as un/loading zones, parcel lockers and micro-hubs are often not used to their full potential; these measures are under dimensioned, poorly located and/or badly aligned with the local context.

LOGI-TOOLKIT aims to close this knowledge-gap by providing a tool for estimating local freight (trip) generation, identifying, and dimensioning suitable urban logistics measures, and providing good-practice recommendations on their implementation.

2.1 Data Requirements

There are two key requirements for planning freight transport at the district level. First, planners must be able to estimate the demand for goods and the potential delivery trips generated. And second, they must be able to assess the need for suitable urban logistics infrastructure including measures for goods transhipment and consolidation.

Existing data sets are often ill-suited for this challenge since they are aggregated on a macro or meso-level; more detailed data are necessary for logistics planning in such a small-scale analysis. Here, spatial differences are particularly important; a simple disaggregation of higher-level data would not be effective. Thus, a literature survey was conducted to identify data for various spatial types and possible correlations.

Data on freight and trip generation and other relevant indicators are mostly on a city-level or for specific urban districts, with a focus on creating the baseline for a given project rather than generating comparable and validated data within cities or beyond. On the district level, a more detailed approach is needed, since spatial factors influence several freight transport indicators [2–4]. Therefore, the LOGI-TOOLKIT project carried out a search for existing, comparable, and transferable datasets for a set of urban district-types. The literature review shows (a) a lack of comparable data sets, (b) strongly differing survey designs and results, and (c) a general need for more research on correlating freight data (see Table 1).

Table 1. Selected studies indicating freight (trip) demand (for two district types). Due to differing methodologies and survey designs, the data is mostly not directly comparable.

	Location	Estimated number of deliveries	Indicator categories	Description
Historic Center	Szczecin [5]	1.2 deliveries per establishment / workday	F(W)A, FTA	Generalised number of deliveries divided into three sectors of economic activity (50% of general deliveries connected to retail)
	Angers [4]	4 – 6.6 deliveries per establishment / week	FTA	Study also shows number of deliveries for eight sectors of economic activity and nine urban types
	Domkyrkin (Gothenburg) [2]	8 deliveries per establishment / week	FTA, FWA, FTP	Study shows shipments as well as deliveries for five economic sectors
	Düsseldorf [6]	0.5 deliveries per establishment / workday	FA, F(W)A, FTA	Deliveries and consignments surveyed alongside a spatial differentiation
Shopping street	Oslo (Grensen, Bogstadveien, Karl Johan) [5]	5 deliveries per establishment / week	F(W)A, FTA	Besides indicated deliveries, also the weight of deliveries and their shares along three sectors of economic activity are described
	Angers [4]	5.7 deliveries per establishment / week	FTA	See above

(*continued*)

Table 1. (*continued*)

	Location	Estimated number of deliveries	Indicator categories	Description
	High Street (Winchester) [7]	2.05 deliveries per week, establishment and $100m^2$	FTA	Besides deliveries per week, the study also quantifies the share of different vehicle classes in deliveries
	Friar Street (Reading) [7]	23 deliveries per establishment / week	FTA	

In the following subsection, our approach used to gain additional insights in the acceptance of different pick-up points for parcels on a district level is presented.

2.2 Assessing e-commerce Delivery Options

Delivery of goods ordered on-line has significantly increased in recent years at least partly due to the COVID pandemic. Logistics companies have optimised their delivery services with respect to technology and organisation but have not fully integrated the delivery preferences of consumers into their business models. Currently, there are data on how many packages are ordered on average by which target groups in the business to consumer (B2C) sector. What is mostly missing, however, is valid data that depicts individually varying delivery preferences and consequently also the choice behaviour between the options of home delivery and deliveries to pick-up points (e.g., parcel lockers or stores). To close this data gap the project conducted a representative online Stated Choice (SC) survey with 505 respondents in Austria. The respondents were drawn according to the distribution of the characteristics of age, gender, and federal state within the total population of Austria. Findings from similar studies were considered in the survey design, although data transferability was limited due to different research questions, methods, and local conditions.

In a SC survey respondents choose from a series of decision situations (in this research 12 per participant) between the two alternatives of home deliveries or deliveries to a pick-up point. In determining the attributes and levels of these alternatives, care was taken to ensure that the attributes (a) describe the general problem well, (b) have a strong influence on the decision choice, (c) are easy to understand for respondents, and (d) are well suited for modelling different use cases and forecasting scenarios. In addition to the alternative-specific attributes, the following attributes are included in the utility function of the two alternatives:

1. Pick-up point (parcel shop/locker): ordered product type/product size, distance to residence, location, access/opening hours, availability of free parking
2. Home delivery: ordered product type/product size, price surcharge for home delivery

The variation of the different attribute levels per choice situation was done by efficient D-design with the software Ngene. In addition to the delivery decision attributes,

the survey collected information on sociodemographic and previous online shopping behaviour. Sociodemographic data was queried according to the available 250-m grid data from Statistics Austria.

Based on this representative dataset, a binomial logit model was developed in ALOGIT to estimate future delivery behaviour and the potential market share of home deliveries and deliveries to pick-up points for a given planning area.

Parameter estimation was conducted in a multistep process. In the first step, all SC attributes were included in the so-called basic model. Subsequently, the basic model was successively extended by attributes of sociodemographic and surveyed delivery behaviour. This procedure has the advantage that the robustness of the parameters estimated in advance can be controlled.

It was found that very robust results were obtained with small ranges of variation. For the identification of the final model, all non-significant attributes were removed from the model. Thus, the final model (6060 data sets, $\text{Rho}^2 = 0.11$) contains only statistically significant parameters. The most important attributes affecting individual behaviour were found to be a price surcharge for home delivery, the distance from the pick-up point to the place of residence, the parcel size, and free parking for a car. The temporal possibility of picking up parcels and the location of the pick-up point have no significant influence.

Overall, these results show that the underlying model approach and the selection of attributes and levels were appropriately chosen since a high number of factors have a statistically significant impact on delivery choice behaviour. For planning at the district level, a wide range of parameters are available that can be used to model a variety of scenarios and use cases. Consequently, it becomes possible to identify and justify urban logistics measures supporting more efficient, climate- and user-friendly delivery services for the last mile.

3 The LOGI-TOOKIT Concept

The LOGI-TOOLKIT project objective is to build a digital platform offering users a variety of software applications designed to help better consider sustainable transport logistics measures in urban planning (specifically: the number and dimensioning of loading/unloading zones, parcel shops and lockers). The software was developed in an iterative and agile process using prototypes. It has been designed to encourage users to contribute improvements and additional data. Finally, since the tool is intended for use by a variety of stakeholders (including, at the end of the project, the public), it has been designed to be accessible at varying skills levels and interests.

The toolkit applications are wizard-like applications that combine (a) multiple data sources, (b) algorithms, parametrized with those data sources and providing further data sources, and (c) visualizations and managed content for presentation. These components should be easily exchangeable and/or extendable and could have a value on their own (see Sect. 2.2). Further, there could be variants of the same application using different data sources, algorithms, or presentations to have a comparison during the detailed planning and engineering process.

To maximise availability, accessibility and scalability, the platform should be a set of web applications and web services. It should not have any lock-ins regarding programming languages or developing frameworks, on the one hand to make use of skills of the researchers involved, on the other hand to be flexible over time.

A cloud-based environment can fulfil these requirements. Selecting a commercial platform at this stage of the project would be quite expensive and could lead to a technology lock-in. So, it was decided to start with a self-hosted Kubernetes platform configured for the project's needs. In case of a large user base or need for increased computational power in the future, the configurations could be easily moved to a commercially hosted cloud environment. The free software MicroK8s (http://microk8s.io) was used to set up a cluster on three rented Linux root servers. This solution provides the possibility to run and combine web applications in different technologies, i.e., to use different kinds of (containerized) database systems, visualization toolkits or other components with low administrative effort.

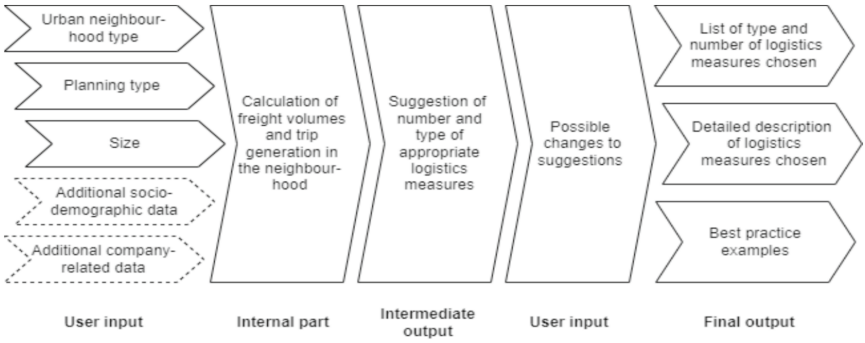


Fig. 1. LOGI-TOOLKIT process

The platform was created using the framework Shiny (https://shiny.posit.co/) since it offers input and output methods as well as visualisation components that can be combined to build wizards in an evolutionary approach. It further provides programming interfaces in both R and Python. A common version control system was integrated with cluster deployment tools to set up a continuous delivery pipeline, i.e., changes or extensions to the software can be immediately shipped to the collaborators for evaluation.

The application is a wizard including data input by users (district type, planning type and size), freight volume and trip estimation, and output of recommendations for appropriate urban logistics measures (number and type) as well as additional description and best practice examples (see Fig. 1).

4 Initial Results and Conclusions

The first prototype of the LOGI-TOOLKIT is currently being used to gather feedback from urban planners of two Austrian cities: Vienna and St. Pölten. The planners are being asked to apply the tool in several different districts in their cities. On the one hand

brownfield districts will be used to validate the appropriateness of the underlying data used in the toolkit, on the other hand greenfield districts will be evaluated by the toolkit to check the suitability and usability of the LOGI-TOOLKIT.

The initial feedback from urban planners confirms their interest in, as well as the need for, the LOGI-TOOLKIT. Nevertheless, additional logistics data on the district level is needed in the future to further improve the accuracy of decision support provided by the toolkit. Due to the work-in-progress state of the project detailed results of the use cases will be presented at the TRA conference 2024 in Dublin.

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Accounting for Environmental Impact in Air Traffic Network Operations: Carbon Dioxide, Costs and Policies

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Abstract. The work presented here has been developed in the framework of a research project entitled ERA (Environmentally Responsible Aviation, funded by Red.es). The objective is the development of a tool that enables, on one hand the estimation of consumed fuel for aggregated operations and, on the other hand, provides their attached environmental cost in the most likely scenario taking into account the different policies that are being developed to help the decarbonisation of the sector. A fuel consumption model that is able to estimate consumed fuel for a large amount of flight operations has been validated and a tool that translates this fuel consumed into cost within the most probable scenario based on policies has been created. The coupling of both enables the analysis of different future scenarios regarding fuel consumption and environmental policies, thus contributing to gain understanding of the impact on such policies and their viability.

Keywords: Air transport · Environmental policies · Sustainability · Fuel consumption

1 Introduction

Society is becoming more and more aware of the climate impact of different activities and major policies and agreements are being developed in order to minimize the impacts of climate change (The Paris Agreement, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), among others). Around 2% of human-produced CO_2 emissions come from aviation [1], and needs to be accounted for as a sector having an impact on climate and as an agent of change. So, the future of aviation is linked with its environmental impact. The work presented here has been developed in the framework of the research project ERA (Environmentally Responsible Aviation), funded by Red.es. The objective is the development of a digital prototype able to forecast demand, passenger distribution and the environmental cost of future aviation operations according to the current and upcoming policies.

The project seeks to respond to one of the most important challenges facing the air transport industry: ensuring the financial viability of the business to meet society's

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transport needs while accounting for the environmental impact of its operations in a way that does not compromise the future of generations to come. The objective of the project is to forecast demand and passenger flow at network level, considering all operations from US to Europe and vice versa, along with their environmental impact. This project relies strongly on data for its development, so a data lake composed of several different datasets involving demand, flight operations, fares, etc., data has been built.

May an example illustrate the scope of the project: the passenger flow between two airports (also known as an Origin Destination (O&D) pair). The first module of the project forecasts the demand between these two airports, that being the total number of passengers flying from one airport to another. However, there can be many itineraries that cover this trip, from a single direct flight to trips involving one or more air connections between this origin-destination combination. The second module of the project is able to predict the traffic allocation (percentage of passengers taking each itinerary) using artificial intelligence techniques and; lastly, a third module estimates the environmental impact and cost of each one of the different solutions.

2 Emissions Quantification

The environmental module of ERA consists of a model able to provide estimated fuel consumption for aggregated metrics. The challenge in this part resided on the fact that most of the widely used models rely on granulated data, such as trajectory data, meteorological data, etc., as these data have an impact on the total consumed fuel. However, in this case, the objective is to be able to perform analysis at network level, meaning for the total number of flights flying a given itinerary during a large period of time. By doing so, we aim at reducing the dimensionality of the data required and thus, the computational cost. A new model has been developed and validated using both different aircraft performance data, and actual fuel consumption in a wide range of routes provided by airlines.

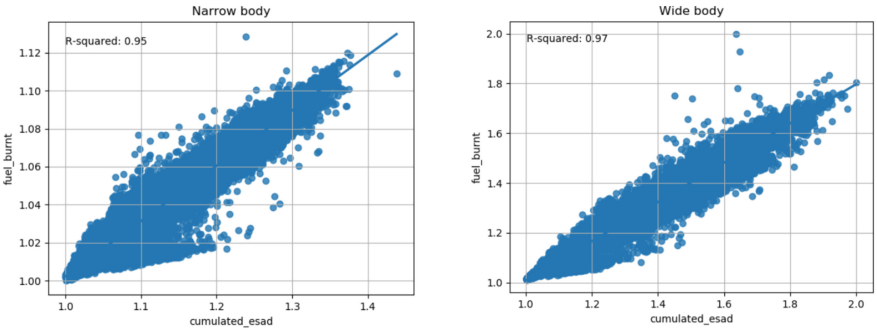


Fig. 1. Fuel consumption as a function of ESAD for a typical narrow body and a typical wide body aircraft. (Source: own elaboration)

The result is a linear correlation of fuel burnt vs ESAD (Equivalent Air Distance, which takes the effect of winds into consideration) for each aircraft model. An example of

this type of function is shown in Fig. 1. The model thus provides the fuel burnt for a flight using the origin, destination, month and aircraft type as only inputs. The average ESAD for a given route at a given month is obtained from historical data. This approximation enables us to estimate the fuel burnt for large amounts of flights in aggregated metrics. The consumed fuel is then translated into CO_2 emissions using a linear relationship and finally, it is translated into cost for the airline.

3 Environmental Scenarios

The need to apply all possible efforts to control and reduce air transport CO_2 emissions was introduced in ICAO's policy after the publication of the International Panel on Climate Change (IPCC) study in 1999 [2]. The adopted action line covered four groups of measures, colloquially baptized as *four pillars*, including new reduction technologies in the new aircraft, engines and systems, Air Navigation and operating procedure improvements, Environmental optimization of aeronautical infrastructures, and finally the introduction of Market based Measures (MBM). Four categories were established and evaluated: Voluntary agreements, Environmental charges, Environmental taxes and Emissions Trading [3].

As no general agreement was achieved within ICAO in these four systems worldwide application, a compromise solution was approved in 2016, establishing a scheme to offset the yearly amount of CO_2 emissions that exceed the global level of the average 2019–2020 years. This CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) has already started although the first three years are a testing period, and the number of participating States will be increasing in the subsequent period [4].

The application of the other MBMs is left to the criteria of each State. For the time being, just the European Union has enforced the EU Emissions Trading System (ETS) to the flights between two points in its territory since 2013. Up to eight People's Republic of China provinces have decided to include air transportation in their local Emissions Trading System. In addition, several other countries around the world have in study or subject to legal approval other MBM economic mechanisms to be applied in this field.

A key element affecting aviation CO_2 economics is the way in which Sustainable Aviation fuels (SAF) are treated in these schemes. For CORSIA purposes, ICAO is evaluating each approved SAF in terms of Life Cycle Analysis (LCA) CO_2 emissions, compared with standard kerosene. Assuming burning 1 kg of kerosene emits 3.16 kg of CO_2, each type of SAF is considered, in terms of CO_2 emissions, as the percentage of its Life Cycle CO_2 emissions compared with the kerosene LCA. The EU ETS has simplified the equivalence and, up to now and in terms of payment, it assumes that SAF is Zero CO_2 emissions.

As the present situation is very dynamic, some of the ruling likely to be approved (mainly taxes on fuel and/or CO_2) in the short-medium term are added to the enforced legislation. Then, in terms of environmental cost, the model allows the evaluation of the following measures:

- CORSIA emission units to be compensated (where and when applicable)
- ETS emission allowances (where and when applicable)
- Extra cost of the SAF amount uploaded for the flight (if applicable)

– Fuel tax (if applicable)
– CO_2 tax (if applicable)

The CORSIA mechanism has been slightly changed by the pandemic effects of COVID-19. As it is now, the reference level is the 2019 CO_2 emissions from international flights of participating States. The first three years (2021–2023) are a pilot period to prove the system performance. The initial payments will be done in 2024–2026 by the voluntary states that have joined the program. Starting in 2027 up to 2035 all states with high international traffic will be participating. The present status of participation in CORSIA is shown in Fig. 2.

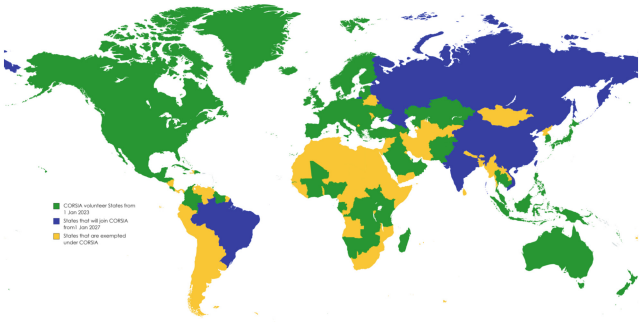


Fig. 2. States having confirmed their participation in different CORSIA phases. Green color are States participating in the voluntary phase 2024–2026, blue color are those States joining in 2027. In yellow are those not having communicated their decision yet. (Adapted from IATA (2024))

CORSIA system tries to apply CBDR (Common But Differentiated Responsibility) principle. Then, payment for emission excess in 2004–2026 will be the same for all participating airlines, proportional to their size. Starting in 2027, payments will begin to have a common part, paid in the same way, and another one depending on each individual airline emissions and paid according to the emission growth of each individual airline.



Fig. 3. Price evolution of 1 CO_2 ton emission allowance in euros. (Source: Trading Economics, May 2023)

The EU ETS works as a cap-and-trade system, and it has been well accepted while free emission allowances were plenty and allowance price was low. However, the UE

declared purpose is to progressively reduce free allowances during the 2024–2026 period. In 2027 all CO_2 emissions from standard kerosene will have to be paid at relatively high prices (see Fig. 3). Therefore, from 2027 CO_2 emissions in intra-European flights will be paying a charge proportional to their weight. Assuming SAF rule remains the same, the paying amount of fuel will be only the standard kerosene and SAF will be exempted, although there are some proposals to adopt the same ICAO CORSIA criteria in the near future.

The introduction of relevant SAF quantities will increase the fuel cost for the airlines, because SAF is assumed to be more expensive than conventional kerosene. By that reason, it is generally accepted that the States will do the introduction through legal mandates. In the EU, the proposal recently approved by the Parliament mandates all European airports to provide fuel with a minimum SAF content, starting with 2% between 2025 and 2030, and increasing progressively up to 63% in 2050 (with a minimum of 28% *e-kerosene*). At present, SAF is between 3 and 4 times more expensive than standard kerosene, then fuel price should be corrected with the adequate factor reflecting SAF prices in each period.

The tax on aviation fuel is one of the most exhaustively studied measures. The main problem is that ICAO Chicago Convention recommends not to tax elements uploaded to be consumed during the flight. This applies to international flights and different States tax fuel for domestic flights as it can be seen in Table 1.

As there is a direct relationship between the consumed fuel and the emitted CO_2 the economic effect of a tax on CO_2 would be similar. However, there is an important difference: tax on fuel would be paid when buying fuel while tax on CO_2 would correspond to the burned fuel and both actions might be done in different States. The calculation of SAF effects might also be different.

Table 1. Fuel tax on domestic commercial flights (Source: CE Delft [5] and own elaboration).

State	Tax (€/liter)	% of tax on the average fuel price
Australia	0.02	6%
Canada (average)	0.08	7%
Hong Kong	0.70	175%
Japan	0.14	34%
Mexico	0.13	25%
Philippines	0.07	17%
Saudi Arabia	0.02	5%
Thailand	0.10	25%
USA (average)	0.01	9%
Vietnam	0.11	28%

The application of the majority of these cost concepts depends on two variables: the States of the origin and destination of the flights and the calculation year. Therefore,

modeling environmental route cost needs the preparation and actualization of some tables that reflect the economic impact of the different measures:

- ETS evolution, including the list of EU and associated States applying this system and the percentage of free emission allowances in each year
- CORSIA evolution, including CORSIA States participation and the way of payment in each year
- SAF percentage mandate in different States each year
- Different approved SAF prices and CO_2 savings in terms of LCA
- Fuel tax in each State
- CO_2 tax in each State

4 Conclusions

In the context of the ERA project, a fuel consumption model that is able to estimate consumed fuel for a large amount of flight operations has been validated and a tool that translates this fuel consumed into cost has been created. The coupling of both enables the analysis of different future scenarios regarding fuel consumption and environmental policies, thus contributing to gain understanding of the impact on such policies and their viability.

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Energy Consumption Evaluation of Emerging and Current Vehicle Fleets in Urban Logistics

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Abstract. Driverless multipurpose vehicles (DMVs) are an emerging vehicle concept for urban heavy-duty transport. However, little is known about their effect on urban road transport systems. Thus, the aim of this study is to analyse the total fleet energy consumption of DMVs for specific transport operations in urban logistics compared to heavy-duty battery and combustion vehicles. A novel electric vehicle routing problem was used to simulate in total 96 case-studies of operations with varying network and vehicle fleet properties. We found that the combustion vehicle fleets consumed significantly more energy for the same operation compared to the electric vehicle fleets. Although the DMV fleet and battery electric vehicle fleet showcased similar energy consumption for most case-studies, there were several operations where the DMV fleet consumed less energy and required a smaller fleet size. This study highlights the potential benefits of DMV fleets in urban logistics operations in terms of reducing total fleet energy consumption and fleet size.

Keywords: vehicle routing · energy efficiency · urban transport · green logistics · reverse logistics · autonomous modular vehicles · electric vehicles

M. Nybacka, E. Jenelius, C. J. O'Reilly and E. Falkgrim—Contributing authors.

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1 Introduction

Road transport activities are predicted to increase globally. By 2100, global freight and passenger road transport is estimated to have increased between one-half to over four times compared to 2020 depending on the scenario [1], and around 85% of the global population of over 10 billion will live in urban areas [2][3]. These predictions stress the importance that systematic changes and transformations are needed in urban transport systems to meet rising transport demand while reaching sustainability targets. Currently, the transport sector is undergoing a transformation driven by the technological trends of electrification, automation and connectivity [4]. New transport solutions, business models and vehicle concepts are emerging as a response to these challenges and trends.

Driverless multipurpose vehicles (DMVs) are an emerging electric road vehicle concept for heavy-duty transport in urban environments that can change their transport application or combine different applications simultaneously during transport operations. They have the potential to significantly improve urban road transport by enabling a higher degree of vehicle utilisation compared to conventional vehicles with a fixed transport application [5]. Despite these potential benefits, there is a lack of understanding of how emerging modular vehicle concepts such as DMVs influence efficiency and sustainability in the urban road transport system.

In this study, the purpose is to investigate the research question: *What is the impact of DMVs on the total fleet energy consumption for a specific transport operation in urban logistics compared to conventional heavy-duty road vehicles?* This question is analysed by using a mixed-integer linear programming model to simulate a number of different transport operations performed by either a homogeneous heavy-duty vehicle fleet of battery electric vehicles (BEVs), and combustion vehicles (CVs) or DMVs.

2 Methodology

The mixed-integer linear programming model considered in this study was formulated as a novel variant of an electric vehicle routing problem with similarities to the studies by Basso et al. [6] and Kopfer and Vornhusen [7]. The flow diagram in Fig. 1 summarises the modelling process that consists of three main phases: pre-processing (1–5), solution process (6–7) and post-processing (8).

The first step was to generate a network of customers. The customers were spatially distributed around a single depot according to a uniform distribution within a flat circular area with radius of 20–40 km in line with distances found in metropolitan areas of Stockholm, Sweden. These networks consisted of six or twelve customers with randomly generated freight delivery and waste pickup demand within a case-study specific limit. For instance, the case-study 01D01P denotes that each customer request can vary up to 0.1-ton freight delivery and waste pickup demand. No charging stations or service time considerations were included. In addition, all operations were assumed to occur at an ambient temperature of 20° Celsius. The maximum allowed speed (30, 50, 70 km/h) on the

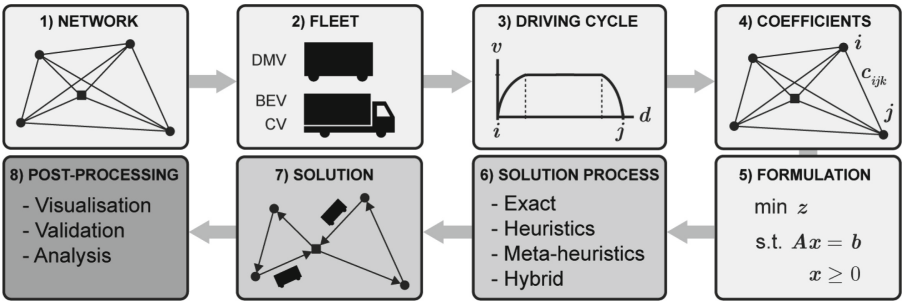


Fig. 1. Flow diagram of the implemented modelling process

edges between customers were randomly assigned and the rolling resistance coefficient was considered to be the same on all edges.

In the second step, the properties of each fleet type and vehicle class were decided. Table 1 provides a summary of the three fleet types with two vehicle gross mass classes and their parameters. Each parameter in the table was further divided into two instances of lower performance values to the left and higher performance values to the right.

Table 1. Vehicle parameters for all vehicle fleet classes with 4×2 axle configuration

Vehicle type	DMV(7.5)	BEV(7.5)	CV(7.5)	DMV(18)	BEV(18)	CV(18)
Vehicle mass (tons)	4.0/3.0	4.5/3.5	4.0/3.0	6.5/5.5	8.3/7.3	6.2/5.2
Payload mass (tons)	3.5/4.5	3.0/4.0	3.5/4.5	11.5/12.5	9.7/10.7	11.8/12.8
Energy content (kWh)	60/100	60/100	500/900	200/375	200/375	1800/2200
Power auxiliary (kW)	5.0/3.0	4.0/2.0	0.4/0.2	5.0/3.0	4.0/2.0	0.4/0.2
Powertrain efficiency	0.6/0.9	0.6/0.9	0.1/0.3	0.6/0.9	0.6/0.9	0.1/0.3

There are several significant differences between the fleet types. Firstly, the CV fleet has the highest payload capacity with lowest vehicle mass. The mass values in the table stem from the following: CV(18) FE818 4×2 Platform [8], BEV(18) FE Battery Electric 4×2 Platform [8], CV(7.5) MAN TGL [9], BEV(7.5) ORTEN [7]. The BEV fleet has a lower payload capacity with higher vehicle mass mostly due to heavy batteries. The DMV fleet was assumed to operate with full driving automation, whereas the BEVs and the CVs were manually driven. Hence, the DMV fleet exhibited higher payload capacity than BEVs, yet equal or lower than CVs since it had no driver cabin but heavy batteries. Secondly, the CVs have a considerably higher driving range. The combustion vehicle classes hold 50–90 L and 180–220 L of diesel fuel, respectively [7]. These volumes of fuel were converted into energy by using the conversion factor 35.7 MJ/L [7] to enable a comparison between vehicle types. The energy content values for

the electric vehicles in the table stem from original equipment manufacturers [7] [10]. Moreover, most vehicles have power auxiliary systems running, such as heating systems, battery management systems or autonomous vehicle technology. The power auxiliary value of 3 kW was chosen as an intermediate value for manually driven BEVs [6], and was used as reference to set the values for CVs and DMVs. The DMV fleet was assumed to have the highest power auxiliary demand due to its autonomous systems. Furthermore, electric vehicles have a significantly higher powertrain efficiency compared to CVs [9][11]. The powertrain efficiency was assumed to be constant during acceleration, steady speed and braking. Lastly, it was assumed that vehicle classes with equal masses have the same acceleration (0.6–1.0 m/s^2)[6], braking (0.7–1.1 m/s^2) [6] and aerodynamic properties (drag coefficient: 0.6–0.9, frontal area: 7–10 m^2) [9] depending on the lower or higher performance case. The DMV fleet consisted of a modularity type with a fixed vehicle body attached to a vehicle chassis, where the transport application changes as the inside of the vehicle body changes. For the cases with combined demand, it was assumed that all vehicle fleets consolidate the freight and waste with the same vehicle body in an innovative manner.

During the third step, the driving cycle on each edge between customers was prescribed. We assumed that each vehicle accelerates to the maximum allowed speed on the road and thereafter travels with constant speed until braking to stand still at the next customer. No energy regeneration during braking was considered. In the fourth step, the energy cost coefficients indicating the required energy to travel across edges between customers were determined. These coefficients may significantly differ between vehicle types, classes and edges. An overview of how to compute these coefficients are described by Basso et al. [6].

The remaining steps in the process set the problem formulation with the objective function, solves the problem and visualises the solution. The objective of the model was to find the fleet size and the transport routes that minimised the total energy consumption of the fleet while satisfying the transport demand of the customers in the network. This objective considered the energy related to overcoming motion resistance and power auxiliary systems during operations. To determine the optimal solution for each case-study, the commercial solver IBM ILOG CPLEX 22.1.1.0 with exact algorithms was used.

3 Results and Discussion

Figure 2 presents one example of an optimal solution for a simulated case-study with twelve customers. In this solution with a higher performance 18-ton DMV fleet, four routes were required to serve the transport demand.

Table 2 summaries the total fleet energy consumption (kWh) and fleet size from 96 case-studies for different combinations of vehicle fleets, vehicle classes, performance levels, transport demand, and network size. For instance, 103_5 denotes that the fleet consumed 103 kWh of energy and required five vehicles to perform the operation. Furthermore, 6C-20 stands for a network with six customers and a maximum distance from depot of 20 km. All cases simulated

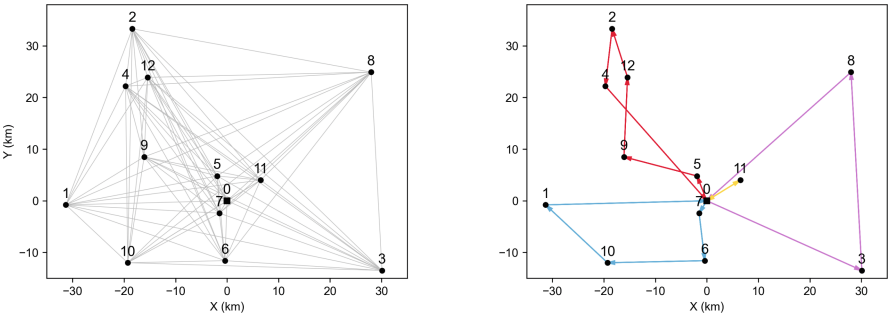


Fig. 2. Original network and optimal solution for the case DMV18-H-12C-40-4D2P

simultaneous operations of freight delivery and waste pickup to serve customer requests, except the business-as-usual scenarios (1D0P, 0D05P, 4D0P, 0D2P) with separate delivery and pickup operations.

Table 2. Summary of the energy consumption evaluation of all case-studies

6C-20	DMV(7.5)	BEV(7.5)	CV(7.5)	6C-40	DMV(18)	BEV(18)	CV(18)
01D01P	$39_1/18_1$	$38_1/17_1$	$161_1/33_1$	1D1P	$81_2/38_2$	$85_2/40_2$	$379_2/86_2$
3D1P	$103_5/42_4$	$110_6/41_5$	$528_5/95_4$	8D1P	$116_4/56_4$	$139_4/61_3$	$572_4/132_4$
1D05P	$52_2/24_2$	$51_2/22_2$	$240_2/50_3$	4D2P	$125_3/61_3$	$131_3/63_3$	$604_3/140_3$
12C-20	DMV(7.5)	BEV(7.5)	CV(7.5)	12C-40	DMV(18)	BEV(18)	CV(18)
01D01P	$74_2/33_1$	$72_2/30_1$	$298_1/62_1$	1D1P	$229_2/105_2$	$239_2/110_2$	$1136_2/259_2$
3D1P	$155_{10}/54_8$	$163_{11}/58_{10}$	$793_{10}/124_8$	8D1P	$302_6/143_6$	$354_8/161_7$	$1533_6/345_6$
1D05P	$92_3/42_2$	$90_3/40_3$	$407_3/86_3$	4D2P	$244_4/123_4$	$270_4/132_5$	$1175_4/292_4$
1D0P	$89_3/40_2$	$87_3/38_3$	$387_3/79_2$	4D0P	$218_4/109_3$	$247_4/118_4$	$1018_4/244_4$
0D05P	$78_2/35_1$	$76_2/32_1$	$310_1/66_2$	0D2P	$187_3/93_3$	$196_3/96_3$	$863_3/201_3$

It is apparent from the table that CV fleets showed the highest energy consumption for all cases. This is mainly due to CVs low powertrain efficiency compared to electric vehicles. Closer inspection of the table showed that the DMV fleet consumed energy similar to the BEV fleet in most of the case-studies. However, a few cases stand out. The DMV fleet requires less energy and smaller fleet size than the BEV fleet in case-studies with more than six customers and high vehicle utilisation. This is illustrated in the cases: 12C-20-3D1P, 12C-40-8D1P and 12C-40-4D2P. In the business-as-usual scenario, all the case-studies consumed around 50–80% more energy than their corresponding case with simultaneous pickup and delivery operations.

4 Conclusion

This study compared the total energy consumption of emerging driverless multipurpose vehicle and battery electric vehicle fleets against current combustion vehicle fleets for specific transport operations in urban logistics. We found that the BEV and DMV fleets exhibited a significant lower total fleet energy consumption compared to the CV fleets for all cases. The CV fleets consumed on average around two to five times more energy for the same operation. Furthermore, the differences in energy consumption between the DMV fleet and BEV fleet were small in most case-studies. Nevertheless, in a few but important cases the DMV fleet consumed less energy and required a smaller fleet size. Thus, these findings highlight the potential benefits of DMV fleets in urban logistics operations in terms of reducing total fleet energy consumption and fleet size.

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Sustainable Mobility: The Contribution of Railways to Decarbonization

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Abstract. The transport sector plays a key role in the socio-economic development of countries. Currently, this sector faces challenges as one of the largest emitters of greenhouse gases. Implementing new policies to reverse these emissions may face some social challenges, considering the need to rethink habits and mentalities. In the context of climate transition, will the sector be able to ensure that the mobility needs of people and goods on cross-border journeys in Portugal and Spain continue to be met? The future of the railroads in Portugal, as part of the European network, will be determined by the investments planned for the coming decades, especially in terms of reducing travel times and increasing connections. This study analyzes the viability of high-speed rail as the main mode of transport for medium-distance journeys, comparing air and rail bridges on an Iberian scale. The emissions balance demonstrates that the electric train is considerably less polluting than the airplane. The survey findings show that the main criteria for choosing a mode of transport are travel time and ticket cost. The train proves to be more advantageous than the plane for short journeys, but as the distance increases, the train becomes less advantageous than the plane. In conclusion, the high-speed rail is an alternative to air travel if the travel time and costs are lower or identical, although the connections analyzed show that there is currently no high-speed rail in Portugal and that the network is poorly connected to the rest of Europe.

Keywords: High-speed rail · Air passenger transport · Iberian Peninsula · Climate action · Mobility strategies · Trans-European Transport Network (TEN-T)

1 Introduction

The latest variations in global climate are a warning of the need for change. Sustainable Development implies limits [1] and is based on meeting the needs of the present without compromising the ability of future generations to meet their own needs (Binder, 2013, cited in [2]). As well as contributing to mobility, transport is essential for meeting the objectives relating to the sustainable development processes of cities, regions and

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countries [3]. The mobility and transport sector is one of the biggest contributors of global emissions [4]. Reducing greenhouse gas (GHG) emissions in the sector is a priority in the effort to limit climate change and global warming. In 2019, the sector accounted for 33.5% of total transport GHG emissions in the 27 Member States of the European Union compared to 1990, representing an upward trend [5].

This paper intends to study the possibility of replacing Portuguese and Iberian air bridges with HSR, whenever this is an alternative. Accordingly, it is intended to analyse the evolution of demand associated with the environmental impact of the two modes of transport, considering the influence of GHG emissions, driving towards sustainable mobility. The necessary evolution of national infrastructures will be considered, as well as how new rail infrastructures can contribute to reducing travel times and the costs associated with travel.

2 Methods

In order to examine the viability of rail transport as an alternative to air transport on the major Portuguese and cross-border routes between Portugal and Spain, it was necessary to identify the most important routes on which most of the traffic between the two countries falls. Following this, for each of the routes identified, in order to be able to compare a journey by plane and train with the same origin-destination, CO_2 emissions were calculated using the *EcoPassenger* calculation tool [6]. To obtain the results, the distance, average occupancy, and type(s) of fuel used by each means of transport throughout the journey were considered, allowing the most critical routes and the most environmentally efficient type of transport to be identified. An important part of the study is to see how receptive the general population is towards the option of high-speed rail for their short and medium-distance journeys, as an alternative to air travel. It should be noted that for air travel from Lisbon to Badajoz (Lisbon-Madrid-Barcelona axis) and from Porto to Vigo (Porto-Madrid and Madrid-Vigo) it was necessary to estimate CO2 emissions based on journeys with similar specifications, as it was not possible to obtain specific data.

A survey was created using the Google Forms tool and made available to respondents on site and on online platforms, for a period of 2 consecutive months. The main intention was to investigate the major criteria when choosing a type of transport and how receptive passengers were to choose to travel with environmental criteria into account. For each route, up-to-date data was made available such as the journey time (including check-in and boarding time), the number of stopovers/transfers, the price of the journey (cheapest, bought 15 days in advance) and the type of fuel used. In addition, the main challenges and advantages associated with the construction of these high-speed lines were identified. Subsequently, the answers obtained by the respondents were processed analysed to carry out the discussion of the results.

3 Results and Discussion

The specific emissions obtained (Table 1) consider the average occupancy and the type of vehicle for each of the routes considered, including the emissions associated with the production and distribution of fuel. Regarding the emissions obtained on the route

between Lisbon and Oporto, the train journey results in around 15 times fewer CO_2 emissions than an airplane journey and, in the case of the journey between Lisbon and Faro, this difference is even more evident, since the impacts of an airplane journey are around 19 times greater. On the Lisbon-Madrid-Barcelona routes, the differences in emissions are once again in favour of journeys made by train, although they're not as pronounced as the previous ones (in both cases around 4 times lower), due to the increase in distance and the type of fuel used by the different trains. In this case, the lower difference could be explained by the need to run diesel trains.

Table 1. CO_2 emissions are accounted for by mode of transport and specific routes.

Current routes	CO_2 emissions per passenger "well to wheel"			
	Plain		Train	
	Distance	Emissions (kg CO_2)	Distance	Emissions (kg CO_2)
Lisbon-Oporto	277 km	102,1	306 km	6,7
Lisbon-Madrid	513 km	195,7	625 km	73,6
Lisbon-Barcelona	994 km	310,6	1236 km	83,9
Lisbon-Faro	222 km	109,6	274 km	5,8
Oporto-Vigo	905 km	[1] 403,3	151 km	[2] 56,1

The connection between Oporto and Vigo has no direct flight and the journey has to include a stopover in Madrid, contributing to a substantial increase in the number of kilometres travelled and the number of take-offs and landings. As a result, this is naturally the route with the highest emissions per passenger-kilometre. Although the distance between these cities is the shortest in the study, the emissions resulting from train journeys are considerable, as the journey is made on a diesel-powered train, even though the track is fully electrified. This means that CO_2 emissions are substantially higher, but compared to the airplane, they are still around 7 times lower.

The results show that CO_2 emissions per passenger on journeys with the same origin-destination differ considerably depending on the distance, the type of vehicle and the fuel used. Airplanes are the most CO_2-intensive, especially over short distances where the differences are more pronounced than trains. Take-off and landing contribute significantly to airplane emissions, but as the distance increases, the differences in emissions compared to the train gradually become smaller. When the journey is taken exclusively by electric train, the differences in emissions are considerably smaller (Lisbon-Oporto and Lisbon-Faro), especially when the production of electricity includes the use of a share of renewable sources. However, even when it involves the use of one or more fossil fuel trains (Lisbon-Madrid, Lisbon-Barcelona and Oporto-Vigo), the train maintains a lower carbon intensity than the plane.

Survey Results

The aim of the survey was to assess people's main motivation, demotivation and the weight of the environmental impacts inherent in choosing to fly or take the train. It

generated 352 responses. Among the main motivations for choosing the plane is travel time, where the vast majority (around 70%) consider it to be a very advantageous factor. In addition, safety, comfort and infrastructure are also advantages related to this type of transport. The disadvantages include the associated pollution, the need for additional transport and the cost of tickets. For rail, the motivations are the cost of the journey, the reduced pollution and the safety of the transport. There is no evidence of any very disadvantageous indicators, although infrastructure and the need for complementary transport are the ones with the highest number of "slightly unfavourable" responses. Figure 1 shows a direct comparison, relating each parameter in order to choose the transport mode they consider most beneficial. Travel time is the main aspect associated with air transport and boarding time with the train.

Approximately 76% of people are willing to have a maximum of 1 stopover per plane journey and more than 60% consider it acceptable to make a maximum of 1 transfer. For a trip with the same origin-destination, assuming the train as an alternative to the plane, there is an increase in acceptance of making more transfers as long as the journey time is similar.

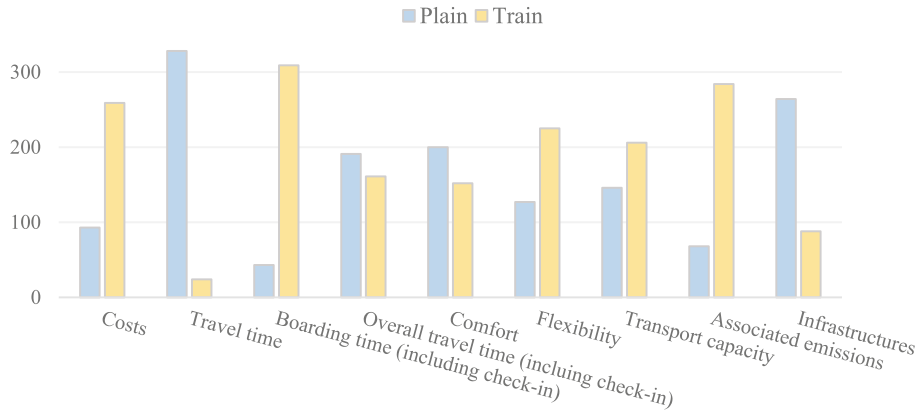


Fig. 1. Comparative analysis between plane and train, considering different parameters.

In order to assess each participant's ecological concerns regarding the choice of transportation, more than half of the respondents agree that the train is less polluting than the plane and a large proportion express concern about the GHG emissions associated with their journeys. However, it can be seen that environmental issues are not the main criteria for choosing a particular type of transport. Slightly more than 6% say they always consider the ecological footprint associated with their journeys when choosing their mode of transport and 9% opt always for environmentally efficient transport whenever possible. Although more than 45% of people say they always or almost always feel that their choices can make a difference, there is a noticeable reduction in the number of positive responses when it comes to influencing others to choose more sustainable forms of travel.

The national connections (Lisbon-Oporto and Lisbon-Faro) represent a high passenger demand. For those corridors, both modes have direct connections. The findings show

that the plane has the most beneficial criteria in terms of total travel time and comfort. In the case of the train, the vast majority of people selected ticket price and emissions as the main advantages. For the cross-border connections (Lisbon-Madrid-Barcelona), the lack of direct train links is reflected in a long journey time, and, despite the cheaper price, people do not see it as a benefit. The only benefit associated with the train is emissions. On the other hand, the direct nature of an airplane trip in a shorter travel time, even considering the time needed to get to the airport for check-in, makes this the main advantage selected for the airplane, with comfort, the quantity of supply and price also standing out.

4 Conclusions

The links analysed show that there is no high-speed railroad in Portugal, which makes it difficult to choose more environmentally friendly transport. The findings revealed that, for short journeys, respondents consider the train to be more advantageous in terms of travel time, cost and emissions. For long journeys (Lisbon-Madrid-Barcelona), the benefits that were associated with the train are now associated with the plane (time, cost, comfort, quantity offered), with the exception of emissions. The results show that the majority of respondents consider that they would use the train as an alternative to the plane if the journey time and cost were similar and if there were not a higher number of transfers.

Most respondents consider HSR to be a good alternative to flying and believe that cross-border connections would help to connect Portugal with the European network. A significant proportion believe that domestic air travel is not justified when there's an alternative like HSR, but when cross-border travel is considered, the number of positive responses is not as strong. When considering the influence of the ticket price on the choice of HSR over air travel, it is confirmed that this is one of the main criteria, but the time factor remains more decisive.

The challenges identified are mainly related to economic issues, including the high construction investment and the costs of maintenance, and rolling stock, or the risks related to lack of attractiveness and low demand. Concerning the benefits identified, time savings are the main one. Revenue gains and income from operating fees, improvements in accessibility and connectivity between Portuguese and Spanish cities with high population density, as well as environmental benefits.

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Review of the Algorithms Used in Electric Vehicle Routing Problems for Last Mile Logistics and Shared Mobility Options

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Abstract. Vehicle routing problems (VRP) are one of the most widely studied problems in combinatorial optimisation. The Electric VRP (EVRP) is an extension of the VRP that has added constraints due to the restrictions of electric vehicles (EV). Transport emissions amount to around one fifth of global carbon emissions. Electrification of transport provides promising solutions to minimising transport carbon emissions. Both last mile logistics and shared mobility options show promising potential as solutions to reduce transport emissions through electrification. This paper presents a review of the algorithms used in EVRPs in last mile and shared mobility options. The algorithms used to solve these problems are analysed and discussed.

Keywords: Electric vehicles · Last mile logistics · Shared mobility · Vehicle routing

1 Introduction

In 2015, 196 parties adopted the Paris agreement, an international treaty on climate change [1]. The European Climate Law followed, setting a legally binding target of net zero greenhouse gas (GHG) emissions by all EU member states by 2050. Electrification of transport has shown promising possibilities in the area of reducing GHG emissions [2], leading to a significant increase in the number of EVs, causing two main concerns. Firstly, that there will not be sufficient charging points to meet consumer demand, and secondly that the increased load on the electricity grid in specific areas will lead to network overloading and unacceptably low voltage levels [3].

A high level objective of this paper is to identify how the transition to electrified transport will affect the electrical grid and the wider power system. This study provides analysis of algorithmic approaches used to solve electric vehicle routing problems (EVRP) in last mile logistics and shared mobility from the existing literature. A computational algorithm is a formal procedure for solving a well

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defined computational problem. The EVRP is derived from the capacitated VRP. It is NP-hard, meaning that substantial computational effort is required to gain optimal solutions even for medium size instances (larger than 100 customers). The approaches used are analysed, discussed, compared and contrasted. The literature was identified using a systematic literature review (SLR), which aims to answer the following research questions.

1. What are the state of the art algorithms used to solve EV last mile routing problems?
2. What are the state of the art algorithms used to solve EV shared mobility routing problems?

2 Methodology

This SLR aims to achieve a clear and comprehensive understanding of the information while helping to find gaps in the research field [4]. The goal of this SLR is to identify and analyse the algorithms used in EVRPs for last mile and shared mobility options, and to discuss the similarities, differences, crossovers and contrasting elements of the solution approaches. The search was restricted to the following string to identify the relevant papers: ("last mile" OR "shared mobility") AND ("optimisation") AND ("electric vehicle" OR "EV").

The search string was entered in the ScienceDirect database, where 22 results were obtained, and in the IEEE database, where 2 results were obtained. For the purpose of this short review, the 14 papers with a clear solution approach to an EV routing optimisation problem were deemed relevant. This is a new and active research area, with the earliest published paper from 2015, and the majority published after 2019.

3 Results

Table 1 shows a taxonomy of the reviewed papers, grouped together to gain a better understanding of the problems addressed. The papers are first split into two categories in which there was no overlap, last mile logistics and shared mobility. These two categories are further broken down by the solution approach used to solve the EVRP element of the problems. The three categories are exact solution approach, heuristic and simulation. An exact solution approach is where a precise set of rules are used to solve a specific task, an optimal solution is guaranteed (if it exists) and the results are reproducible because the approach is deterministic. A heuristic solution approach consists of a collection of steps that guide one to a fast and feasible solution that is not necessarily optimal. When exact approaches are time consuming, heuristics are useful tools to obtain feasible solutions in a reasonable amount of time, trading optimality and accuracy against speed. Simulation modelling is the imitation of a system using a statistical model to enhance the understanding of the performance of the system that is being optimised.

Last mile can refer to the last stretch of the supply chain of goods, from the last distribution centre to the recipient's preferred destination. It can also refer to the last mile of a person's journey, from their transportation hub to their final destination.

For the shared mobility options, two different business models are evident in the analysed papers. Shared vehicles, where the vehicles are not privately owned, but the trip is private and shared trips, where customers going to different locations are transported in the same vehicle.

Table 1. Solution approach for different last mile and shared mobility problems

	Last mile		Shared mobility	
	Transporting goods	Transporting people	Shared trips	Shared vehicles
Exact	Breunig et al. [7], Raeesi [8], Al-dal'ain [10], Wang et al. [14], Zhenfang et al. [16]	–	–	Enzi et al. [5]
Heuristic	Breunig et al. [7], Raeesi [8], Lin et al. [17], Yang et al. [18]	–	Ma [13], Ma et al. [15]	–
Simulation	Napoli et al. [11], Martinez et al.[12]	Noussan [9]	Militao [6]	–

3.1 Last Mile Problems

Goods. Nine papers focus on the last mile logistics of distributing goods using three solution approaches. The papers that focus on an exact approach are limited to solving instances with smaller numbers of customers (less than 100). Al-dal'ain and Cebi's exact approach to planning a mixed fleet of EVs and internal combustion engine vehicles under routing and replacement is able to solve instances of up to 50 customers in a reasonable amount of time [10]. Wang et al. design a location routing problem (LRP) with pick up stations, where the delivery company can decide to deliver directly to the customer or to a pick up station. The LRP integrates operational decisions on vehicle routing with strategic decisions on the location of the facilities from which distribution will take place. The largest instance solved is 75 customers [14]. Zhenfang et al. solved instances of up to 25 customers for an EVRP with time windows, where there are penalty costs for violating the time constraints [16].

Two papers focus solely on using a heuristic approach. Lin et al. proposes an EVRP with time windows under time variant electricity prices, where the routing of the fleet is jointly optimised with the scheduling of the charging/discharging of the EVs from/to the grid, where discharging is defined as a vehicle to grid technology that allows EVs to inject power back into the grid at times of high

electricity prices [17]. This is a difficult problem that needs to be solved quickly as the optimal strategy is reliant on time of use electricity prices, meaning that good quality feasible solutions are required quickly. In practice, lagrangian relaxation (LR) along with a hybrid variable neighbourhood search (NS) is used here to obtain lower and upper bounds in a short amount of time. A hybrid LR and alternating direction method of multipliers (LR-ADMM) decomposition solution framework is constructed by Yang et al. and is used to solve instances of up to 149 customers of an EVRP with mixed backhauls and recharging strategies [18].

A combination of exact and heuristic approaches are used in [7,8]. Breunig et al. investigates a two echelon EVRP, where goods are transported from the depot to intermediate satellites and then transported from these satellites to their destinations. The first level is serviced by internal combustion engine vehicles (ICV) and the second level is serviced by EVs. The exact approach failed to solve instances of over 100 customers in a reasonable amount of time, whereas a large NS heuristic was able to solve larger instances [7]. Raeesi and Zografos propose a multi-faceted approach to increase the range of EVs by introducing a synchronised en-route battery swapping service performed at a pre-planned time and place, by battery swapping vehicles. Despite the introduction of a pre-optimisation procedure, the exact approach for this complicated problem failed to solve half of the problems with 100 customers as it is computationally expensive and time consuming. The multi-graph denominated path intensified large NS heuristic successfully solved all instances of 100 customers, showing that this heuristic can successfully solve the computationally expensive problems that exact approaches fail to solve in a reasonable amount of time [8].

TransCAD and ArcGIS are used in [11,12] respectively, as simulation tools. TransCAD is used on a small problem (84 customers), whereas ArcGIS is used to solve a postal fleet delivery problem of 25000 packages. Martinez et al. also investigate the impact that the routes will have on the distribution network [12].

People. There is one paper that investigated last mile mobility for humans. Based on a simulation, Noussan and Tagliapietra analyse the effect of digitisation on CO_2 emissions, comparing two digitisation scenarios [9].

3.2 Shared Mobility Problems

Trips. Ma and Xie aim to minimise total fleet idle time for eight seater electric buses in a dynamic vehicle charging station assignment model. Instances of up to 2000 customers were solved using a LR heuristic [13]. Ma et al. introduce a shared autonomous EV service with battery swapping stations. A speed optimisation procedure is incorporated into the optimisation of the routing, where the optimal speed across each arc is found. The problem is solved using an adaptive large NS heuristic, which successfully solves up to 108 customer requests, compared to the exact model that failed to solve 10 customer requests in 3 h [15].

Militao and Tirachini investigate the optimal fleet size to minimise cost for a shared demand response transport system with human driven vs automated

vehicles. The simulation tool MATSim is used to investigate fleet sizes of 50 to 4000 vehicles [6].

Vehicles. Enzi et al. propose a sustainable corporate mobility problem, with shared vehicles based at the office. This was a small problem with 5 users and 10 customers, therefore an exact approach successfully solved the problem [5].

4 Discussion

The most prominent problem addressed in the reviewed papers was the last mile logistics of goods. It is clear from analysing the papers that the heuristics used were able to solve larger instances of the problems than exact solution approaches in a reasonable amount of time. The heuristics used were based on neighbourhood search (NS) and lagrangian relaxation (LR).

The heuristics used to solve the problems in shared mobility, specifically shared trips, were also based on NS and LR, showing that there is overlap in these two fields, giving an answer to the first two research questions. The fact that Ma et al. failed to solve 10 customer requests using an exact approach, but solved up to 108 requests with a heuristic approach, emphasises the fact that heuristics can obtain feasible solutions in significantly less time.

In terms of the high level objective, 3 of the 14 papers addressed potential effects on the electricity grid. Martinez et al. analysed the impact that the chosen charging points in the routes will have on the distribution network. Lin et al. jointly optimise EV routing, with the charging/discharging schedule. Finally, Napoli et al. does not directly address the electricity grid but the paper is motivated by the reduction in cost for the system operator. These three papers have focused on last mile delivery, therefore none of the papers that addressed shared mobility options addressed the potential effects on the electricity grid. The vehicles under consideration were electric vehicles but the interaction with or dependence on the electrical grid was not considered, presenting a research gap.

5 Conclusion

The analysis of the SLR in this paper provides an insight into algorithmic approaches used in both last mile logistics and shared mobility options. The categories are further broken down and discussed to provide answers to the research questions posed in Sect. 1.

LR and NS based heuristics are identified as the state of the art algorithms used in both last mile and shared mobility EVRPs. The research gap has been identified by the lack of literature concerning the interaction with and dependence on the electrical grid. There is scope to build on the existing research to blend optimisation of the electrical charging infrastructure, charging strategies and the routing of EVs.

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Reduction of CO_2 Emissions Through Reusable Packaging

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Abstract. Within this paper, we present a case study on the potential CO_2 emission savings related to the employment of reusable packaging in the Courier, Express, Parcel (CEP) sector. We show an a hypothetical, yet realistic example the potential savings when the delivery of empty boxes (packages) to shippers and the delivery of full boxes to customers is combined with each other. In addition, the number of waste collection tours for paper/cardboard can be reduced. A reduction of up to 90% of transport related CO_2 emissions seems to be realistic.

Keywords: CO2 reduction · reusable packaging · circular economy

1 Introduction

During the COVID-19 pandemic, e-commerce underwent a major growth. E.g., for Austria, the daily parcel volume is at approximately one million parcels per day, cf. [8]. Although investigations exist showing that efficient (CO_2 saving) parcel logistics are possible [7], one major drawback still remains. Most e-commerce parcels are packaged with one of two methods: The first one relies on polybags [4]. Polybags are typically flexible packages made of polyethylene or polypropylene which could be recycled if properly disposed of. However, the recycling rate could be considerately improved [1]. The second usual packaging method is with cardboard boxes. Theoretically, cardboard boxes are a good alternative as they can be easily recycled. And even if they are not properly recycled and, e.g., burnt, this loss with respect to CO_2 emissions is rather acceptable (in Austria) as the timber growth in Austria is higher than the logging [2]. Therefore, the emitted CO_2 is renewable in a strong sense.

However, even if the CO_2 balance is positive (or at least equalized) the transport sector is not accounted for. On the one hand, the parcels have to be delivered to the customers. Currently, the main distribution method is by using light commercial vehicles. Some courier, express, parcel (CEP) providers are already using

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pure electric vehicles. Others are still using conventional combustion engines. Vehicles, however, return empty to the depots. On the other hand, the waste, i.e., the cardboard boxes and/or polybags need to be collected. This is either done via public collection services (e.g., by the municipality) or receivers have to bring their waste (this is especially true for cardboard boxes in some regions) to waste collection points. Due to the amount of boxes, it is very likely that motorized vehicles are used. The e-mobility rate in Austria is currently 2.7% [9]. The CO_2 emissions related to the waste removal are, however, normally not considered in the discussion related to e-commerce.

Based on these thoughts, it is obvious that reusable packaging might be thought of. The main advantage of reusable packaging is that the amount of waste is reduced. This, obviously, directly reduces CO_2 emissions related to waste disposal. At the same time return trips of delivery vehicles could be used to return the reusable packagings. That is, no further CO_2 emissions are generated.

Contribution. Within this paper, we assess the introduction of reusable packaging in the CEP-sector with respect to CO_2 emissions. For this purpose, we compare the status-quo with a new delivery concept where empty packagings are collected using the delivery vehicles. The assessment is purely on the transport related CO_2 emissions. In addition, we assess whether a combined logistics concept merging last-mile delivery (to customers) and first-mile logistics (from producers) could further improve the CO_2-related statistics.

2 Logistics Concept Incorporating Reusable Packaging

The main idea of underlying this paper is that in future only reusable packaging will be used for the CEP-sector. Furthermore, it is assumed that these packagings are standardised—similar to euro pallets. The following two use cases arise in parcel logistics:

- Delivery of parcels to customers. These can be end customers or business customers.
- Shipping of goods from producers. This is the start of the delivery chain that ends with the delivery to the customers (see above).

Based on these two main use-cases, the following scenarios are defined for further investigation within this paper, whereby the (realistic) assumption is made that parcels are collected from shippers and delivered to receivers via intermediate hubs:

Scenario Base: This scenario represents the status-quo. I.e., all parcels are delivered with one-time packaging (cardboard or polybags). Hence, only the transport from the hub to the customers (B2C) is computed.

Scenario Separate: The distribution of the reusable packaging (empty boxes) to producers is completely decoupled from the parcel delivery. I.e., two parallel processes are done, with one serving the shippers and the second one serving the customers.

Table 1. Density ratios applied. Case 1 corresponds to approx. 3 customers to 1 shipper. Case 2 and 3 correspond to 14 and 50 customers to 1 shipper.

	case 1	case 2	case 3
ratio	ca. 3	ca. 14	ca. 50

Scenario Joint: It is assumed that at the hand-over of parcels also empty boxes are taken along and are redistributed at the same tour to the shippers. Route optimisation incorporating all pick-up points and all drop-off points is done.

Obviously, many variations of these scenarios can be thought of. The main purpose of this paper is not to assess variants in detail but to get a major overview of how (in)efficient the incorporation of reusable packagings might be with respect to transport related issues.

3 Methodology

As we want to assess the impact of reusable packaging with respect to CO_2 emissions, we basically just need the driven kilometres for the different scenarios as CO_2 emissions are directly proportional to tour lengths. Therefore, we first introduce our tour length estimation method followed by an explanation how the relevant input data has been generated. Finally, the overall evaluation procedure is presented.

3.1 Estimation of Tour Lengths

In order to compute meaningful numbers, we decided to apply the following methodology. The goal of the chosen approach is to get an estimation on the mileage relations between the different scenarios defined. To circumvent the extensive and data-demanding process of establishing a dedicated vehicle routing problem model, a simpler estimation methodology based on pre-defined delivery areas and Minimum Spanning Tree (MST) [6] length has been established. The MST is used as proxy/surrogate for the tour length as the following relation between the length of the MST (l_{MST}) and the optimal tour length of a delivery route (l_{OPT}) is given: $l_{\mathrm{MST}} \leq l_{\mathrm{OPT}} \leq 2 \cdot l_{\mathrm{MST}}$

3.2 Data Points

To have most realistic data with respect to pick-up and drop-off points, we use a hypothetical database on demand and location distribution for parcels (customers) as well as for empty boxes (shippers). The data is inspired by Wiener Neustadt, a small city in Austria with about 40 000 citizens and an area of 60 km^2. Locations have been selected on a 100 m × 100 m grid where only those are kept with land-use living area or industrial area. Among those

points, home locations (receivers) and business locations (shippers) are randomly selected based on a density relation as shown in Table 1 meaning that, e.g. in case 1, for each business location three home locations of receivers have been selected. To circumvent statistical outliers, for each of these cases, a set of ten samples has been drawn. We refer to Fig. 1 for a visual example. The shapes define the clusters; the different coloured points refer to the locations (customers and shippers), and the lines are the MST.

3.3 Computational Procedure

First, the city area and the possible drop-off/pick-up points are defined as described above. In addition, they are clustered using a k-means method as implemented in [3]. Then for all 90 instances (3 scenarios with 3 cases with 10 samples each) the actual route lengths are estimated (delivery tour plus connection to hub). Obviously, the number of delivery tours is estimated as well by using an average delivery rate of 140 parcels per tour [5]. Finally, the savings among the scenarios are computed based on the estimates.

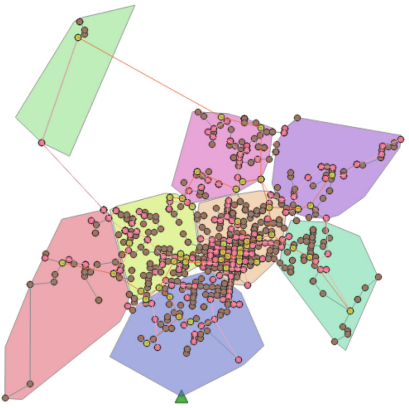


Fig. 1. Graphic representation of one test instance. The triangle represents the assumed depot for all clusters (hatched areas). Points of different colours represent customers and shippers.

4 Evaluation

As outlined in Sect. 3, we used a real-world like setting based on the city of Wiener Neustadt in the south of Vienna, Austria. Customers (recipients) and shippers have been selected on a random basis whereby the ratio among them is presented in Table 1. For each case, we generated ten instances. For each of these 30 instances (three cases times ten instances), we estimated the lengths

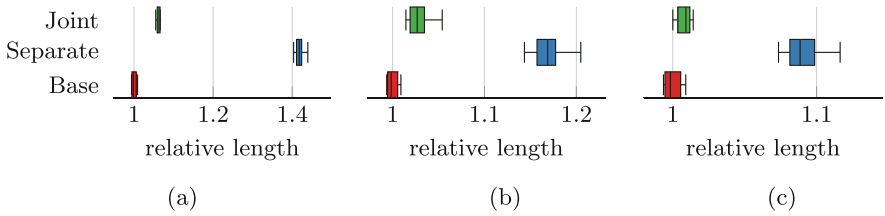


Fig. 2. Box plots of (estimated) tour lengths for the Base, Separate, and Joint scenarios and cases (a) 1, (b) 2, and (c) 3, respectively. Tour lengths are relative to each other, with the median of the Base scenario building the basis.

of delivery tours applying all three scenarios. We refer to Fig. 2 for a graphical representation of the results. (In addition, t-tests were performed testifying statistical significance of the results obtained.) Box plots are shown, with each box plot corresponding to the (estimated) tour lengths of a scenario (Base, Separate, Joint) and a case (ratio of customers to shippers). It can be seen, that the Base scenario is always the seemingly best case. However, the return of empty boxes (i.e., the disposal of cardboard boxes) is not considered here. As other paper waste is disposed as well a pure doubling would be not correct. However, adding about 50% would be fair as the decrease in waste also leads to less waste collection tours. The Separate scenario is the one with the most kilometres driven as shippers and customers are not served by the same vehicles. Obviously, for case 3 (higher ratio of customers to shippers), the additional needed kilometres get less (as the shippers get less). The Joint scenario, however, performs way better than the Separate scenario. In addition, it is only slightly more CO_2 expensive than the Base scenario with the additional benefit that no waste (through packaging material) is produced.

5 Conclusions and Future Work

Conclusions. Within this paper, we presented a case study on the CO_2 impact of reusable packaging with respect to transport if a novel logistics concept compared to the status quo is applied. The concept can be compared with the conventional euro pallet service with the addition that customers and shippers are served with joint delivery tours. This implies that it is possible to collect empty boxes from customers (either the boxes of the current delivery or empty ones from previous deliveries) and ship them directly to shippers who use these boxes for packing new items to be delivered. If no additional boxes are needed (on average, the number of empty boxes delivered to shippers will be same as parcels delivered to customers) the space in the delivery vehicles is sufficient to transport all boxes (empty or full).

Future Work. Obviously, some additional computations need to be done, as we cannot guarantee that in every area the number of empty boxes is equal

to the number of full boxes. For these cases, future work will contain more detailed computations. Furthermore, we plan to discuss in more detail, how tours actually need to be planned such that delivery vehicles already collected empty boxes from customers before they service shippers as otherwise additional empty boxes would be needed to be taken along from the depot in the morning.

Final Remark. One can easily state that the proposed logistics concept making use of reusable boxes is significantly reducing CO_2 emissions as for the Joint scenario only about 10% of extra emissions are generated while two further CO_2 sources for the status-quo (Base scenario) are not needed anymore: waste collection of cardboard boxes as well as the delivery of empty cardboard boxes to shippers. That is why one can estimate a reduction of up to 50% of transport related CO_2 emissions.

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Overcoming Barriers to Implementing Sustainable Mobility Strategies in Rural Areas: A Case Study in Turkiye

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Abstract. This Turkish case study examines the challenges and solutions of rural sustainable mobility programmes. Limited infrastructure, scattered people, and socio-economic restrictions might hamper sustainable transportation practises in rural areas. This research identifies these barriers and proposes sustainable mobility alternatives for rural communities. The mixed-methods study includes qualitative interviews and on-line surveys with important stakeholders, data analysis, and field observations. Findings show that rural sustainable transportation requires a diverse strategy. This involves customising infrastructure, boosting accessibility and connection, integrating transportation modes, and improving public transit. To influence rural dwellers' behaviour, sustainable mobility knowledge and education are crucial. The case study emphasises the importance of local communities, stakeholders, and policymakers in planning and decision-making. Funding, policy changes, and rural mobility project sustainability depend on government, non-governmental, and private sector collaboration. This study expands sustainable transport knowledge by evaluating rural mobility difficulties and strategies. This research helps policymakers, researchers, and practitioners design and implement sustainable mobility strategies in similar settings, promoting environmentally friendly and comprehensive transport systems in rural regions, especially in Turkiye.

Keywords: Sustainable mobility · Rural areas · Turkiye · Infrastructure · Public transportation · Community Engagement

1 Introduction

1.1 Overview of Sustainable Mobility and Its Importance

Sustainable mobility refers to the provision of transportation that is safe, affordable, accessible, efficient, and resilient, while minimizing carbon emissions, environmental damage, and energy consumption [1]. Transportation currently accounts for a significant percentage of global greenhouse gas emissions [2]. Transitioning towards sustainable mobility can help reduce carbon emissions and air pollution, contributing to the

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mitigation of climate change and improvement of air quality [3]. Sustainable mobility encourages the use of low-carbon transportation modes, such as walking, cycling, public transit, and electric vehicles, which significantly reduce the environmental footprint of transportation [4]. By reducing air pollution and encouraging active modes of travel like walking and cycling, sustainable mobility can also enhance public health [5]. Sustainable mobility can lead to cost savings, both for individuals and societies [6]. It can also minimize the costs associated with traffic congestion, road accidents, and health issues linked to pollution. Sustainable mobility ensures that all individuals- regardless of age, gender, disability, or economic status - have access to safe and convenient transportation. However, most research to promote sustainable, climate-friendly modes of transport has focused on urban areas and rural areas have received less attention [7]. This study focuses on identifying the challenges and opportunities related to sustainable transportation in rural areas, specifically Turkiye, aiming to contribute to the existing body of knowledge and serve as a model for other countries.

1.2 Issues in Implementing Sustainable Mobility Strategies in Rural Areas

Implementing sustainable mobility solutions in rural areas comes with several challenges [8]. One of the challenges is the low population density, which makes it difficult to implement public transportation systems due to low demand, often leads to a lack of economies of scale, making it economically unviable to implement and maintain sustainable mobility solutions [9]. As a result, rural residents mostly rely on private vehicles, leading to increased emissions and a lack of transportation options [10]. Additionally, limited infrastructure, including poorly developed road networks, affects the feasibility of implementing alternative modes of transportation such as cycling or walking, and the deployment of sustainable transport technologies [2]. Furthermore, rural areas are often constrained by limited financial resources, making it harder to address mobility challenges effectively [11]. Rural locations have greater poverty rates and less work possibilities, which lowers car ownership and increases reliance on older, less efficient automobiles [12]. Lack of connectivity and digital infrastructure also impede the implementation of smart mobility solutions, limiting access to ride-sharing platforms and real-time transit information systems [2]. Furthermore, the absence of awareness and knowledge about sustainable transportation options among rural communities can impede the adoption of these strategies [13]. Additionally, strong cultural and behavioural factors favour car ownership, making it challenging to promote the adoption of sustainable mobility practices, necessitating targeted campaigns and community engagement initiatives [14]. Addressing these barriers necessitates a multi-pronged approach involving collaboration between government agencies, community organizations, and private stakeholders.

2 Methodology

As a case study, we select Mugla Province of Turkiye, located in the country's southwestern corner, on the Aegean Sea. We used multiple data sources such as bibliometric literature review, semi-structured interviews (4 muhtars-representatives of citizens at the neighbourhood level, 2 Bodrum Municipality responsible, 3 tourists) relevant documents

and field observations. We used the Google Forms tool to create an online questionnaire. The bibliometric literature review was conducted to reveal the appropriate research questions, which would be included in the questionnaire. We sent the questionnaire via e-mail to around 80 people (55 *muhtar*s (representatives of citizens at the neighborhood level) of Bodrum Municipality, responsible of Bodrum and Mugla Municipality, Chamber of Trade and Industry, South Aegean Development Agency (GEKA), Ministry of Environment, Urbanization and Climate Change and some residents.

2.1 A Bibliometric Literature Review

A bibliometric literature review has been conducted which is a systematic analysis of the literature in a particular field using bibliometric methods [15]. A bibliometric review provides objective insights into the characteristics and dynamics of the research field (Fig. 1).

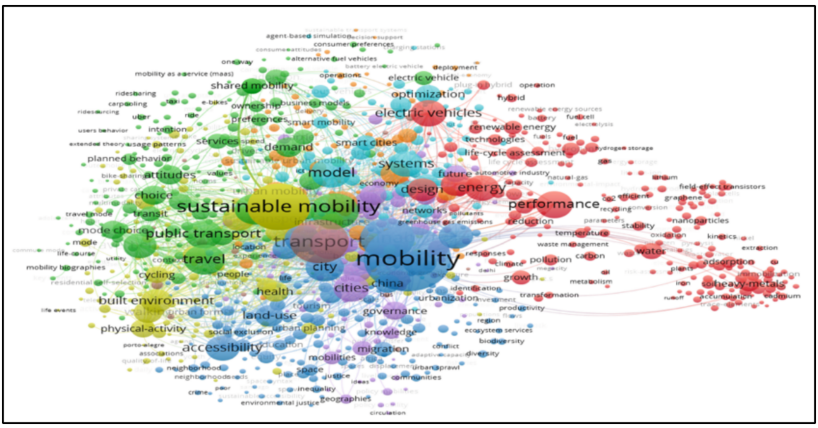


Fig. 1. Bibliometric co-occurrence of literatures (Source: Prepared by the authors, 2023 using VosViewer; Data extracted from Web of Science, 2023)

Existing literature highlights several key factors that hinder the successful adoption of sustainable mobility solutions in rural areas.

3 Sustainable Mobility in Rural Areas in Turkiye

As of 31 December 2022, 17% of the total population lives in settlements classified as rural and constitute 93.5% of Turkiye's surface area [16]. Rural settlements in Turkiye are large in number, less populated, and dispersed, typically requiring long transport distances. Selected case Mugla Province of Turkiye, located in the country's southwestern corner, on the Aegean Sea, with a population of 1,048,185. 29% of the population lives in rural areas, above the average in Turkiye. Within Mugla province, we focus on its famous resort district, Bodrum. A cumulative total of 136,317 inhabitants reside within

the district's borders according to the 2022 census. Peak visitor numbers among temporary residents occur in summer, on weekends, and national holidays and have been exemplified also during the Covid-19 pandemic. This may even outweigh the number of permanent residents. Bodrum is the most developed district of Muğla according to the socio-economic development ranking of the Ministry of Industry. Since March 30, 2014, the peninsula has been governed as a sole municipality. The villages were transformed into neighbourhoods. As representatives of citizens at the neighbourhood level, *muhtar*s participate actively in the local decision-making process. Public Transport (PT) is one backbone of sustainable transport systems in rural areas as it is in Muğla and Bodrum. The public transport mode used in general is medium-sized buses and shared minibuses called dolmuş, meaning "full" or stuffed, as these shared minibuses (vans) depart from the terminal only when sufficient passengers have boarded. However, there is no rail system in the area. Although it is limited, it is possible to see electric vehicles on the Bodrum roads, mostly used by temporary residents. There are various charging stations around the district. The new intercity bus terminal is the first in Turkiye powered by solar energy and contains six electric vehicle charging units.

4 Findings

The findings of the survey indicate that a significant proportion of the participants exhibited a satisfactory degree of awareness and understanding regarding the idea of sustainable mobility (Fig. 2).

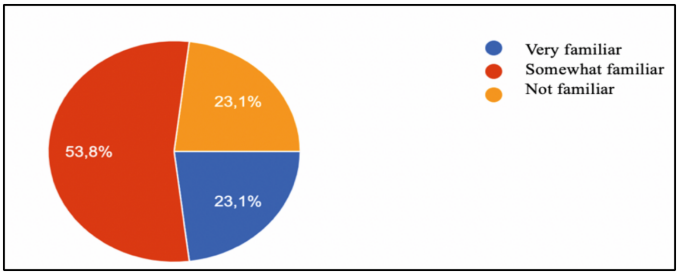


Fig. 2. Familiarity with the concept of sustainable mobility

Sustainable mobility is seen as a kind of transportation that prioritises environmental preservation, while also including economic, social, and ecological considerations. The optimistic recognition of this phenomenon has great potential for the successful execution of sustainable transport initiatives in rural regions. The study found that a significant proportion of participants demonstrated insufficient knowledge regarding the adoption and execution of sustainable transportation solutions within rural regions of Turkiye (Fig. 3).

The study revealed that the main barriers to implementing sustainable mobility strategies in rural areas of Turkiye are insufficient awareness and education on sustainable mobility and inadequate government support, lack of infrastructure and limited financial resources (Fig. 4).

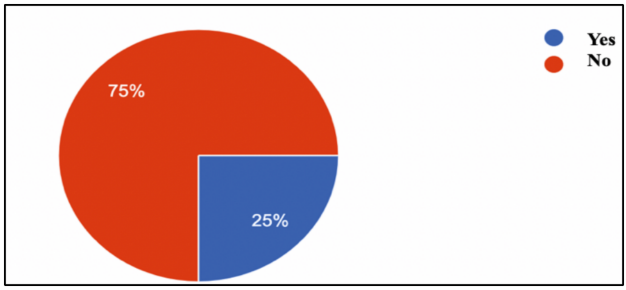


Fig. 3. Awareness of sustainable mobility strategies implemented in rural areas

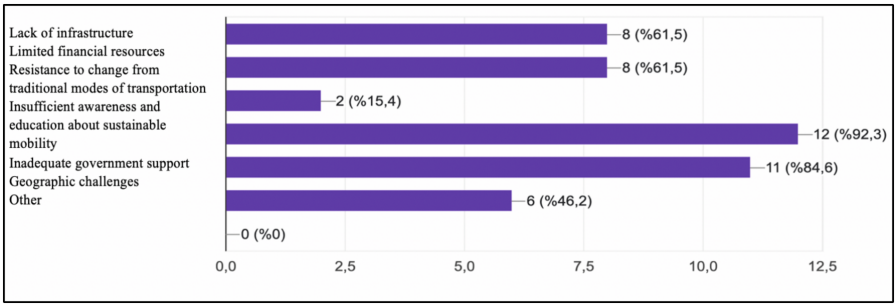


Fig. 4. Perceptual viewpoint of the stakeholder

The study showed that the active engagement of the local community in the formulation and execution of sustainable transportation policies was deemed to be of utmost importance. The participants highlighted the need for active engagement, collective decision-making, and the incorporation of indigenous knowledge and viewpoints to guarantee the effectiveness and long-term viability of endeavours.

The significance of a clearly defined government role in the promotion and facilitation of sustainable mobility in rural regions was emphasised by the participants. The suggested measures encompassed the provision of financial assistance, the augmentation of ecologically sustainable transportation alternatives, regulated backing for small-scale producers, and collaboration between central and local governmental entities.

5 Conclusions

Sustainable transportation in rural Turkiye has numerous challenges. Lack of reliable public transit and well-maintained road networks is a major issue. To provide sustainable and inclusive transportation, public transportation infrastructure must be improved. Socioeconomic barriers impede sustainable mobility in rural Turkiye. Funding sustainable transport infrastructure and low-emission automobiles in rural regions is difficult due to limited financial resources. The low population density makes transportation services expensive. Culture and customs may oppose sustainable movement. People are reluctant to change their culturally-ingrained commuting habits. A lack of awareness

of sustainable mobility's benefits may explain this opposition. To solve these issues, government agencies, local communities, and stakeholders must collaborate.

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Digital Platforms in Localising the Markets and Supply Chains in Rural Areas

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Abstract. This paper presents case studies on the feasibility of a decentralised demand-driven logistics model in sparsely populated area in Finland. A digital logistics platform was initially developed and piloted in Central Ostrobothnia's rural area and later in Lapland's sparsely populated area, alongside integrating another digitalised marketplace platform. During Lapland pilot, the focus of the platform was on local food supply, where the model integrated information on the whole network of cooperation, i.e. food production facilities, processing, terminals, flexible transport, and customers. In addition to field demonstrations, information was collected through surveys, interviews, online surveys, and workshops with a wide range of stakeholders. The experiments showed that: 1) The marketplace and the logistics platform are best suited to a business environment with many small players who can collaborate to save resources and create competitive advantage. 2) A business network of several small actors needs a neutral actor as "referee", who also owns the platform. This role is appropriate for the public sector, i.e. one or more municipalities. 3) In sparsely populated areas, the inherent challenges of logistics optimisation in a large area are difficult to overcome solely through longer deviations from main routes.

Keywords: Digitalised platform · Sparsely populated areas · Logistics

1 Introduction

Around 70% of Finland's land area can be classified as sparsely populated. Lapland, Finland's least populated region, has an average of only 1.9 people per square kilometer (Fig. 1a) [1, 2]. Lapland offers some cultural specificities that were considered encouraging for the pilots. The region has a huge amount of local food production (such as fish, reindeer, berries, etc.) due to its unique environment. Production is carried out by small businesses and even individuals with generations of background in the local food industry. In addition, the area is known for its community spirit and enthusiasm for helping other locals. A challenge for small operators in Lapland is that logistics service providers mainly use main roads and tend to deviate only short distances, which is a challenge for local businesses. This has led to a situation where small businesses with small parcels prefer to deliver their goods to customers themselves rather than buy a logistics service, which is usually more expensive.

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The aim of the pilots was to create a new kind of decentralised demand-driven logistics model and a business model for entrepreneurship and for the whole supply chain and the logistics of local food production by piloting a new type of digital platform. The idea was to provide a virtual place for rendezvous and enable trade and low-carbon, cost-effective optimisation of transport for food buyers, (i.e. restaurants, public food service and private consumers) and the sellers, (i.e. primary and grocery producers and their products), as well as for the food processors and retailers (Fig. 1b and 1c). The operating model forms a platform and system that integrates, e.g., production facilities, terminals, and flexible transport. The aim of piloting the model was to test whether such a digital system can effectively support local economy, enhance business opportunities, and cooperate with different actors. In a wider sense, the goal was to shorten long food supply chains and reduce carbon dioxide emissions, while improving cost-effectiveness.

2 Decentralised Demand-Driven Logistics Model

The model layers comprise users (e.g. food producers, consumers, and logistics providers), services (i.e. the functionalities offered by the platform), the data that is exchanged between actors, and the infrastructures that facilitate the physical flow of goods and services (Table 1).

The reluctance of logistics service providers to deviate from the main routes could be overcome by small terminals located in the rural centers. The cost of the terminals should be low. Therefore, e.g. school canteens and other public kitchens could be used as terminals.

3 Pilots

The pilot locations and infrastructure are shown in Figs. 1a, 1b and 1c.

During pilots in Central-Ostrobothnia during 2018–2020, focused on B2B-logistics, over 600 parcels were delivered. All deliveries were made using the platform that optimises the best logistic providers' and their existing routes. Deliveries were transported by professional logistics companies. To ensure all deliveries, the project had one key-logistic provider that was able to deliver all parcels, if their route or timing didn't better match with any other provider's routes [3].

The aim of pilots during 2021–2023 was to utilise the functional platform in a new area; Lapland, Finland and to broaden the collaboration to public organisations. In addition, the aim was to integrate a digital marketplace (AURORAL Marketplace) for local food markets with the logistical pick-up and distribution management system (VASTE), linking logistics supply and demand. These solutions aim to develop and secure services in sparsely populated areas [4, 5].

The economic effects, namely a functioning business model, are the key enabler of the other benefits. Environmental and social changes are recognised as important and valuable in the long term. As the actors of change in this field are mainly companies, the competitive business case cannot be overlooked. However, publicly funded projects are often based on large scale non-monetary objectives, which creates a discrepancy between projects and actual change in the operating area.

Table 1. Decentralised demand-driven model layers.

Layer	Processes	Platforms
Users (Food producers, buyers, and logistic providers & drivers)	The process includes supply and demand information, purchase orders, transportation operation and transactions	• AURORAL marketplace • VASTE logistics model • VASTE drivers' app
Services	Access to services through user interfaces	• AURORAL Marketplace including payment transaction (STRIPE) • VASTE transportation organisation and management system
Data	Centralised data collection in AURORAL and VASTE databases: • All data is updated in real time in the database and user interfaces throughout the value chain (product, purchase, route, delivery) • Data is handled both anonymously and publicly according to process demands	• Product and purchase information • Company information, transport, and route information • Location information
Infrastructure	Physical infrastructure: roads, railways, terminals and equipment (e.g. parcel lockers)	Telecommunications infrastructure: 4G/5G, broadband, IoT devices, cloud servers etc.

Expected benefits of the usage of decentralised demand driven logistics model with measured results by user group are presented in Table 2.

4 Key Findings

The following findings emphasize the need for a change in the current business culture and modus operandi:

- The idea of collaboration is well-received, but the threshold of acting is high. The existing business culture is very individualised and willingness to take risks is low.
- The businesses are content with the current customer base. There's an opportunity for transformation during a generational change. If the business is viable enough to be continued by the next generation, new ways of working are more likely to be welcomed. Part-time business in food production decreases the amount time and effort the entrepreneur is willing to put into the business. The main professional knowledge

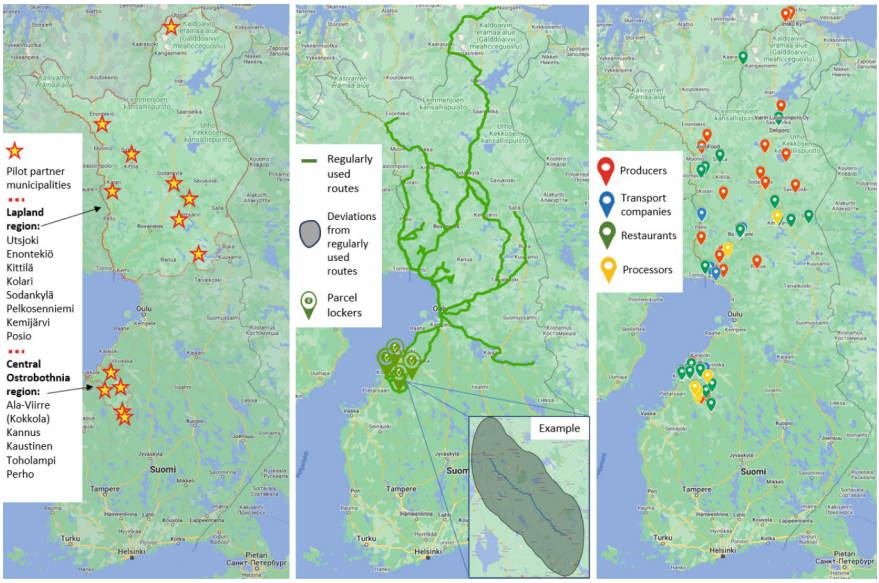


Fig. 1. (a) Pilot locations (b) Regular transport routes and an example of route deviation areas, (c) Location of potential food producers, processors, restaurants, and transportation companies. Image produced using Google Maps, an open source software.

is usually in the food production itself, and the digital and business-growth is "the necessary evil".

- Open, de-centralised digital platforms are successful when some business data, such as routes, are shared. This is considered a risk in the market. The logistic platform is developed to provide delivery options anonymously.
- Restaurants and public kitchens are highly interested in buying locally produced food. They require large and reliable quantities, which is challenging for a small food producer. The business is also seasonal which poses extra pressure on short time periods. This is why collaborating with other producers would open an opportunity to respond to this need.

Deviations from main routes are one of the main challenges in logistic optimisation. A large operating area, with few central terminals increases the difficulty level in covering the whole area. In Central-Ostrobothnia, a small county, the logistic routes including deviations covered approximately 90% of the whole operating area. However, in Lapland, a significantly larger county, the coverage, including deviations, covered only about half of the operating area. In both cases the logistic provider defined the deviations by themselves, considering the time, cost, and efficiency of main deliveries. Generally logistic providers in Lapland can make longer deviations, but it still doesn't increase the coverage to a similar level as in a small operating area.

The lack of digital skills is the main reason for the system's limited adoption. This lack is rooted in cultural and personal factors, as digital systems are often not considered necessary unless mandated by networks or demanded by customers. Embracing new

Table 2. Expected benefits of the model and results during the pilots in 2018–2023 in Central-Ostrobothnia and Lapland, Finland.

	Public actors	SMEs	Citizens
Expected environmental benefits	• Sustainability-driven procurement	• Optimised delivery routes and reduced fuel consumption	• Less private driving, reduction of personal emissions
Pilot results	• 46 MWh saved	• Over 36 000 km of optimized routes driven and over 600 delivered packages	
Expected social benefits	• More efficient local markets • Local food supply chains e.g. in schools and elderly homestay and networking competences	• Digital shift of rural communities	• Support of local prosumerism • Local social and community vitality • Improved local services
Pilot results	• 44 enterprises participated in demontsrations		
Expected economic benefits	• Savings in logistics costs • Higher efficiency of public vehicle fleet utilisation	• More options for logistic services • New business opportunities, revenue, and jobs	• More sustainable food products • Strengthening of local communities economically
Pilot results		• 19 low carbon actions in enterprises demonstrations	• 5 enterprises launching a new or improved product on the market a significantly improved version of a low-carbon product or material

systems depends on network and customer readiness. Nevertheless, the platform holds growth and efficiency potential.

5 Conclusions

In sparsely populated areas, a business network of several small players needs a neutral actor who also owns the digital platform to “referee” the network. In sparsely populated areas, this role is appropriate for the public sector. The public actor can also ensure a critical mass of the business model, for example through public procurement.

Designing a business model for complex digital software with multiple user roles and beneficiaries is a challenge. The first decision is determining the system's owner, while simultaneously showcasing the business benefits for all users. The software operator was chosen as the business case owner. The operator requires a business model which covers the upkeep of the software itself and produces profit. As the food producers are not able to purchase extensive service packages, creating profit is challenging. The project recognised public actors as potential owners or operators of such services.

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15-Minute City: A Holistic Approach in the Frame of SUMPs

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Abstract. With cities growing at a faster rate than ever, and with them transport-related emissions, it is not surprising that new urban models are being proposed. The 15-minute city (15mC) model, based on the idea that one should be able to access daily needs within a 15-minute walk or cycle, has gained popularity. However, there are still many issues to be addressed for its successful implementation. In this work, the main research needs regarding SUMPs (Sustainable Urban Mobility Plan) and planning have been identified. This was done through a collaborative process involving ERTRAC (European Road Transport Research Advisory Council) members belonging to industry, academia and decision-makers. 3 main themes have been discerned: user needs, urban design and digital services and policy and regulations. The identified highlighted research needs and issues to be considered in SUMPs regarding the 15mC are the role of PT and micromobility, street design and coexistence of modes, freight and logistics in the city of proximity, how to adapt the model to peri-urban contexts and correct communication strategies.

Keywords: 15-minute City · Proximity · Density and Accessibility · SUMPs · Integration of Transport and Land Use

1 Introduction

Europe is experiencing unprecedented urban challenges, ranging from a serious energy crisis to societal inequities, demographic changes, and the rise of digitalisation. Despite occupying only 2% of the planet's surface, cities are responsible for 78% of global energy consumption and 66% of Greenhouse Gas Emissions (GHG) [1], a significant portion of which is directly related to transportation.

The combination of unprecedented growth and climate emergency has led to institutions like the European Commission to propose green policies such as the White Paper on Transport, or the European Green Deal with the aim to boost the green transition.

In parallel, urban planners have put forward new concepts and planning models. Owing to the close interaction between transport and urban form, it is of interest for

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academics and practitioners to rethink the city and how people and goods move in it. Among the different urban models proposed, the 15-minute city has gained great popularity in recent years.

This research aims to reflect on the concept and its relation to urban mobility, to the extent of identifying which areas regarding people and goods mobility require further research for the model to be deployed successfully, and additionally, need to be included in Sustainable Urban Mobility Plans (SUMPs). This research has been developed for the European Road Transport Research Advisory Council, by the Urban Mobility Working Group (which belongs to ERTRAC). To this end, a collaborative approach has been followed, involving UMWG partners which belong to industry, academia and decision-makers.

2 The 15-Minute City from a Mobility Perspective

The current state of climate emergency and urban growth has resulted in new urban models being debated, intending to enable more liveable, green and healthy cities. Time has gained value among citizens, meaning that city models based on chrono-urbanism have risen in popularity [2]. The most popular of all seems to be the 15-minute city (15mC), defined by Carlos Moreno as an urban set-up where all citizens can access the daily essentials (living, work, commerce, healthcare education and entertainment) within a 15-minute walk or cycle [3]. This example of proximity-based planning entails reduced need for lengthy journeys, re-balancement of spaces and uses in the city and an overall improved quality of life [4]. To this end, 4 key dimensions make up the framework (see Fig. 1) and must be present:

- Diversity, which addresses the requirement for mixed-use development as well as social and cultural diversity within neighborhoods.
- Density, as in determining the optimal number of people per square kilometer in order to balance economic, environmental, and social sustainability.
- Proximity, temporal and spatial alike to reduce travel time and its economic impact, while also promoting close-knit communities and social engagement.
- Digitalisation, in conjunction with the Smart City concept, enables the three preceding pillars to become a reality.

3 Logic: A Collaborative Approach

The method used to discern new areas of research regarding the 15mC from a mobility point of view is based on previous work carried out by ERTRAC's UMWG. Three ERTRAC Roadmaps were built upon: Urban Mobility Resilience [5], New Mobility Services (NMS) Roadmap [6] and Safe Road Transport Research Roadmap [7]. These roadmaps were selected because of their relation to the model. In fact, the model was already mentioned in the first one, however it was not addressed in depth. The process followed consisted firstly in finding synergies and conflicts between findings and identified research needs in these topics and the 15mC framework. The second phase consisted in presenting these synergies to UMWG members and developing two brainstorming



Fig. 1. The 15-minute city framework

sessions where challenges, barriers, drivers and recommendations were made. In the third phase, these were all classified by theme and underlining the relation among them (see Fig. 2). This results in 3 categories to be addressed:

- User needs
- Urban design and digital services
- Policy and regulation



Fig. 2. Identified main themes

4 Highlighted Findings for Future Research

Following the approach described in Sect. 3, the following points for future research were highlighted. These notions are considered to be the most pressing concerning the role of urban mobility in the 15mC.

4.1 User Needs and User Behaviour

It is critical to listen to citizens and transport users. What are their requirements? How do they act? What do they desire? Many of the points made throughout the discussions were about focusing on what citizens want and how they want to move. At the same time, it is worth noting that users are addressed in all the roadmaps evaluated, but it is also required to actively involve them in regard to the 15mC. The most relevant points are included in the following lines:

- Human behaviour: Preferences and needs, cultural attitudes, nudging and acceptance. New lifestyles, new consumption/economic approaches, travel desires, etc.
- Accessibility and inclusivity
- Interdisciplinary research: Social sciences, urban planning
- Political divides and distorted controversies - Negative perceptions and backlashes
- Road safety in the 15mC.

4.2 Digital Services and Urban Design

How can the 15mC be realized both in the short and long term? Many of the remarks made during the brainstorming sessions were aimed at the actual implementation of the 15mC and refer to two major groups of issues: those concerning digital services and those concerning urban design:

- Physical vs Digital: The intersections and interactions of physical and digital measures in the 15mC – urban planning and design, use of technologies, use of digital services, etc.
- Space allocation and quality of space: From temporary to permanent interventions, dynamic space management, governance and capacity building
- Freight and the 15mC: E-commerce, last-mile delivery, curbside management, business/consumers involvement
- Role of Public Transport. Although the model clearly favours active modes, it seems unattainable without relying on PT, especially in certain urban contexts, such as large FUAs.
- Rural and peri-urban: How can the concept be conveyed beyond city centres?

4.3 Policy and Regulation

For the 15mC to be effective, a variety of actions, such as policy changes, are required. Planning and regulatory frameworks were frequently mentioned throughout the brainstorming session. These planning frameworks should allow the 15mC to be implemented adequately, ensuring that it reaches its full potential and has the greatest possible impact on quality of life.

- Policy and regulatory frameworks: Policy integration, horizontal collaboration between involved actors. At the same time, SUMP and SULP have a vital role to play to enable implementation. The following areas are the most in need of effort to be able to foster the city of proximity:

  - Freight and goods distribution policy. With the introduction of e-commerce and door-to-door delivery, new concerns to sustainable logistics and urban liveability have emerged. At the same time, the 15mC must delve deeper into goods delivery and how it fits into the model, for it to be addressed in the SULP.
  - New Sustainable mobility management. Novel concepts such as MaaS or rising popularity of NMS and micromobility need to be regulated and backed by adequate policy and planning. For instance, in Paris (city where the model was first introduced), e-shared scooters have been banned from the 1st of September of 2023 following a public poll in which 85% supported this decision. This is due

to many factors, mainly safety concerns and problematic co-existence of scooters and pedestrians considering the space available. This is evidence of the need to plan adequately for co-existence of modes in the city of the future.

– Urban design and placemaking. Citizens should be able to have public space to use for non-mobility related purposes.

5 Conclusions

Several key findings can be summarized from the research work developed and explained in the previous points. Figure 3 summarises research findings.

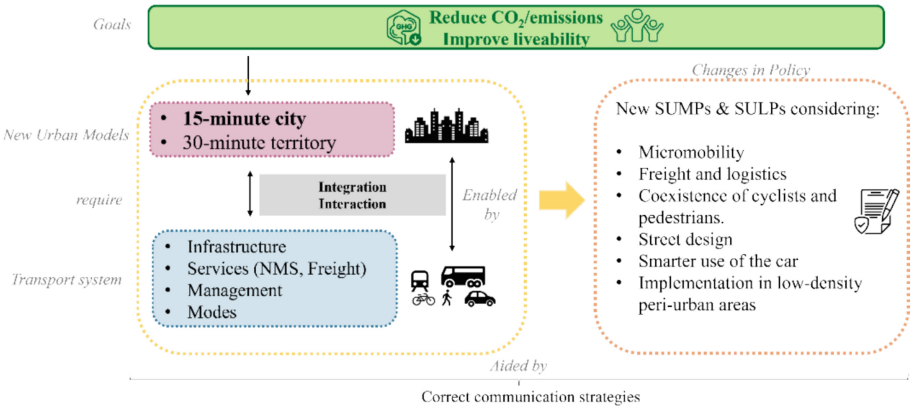


Fig. 3. Key findings diagram

The 15-minute city supports the reduction of long trips and promotes active modes. This in turn, implies a reduction in car-dependency. However, based on the work developed, it is necessary to emphasize further the role of PT. It should be considered as the backbone of mobility in the model. Many urban areas do not comply with Moreno´s framework, in the sense that there is not an optimal density or distances are too long. Workplaces are often not available in residential areas due to low diversity or socio-economic reasons. Therefore, PT must be relied on to avoid car-use. In addition to this, and as response to some of the criticism the model faces, not all citizens wish to go the nearest services for personal reasons. The model does not forbid them in any way to do so, however, it must be promoted they access further away services in the most sustainable mode possible.

Further research is needed concerning NMS, particularly micromobility to ensure its alignment with the model, and avoid negative externalities. The same can be said for freight and logistics, which remain unexplored fully, with how last-mile delivery aligns with the model´s principles. When it comes to active modes, it should also be taken into account how walking and cycling can co-exist to ensure safety for all. This is a pressing matter, since space in cities is limited. Therefore, it calls for improved street design and urban livability. In turn, this means making smarter use of the car,

and possibly reducing its share of space in the city. Finally, low-density and peri-urban areas must not be forgotten. The model is currently being implemented in compact and urban settings such as central Paris, Milan, Rome or Buenos Aires [8]. Other options are 30-minute territories or 45-minute regions. In regard to the time measure, it is vital to improve communication strategies to avoid negative backlash, and portray the essence of the model, which does not lie in the number of minutes, but in possibility to access daily needs in a reasonable time frame without relying on motorized means.

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Sustainable Commuting – An Empirical Analysis of Commuting Considering Changes Due to the Pandemic

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Abstract. Commuting trips constitute a substantial portion of the annual kilometers traveled in Germany, with the distance between home and work having increased significantly in recent years. The reasons for this trend remain largely unexplored. Additionally, commuting conditions have evolved due to the COVID-19 pandemic and the rise in teleworking. This paper examines commuting trends in relation to residential location preferences, offering empirical insights into recent developments and discussing their implications for sustainable commuting practices in the future.

Keywords: Commuting · Home Office · Coronavirus Impacts · Travel Pattern Changes · Empirical Data Analysis

1 Introduction

Commuting constitutes a significant part of a country's mobility, with distances between home and work increasing in recent years. In 2017, commuting represented about one-third of car mileage in Germany, although it accounted for only 16% of all trips [1]. The average commuting distance rose from 14 km in 2008 to 16 km in 2017 [1, 2]. Urban areas have shorter but longer-duration commutes (13.2 km, 33.3 min) compared to smaller cities (19.2 km, 27.2 min) [1, 2]. Reasons for increasing distances are varied and partly unexplored. The COVID-19 pandemic significantly altered commuting patterns due to the rise in remote work.

Despite several studies on residential location choices and travel behavior, there is to our best knowledge no common framework to understand the interrelation between long-term residential decisions and short-term mode choices. With the increase in teleworking opportunities fueled by the pandemic and simultaneously the high increase of the population in cities and consequentially also housing prices in cities, we can expect several changes also in commuting behavior. Key questions include how commuting has changed recently and how these changes impact residential choices. For instance, would people move farther from the city if regular commuting becomes unnecessary?

The project MOBITAT 2050 examines the link between commuting, residential, and workplace choices. This paper explores how the pandemic has affected commuting preferences and discusses implications for sustainable commuting in the future.

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2 Methods

The analysis is based on three datasets, two of them collected at the German Aerospace Center's (DLR) Institute of Transport Research. Furthermore, these datasets span different periods: pre-pandemic, during various pandemic phases, and post-pandemic.

The first dataset is from the 2017 national household travel survey "Mobility in Germany (MiD)," with 316,000 respondents and nearly a million trips. This data describes the baseline situation before COVID-19, analyzed using descriptive statistics.

The second dataset is a multi-wave survey starting in April 2020, conducted during the COVID-19 pandemic to track changes in travel behavior, including commuting and teleworking. The survey, conducted online by KANTAR GmbH, includes eight waves from 2020 to 2023 with sample sizes increasing from 1,000 to 2,500 participants in the last two study waves, representative of the German population aged 18 and over. This data helps visualize travel behavior trends during different pandemic periods.

The third dataset is a 2022 stated preference survey with 1,169 working respondents, focusing on residential location, workplace, and mode choices. The survey included two experiments on housing and commuting choices, considering teleworking scenarios. The first experiment focused on residential location and commuting choices. Respondents were asked to choose between two housing options, each defined by size, monthly cost, residential area (urban, suburban, rural), and commuting duration. The second experiment examined mode choices, where respondents selected between walking, bicycling, driving, and public transport for their regular commute. Each alternative was characterized by travel time and cost. For public transport, this included in-vehicle travel time, access/egress time, and waiting time. Both experiments featured two different scenarios – teleworking (commuting 2 days a week) and regular commuting (commuting 5 days a week). The data was analyzed using logistic regression models to understand the impact of residential location and transport modes on commuting preferences.

The results of the analyzes provide comprehensive empirical insights into changes in commuting preferences and choices due to the pandemic.

3 Results and Discussion

3.1 Commuting Travel Patterns Before the Corona Pandemic

Work trips are longer than other trips (16 km vs. 12 km) and more often made by car (60% vs. 43%). However, 36% of work trips are under 5 km and could be suitable for biking. Commuting distance increases with income and education level; full-time workers travel farther (17 km) than part-time workers (10 km), often a gender difference since part-time workers are mostly women. Gender differences in commuting are minimal when young but increase with children in the household.

Residence and workplace locations show clear patterns: 82% of big city residents also work there, commuting 10 km on average. In small towns and villages, only 40% work locally with similar commuting distances. Most small-town residents commute long distances (20–36 km) to city jobs, mainly by car. City dwellers who work in cities often use public transportation.

3.2 Commuting Mode Choice Changes Due to the Pandemic

Based on the DLR Corona panel survey with eight waves since April 2020, changes in transport demand during the pandemic are highlighted.

Mobility behavior is categorized into following modal groups: monomodal (using only car, bicycle, or public transport) and multimodal (using a mix). Preferences shifted significantly towards car use during the pandemic. Before the pandemic, 50% of respondents used cars exclusively. This figure rose to around 60% after initial fluctuations during the pandemic, while multimodal behavior, especially involving public transport, declined due to discomfort using public transport.

The 9-Euro-Ticket, a low-cost monthly pass available from June to August 2022, reversed this trend. Monomodal car use dropped by 10 percentage points to pre-pandemic levels, and multimodal behavior increased. However, after the campaign, mobility behavior stabilized between pre-pandemic and pandemic levels (Fig. 1).

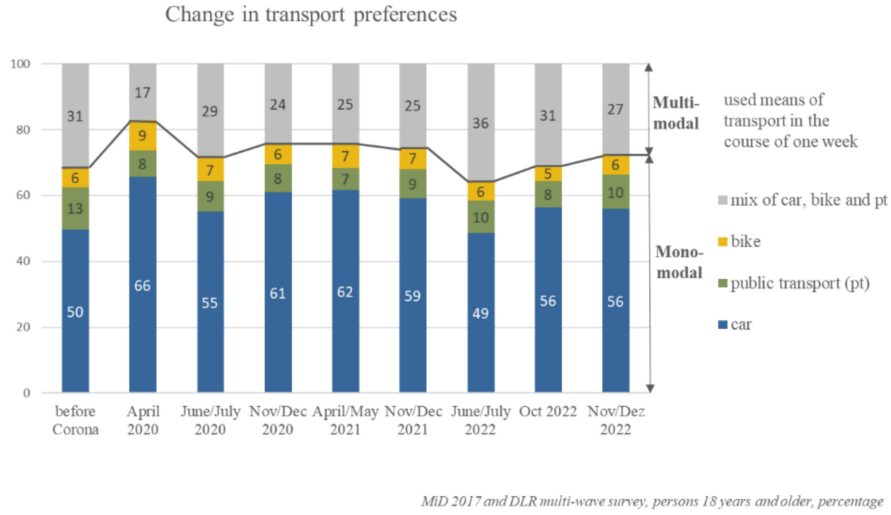


Fig. 1. Development of the proportion of teleworkers during the pandemic.

3.3 Changes Due to the Increase of Teleworking

Before the pandemic, 13% of employed persons worked at home occasionally according to MiD. With the onset of COVID-19, many employees had to telework almost overnight. During the first lockdown, teleworking jumped to 32%, peaking at 50% in summer 2021, and then settling at 40% by fall 2022. Thus, working and commuting patterns have fundamentally changed due to the pandemic.

We examined potential changes in residential location due to teleworking, summarized in Fig. 2 from the fifth wave of the DLR Corona panel survey. Among city residents, 19% are willing to move to suburban areas, and 18% to rural areas. This may be influenced by the high number of current teleworkers living in cities. In suburban areas, 20%

would move to rural areas, while only 10% would move to the city. For rural residents, only 7–8% would consider moving to the city or suburbs. Rural residents also showed the highest reluctance to move due to teleworking. The trend indicates that more people are willing to move from cities than from other areas, suggesting that the need for shorter commutes is less important with teleworking opportunities.

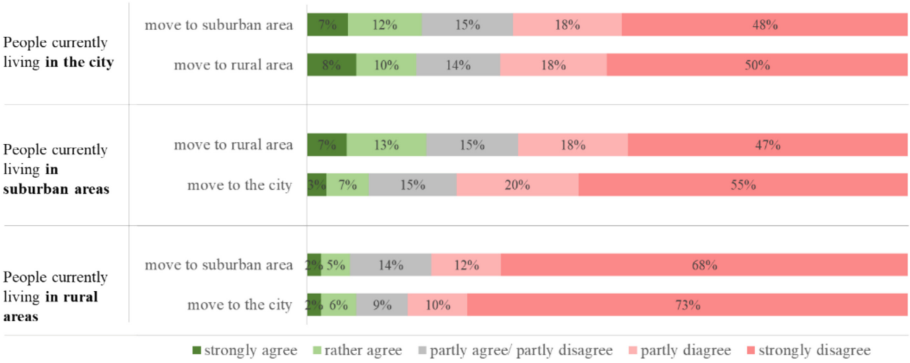


Fig. 2. Descriptive analyses of the willingness to move to other residential areas due to the availability of teleworking

The stated choice experiments reveal insights on how teleworking might affect commuting decisions, such as mode and distance choices. Table 1 shows that in a teleworking scenario (commuting only 2 out of 5 days), the negative impact of commuting time is less significant compared to a regular daily commute. This suggests that with teleworking becoming more common, people might be willing to travel longer distances or move further from their workplace, as travel time becomes less burdensome. This aligns with the findings from the DLR Corona panel survey.

Teleworking impacts mode choice preferences, as shown in Table 2. Overall, travel time has a less negative effect on mode choice in a teleworking scenario compared to regular commuting. The biggest difference is observed in walking and driving: walking is perceived 31% less negatively, and car use 28% less negatively when commuting only 2 days a week. This suggests that commuting time is less burdensome, potentially leading to longer distances traveled by these modes (though walking is still preferred for short trips). For cycling and public transport, the effect of teleworking is smaller. Notably, waiting time becomes less significant in teleworking scenarios, indicating a potential increase in the attractiveness of public transport.

The choice experiments suggest that teleworking may alter preferences for commuting distance and mode of transport, but predicting future commuting preferences is complex due to the interplay of short-term mode choices and long-term decisions like residential location and car ownership. Our study provides new insights into how teleworking influences these factors, which has been minimally explored before.

We further analyzed travel behavior patterns of teleworkers versus non-teleworkers. Key differences include mode choices: 52% of teleworkers use a car regularly compared

Table 1. Results of the logit model on residential location and commuting choices.

Coefficient	Estimate	t-value
ß cost for dwelling	-0.002	-21.45
ß sqm (size of dwelling)	0.022	20.43
ß city area	-0.156	-3.23
ß suburban area	*Reference*	-
ß rural area	*Reference*	-
ß commuting time (teleworking scenario)	-0.047	-29.50
ß commuting time (regular commuting scenario)	-0.036	-24.46
LL (0)		
LL (final)	-4861.73	
Number of individuals	-3640.11	
Number of observations	1169	
	7014	

Table 2. Results of the multinomial logit model on mode choices.

Coefficient	Estimate	t-value
ASC walking	2.561	4.52
ASC bicycle	0.982	14.92
ASC car	*Reference*	-
ASC public transport	-0.566	-5.61
ß walking (teleworking scenario)	-0.195	-7.38
ß walking (regular commuting scenario)	-0.284	-7.55
ß bicycle (teleworking scenario)	-0.083	-16.71
ß bicycle (regular commuting scenario)	-0.107	-27.11
ß car (teleworking scenario)	-0.035	-5.82
ß car (regular commuting scenario)	-0.048	-11.86
ß public transport (teleworking scenario)	-0.038	-7.17
ß public transport (regular commuting scenario)	-0.046	-13.40
ß access/ egress time (teleworking scenario)	-0.037	-3.10
ß access/ egress time (regular commuting scenario)	-0.056	-3.94
ß waiting time (teleworking scenario)	-0.007	-0.60
ß waiting time (regular commuting scenario)	-0.043	-3.31
ß cost	-0.101	-3.99
LL (0)	-9723.47	
LL (final)	-5492.49	
Number of individuals	1169	
Number of observations	7014	

to 63% of non-teleworkers, despite non-teleworkers having a higher rate of not owning a car.

4 Conclusions

Commuting significantly impacts overall mobility. Unlike other groups, employees can be effectively reached through company mobility management. The MOBITAT 2050 project explores various measures related to commuting.

The pandemic has fundamentally changed commuting patterns, notably increasing teleworking. It has also altered perceptions of transport modes, with more people feeling uncomfortable using public transport and favoring individual modes like bicycles and cars, despite higher fuel costs.

The 9-Euro-Ticket demonstrated that attractive pricing can influence travel behavior, though its effects were short-lived. Post-ticket, travel patterns returned to pre-pandemic levels, indicating price can mitigate some negative pandemic impacts on mobility.

Teleworking has reduced the value of travel time savings, making longer commutes more acceptable and hinting at a willingness to relocate. However, residential choices are influenced by more than just commute distance.

In summary, the paper provides evidence of changing travel and commuting behaviors due to pandemic conditions, especially teleworking. These findings offer a foundation for further analysis on optimizing teleworking to avoid increased commuting distances.

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Hard Shoulder Bus Priority Measures on Motorways and Type 1 Dual Carriageways

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Abstract. Transport Infrastructure Ireland (TII) supported by the National Transport Authority (NTA), having identified that improving the performance of Ireland's public transport on the national road network can increase the social and economic benefits of the network, approached Arup to aid in the development of a design standard for the incorporation of bus priority measures in the hard shoulder of Motorways and Type 1 Dual Carriageways. Providing for public transport has the potential to create a more sustainable and resilient transport network in Ireland and potentially reduce the cost of upgrading existing infrastructure in response to relieving existing congestion and providing for future population growth. In collaboration with TII and supported by the NTA, Arup identified and reviewed the provision and application of bus priority measures internationally on road networks equivalent to the Irish national road network. We reviewed the wider context of provision such as legislation changes, operational safety performance, public acceptability, supporting bus facilities, economic business case, in addition to the geometrical layouts provided (including technical standards where available) and other applicable engineering considerations. Case studies included examples in Northern Ireland near Belfast, the M4 into London, the M32 into Bristol, and the approach in the United States, Canada and New Zealand. Hard shoulder bus priority measures refer to the general allocation of road space to buses, on either a periodic (specified hours), dynamic (traffic flow/congestion) or a permanent basis. In the case of periodic usage, the period of operation shall be indicated on signage or information plate. In the case of dynamic usage, the period of operation is indicated using a combination of ITS data and VMS. Hard shoulder bus priority measures shall either be used by buses only (such use will require a specific Statutory Instrument for each scheme) or shall function as a bus lane as defined in Section 32 of the 1997 Road Traffic Regulations (as amended).

Keywords: Hard Shoulder · Bus Priority · Public Transport · Sustainability

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1 Introduction, Background and Overview

Enhancing the performance of public transportation within the national road network in Ireland holds the potential to amplify both its social and economic advantages. Interventions aimed at encouraging a shift from private car usage to public transport not only have the capacity to mitigate the expenses and consequences associated with addressing existing congestion and accommodating future population growth but also to prioritise the capacity to carry people over vehicles.

It is undeniable that decarbonising the transportation sector represents one of the most urgent and intricate challenges confronting the global transportation industry. It stands as a pivotal element in the battle against climate change. To meet the Irish Government's Climate Action Plan goal of achieving net-zero emissions by 2050, there is an immediate imperative to reduce carbon emissions within this sector.

2 Need and Justification

The incorporation of hard shoulder bus priority measures on motorways and type 1 dual carriageways offers an opportunity to realise the benefits of a shift towards higher occupancy vehicles on the TII national road network. This can increase the people carrying capacity of the road network at a relatively low cost, without the need for additional traffic lanes. Modal shift has the potential to reduce traffic congestion and is in line with Ireland's government policies. Therefore, this option should always be explored early in the evaluation of options.

Service frequency is a key factor in determining project benefits, and projects should prioritize improvements in journey time reliability and service frequency to maximize the value of the infrastructure investment. When establishing project objectives, design organisations should ensure the creation of a clear set of objectives, allowing for a range of options to be evaluated using the SMART (Specific, Measurable, Achievable, Realistic, and Timely) principle.

3 Objectives and Key Benefits

Objectives and key benefits of implementing hard shoulder bus priority measures include the following:

- Deliver a practical solution to support Ireland's climate action policies;
- Encourage a modal shift to more sustainable transport modes;
- Increase the people carrying capacity of Ireland's road network, with emphasis on radial routes for Dublin, Cork, Limerick, and Galway;
- Provision of a transport solution that allows public transport to move more efficiently during peak times;
- Reduced car mode share and reduced car traffic on Ireland's road network;
- Accommodate long-distance point-to-point coach services;
- Support reduced journey times for buses, more reliability for timetables and schedules, opportunities for schedule improvements and associated environmental benefits (Fig. 1).

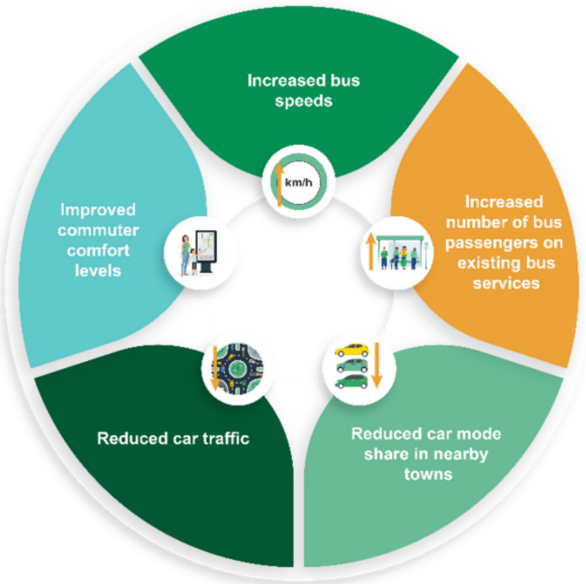


Fig. 1. Key Benefits of Bus Priority Measures (©Arup, image produced using Adobe InDesign)

4 Guidance Documentation

Arup were approached by TII as their Standards Commission Partner, to prepare a new Standard entitled *Hard Shoulder Bus Priority Measures on Motorways and Type 1 Dual Carriageways.* This document sets out early design considerations, types of operation and geometric requirements, emergency refuge areas and intelligent transport systems. This document was published in July 2022.

The design guidance document provides specific information regarding the prerequisites and factors to consider when introducing hard shoulder bus priority measures on motorways and Type 1 dual carriageways within the Ireland national road network. The guidance document is specifically applicable to projects that aim to incorporate these measures on existing motorways or Type 1 dual carriageways on Ireland's national road network.

5 Application of Guidance Documents on Projects

Supported by TII and the NTA, two schemes were tendered, one by Kildare County Council/South Dublin County Council and one by Wicklow County Council/Dun Laoghaire-Rathdown County Council for which a decision was taken to investigate the possibility of the use of these bus priority measures. The international literature, case studies review, and guidance document referred to above, have been applied in the development of these two projects. These projects are located on the M4 and N11/M11. Both are radial routes into Dublin, with the M4 providing access from the west and northwest of Ireland to

Dublin and the N11/M11 providing access from the southeast to Dublin and also serves Rosslare Port. Bus priority measures on the M4 in the eastbound direction were progressed by Arup in conjunction with TII, the NTA, Kildare County Council and South Dublin County Council through a Part 8 planning process which was granted planning permission in February 2023 and is progressing to detailed design and construction in 2024. The N11/M11 bus priority measures project is being progressed by TII, the NTA, Wicklow County Council and Dun Laoghaire-Rathdown County Council in conjunction with the Kildare National Roads Office and with Arup appointed as Technical Consultants. The N11/M11 project is currently at Design and Environmental Evaluation phase. Figure 2 presents a graphic of a proposed cross section of bus priority measures on a motorway in Ireland.

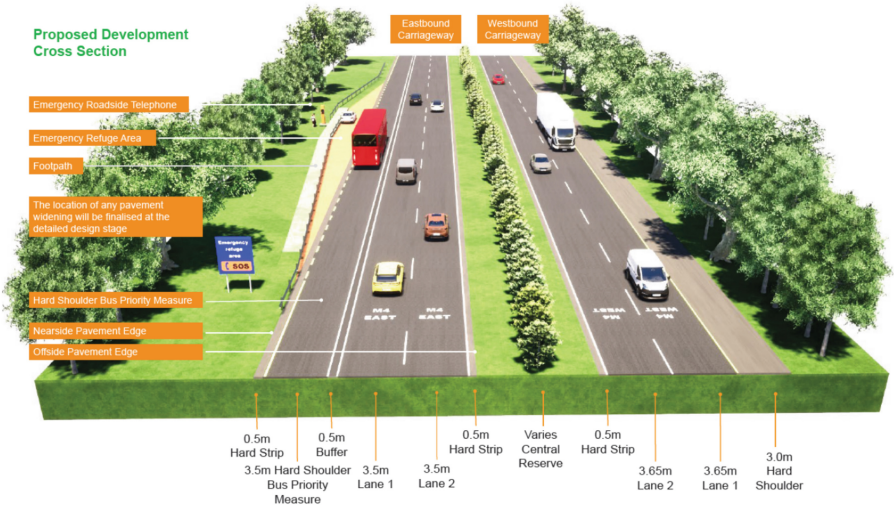


Fig. 2. Typical Proposed Cross-section of Bus Priority Measures (©Arup, image produced using Adobe InDesign)

Both projects were assessed based on guidance documentation with recommendations that objectives are based on Economy, Safety, Environment, Physical Activity, Accessibility & Social Inclusion, and Integration.

Below is a visual representation of the M4 bus priority measures proposals. This visual representation was prepared to disseminate the proposals to the general public as part of the planning process presented by Kildare County Council and South Dublin County Council supported by the NTA and TII (Fig. 3).

The M4 project does not increase noise, and it is notable that it will provide circa 3.8 km of noise mitigation to support the reduction of existing noise. Low noise surfacing will be installed to achieve this objective. The project requires no landtake beyond the current road reserve, thus reducing the project's environmental impacts, landowner impacts and cost.

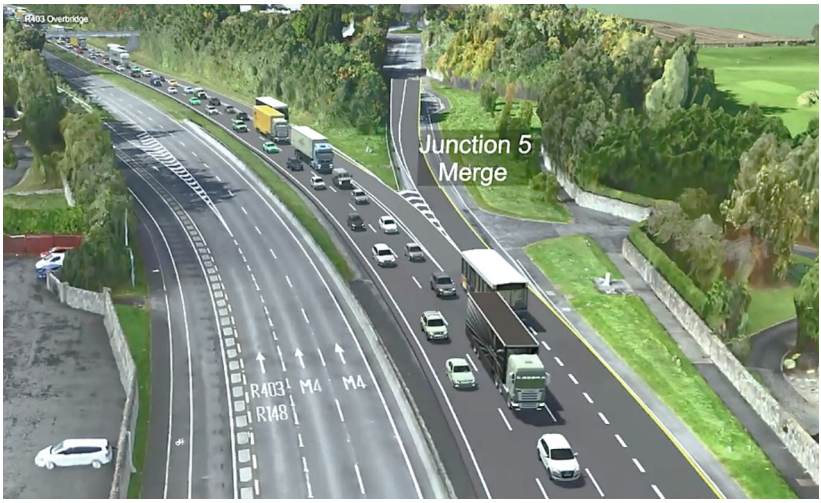


Fig. 3. Visual Representation of M4 Bus Priority Measures (©Arup, image produced using Bentley Open Roads Designer and Bentley LumenRT)

6 Summary

Delivered by a collaborative team of Transport Infrastructure Ireland, the National Transport Authority, Kildare County Council, South Dublin County Council, Wicklow County Council, Dun Laoghaire-Rathdown County Council and Arup, the M4 and M11/N11 schemes will be the first hard shoulder bus priority measures in a motorway environment in the Republic of Ireland.

Novel pilot schemes such as these represent a significant step in the delivery of sustainable transport in Ireland and support the Irish Government's Climate Action Plan goal of achieving net-zero emissions by 2050, and Transport Infrastructure Ireland and the local authorities' own sustainability policies and climate action plan objectives.

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Supercabatteries for a New Sustainable Mobility

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Abstract. The escalation in private vehicles because of urbanization poses one of the major challenges which have both economic and environmental implications. Facts show that about 25% of carbon dioxide emissions result from vehicles. While electric mobility is a potential solution to mitigate pollutants, it is heavily dependent on power generation methods. Furthermore, the limited lifespan of the battery hinders the full utilization of other vehicle components. Technical term abbreviations will be explained upon first use. The language will remain clear, objective, and formal with a precise choice of subject-specific vocabulary. Recently, hybrid supercapacitors, a new type of electrochemical energy storage, have gained attention in the industrial sector due to their potential to provide up to 20 times longer service life than conventional lithium-ion batteries. This conference paper aims to analyze how supercabatteries, a specific category of hybrid supercapacitors, can reduce the environmental impact of vehicles by extending their service life.

Keywords: Supercabatteries · micro-mobility · micro-vehicles · supercapacitor · hybridization · Li-ion

1 Introduction

According to recent studies, urbanization is rapidly increasing, earning the title "The Century of Cities." [1, 2]. United Nations (UN) reports from 2019 show an urbanization rate of 56%, projected to reach 68% by 2060 [1].

One of the most concerning outcomes is the inability of pre-existing urban road networks to accommodate a fast-growing number of vehicles, leading to unsustainability. Despite various interventions to limit traffic, such as Limited Traffic Zone (LTZ) or restrictions on older vehicles, this phenomenon has significant economic and environmental consequences. The so-called "congestion price" [3] is a crucial variable in the economic sphere due to increased costs resulting from delays and excessive fuel consumption. Moreover, it has a detrimental impact on the environment, leading to a rise in pollutant emissions. Indeed, CO2 emissions from the global transportation industry have increased in recent years, rising from 5.8 GT in 2000 to 8.2 GT in 2018. Road vehicles are responsible for approximately three-quarters of these emissions. [4] Transportation accounts for more than 25% of global carbon dioxide (CO2) emissions from fossil fuels in internal combustion engine vehicles. [5].

Battery Electric Vehicles (BEV) have been suggested as a potential solution, but their effectiveness is not guaranteed as their carbon footprint is heavily influenced by both

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the national energy mix and the time of charging, resulting in up to a 73% fluctuation in indirect GHG emissions [6].

Studies have shown varying results regarding the carbon footprint of electric vehicles when compared to internal combustion vehicles. Some articles [6] suggest that in countries where electricity generation is predominantly fueled by fossils, electric vehicles have a higher carbon footprint. However, other articles [6] report the opposite.

The disposal of electric vehicle batteries presents a second challenge. For vehicles like cars and buses with a lifespan of over 10 years, battery disposal contributes to 7% of the carbon footprint. Moreover, it is 35 times more expensive than disposing of internal combustion engine vehicles. On the other hand, micro-mobility vehicles have a much shorter life, making battery disposal a major concern for them. Based on reports, the first generation of electric scooters for sharing had an average useful lifespan of under 6 months [7]. This period was completely inadequate in offsetting the CO2eq emissions produced during the manufacturing and transportation of the vehicles. However, there have been improvements as VOI [8] indicates their electric scooters now have a useful lifespan of 60 months, resulting in a 20% reduction in GHG emissions per pkm [7]. However, the report indicates that the carbon footprint of various electric vehicles is still too high. This conference paper aims to analyze the use of hybrid supercapacitors, specifically *supercabatteries*, as an alternative to batteries. The study will assess their potential for reducing the environmental impact.

2 The *Supercabatteries*

Hybrid supercapacitors (HSC) are energy storage devices that offer the benefits of both supercapacitors and batteries. Supercapacitors provide high power capacity and long cycle life, but they have lower energy density. Conversely, batteries possess high energy density but lower power capacity. Hybrid supercapacitors aim to conquer these limitations by combining supercapacitive and battery-like materials [9].

Another aspect to consider in developing hybrid supercapacitors is distinguishing between pseudocapacitive and battery materials. Pseudocapacitive materials provide high capacitance and rate capability, making them attractive for energy storage applications. However, the use of nanomaterials in batteries has allowed battery materials to achieve fast redox kinetics like those of pseudocapacitive materials, confusing in defining these materials. To precisely differentiate between pseudocapacitive and battery materials, the proposal by Zhang and Liu [10] recommends combining electrochemical signatures with quantitative kinetics analysis.

Hybrid supercapacitors offer a fusion of the best features of batteries and supercapacitors, resulting in advanced power capability, extended cycle life, and enhanced energy density. The utilization of nanomaterials, like carbon nanotubes and titanium dioxide-boron nanowires, in electrode components augments the efficiency of hybrid supercapacitors. Nonetheless, it is imperative to distinguish accurately between pseudocapacitive and battery materials to evade misunderstandings during the design of these energy storage devices [9, 10].

Hybrid supercapacitors with a battery-like electrode, are also called supercabatteries, and their main advantage is to have a considerably high cycle life, compared to the battery from which is hybridized [11].

3 Devices Considered and Methodology

3.1 Supercabatteries Taken into Account

The hybrid supercapacitors being analyzed for various types of vehicles are produced by Gonghe Energy Ltd.

Two models have been selected: one with a cylindrical shape, a maximum voltage of 4.2V, and a capacitance of 4000F, which is suitable for micro-mobility vehicles due to its small size and sufficient discharge C-rate. The datasheet [12] indicates that the useful life of these supercapacitors is 20,000 charge and discharge cycles.

This data has already been analyzed and cited here [13].Supercapacitors with a maximum voltage of 4.2 V and a capacity of 21000 F are available in a pouch-type suitable for heavier mobility like electric scooters or private cars. They are capable of being charged and discharged up to 50000 times and provide a slightly higher C-rate than the preceding versions. For both types, the shelf life is above 20 years, 2 times higher than the common Li-ion cells.

Refer to Table 1 below for a summary of the costs associated with these two categories of supercapacitors.

Table 1. Other relevant data for HSC compared to NMC Li-ion.

HSC type	Specific energy [Wh/kg]	Cost per kWh [$/kWh]
4000 F	200	440
21000 F	240	486
Li-ion		
NMC Li-ion	265	<200

These prices are over twice as high as those of Lithium-ion batteries. Nevertheless, upcoming chapters will assess if the longer lifespan of these supercapacitors when compared to Lithium-ion batteries justifies the higher investment regarding the carbon footprint. Furthermore, the reduction in carbon footprint will be assessed.

3.2 Italian Electric Generation Scenario

As previously stated, the national energy mix has a profound impact on the carbon footprint. For this conference paper, we selected the Italy energy mix as a benchmark, utilizing data from 2019 [14].

Figure 1 reveals that over 50% of the electricity generated by thermoelectric plants is powered by natural gas.

For every kWh of electricity produced, according to [15, 16] estimates the release of 306.94 gCO2eq into the atmosphere. The data from [16] and Fig. 2 demonstrate that renewable sources have a negligible impact compared to thermoelectric plants. The obtained value is reasonable and shows a 25% decrease from the U.S. average. This outcome supports the viability of electric car usage in the Italian environment.

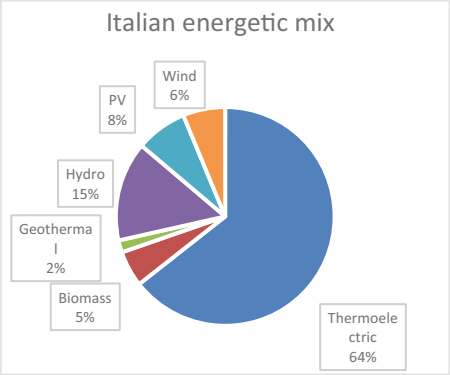


Fig. 1. Italian energetic mix power sources percentage

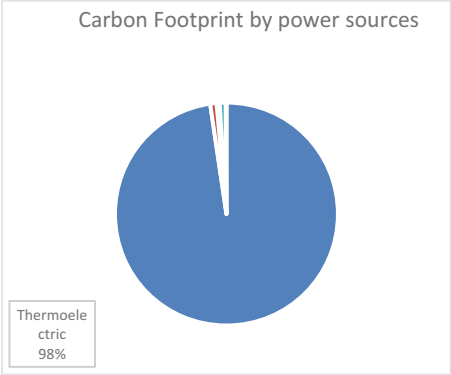


Fig. 2. Carbon footprint of the power sources for electric generation in Italy by percentage

4 Carbon Footprint

4.1 Carbon Footprint of Micro Vehicles

Micro-mobility vehicles frequently face criticism for their poor durability resulting from subpar battery management or low quality [7]. Early electric scooters, for instance, had an average lifespan of less than a year. Additionally, their manufacture primarily in China weighs heavily on the calculation of their carbon footprint. According to reports [7], electric scooters travel 2,000 kms per year, while electric bikes travel 2,400 kms per year. The average lifespan of electric scooters and electric bikes is limited by the technical obsolescence of the battery. The battery often fails before the motor, which has an average life between 10,000 and 25,000 km, and the control electronics. To compute carbon footprint calculations, we used data and formulas cited in the following articles.

Using supercabattery-based accumulators can maximize vehicle performance and prolong its lifespan. The use of supercabatteries has shown an extension of medium useful life for scooters up to 10,000 km and up to 20,000 km for electric bicycles. All calculations were objective and based on factual data [7]. Triple mileage scenario figures are calculated considering various interventions of maintenance.

According to Fig. 3, the use of HSC-based accumulators in electric scooters can decrease their carbon footprint by 32%, thereby significantly reducing both emissions and raw material usage CO2 cost. However, for longer distances, this reduction shrinks to 22%, as distance travelled has a much greater impact.

In the case of electric bicycles, Fig. 4, supercabatteries can reduce the carbon footprint by 28% and 22%, respectively. Their carbon footprint is lower than in the case of electric scooters because they are more robust vehicles and allow them to travel longer distances.

4.2 Carbon Footprint of Battery Electric Car (BEV)

As noted previously, the environmental sustainability of electric cars is in question since most nations generate electricity using thermal power plants.

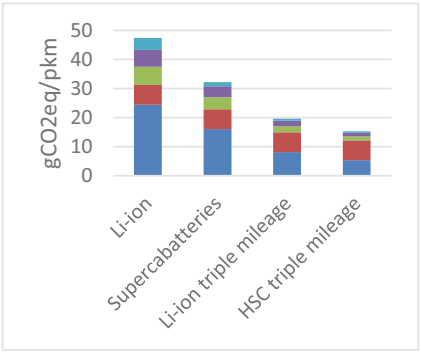


Fig. 3. Carbon footprint of electric kick scooter on various scenarios

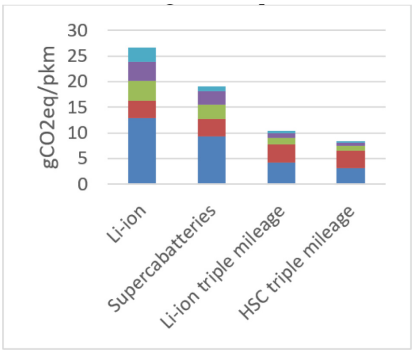


Fig. 4. Carbon footprint of electric bike in various scenarios

The graph presented below indicates that the term related to transportation is much less significant in comparison to micro-vehicles. Extending the useful life of electric cars can reduce carbon footprint by 27% and 21%, respectively. The extended lifespan's impact is minimized by the fact that maintenance expenses are considerably less burdensome on the budget (Fig. 5).

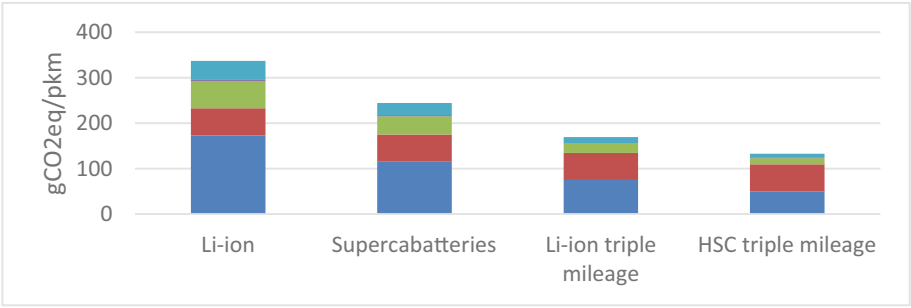


Fig. 5. Carbon footprint of BEV in various scenarios

5 Conclusions

Adopting HSC technology can reduce the carbon footprint of multiple vehicle types by over 20%. This reduction occurs even in scenarios with significant renewable electricity generation, thanks to the long lifespan of HSCs compared to the vehicles they power. Additionally, HSCs improve vehicle efficiency by enabling greater mileage coverage. It remains to be assessed from an economic standpoint whether it is sensible to invest in advanced power units and at what point this becomes financially feasible for those who drive their vehicles infrequently, as the additional expenses could render their adoption economically infeasible.

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Medical Applications of Urban Air Mobility: A Study on Acceptance

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Abstract. In recent years, urban air mobility (UAM) has emerged as a transformative force in transportation, powered by unmanned aerial vehicles (UAVs) or drones. UAM promises to revolutionize air transport services by establishing efficient and innovative connections between cities, suburbs, rural areas, and previously inaccessible regions. This study delves deeper into one of the most promising applications of UAM, the healthcare sector, by analyzing ongoing survey data collected from healthcare workers (N = 154). The survey investigates the perceptions and attitudes of these professionals, with a specific focus on the potential applications to the Portuguese medical and healthcare services. Early results find a limited prior knowledge of using drones for medical purposes among healthcare workers. Furthermore, concerns related to safety and security are apparent. However, it is noteworthy that healthcare workers generally hold a positive outlook on both urgent and non-urgent applications of drones in their field. By recognizing and addressing these diverse perspectives, encompassing both the negative and positive aspects, through deliberate and systematic design, valuable insights can be gained. These insights have the potential to guide the development of UAM technologies in healthcare, ultimately contributing to improved services, enhanced safety, and more efficient and effective healthcare delivery.

Keywords: urban air mobility · urban logistics · user perception · acceptance · medical drones

1 Introduction

The topic of urban air mobility (UAM) has been gathering much attention, due to its great potential for innovative solutions and the disruptive nature of the concept itself. There is potential for new business models, more efficient air travel, increased safety, and reduced congestion and pollution [1]. The increasing prevalence of e-commerce has also led to a greater demand for cost-effective and sustainable delivery options, which in turn requires logistics operators to develop more complex and diverse solutions to meet this demand [2].

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However, a widespread implementation of UAM is quite complex, as it requires to overcome several technical and regulatory barriers related to: (i) the development of vehicles for specific purposes (e.g., freight and passenger transport, infrastructure monitorization and maintenance, surveillance, etc.), (ii) air traffic management and availability of landing infrastructure, (iii) safety and liability in case of an accident, and (iv) data protection and security issues.

Beyond these aspects, and as when any disruptive technology is introduced, public acceptance is crucial for a successful rollout of UAM [3]. The idea of adding a third dimension to urban logistics and public transport networks, with numerous drones flying over densely-populated areas, is controversial and associated to sci-fi movies representative of a more-or-less distant future. Therefore, despite that the general public is a key actor in the implementation of this technology, the opinions and mental representations of people about UAM have been relegated to a secondary role in relation to the technical feasibility [4].

In this way, bringing the general public to the forefront of this discussion and evaluating prospective users will stimulate the gradual implementation of the technology through the most promising, efficient and acceptable applications. This work follows a previous study that analyzed the potential of drone usage for e-commerce deliveries in three European regions [2], but expanding this analysis to the healthcare sector.

2 UAM in Healthcare Services

One of the applications that shows significant potential for acceptance and overall success within the realm of UAM is the utilization of UAVs in medical and emergency situations [3]. These specific use cases hold immense promise due to their direct impact on improving public health and safety, as well as enhancing the efficiency and timeliness of critical services. This is corroborated by the common understanding from the public of the potential for medical/emergency drones as they seem to be becoming more ubiquitous and accepted [5]. This could be the transport of medicines, blood, or devices such as Automated External Defibrillators [6, 7].

By leveraging UAM technology, medical professionals can gain faster access to remote and hard-to-reach locations, enabling them to provide prompt medical assistance and improve patient outcomes as already is a common occurrence in some African nations [8]. Additionally, emergency response services can benefit from UAM by reducing response times [9] and swiftly reaching areas affected by natural disasters or accidents. Furthermore, the integration of UAM into delivery services offers the potential for expedited and environmentally friendly transportation of essential goods, leading to increased efficiency and reduced traffic congestion on the ground [1].

Understanding the factors that contribute to the acceptance and adoption of UAM in these crucial areas is pivotal, as it can help to ensuring a successful widespread implementation, ultimately improving the lives of individuals and communities. Since emergency and common-good applications benefit from higher acceptance, a survey targeting workers of the healthcare sector was developed to explore their perceptions and attitudes towards UAM medical application. The implementation of this survey was done online in Portugal, mostly focusing on the northern region.

3 Materials and Methods

3.1 Questionnaire

The questionnaire targets professionals working in the healthcare sector, including staff in direct contact with patients, holding an administrative position, dealing with healthcare logistics, or engaging in research or laboratory activities. The objective is to gather information on the perception and attitude of these professionals towards the use of drones in healthcare services, namely in the transport of medicines, vaccines, and medical equipment, among others. The survey contained 32 questions divided by the following dimensions: demographics and questions about professional career and position; knowledge and attitudes about the use of drones for medical or emergency purposes; intention to use drones for medical purposes; perceptions of using drones for medical purposes; and risk of using drones for medical or emergency purposes.

Participants were asked to rate their agreement or disagreement on a 6-point Likert scale for some statements related to drones in healthcare. Statistical measures, including mean, median, variance, and standard deviation, were calculated for each Likert scale question to provide an exploratory understanding of the participant's responses.

3.2 Data Description

The survey responses (N = 154) aimed to explore their knowledge and attitudes regarding the use of drones in medical applications. Most of the respondents fall into the age range of 18–34, comprising 60,4% of the sample. The distribution of respondents across different regions shows a significant concentration in the Porto Metropolitan Area, accounting for 73,4% of the sample. This regional skew should be considered when generalizing the findings to other areas. Urban areas are the most common typology of regions, representing 86,4% of the respondents, followed by suburban areas (7,8%) and rural areas (5,9%).

In terms of professional roles, medical doctors are the largest group, representing 24,7% of the sample. Other notable professional groups include nursing professionals (21,4%) and pharmacists (16,2%). The sample also comprises individuals with various levels of experience in their roles, ranging from less than six months to over 10 years. Additionally, respondents have diverse workplace typologies, with large hospitals being the most common (41,6%), followed by laboratories and pharmacies (21,4%). In addition, most respondents (85,7%) have direct contact with patients, while 47,4% have direct contact with the process of delivering medical supplies/materials in their daily activity.

4 Perceptions and Attitudes

The analysis of the survey results revealed some relevant findings. Participants demonstrated a moderate level of knowledge about the use of drones for delivery purposes (mean = 2.5; SD = 1.7) and for medical purposes such as emergencies or deliveries (mean = 2.6; SD = 1.7). These findings suggest that participants have some awareness of the use of drones in healthcare, although there is some variability in their level of knowledge, as indicated by the standard deviation.

Regarding attitudes towards the use of drones in healthcare, participants expressed a generally positive view. They considered the use of drones for non-urgent health services (mean = 4.3; SD = 1,4) and urgent and emergency medical services (mean = 4.7; SD = 1.2) as favorable ideas. This indicates that participants perceive the potential benefits of utilizing drones in healthcare, with relatively low variance in their responses, suggesting a degree of consensus.

Participants also exhibited a supportive stance towards the use of drones for non-urgent healthcare services (mean = 4.2; SD = 1.5) and urgent medical care and emergency services (mean = 4.7; SD = 1.2). They recognized the benefits associated with drone usage in the medical field (mean = 4.8; SD = 1.1) and expressed interest in utilizing drone delivery of medical supplies (mean = 3.7 SD; = 1.5). The low variance values indicate that there was a relatively narrow range of responses, suggesting a high degree of agreement among participants in these aspects.

Participants also perceive the use of drones for the delivery of medical materials as a concept that is relatively easy to understand (mean = 3.9; SD = 1.5) and use (mean = 3.5; SD = 1.3). This suggests that participants believe that incorporating drone technology into healthcare operations would not pose significant challenges in terms of comprehension and usability.

Participants recognized the potential benefits of using drones for medical purposes, particularly in terms of faster access to items that are not easily available everywhere (mean = 4.6; SD = 1.1). This indicates that participants acknowledge the role of drones in improving the accessibility of medical supplies, especially in remote or underserved areas.

While participants generally demonstrated acceptance of drone technology in healthcare, some concerns and apprehensions were also evident. Participants expressed moderate levels of fear related to potential drone failures and damage to the carried materials (mean = 4.4; SD = 1.3). Additionally, concerns about privacy, security, and criminal activities, such as theft or hijacking of drones (mean from 3.5 to 4.2; SD from 1.4 to 1.5), were reported. The means indicate variable levels of concern with different security issues, but the relatively low standard deviations show some agreement in relation to each individual aspect.

5 Group Comparisons

Group comparisons were conducted to examine the impact of various factors on participants' responses. These factors included age groups, experience in the medical field, role in the healthcare sector, type of workplace, and type of region. We used the Kruskal-Wallis test to determine if statistically significant differences existed among groups.

Age was one of the factors we explored, as previous research suggested its relevance in perceptions of UAM [5]. However, age groups among medical workers did not show significant differences, except for fear of hijacking for criminal purposes, where the age group of 45–54 expressed a higher concern in this regard in relation to other groups.

In contrast, when examining experience in the medical field, we identified significant differences across several variables, including knowledge about drone technology,

support for different types of medical services, ease of understanding and use, and concerns related to privacy and security. Post-hoc analysis, particularly the Dunn test, highlighted pronounced differences between individuals with over 10 years of experience and those with 5–10 years, indicating that experience plays a role in shaping perceptions of drone technology in healthcare, and may be a better indicator than age for acceptance evaluation.

Professional roles also showed significant differences, especially regarding agreement on the potential benefits of using drones in healthcare. Academic/research roles have a more positive view on efficiency improvement than practical roles like nurses and pharmacists. Similarly, nurses expressed a less favorable opinion regarding the compatibility of drone deliveries with their work, likely influenced by the nature of their responsibilities and patient privacy and safety concerns.

Concerns about drone reliability and safety revealed significant differences among professional roles, with paramedics and emergency responders expressing more pronounced apprehension, likely due to the critical and time-sensitive nature of their work. However, the type of workplace did not yield significant differences in participants' attitudes and perceptions, suggesting that professional roles had a more substantial influence than workplace conditions.

6 Conclusions and Future Research

Preliminary results regarding healthcare workers' perceptions show low knowledge of usage drones for medical applications. However, both urgent and non-urgent medical applications of UAM were viewed quite positively. The gaps between low knowledge and high support must be confirmed by future research. Nevertheless, the high support for medical applications is in line with the findings from previous research [3], as the healthcare sector is one of the few where the concerns with drone technology less valued by the society in relation to the benefits in accessing to medical provisions, especially in emergency situations. This contrasts with an early development stage and a relatively low priority currently given to drone applications in the healthcare sector that is restraining the knowledge of professionals about its practical implementation.

Concerns related to safety and security, particularly the fear of drones failing or being hijacked, negatively influenced the support for these services. As for determining acceptance amongst groups, the years of experience and professional role seem to be better indicators than age and the type of healthcare facility where participants work, respectively.

If these perceptions, encompassing both negative and positive viewpoints, are carefully considered and systematically addressed through intentional design, they can serve as valuable insights. These insights can help bridge the existing gaps, including low knowledge and awareness of drone technologies, and the need for specialized training in such a sensitive field. Furthermore, addressing concerns related to safety and security, particularly the fear of drone failures or hijacking, is crucial.

By proactively addressing these challenges, the potential benefits of utilizing drones for medical applications become even more evident. Such enhancements could significantly contribute to improving society, potentially saving lives, and increasing the efficiency and quality of patient assistance within healthcare systems.

On the note of future research, this survey intends to keep gathering answers to ensure a stronger sample that would allow for more robust analysis and more complex insights that would helpfully make possible the creation of said services, whilst focusing on the requirements and needs of the involved stakeholders. Particularly, an increased effort to have a higher representativeness of professionals driving the decision to adopt drones in the sector (e.g., logistics managers, hospital administrators, and regulators) should be made. Qualitative methods employed simultaneously with a stronger statistical analysis (e.g., using structural equation models) is planned in the future to deepen this analysis and strength its results.

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Last-Mile Delivery Through Electric Motorbikes: Modelling Considerations for Parcel vs. Food Delivery

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Abstract. The use of electric motorbikes for last-mile delivery fills a gap between electric cargo-bikes and electric vans in cities, suburban and rural areas. Planning and sizing the use of electric motorbikes for delivery poses several challenges to meeting fleet managers' eco-efficiency and cost-effectiveness objectives while maintaining high levels of customer satisfaction. Consolidating deliveries and using optimised routes helps reduce consumption and reduce the overall footprint. In this paper, we address and describe modelling considerations that are significant for planning delivery services using electric motorbikes: battery consumption and route planning. We address these modelling considerations differentiating particularities between parcel and food delivery. The two approaches share multiple similarities but they face variances regarding customer demand and delivery procedures.

Keywords: goods delivery · modelling · electric motorbikes

1 Introduction

The adoption of electric vehicles for shared urban mobility and last-mile goods delivery is increasing mainly pushed forward by the need to reduce the environmental impact in the cities. In particular, electric motorbikes (also known as E2W) are two-wheeled vehicles powered by electricity instead of traditional internal combustion engines. They are relatively lightweight vehicles and take up little parking space. Thus, the use of these types of vehicles for last-mile delivery fills a gap between electric cargo-bikes and electric vans, valid not only in cities but also being able to reach suburban and rural areas (less accessible for bikes) with ease.

However, fleet owners face several challenges. Data-driven simulation and planning technologies, based for instance on Digital Twins (DT), are emerging as valuable tools for the assessment of initial investment and monitoring of fleet operations. Model-based DT and Data-driven DT (without explicit knowledge of

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the physical behaviour), while some authors also refer to Hybrid DT. Some works conclude by stating the superiority of data-driven solutions over model-based ones due to their ability to handle systems with high complexity [2]. Applications for transportation and, more concretely, electromobility, the behaviour of the electric vehicles and real-time battery management have been addressed in the literature [1–3]. Even though some works address design optimisation as one of the purposes of using DTs [2], they are applied from the vehicle design perspective. Nevertheless, literature focused on electric motorbikes is limited and the availability of data able to support comprehensive and detailed studies is lacking.

In this context, this paper aims to describe the lessons learnt during our process of building delivery demand estimation and motorbike battery consumption estimation models and the main considerations to be addressed before tackling the development of fleet and charging station planning solutions for goods delivery. To the authors' knowledge, no works have addressed modelling last-mile goods delivery services using electric motorbikes based on real data. This paper wants to contribute towards this direction.

2 Problem Statement

Building planning software to help dimension the use of electric motorbikes to serve goods delivery in the last mile requires modelling the trips that will be required and the estimated energy consumption pattern of the fleet. A data-driven approach based on machine learning models is proposed, using real current motorbike trips (electric and conventional) of goods and parcel delivery services in multiple European cities.

The final objective of these models will be to be able to determine the demand of requests from each geographical region at a given time frame, including cities currently covered by the delivery services and new cities where future service deployments are being planned, and to what extent this demand can be satisfied by a fleet of E2Ws of a given size.

2.1 Study of Available Information

Real data from delivery companies is the main source for training machine learning algorithms to build electric motorbike battery behaviour models and to build demand prediction models for parcel and food delivery services, named HDPE (Home Delivery Parcel Electric) and HDFE (Home Delivery Food Electric).

The information consists of tracks with geolocated positions every few seconds and battery State-of-Charge (SoC) value every few seconds. A track begins when the engine is started and it ends when stopped, in addition, stops during the track are identified.

2.2 Auxiliary Data

In order to build a solution as generic as possible, the following well-known existing socio-economic city indicators and geographical zoning scheme data sources have been identified.

- City cartography source: OpenStreetMap [4] to build the transportation network and open data Digital Terrain Model for the elevation.
- Geographical zoning source based on census sections.
- Socio-economic indicators for each section such as: Population, Average age, Percentage of population with higher education over the population aged 16 or over, Percentage of people over 64 years of age, Percentage of people between 16 and 64 years of age, Percentage of foreign population, Average level of studies, Percentage of active population over population aged 16 or over, Average household income.

Socio-economic indicators are useful to characterise the type of end-users that are served by the E2W fleet in the delivery area, affecting the demand. Moreover, city cartography and zoning data are useful for determining the layout of the transportation network and the geographical extension covered by the E2W fleet, affecting the service operation (deliveries according to travelled distance, e.g.). They are key to plan and size fleets for delivery services in new locations.

3 Methodology

3.1 Initial Exploratory Analysis and Cleaning

The route duration of the tracks using the timestamp of the origin and destination was calculated as a first step. Some differences in the average duration of the route between food and parcel delivery were found and multiple outliers were also identified, since, for example, the duration of some journeys was greater than a whole day. Before cleaning measurements that fall out of quartiles, it was noticed that the tracks existing in the dataset did not homogenously reflect journeys from depot to depot because the behaviour of all drivers was not consistent. In some cases, the motorbike engine is not stopped when it returns to the depot, and in some delivery stops, the engine may or may not be stopped, representing a new track beginning. An example can be seen in Fig. 1. This has required a process to clean and process the tracks into a new entity called "trip", where each trip must begin and end in a depot.

3.2 Depot Detection

This process identifies depot locations since this information was not included in the dataset. A density-based spatial clustering of applications with noise (DBSCAN) algorithm, which is an unsupervised density-based grouping method, was selected to perform this task, based on the rationale that motorbikes should pass from the depots more frequently than any other locations. However, for

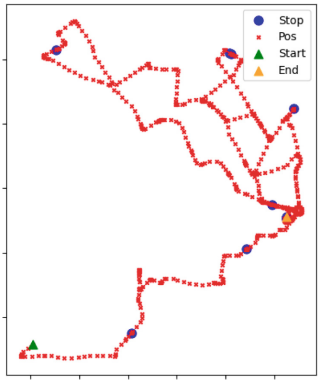


Fig. 1. Example where the start and end of a track are not the same depot

parcel delivery, the analysis shows that many motorbikes do not return to the depot as much as the food delivery motorbikes do, as shown in Fig. 2. Moreover, from day to day, the stops that these motorbikes visit are very similar. Therefore, it was demonstrated that the density of points was not a valid criterion.

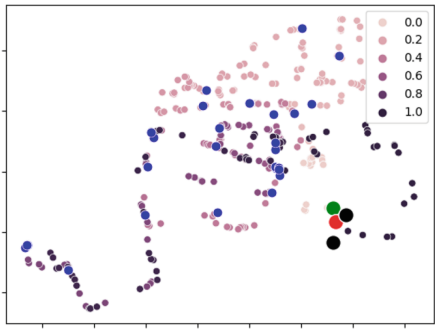


Fig. 2. Example of a full-day trip, where the vehicle only returns to the depot at the end of the day.

Therefore, the procedure to identify the location of depots for each service type is as follows (as a ground-truth, locations of well-known delivery offices were obtained from OpenStreetMap data):

– For food services, the DBSCAN algorithm is applied for each vehicle. The parameters that have been used are eps = 0.02 m and min_sample = 20. These are values set experimentally, seeing that it runs fast and that the results are good. The points that are entered into DBSCAN are points that are 5 h followed by a random day. If, when applying the DBSCAN algorithm, it is able to differentiate more than one cluster, the centroid of the cluster

is calculated and this is the depot assigned to the vehicle. Otherwise, the DBSCAN algorithm is applied again using data from another day.
– For parcel delivery, the algorithm iterates over all the vehicles, and all the data for each vehicle is saved but differentiated by day. In this way, a centroid is calculated with the first data of each day and another centroid with the last data of each day. This is done because it has been seen that motorcycles often leave and arrive at the same place. Calculating the distances of the two centroids, the maximum distance has generally turned out to be very small, and in most cases the two centroids are very close, which would indicate that it reflects a DEPOT. Each vehicle is assigned the centroid calculated with the first points of each day.

3.3 Trip Model and Statistics

Once the depot locations are obtained, consecutive tracks are joined and then divided every time a visit to a depot is detected, obtaining a set of circular trips.

For HDFE services, the duration and speed of these trips have a very skewed distribution to the left, having an average of t = 25.69 min for the duration and d = 4.14 kilometres for the distance travelled. The delivery time windows for an acceptable quality of service specified by the food companies are unknown but the duration statistics can be used to model them. For HDPE services, the distribution is more balanced, but there are many outliers that have a very high value for the duration and length of the trip, while their means are t = 206.60 min and d = 21.53 kilometres, respectively. To filter this data, it has been decided to use a variable that relates duration and length: average speed (speed = duration/length). Its distribution is also a little skewed by outliers. The data is filtered according to speed values so that a more centred distribution of the three variables is obtained.

For HDFE, values that are above the 97th quantile in speed have been discarded. So that there are no values with the speed very close to 0, values below quantile 1 have been discarded. For HDPE, values with d = 0 are discarded. In this case, the values that are within the 1st and 92nd quantile are selected. By doing this cleaning, almost 7% of the data is lost. Furthermore, the quartiles have not changed much, while the maximums have decreased considerably.

3.4 Battery Consumption vs. Trip Relation Modelling

Each battery SoC data is associated to a geographic location in the trip (the trip-points) corresponding to the same motorbike, according to the timestamp. Then, trip-points are grouped into short-distance segments using a random 500m-1000m segment size. These segments will be the basis of the training model. For each segment, we calculate the following: elevation difference between the start and end point locations, distance of the segment, SoC deviation from start point to the end point, as well as the average speed limit of the road between the points of the segment according to OpenStreetMap.

4 Application Use Case

Two main modules will be built after applying the procedure presented above: 1) the Route Planning module and 2) the Battery Consumption and Fleet Behavior module. In each process, multiple combinations constructed as the combination of potential locations and sizes will be built. In a third stage, the KPIs obtained from the aggregations of journeys and charging stations usage are computed.

The objective of the Route Planning module is to create a series of user requests, consisting of a pair of origin-destination and origin datetime, and to assign motorbikes to serve sequences of requests. Since parcel and food delivery journey tracks are available and have been modelled according to the previous section, machine learning models can be built to create the user requests. The stops contained in each trip refer to a user request. Each stop is therefore associated with the census section identifier according to a point-to-polygon map-matching relation, so that the aggregated demand (sum of stops) each day is translated into a set of socio-economic indicators by timeframe, and delivery type, indicating day of week, holiday or not, weather type and temperature.

Once the demand is created, the Battery Consumption and Fleet Behaviour module is aimed at estimating the battery consumption of each motorbike due to the route assignments. In addition, this module will need to evaluate energy consumption and cost due to the selected charging strategy.

5 Conclusions

In this paper, we have presented the battery consumption and route planning modelling considerations for food and parcel delivery through the use of a fleet of electric motorbikes. The presented work is part of the ongoing process to build a charging station location and dimensioning tool for electric motorbikes through a digital twin. Sizing electric motorbikes fleet and their associated charging station infrastructure, opens multiple optimisation problems. In this context the analysis of the challenges presented by a real-life dataset and the processes required to prepare the data before the creation of the models have been presented.

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Digital Automatic Coupling as an Enabler for Rail Freight Innovations

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Abstract. Rail freight is the backbone of a sustainable transport system, but innovations are necessary to increase its competitiveness. The Digital Automatic Coupler (DAC) is such a promising innovation to transform the rail freight sector. So far, harmonized definitions of its potential functionalities and use cases are missing in literature. This paper presents the DAC and the Full Digital Freight Train (FDFT) and gives an overview of its functionalities and potential benefits. First, the harmonized operational procedures for the future operation of the FDFT are presented. These provide the basis for potential applications of the DAC. Second, the future functions enabled by the DAC are outlined, categorized and evaluation criteria are discussed. The number of different use cases is large and illustrates the great potential of the DAC. However, challenges of complex technical development and decision-making processes are accordingly large. To tackle these, the current DAC development takes place within the Europe's Rail project Transforming Europe's Rail Freight (TRANS4M-R) which will also be introduced. This overview provides a starting point for further standardization of processes and definitions.

Keywords: Digital Automatic Coupler (DAC) · Full Digital Freight Train (FDFT) · rail freight · automation · digitalization · freight transport

1 Introduction

Rail freight transport faces significant challenges like asset utilization, poor data quality or complex processes. At the same time, freight transport by rail offers great potential regarding various aspects. To exploit these capabilities, the share of rail freight in the overall freight transport must increase substantially. To cope with these challenges, changes are required. Automatization and digitalization play a crucial role in enhancing the competitiveness of rail freight. One groundbreaking innovation to enable these developments is the DAC, which has the potential to significantly accelerate the transformation of rail freight transport. The vision of future freight transport involves an intelligent system that interconnects various stakeholders, processes, and technologies. The DAC aims to optimize the coupling process between freight wagons and comprehensively replace the manual screw coupling system. This leads to substantial time

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savings in train composition, resulting in increased productivity and capacity. In addition, the DAC enables power and data are transmitted between the wagons. The resulting intelligent and interconnected system (Full Digital Freight Train - FDFT) can transmit information regarding freight occupation, condition, or destination, among other things. It thus offers the possibility of optimizing the management and monitoring of the freight train and improves the safety and efficiency of the freight transport. However, since the DAC and the currently used screw couplers are not compatible, only a harmonized approach for DAC deployment on European level will be successful. The development of the FDFT is part of the European funded project Transforming Europe's Rail Freight (TRANS4M-R). The TRANS4M-R project is part of the Europe's Rail Joint Undertaking (ERJU). The ERJU is a public-private partnership established by the Council of the European Union in cooperation with the railroad sector with the aim of creating an integrated railroad through joint research and innovation projects. For this purpose, the ERJU is divided into the system pillar, which aims for standardization in the sector and the innovation pillar, with the development projects. For the implementation within the innovation pillar, 71 companies have formed a consortium covering all relevant stakeholders of the railroad sector including railroad undertakings, infrastructure managers, industrial partners, research institutions as well as shippers. TRANS4M-R will serve all steps of the V-methodology (according to EN50126) up to the verification of the system acceptance.

2 Harmonized Procedures and High-Level DAC Architecture

For the first time, the future operation for the FDFT has been designed prior to the development of the functionalities and components. This approach enables a common development with the industry on a more detailed and consensual level than in the past. Within TRANS4M-R, a team with experts from different operators was founded to design these processes on a generic level. Figure 1 shows the full circle of operation from shunting, via wagon processing and train preparation to train run. In total, 26 processes and subprocesses were designed. These processes are now the foundation for the development of the FDFT and formulate the commonly agreed goal of the project.

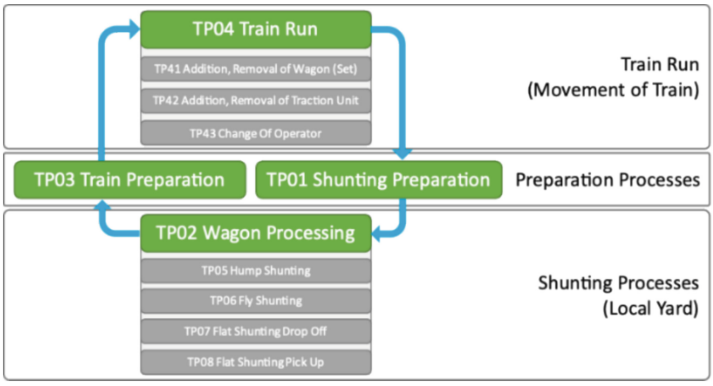


Fig. 1. Process overview with four main processes [1].

Because EN standards require development according to the V-model, it has been decided, that a classic waterfall approach will not enable a development fast enough to keep the project timeline. Feedback loops were introduced to every step to speed up and have a possibility of intensive exchange in-between partners, to grant a determined development. With this accelerated approach, a common freight system architecture has been developed. It all starts with the use cases which were extracted from the operational procedures. Out of the use cases, features and functions are derived and linked to the requirements that are identified in parallel. With the logical elements, the System of Interest is defined and contains all assets developed in the TRANS4M-R project.

3 Digital Automatic Coupler and Full Digital Freight Train

In September 2021, the sector decided in the European DAC Delivery Programme (EDDP) to use a modification of the latch type design (DIN EN 16019) from European passenger transport [2, 3]. Compared to the screw coupler, the automatic coupler allows higher forces in the train set and thus operation of heavier and longer trains. The breaking loads for screw couplers and buffers (DIN EN 15566 & DIN EN 15551) should be clearly exceeded and the DAC should be able to reach the static limit loads of the wagon structure (DIN EN 12663-2). However, to be able to operate longer and heavier trains, in addition to the static loads, the operational limit loads must be increased compared to the current system. In addition to the operational fatigue strength, these include the maximum achievable longitudinal compressive forces for derailment safety (DIN EN 16235). The technical determination of the new limit values is one of the current challenges for the validation of the coupler design for rail freight transport. Figure 2 shows the main components of the DAC.

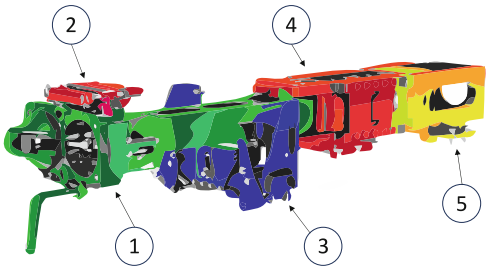


Fig. 2. DAC assembly overview (1) coupler head, (2) electric coupler, (3) vertical support, (4) draft gear, (5) support plates

The coupler head (1) contains the mechanics for coupling and uncoupling, as well as for force transmission in the coupled state. The pneumatic coupler and the air system with automatic closing flap valves are also located here. The forces are transmitted through the coupler shaft and the socket joint into the draft gear (4). The socket joint enables the horizontal and vertical deflection of the DAC. Draft gear and support plates (5) represent

the interface to the vehicle. Numerous freight wagons were therefore produced with a standardized installation space (UIC Leaflet 535). To be able to position the coupler head on the wagon and to implement stops for the horizontal movement, the coupler head is braced by the vertical support (3). To make a DAC fully usable for the target processes, it must also enable a so-called prevent to couple state. This enables the transmission of compressive forces through the coupler without automatic coupling.

The DAC provides an interface for coupling of power and data lines. For this purpose, an electric coupler (2) is installed on the coupler head. The availability of data and electrical energy turns a train into a FDFT. However, just as with the mechanical and pneumatic interfaces, the electrical interfaces must also be defined and standardized for interoperable use. Latest developments in TRANS4M-R specify a nominal voltage of 400 V AC two-phase for the power line and the use of Single Pair Ethernet (SPE) as the protocol for data transmission. Also, vehicle internal components, referred to as wagon onboard system, are required. It consists of voltage converters which transform the 400 V AC from the train power distribution line to 48 V DC for internal use in the wagon. In addition, a onboard battery is needed to provide electrical energy even if electrical energy from a locomotive is not available. An energy management system is also needed to monitor the system status and control the power supply and battery charging. For communication, a central computer unit, the wagon onboard unit (WOBU), is required. The WOBU controls the interface between train and internal wagon communication and ensures the connection of further devices. The next step would be a DAC type 5, that can be uncoupled by a data message [4]. With a DAC 5 uncoupling can be triggered regardless of location. For example, the train driver can now send a message through the data line and the corresponding freight wagon to the relevant DAC and the actuator, which finally executes the uncoupling process.

4 DAC Enabled Train Functions of the FDFTO

All the DAC enabled use cases or train functions can be viewed from two perspectives. First, from the user perspective, the use cases can be distinguished according to their application from a functional view. Second, use cases can be categorized depending on the technical capabilities of the DAC and additional components.

FDFT Functions General
Train functions are needed to automate and accelerate train operations, especially in shunting. The so-called train functions are functions that the technical FDFT system provides in each train formation to ensure automation of today's manual processes [1] (Table 1).

DAC Enabled Train Functions Based on the general functionality, an additional layer of functions can be implemented (Table 2).

DAC Enabled Logistics Applications
The enabled logistic functions allow a better user experience for the customer in terms of traceability, additional information, and functionalities, such as surveillance of goods. These functions can be summarized - simplified - as comfort functions (Table 3).

Table 1. General Full Digital Freight Train (FDFT) functions. Acc. to [1].

Functions	Value proposition	Necessary DAC capabilities
Coupling	Automatic coupling allows faster shunting processes and higher system's safety	Mechanical, air, data, power
Uncoupling	Similar to coupling but due to safety aspects the uncoupling is more difficult to implement	Mechanical, air, data, power
Prevent coupling	Transmission of compressive forces (pushing wagons) without coupling	Mechanical
Train composition detection	Automatic detection of wagons in the train. Automatic creation of composition list	Data line
Train integrity monitoring	Permanent monitoring of last consist to ensure train integrity. Makes rear end signal obsolete. Necessary for ETCS Level 3 and moving block	Data line
Train length determination	Determination of train length with additional wagon meta data	Data line
Automated brake test	Necessary brake test can be automated with DAC and additional sensors	Data line, power line, air line
Automated parking brake	Automatic application (and release) of parking brake in standstill. No safety shoes necessary	Data line, power line
Electro-pneumatic-brake	The ep-brake allows for longer and heavier trains and/or higher speed	Data line, power line, air line
Distributed power system (DPS)	Data line allows for communication of locomotives within the train which enables longer trains	Data line, power line, mechanical coupling
Air management	Control of air shut-off valves and release cables avoids additional walking distances	Air line, data line

The large number of different use cases illustrates the great potential of the DAC. The success of the DAC depends on a European-wide and standardized implementation. Consequently, it is not sufficient to find a solution that works only for many of the

Table 2. DAC enabled train functions

Functions	Value proposition	Necessary DAC capabilities
Technical wagon inspection	Digitization of technical wagon inspection through additional sensors and data line	Data line
Driving in brake position P	DAC allows for more accurate addressing of the brakes. Higher speeds are possible	Data line, air line
Derailment detection	Continuous status monitoring with additional sensors increase safety	Data line
Higher pressure and tensile forces	Higher forces allow for heavier and longer trains, which brings additional advantages	Mechanical coupling

Table 3. DAC enabled logistics functions

Functions	Value proposition	Necessary DAC capabilities
Additional Information/Displays	The availability of the data line and additional sensors allows for status information	Data line
Interfaces to customer systems	The data line and backend system allow for interfaces to customer systems	Data line
Telematics and goods monitoring	The backend system allows for traceability and high availability of transport data	Data line
Lighting	Power line enables equipment of all wagons with lighting, e.g., safety or interior lighting	Power line
Data analysis for CBM	The availability of additional sensors can be used to gather CBM relevant data	Data line
Surveillance	The power and data line allow for surveillance of the wagons with cameras. New markets for high-value goods can be developed	Power line, data line

stakeholders, but it is necessary to consider the interests of all stakeholders. Thus, a decision on the basic functionalities has not yet been agreed upon on European level.

5 Conclusion

In summary, the DAC opens a wide range of opportunities to fundamentally transform rail freight. Besides the automatic coupling and decoupling, especially the digitalization of the freight train enables significantly more efficient processes, the implementation of new functionalities as well as the development of new markets. Shortly, the DAC is a unique opportunity. Yet, the challenges of complex technical development and political decision-making processes at supranational level are accordingly large. To overcome these, major joint efforts are being made at the European level.

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Data for Shifting to Rail Freight Transport: A Review of Free Online Tools

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Abstract. This work summarizes the first results of the project European Shift Enabler Portal for Freight (ESEP4Freight). An analysis of 8 online tools providing information in map format about the European freight transport system has been carried out. The analyzed tools provide information on the infrastructure or on the transport services but rarely on both aspects. In addition, non-commercial tools offer a limited range of quantitative features, such as CO_2 emissions tools or transportation time estimations. Information about transport services connecting terminals or first and last miles services from the terminals is also frequently missing. These results will be considered for the development of the new tool to be developed as part of the project.

Keywords: logistics · rail freight transport · multimodal freight transport · information tool · map

1 Introduction

Reducing CO_2 emissions in the transport sector is critical to achieving the objectives set by the European Union (EU). A significant part of CO_2 emissions is produced by freight transport and specifically by road transport [1]. Therefore, since rail freight is one of the mainstays for decarbonizing the transport system in Europe, the reduction plans' success relies on shifting freight transport towards more sustainable modes, such as train or multimodal transport where train covers medium and long distances. To facilitate the shift to rail, supply chain stakeholders need to access relevant information during the decision stage. However, information needs differ according to whom the information is addressed and other several factors, such as railway carriers, shippers or the type of goods to be transported. This information can be challenging to obtain, and additional efforts required to access the data may involve devoting valuable resources to this task, leading to the continued use of high-emissions transport services.

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In this work, an analysis of free access online tools providing static information has been carried out. This analysis is part of the first stage of the project ESEP4Freight, that aims to develop an online tool organized around an interactive map to provide static information to logistics stakeholders to facilitate the modal shift to rail in freight transport.

The first step of this work has consisted in identifying tools candidate for further analysis. In second place, a methodology has been developed by identifying relevant attributes for the assessment of tools. Lastly, the application of the methodology has enabled to identify gaps in the existing tools that could be of interest for logistic stakeholders and could be possibly covered by the new tool developed by ESEP4Freight.

2 Methodology

The preparation of this document has started with the scanner of the web to identify candidates to be assessed. To do this, the following five search strings in the search engines Google and DuckDuckGo have been used: *Intermodal Map Europe*, *Intermodal Map Facilities Europe*, *Intermodal Map Terminals Europe*, *Intermodal Routes Map Europe,* and *Freight Infrastructure Map Europe*. The results of the first page of results of each search were scanned and suitable results identified. This process was completed with additional sources known by the authors, such as the projects iFreightMED-DC [2] or TRAILS [3].

The result of this process has yielded a first list of 14 candidate tools to be analyzed. After the first preselection, the following tools have not been further considered:

- Tools with limited geographical scope, such as those with a single origin/destination or with a heavy focus on a limited group of countries (TP Nova [4], Comité de Serveis Multimodals [5], Port of Barcelona [6])
- Heavily based on OpenStreetMap (OpenRailwayMap [7])
- Not digital (RailFreight EU Terminal Map [8])
- Not working properly (Open Transport Map [9])

After this first preselection, 8 tools were shortlisted. The attributes identified for further assessment have been clustered in 4 groups. These groups and their attributes are presented below:

1. Information on transportation services
   a. Modes of transport included (rail/road/see/aviation)
   b. Transport connections (rail/road/see/aviation)
   c. First/last mile providers (yes/no)
2. Information on infrastructure
   a. Transport network (rail/road/see/aviation)
   b. Terminal services and equipment (yes/no)
3. Quantitative features
   a. Cost estimations (yes/no)
   b. CO_2 emissions (yes/no)
   c. Estimated time of transport (yes/no)
4. Tool usability

a. Possibility of external update of information (yes/no)
b. Geographic area represented (country level/European level/other)
c. Availability of premium (paid) version (yes/no)
d. Map background (background provider, e.g., OpenStreetMap, Google Maps…)
e. Interactive route planning (yes/no)
f. API provided (yes/no)

5. Other
   a. Tool publisher/manager (publisher/manager name)
   b. Tool exploitation (commercial/non-commercial)

The attributes above were identified following an incremental process, started with a core of basic attributes and completed with other attributes present in any of the tools selected and considered relevant. The assessment was performed using the categories shown above and completed with additional information of specific attributes. Based on the information gathered, a qualitative assessment of the tools was carried out. The most relevant features of each tool are presented and discussed in the following section.

3 Tools Analysis

The 8 tools selected can be seen in the table below.

Table 1. Summary of analyzed tools and assessment of main attributes

Tool name	Publisher/Manager	Information on transportation services	Information on infrastructure	Other relevant features
European Transport Maps [10]	Baltic Press	Yes (mainly maritime)	No	Commercial tool
Rail Facilities Portal [11]	UIRR/RNE	No	Only terminals (focus on rail)	Comprehensive information on terminals
Intermodal Terminals [12]	KombiConsult	No	Only terminals	–
Intermodal Map [13]	SGKV	Yes (only in a few cases)	Only terminals	–
Route Scanner [14]	Route Scanner	Yes (comprehensive selection)	No	Commercial tool Offers an API Estimated time of transport and CO2 emissions of routes

(*continued*)

Table 1. (*continued*)

Tool name	Publisher/Manager	Information on transportation services	Information on infrastructure	Other relevant features
Study of traffic and modal shift optimization [15]	FERRMED	No	Yes (mainly RFC corridors), no terminals	Additional information on transported volumes
RNE-CIP [16]	RNE	No	Yes (mainly RFC corridors), basic information on terminals	Tools for routing planning
TENtec Interactive Map Viewer [17]	DG Move	No	Yes (comprehensive for infrastructure networks)	Comprehensive information on TEN-T infrastructure

As can be seen in Table 1, the analyzed tools can be divided into two main groups: those with focus on infrastructure and those with a greater focus on transport services. The infrastructure focused tools can, in turn, be divide in two groups, those providing information on terminals and those providing information on transport infrastructure. The only tool that offers a combination of information on infrastructure and transport services offered is the Intermodal Map [13]. However, the number of connections offered in the Intermodal Map is reduced and mainly limited to the German speaking countries.

The modes of transport included in each tool also differ among tools. While tools such as RNE-CIP [16], Rail Facilities Portal [11] or European Transport Maps [10] aim at providing information on a specific transport mode (rail and maritime respectively), the other tools analyzed adopt a more intermodal approach an provide information about other modes of transport. On this level, TENtec Interactive Map Viewer [17] offers the most comprehensive range of information, covering all modes of transport (including aviation).

Most of the tools analyzed are non-commercial tools. Only two of them, European Transport Maps [10] and Route Scanner [14] present a commercial exploitation approach and offer a paid version. The tool developed by Route Scanner stands out over the other tools due to its focus on providing freight transport services. Additionally, this tool offers very interesting features for the users, such as the possibility of accessing information via API (payment option) as well as information about the transport time and the assessment of the CO_2 emissions of each transport option.

Despite not being included in Table 1 summary, it is important to highlight that none of the tools offers information about first and last mile services in terminals. Similarly, none of the tools provided information on costs; neither for terminals services nor for transportation services between terminals. This is not surprising as the burden to keep general information updated, and especially information on costs, are high.

The results of the assessment of all the attributes can be found in the repository Zenodo under the following link: https://doi.org/https://doi.org/10.5281/zenodo.8429876.

4 Conclusions

The analysis of the tools from Table 1 allows to draw the following conclusions:

- A significant amount of data is available online in the identified tools. However, the type of information available greatly differ from tool to tool.
- Available information is divided in two large groups: information on infrastructure and information on transportation services. Only one tool provides a combination of both but the information on transportation services is limited.
- The non-commercial options have a limited number of quantitative features, such as CO_2 emissions calculator and transportation time. None of the analyzed tools offers cost estimations.
- No information about first and last mile providers in terminals are provided by the analyzed tools.
- Information about transport services is limited. Only a commercial tool offers detailed and comprehensive information on services.
- Most of the analyzed tools do not offer an easy manner to collect data via API.

The main conclusion of this work is the need of a comprehensive and free accessible online tool at European level that comprises the information about the infrastructure (both terminals and infrastructure) as well as transportation services. Ideally, this new tool should also incorporate features covering the gaps identified in this work. However, the technical complexity of the task due to the wide range of data sources with different formats, the difficult access to specific data (e.g. transport services schedules) as well as financial constraints to ensure its long-term viability (e.g. tool maintenance, data update) are challenges to be overcome in the development of the map.

The findings of this work will contribute to the elaboration of a new online tool to be developed under the project ESEP4Freight. A confirmation of the main findings of this work will be sought after consultation with relevant stakeholders of the logistic chain. To do this, empirical research identifying actual information needs from the stakeholders will be conducted as part of the ESEP4Freight project at a later stage.

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Conflict of Interest. One of the analysed tools (Intermodal Map) is managed by SGKV and another tool (Rail Facilities Portal) is co-managed by UIRR. SGKV and UIRR are both involved in the project ESEP4Freight which has supported the preparation of this work. This work, however, has been prepared without the involvement of SGKV and UIRR in order to avoid any possible conflict of interest.

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Hyperloop as an Innovative New Mobility Mode: Squaring the Circle in High-Speed Transportation Systems?

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Abstract. The Hyperloop innovation is a carbon-free high-speed concept for mid/long-distance connections as a complement to the railway network both in preserving investments already completed and planned and in unlocking the full economic and social potential of areas not yet adequately served. A low-pressure tube system results in substantially reduced air friction, thus allowing speeds to increase while significantly lowering energy consumption in comparison to conventional modes of transport. Hyperloop has a similar network topology as highways, enabling direct connections between origins and destinations without intermediate stops. Hyperloop has a small infrastructure footprint while enabling for a high transport capacity at minimal energy usage. Flagship 7 of the EU's Sustainable and Smart Mobility Strategy – Innovation, Data and Artificial Intelligence for Smarter Mobility - identifies Hyperloop as one of the game changing mobility technologies. The European Commission is working on a regulatory framework (Q1 2024) covering health, safety, security and environmental standards for the construction and operation of Hyperloop systems with autonomous levitating pods carrying passengers or goods at high speed inside low-pressure tubes.

Keywords: Hyperloop · climate impact · transportation · mobility

1 Introduction

Transportation is heavily challenged by global phenomena such as population growth, urbanization and climate change leading to contrasting needs of providing more frequent and faster connections while reducing the impact on the environment. A substantial share of the high standard of living in the modern world is attributable to the availability of excellent transport infrastructure. It grants access to goods, services, employment, recreation and interconnection. While the transport sector fulfils a pivotal socio-economic role, the sector is simultaneously one of the largest energy consumers, responsible for about

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25% of the global CO_2 emissions [1]. Unless immediate measures are taken, global transport emissions are proposed to grow by 60% by 2050 [2], causing the international community to fall dramatically short of the Paris Agreement's goal of limiting global warming to well below 2 °C as well as the recent goal of Europe to become a CO_2 neutral continent by 2050. Therefore, the transport sector has a large responsibility in implementing clean transportation alternatives to combat climate change.

The emission reductions and energy savings must be very significant. This is why new paths should be explored with approaches different to the incremental improvements made in traditional transportation today. An energy reduction of more than 90% with today's transport modalities is not possible as a matter of fact. Air resistance – governing predominantly the energy loss in high-speed transportation - cannot be avoided for any future vehicle iterations. Hyperloop and CargoTube propose a guided vehicle in low-pressure tubes at 1% to 1‰ of atmospheric pressure, drastically reducing drag and avoiding much of the energy use otherwise wasted in high-speed transportation.

Hyperloop strives for a radical new paradigm and technology on high-speed transportation which will be developed within a Pan-European context from the very beginning, therefore bypassing the traditional problems of technologies derived of national developments such as the non-yet interoperable European railways systems. The innovation setup in terms of high-speed infrastructure relies on having a European wide system without interoperability barriers, very focused in the business cases point to point, with a European dimension and therefore without the traditional national-devoted vision of the High-Speed Rail (HSR).

2 Hyperloop Concept

The old vision of a vacuum tube transportation (VTT) system, combined with contemporary technologies, has recently successfully attracted great interest worldwide and represents a modern and alternative means of ground-based high-speed and sustainable transportation to counteract the ever-increasing global CO_2 emissions.

The system consists of tubes above or underground containing a partially evacuated, low-pressure environment to minimize air resistance through which a vehicle travels at up to the speed of an aircraft and even lower energy consumption compared to current HSR. A vehicle travels by means of magnetic levitation to achieve a low-friction suspension with minimal maintenance and is accelerated e.g. through an external linear motor propulsion system. Its expected high transport capacity, tiny infrastructure footprint and the unique possibility to connect cities along a line without disrupting long-distance travelers, make the Hyperloop an exceptional solution. Furthermore, Hyperloop will be independent of outside factors like weather for example. This makes Hyperloop an alternative to rail and aviation that people will be more likely to use, as reliability and speed increase while the carbon footprint decreases.

The general structure of Hyperloop includes: a superstructure (two parallel tubes), a substructure (columns elevated infrastructure (cf. Fig. 1), segmentation doors, environmental control (pump stations to maintain low-pressure environment), emergency and contingency exits, a tractive system (specifically for acceleration and cruising segments) and a power infrastructure. Hyperloop has a small infrastructure footprint while enabling for a high transport capacity at minimal energy usage.



Fig. 1. Part of the northern loop of the TVE's maglev guideway at Lathen, Germany. Continuous loop layout, 32km length. Inset: Elevated Hyperloop bi-tube design [3]

The Hyperloop concept for mid/long-distance connections serves as a complement to the railway network both in preserving investments already completed and planned and in unlocking the full economic and social potential of areas not yet adequately served. The network topology is like highways, enabling direct connections between origins and destinations without intermediate stops. In the network, vehicles can enter and exit the mainline through on and off ramps without slowing down or interrupting the flow of traffic.

3 The Nub of the Matter - Aerodynamics

Any object moving at a given speed through a fluid or compressible medium like air experiences a force, the so-called drag force, acting opposite with respect to the relative motion. While being linearly depending on the velocity at low speed, the drag force is proportional to velocity squared at high speed. The Reynolds number (Re) associated to the flow and characterizing laminar or turbulent flow distinguishes between low and high, i.e. at ca. $Re > 1000$. Aerodynamic losses scale with the velocity cubed due to aero- and thermodynamics and cannot be recuperated by any means like all friction-based losses. In HSR transportation at 250 km/h and above these losses account up to more than 83% of power used to push even a streamlined train through air at atmospheric pressure [4].

Hyperloop is a very specific case of aerodynamics since the vehicle travels in an unconventional flow regime at rather low Reynolds numbers but at high Mach numbers surplus restricted to the confined environment of the vacuum tube, thus potentially leading to supersonic effects like choking the gas flow at the Kantrowitz limit. Thus, designing the pod's geometry, size, and tube dimensions is crucial to be able to take full advantage of the Hyperloop approach, which needs to be avoided by the system design. (cf. e.g. [5, 6] and bibliography within).

Even within the evacuated tube, the dynamics of the remaining air sets the boundaries of this technology. The flow dynamics in the narrowed gap between a pod and tube wall

limit key design parameters such as diameter and target speed of a pod. Exceeding a certain threshold will nullify the benefits of this concept. Due to the constrained space, the only option to increase room for payload is to increase the pods length. This approach, however, introduces new fluid dynamical challenges such as the development of a viscous layer which effectively increases the pods diameter. Depending on the considered pod length, the results of laminar and turbulent boundary layer model vary substantially [7].

Oh et al. performed a thorough modelling and simulation of an exemplary comparison between traveling at ambient air pressure (1013 mbar) and within an evacuated tube (1 mbar) to evaluate the power savings. Assuming a travel duration of 15min covering a distance of ca. 315 km at a speed of 1260 km/h the drag force was reduced by a factor of 371 resulting consequently in a power drop from 35,661 kW to 96 kW. Experiments conducted at the Korea Railroad Research Institute showed, that other external costs like initial evacuation of the tube and maintaining the pressure at 1mbar can be neglected in case of a steel tube with low leakage rates. This also includes the CAPEX costs of the vacuum pump equipment required [8].

4 Infrastructure and Network

Network simulations and transport models indicate a modal shift, with people choosing Hyperloop over cars and flights, leading to a reduction in short-haul flights and congestion. The energy-efficient design of Hyperloop and the resulting shift contributes to lower energy consumption and positive climate impacts by reducing emissions and addressing environmental concerns. Improved connectivity between regions drives economic growth and facilitates movement of goods and people. Significantly reduced travel times enable expansion of daily urban systems, granting individuals freedom to live and work in a wider range of locations, promoting flexibility and creating economic opportunities. Moreover, existing high-speed rail networks can benefit from integration with Hyperloop, increasing their ridership and improve overall transportation efficiency. Potential routes are evaluated to be added to a more sustainable TENT-T network of the future.

Hyperloop requires a strip of land only 8 m wide for routing, compared to higher values for high-speed trains and even greater values for highways (cf. Fig. 2). Moreover, because the Hyperloop's noise emissions are virtually zero and there are no other harmful emissions, it can be connected much closer to urban infrastructure. This makes integration much easier than with existing solutions such as rail, road and subway, which are difficult to expand due to their space requirements, land acquisition and noise emissions [9].

Flagship 7 of the EU's Sustainable and Smart Mobility Strategy – Innovation, Data and Artificial Intelligence for Smarter Mobility - identifies Hyperloop as one of the game changing mobility technologies. The International Hyperloop Association, based in Brussels, was founded in 2023 and testing infrastructure is planned at several European locations. The European Commission is working on a regulatory framework (Q1 2024) covering health, safety, security and environmental standards for the construction and operation of Hyperloop systems with autonomous levitating pods carrying passengers or goods at high speed inside low-pressure tubes [10].

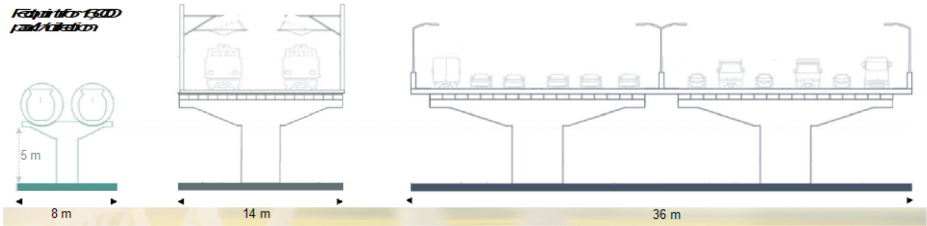


Fig. 2. Land use with comparable passenger volumes for road, rail, and Hyperloop transportation systems [9]

5 Conclusion

As transport infrastructure plays a substantial role in the high standard of living of modern societies, technological progress in vehicles, in infrastructures and in Information and Communication Technology (ICT) solutions have facilitated the globalization of the world economy, reduced trip times and provided more comfort at a cheaper price. In high-speed transportation, drag forces induce by far the largest energy losses, scaling with the velocity cubed due to aerodynamics. Basic physics rules out the possibility that this energy can be recovered in any way. Essentially minimizing the high energy consumption due to air friction is thus the key parameter for the sustainability of future transport modes. The vision for 2050 is a zero-emission Hyperloop transport network seamlessly integrated with other environmentally friendly transport modes [11, 12].

Hyperloop could provide revolutionary benefits. The relatively low energy usage predicted, together with a dedication for using green power sources, puts Hyperloop in a strong position in relation to other modes of transportation. Simulations show that a Hyperloop system is likely to be less energy demanding than HSR and air transport, due to less friction with the track, low air resistance and electrical propulsion.

However, it has become apparent that the contemporary transportation system also has severe drawbacks related to increased air pollution, noise nuisance and traffic congestion that can deteriorate the quality of life they are meant to support instead [1, 2]. All of these drawbacks are overcome by a Hyperloop transportation system facilitating an intermodal new mode of transportation.

A return on investment is estimated to be achieved much earlier than for high-speed rail, as operating costs can be kept to a minimum through significantly lower operational energy requirements and maintenance needs of hyperloop solutions. Another big improvement with regard to CAPEX spending is the minimal land use and lower superstructure cost of an elevated Hyperloop system, compared to e.g. high-speed rail [9].

In a nutshell: Hyperloop is a unique approach that literally squares the circle in sustainable high-speed transport without emissions!

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Technological Design Considerations of CargoTube Low-Pressure Tube Transport for High-Speed Sustainable Logistics Networks

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Abstract. CargoTube offers the unique advantage of combining existing technologies with innovative hyperloop systems in order to provide a solution for production logistics in urban areas. By offering not only zero emission operation through electrification, but also a confined environment for particle, fine dust, noise, and light pollution, CargoTube is perfectly suited to be applied in urban areas where big production facilities and industrial plants meet growing cities. For the design of the system, various different technologies are available to be operated inside of the low-pressure tube environment. Depending on the operational speed, a wheel-rail system can be used for speeds up to 300 km/h, while a network with higher speeds requires magnetic levitation and contactless high-speed switching. Two systems for propulsion are available, onboard motors and linear electric motors, while the latter can have power supplied either from the vehicle or the infrastructure. The choice of the drive system is heavily dependent on the use case. Lastly, airlocks are necessary to enable high capacity and high throughput for low-pressure tube technologies (LPTT).

For the beginning, networks such as a regionally confined CargoTube networks for production logistics can be seen as point to point connections, as speeds above 300 km/h are not required to link regional logistics hubs and production facilities. This reduces complexity and allows for a combination of innovative technologies with established systems such as the wheel-rail system.

Keywords: Hyperloop · CargoTube · Low Pressure Tube Transport · Tube Network · Sustainable Logistics Transport · Energy Efficient Transport

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1 CargoTube Low-Pressure Tube Transport

The reduction of greenhouse gas (GHG) emissions in transport is one of the major goals of the European Union to become climate neutral. While transport is contributing more than 31% of the emission of EU-28, the effort of electrification is reducing emissions in most sector. Therefore, since 1990 all sectors showed a decline in emissions of 20%, while the transport sector increased its emissions by 20% [Tiseo 2023].

Innovative transport solutions are needed to change the transport fundamentally in order to become climate neutral. Europe needs to cut down on GHG emissions, but also on pollutants like NO_x, particle- and fine dust emissions as well as decrease noise and light emissions to reduce human made influences on the environment.

LPTT technologies such as CargoTube enable a very low environmental impact not only with regard to Greenhouse gas emissions, but also for multiple other key factors that have an influence on decisions within industrial logistics, especially in urban areas. Through drastically reducing the aerodynamic drag inside of the low-pressure environment, hyperloop technologies can save up to 80% of the operating energy demand of current high-speed transportation. Operating the tube pressure between 1% and 0.1% of normal atmospheric pressure dramatically reduces losses, allowing for the fundamental change in transport emissions that is needed to reach climate neutrality [Oh 2019; Zhou 2022].

CargoTube is designed to for a point-to-point connection of a logistics hub with a large industrial production facility for high-capacity throughput of standardized containers. While regional logistic hubs and production plants can be served by a known technology stack, the application of CargoTube networks requires more extensive analysis. While the economic and environmental impacts for point-to-point connections are evaluated through discrete event simulation [Duin 2023] and Life Cycle Performance Assessment (LCPA) the technological design considerations are based on literature research and the evolving CargoTube basic data model and technology stack.

2 CargoTube in Production Logistics

Production logistics is facing major challenges to adopt to more environmentally friendly and healthier urban areas as well as increased productivity in industry and therefore a need for higher capacity of the logistics network. LPTT technologies such as CargoTube offer an automated solution for shuttle logistics between two major points in a physical internet, called ePI Nodes, for a high frequency, high volume and reliable cargo connection.

In the ePIcenter project a CargoTube connection is considered to connect an industrial automotive plant with a Logistic Service Park 10 km outside of a city in order to save on logistics space needed inside of the plant and consolidate inbound goods [ePIcenter 2023]. CargoTube is considered as one option for connecting to the production plant, supplying around 10.000 m^3 daily. Compared to other possible solutions, like a shuttle trucks, CargoTube can also save on personnel, saving valuable truck driver time. For the use case, a vehicle inside of the tube, called pod, is designed to fit 10 standardized containers (or pallets) with approximately 1 m^3 each, representing more than 80% of

inbound traffic to the plant. By making use of CargoTube's high-frequency, high-capacity capabilities, the need for storage and truck parking at the production plant as well as space concerning the route is reduced to a minimum as well [Hardt 2023]. Figure 1 shows a logistic service park displaying many innovative technologies as well as CargoTube specific solutions.

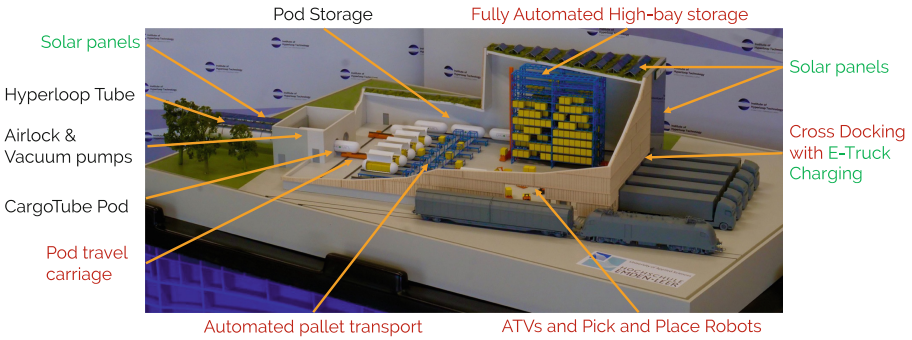


Fig. 1. Logistic Service Park with innovative technologies and CargoTube connection

In summary CargoTube offers the following advantages next to the savings in GHG emissions due to its high efficiency:

- High degree of automation, aligning well with industry optimization and just in time as well as just in sequence supply chains
- Resilient transport operation, cut off from extreme weather and personnel influences as well as unforeseen disruptive events, providing a reliable stream of goods
- Low operational energy demand resulting from lower aerodynamic drag
- Reduced noise impact, fine dust, particle, and light pollution through a confined tube environment

A network of production facilities and logistic hubs can also be considered with CargoTube, while a more in-depth technological analysis is required when speeds go up and a more complex network with high-speed switching is introduced.

3 Technological Design Consideration

For the technical design considerations of CargoTube, point to point connections are assumed at first. A small-scale network like a CargoTube Physical Intranet is also assumed as point-to-point connections, as distances would be short. Therefore, velocity can be kept below 300 km/h, decreasing the wear and eliminating the need for high-speed switching or contactless levitation systems. These would on the other hand need to be considered for high-speed connections and a large-scale LPTT network.

CargoTube makes use of innovative hyperloop solutions such as the low-pressure tube environment and airlocks while combining the system with established technologies such as the wheel-rail system. This is made possible by keeping speeds below 300 km/h,

above wear and maintenance is drastically increased for wheel-rail systems, but also possible systems for energy transfer such as pantographs and current collectors. The ePIcenter use case of CargoTube considers a speed of approx. 100 km/h, balancing speed, capacity and energy demand.

Specific to the use case different technological variations of LPTT are proposed. Some of the design decisions and implications for the transport system are outlined. Cargo applications require several choices with regard to the infrastructure and the pod to be weighted and well-balanced to optimize the exchange of cargo with high throughput: an energy efficient propulsion and recuperation, a high degree of automation as well as an efficient airlock design using very little volume to be pressurized and therefore very little energy to transfer goods into and out of the vehicles in the tube.

Technological design choices for the CargoTube system are also highly dependent on quick deployment, providing a solution for current logistic needs. On the cost side, the net present value is an indicator for balancing the cost of subsystems with regard to the overall expenditures. At the same time the carbon footprint in form of the lifetime emissions, calculated as the carbon dioxide equivalent is very important to the choice of materials and form of operations.

3.1 Tube

With regard to tube technologies there are currently two readily available options that can be manufactured to the dimensions that are necessary for low-pressure tube transport technologies: concrete and steel tubes. While there is a general roadmap for steel to become carbon neutral, especially when looking at green hydrogen, there are fundamental emissions coming from the production of cement that cannot be avoided [Peper 2019]. Due to its widespread use, availability and the proven strength and durability, steel tubes are currently considered the first choice with regard to CargoTube logistics applications.

Fiber reinforced plastics, fiber metal laminates with polymeric or cement-based foams and various new composite materials are also suggested for more rapid deployment of the infrastructure while reducing cost for transport and construction of the superstructure as well [Zeleros 2021]. Nevertheless, these materials are not ready to be used for large infrastructure projects yet.

3.2 Airlock

CargoTube's ability to transport goods with a high frequency is deeply dependent on the ability to transfer cargo from and to the pods in the low-pressure environment with highly adapted airlock solutions. The faster the airlocks can transfer cargo, the lower the number of required airlocks and therefore also the footprint of the station. Gate valves which in pairs form an airlock chamber are available even for larger diameter tubes but require a large volume around the pod to be evacuated due to aerodynamic surfaces and systems mounted inside of the tube, which makes an airlock chamber solution with this technology slow and costly. For a more rapid cycling time in the airlocks the gas exchange during each cycle of the airlock must be minimized. Additionally, this saves on energy consumption as well, as less pumps are needed for the same number of airlocks.

One solution, mostly talked about in LPTT for passengers are bridge door solutions, where an airtight seal is created between the vehicle and the tube, allowing for pressurization of the remaining volume and opening of hatches on the tube and the vehicle. While this solution is great for passenger transport, as can be seen in subways where these are used in a pressurized way with sliding doors on the vehicle and the platform, such a solution would require a more complicated design for the automated process of loading and unloading goods, as is seen in airplanes [Gerritse 2021].

Another solution is an end-door airlock, which similar to the bridge door relies on seals and a strong connection to enable a reduced low-pressure volume. An advantage of the end-door airlock is the possibility for a moveable floor, allowing for a quick exchange of cargo as can be seen in the truck industry already. Nevertheless, the construction and operation of such an airlock would be very difficult [Gerritse 2021].

A low-pressure tube transport system can probably be operated with an adapted design for a bridge-door airlock solution or an end door airlock, whereas both systems need to be optimized for a rapid exchange of cargo with minimal handling times. With regard to the time necessary for the required movement and alignment of the pod with the airlock and the required handling steps, a solution with a one step process and combined exchange of all cargo units simultaneously is probably most beneficial for the system, if costs can be kept in an acceptable range. In general, airlocks are certainly still one of the most crucial technologies for LPTT as well as CargoTube solutions.

3.3 Propulsion

All propulsion systems that are evaluated are electric propulsion systems, limiting the emissions and allowing for recuperation of energy during braking. While onboard rotary motors are currently used in most electric vehicles due to lower capital expenditures, a linear drive powered by the infrastructure can be very effective for high-frequency connections. Implementing the drive and power systems in the tube, results in lighter vehicles which reduces energy demand and losses during acceleration and braking. Additionally, thermal losses by power electronics do not need to be mitigated in the vehicle but instead are diverted by the tube. Considering the timely deployment of CargoTube, this is a major part of the design choice, making an infrastructure powered linear drive system a good choice, despite the increase in capital expenditure.

4 Evaluation and Conclusion

The CargoTube transport system combines the advantages of innovative hyperloop solutions that reduce the impact of transport on the environment with existing and proven technologies in order to rapidly deploy a reliable and high-frequency transport of industrial cargo. Point-to-point connections and small-scale networks that can be assumed to be direct connections show the capabilities of connecting production plants and logistics hubs to reduce the impact on the environment.

Some of the outlined technologies such as the vacuum systems and the steel tube environment will be proven with a demonstrator that is constructed at the University of Applied Sciences Emden/Leer. A linear motor is set to be included in a later stage with

airlock technology to be tested in small-scale lab demonstrators before being scaled up for large-scale testing.

Lastly, network simulations are planned to evaluate the underlying technological design choices and assumptions with regard to feasibility, economics and environmental impact and compare the results to other modes of transport.

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Unlocking Green Maritime Corridors: Lock-Ins, Barriers, and Enablers for Decarbonizing RoPax Maritime Transport in Europe

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Abstract. Maritime transport plays a critical role in decarbonizing global supply chains. Recent international initiatives highlight the importance of green shipping corridors for accelerating maritime decarbonization and enhancing value chain partnerships. This article focuses on green corridors along RoPax routes, central to the EU's transport strategy. The study delves into policy and regulatory instruments affecting RoPax green corridors, examining international, EU, and national regulations. It acknowledges that the impact of the policy landscape on these initiatives extends beyond maritime shipping, encompassing land logistics, goods transportation, shipbuilding, and energy production. By analyzing relevant regulatory, economic and voluntary policy instruments, this research contributes to the discourse on maritime sector decarbonization within the existing policy landscape.

Keywords: Decarbonization · Short Sea Shipping · Maritime Logistics

1 Introduction

Maritime transport represents 2–3% of global GHG emissions and plays a crucial role in decarbonizing global supply chains due to the substantial volume of seaborne trade. Achieving reductions in the GHG footprint of transport systems requires collaborative efforts and integrated value chains with aligned objectives. At the 26th UN Climate Change Conference (COP26) held on November 10, 2021, 19 original signatories expressed their concern over the increasing emissions from international shipping and declared their commitment to support the establishment of green shipping corridors. Through these corridors, the signatories wish to facilitate the establishment of partnerships along the value chain to accelerate the decarbonization of the shipping sector and its fuel supply. The signatories recognized that such corridors could unlock business opportunities and socioeconomic benefits for communities worldwide.

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Green maritime corridors hold the potential to drive this decarbonization process by setting a common target and triggering collaborative efforts across the logistics ecosystem. In this article, we focus on green corridors along RoPax (roll-on, roll-off passenger vessel) routes. These routes are an important element in the EU's transportation policy that aims to move cargo from the roads to different modes of maritime transport.

To further advance the understanding and implementation of green maritime corridors, this study investigates the regulatory and policy landscape that influences countries' ability to reach the full systemic impact of new investments and technologies in RoPax green corridors. This research contributes to the discourse on the decarbonization of maritime transportation by scrutinizing the relationship between the transformative potential of green corridors and the current regulatory and policy environment.

2 Literature Review

Maritime transport has historically been excluded from climate change mitigation efforts due to its international nature, pivotal role in the global economy, regulatory complexities, and challenges in attributing emissions [1]. While regulations have addressed some pollutant emissions like nitrogen oxides and sulfur oxides, greenhouse gas (GHG) emissions remained largely unexamined until recent political attention shifted towards including maritime transport in climate mitigation [2].

The International Maritime Organization (IMO) aims to reduce CO_2 emissions per transport work by 40% by 2030 and reach 100% reduction in total annual GHG emissions from shipping by 2050 as compared to 2008 [3]. Simultaneously, the European Union (EU) seeks a 55% GHG emissions reduction and 5–10% adoption of zero or near-zero GHG emission technologies, fuels, or energy sources in international shipping by 2030 [4]. Actions for achieving these goals are initiated within its 'Fit for 55' package.

Both entities propose measures to facilitate shipping decarbonization, including requirements for energy-efficient vessel design, GHG emissions during operations, and the development of alternative fuel infrastructure and on-shore electricity for increased electrification. However, the conventional regulatory and incentive mechanisms may fall short of achieving the rapid transitions needed to meet international climate goals. Green maritime corridors can act as transition mechanisms that catalyze the shift towards sustainable and carbon-neutral shipping practices by allowing for, first, aligning the necessary actors in the value chain at the local level, and second, being scaled up globally. The scope of establishing such corridors thus spans beyond traditional maritime and logistics corridors (see Fig. 1).

The concept of 'green maritime corridors' originated with the Getting To Zero Coalition and was publicly announced during COP26 as part of the Clydebank Declaration. They have been defined as "specific shipping routes where the technological, economic, and regulatory feasibility of the operation of zero-emission ships is catalyzed by a combination of public and private actions" [5]. Given the novelty of this concept, not much academic research is devoted to green corridors. However, recent studies underline the critical role of green corridors for decarbonizing shipping [6, 7].

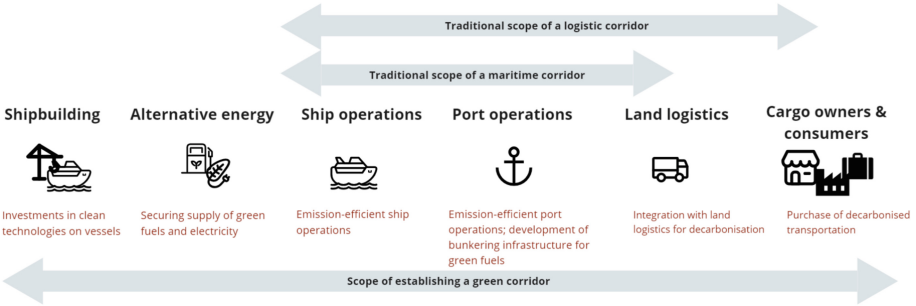


Fig. 1. The scope of establishing a green maritime corridor and necessary elements

3 Methodology

This study is conducted within the framework of the DECATRIP project, which seeks to explore the potential of RoPax green corridors in decarbonizing maritime transportation. This paper presents the results of a study into the regulatory and policy landscape that impacts the ability of countries to achieve the full systemic impact of new investments and technologies in RoPax green corridors (see Fig. 2).



Fig. 2. Research process

The initial step in this study was to build a framework to identify potentially relevant regulations through a desktop study. This was followed by interviews with experts to validate and refine the framework. The desktop study involved a literature review of these instruments and their impact on maritime decarbonization, as well as secondary sources related to green maritime corridors by entities like the Global Maritime Forum [8], DNV, and MMMCZCS [9]. To gain a deeper understanding of the regulatory landscape and refine the framework, semi-structured interviews were conducted with various stakeholders involved in the decarbonization project (Table 1). These interviews explored the interviewees' perceptions of regulations, gaps in the current regulatory landscape, and insights on green maritime corridor characteristics.

The data collected from both the desktop study and interviews underwent a thematic analysis, where recurring themes and patterns were identified and organized into meaningful categories. The data obtained through the desktop study was synthesized to identify and categorize key regulatory and policy instruments acting as enablers or barriers for establishing green RoPax corridors. The interviews helped refine the initial framework established during the desktop study.

Table 1. List of interviewees.

Interviewee position	Organization	Interview length
Ministry advisor	Ministry of transportation	60 min
Professor in Maritime Law	Higher education institution	70 min
Sustainability manager	Ship operator	50 min
Project coordinator	Research Institute	60 min
Project engineer	Shipyard	30 min
Technical director	Port authority	50 min

4 Findings and Discussion

4.1 Regulatory and Policy Landscape for Green Maritime Corridors

The path to maritime sustainability involves a multifaceted approach that combines regulatory, economic, and voluntary instruments. Regulations provide the essential legal framework for emissions reduction, while economic instruments mobilize financial resources. Simultaneously, voluntary initiatives, such as different agreements among financial institutions, guide sustainable investment decisions in the maritime industry.

Some key regulations concern ship design and performance in terms of energy efficiency. The Energy Efficiency Design Index (EEDI), introduced by the IMO, sets minimum energy efficiency standards per capacity mile for various ship types and sizes (for newbuilds). Moreover, the Energy Efficiency Existing Ship Index (EEXI), scheduled for most ships in 2023, focuses on efficiency requirements for existing vessels. Legal obligations to enhance ships' energy performance encompass initiatives like the Ship Energy Efficiency Management Plan (SEEMP) and the Carbon Intensity Indicator (CII), stipulating CO_2 emissions per transport work.

Market-based measures complement regulatory efforts to encourage the adoption of low-GHG fuels. FuelEU Maritime strives to promote alternative low-GHG fuels, targeting a 2% improvement in GHG energy intensity by 2025 and an ambitious 75% by 2050. The revision to the EU Energy Taxation Directive adds fiscal incentives for sustainable marine fuels, while at the same time removing tax exemptions that affect fossil fuels. Furthermore, the EU and IMO are working on emission trading schemes or levies in order to tax carbon emissions.

Facilitating the transition to alternative marine fuels, regulations mandate the development of fuel infrastructure within ports. The EU's proposed Directive on Deployment of Alternative Fuels Infrastructure mandates minimum requirements for electric shoreside power supply by 2030. Starting from 2030, passenger and container ships staying over two hours will be required to connect to shore power. Recent amendments to the proposed Alternative Fuel Infrastructure Regulation (AFIR) have included hydrogen and ammonia as vital refuelling points alongside LNG.

In the maritime industry, sustainability considerations have extended into the financial sector through the adoption of green financing initiatives. Driven by regulatory frameworks like the EU taxonomy, green financing aims to redirect capital flows towards

sustainable development priorities. Private financial institutions are proactively embracing these initiatives to mitigate reputational and transition risks in the face of tightening climate legislation. Notably, the Poseidon Principles serve as an essential worldwide framework for assessing the sustainability of projects and investments in shipping finance, with a significant number of leading banks pledging commitment to these principles.

Several regulatory instruments were mentioned by the interviewees, which do not directly relate to maritime transportation. These include Electronic Freight Transport Information (eFTI) which can enable the collection and sharing of emission-related data in transportation, Corporate Sustainability Reporting Directive (CSRD), Green Claims Directive, Digital Product Passport and Count Emissions EU. The resultant framework for the regulatory and policy landscape for green corridors is presented in Fig. 3.

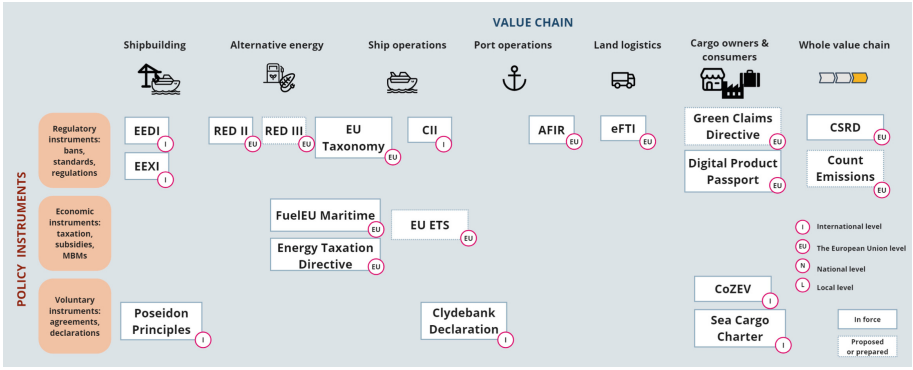


Fig. 3. The policy landscape that affects the successful development of green maritime corridors

4.2 Lock-Ins, Barriers, and Enablers for the Establishment of Green Corridors

Key instruments that will affect green corridors in the EU, as mentioned by almost all interviewees, include the inclusion of shipping in the European Union Emission Trading System (EU ETS), FuelEU Maritime, and the Alternative Fuel Infrastructure Regulation. The EU ETS aims to promote the competitiveness of alternative fuels by including shipping in its emissions trading system. FuelEU Maritime also aims to promote the competitiveness of alternative fuels, while the Alternative Fuel Infrastructure Regulation sets minimum requirements for the development of alternative fuel infrastructure in transportation, including in ports. These instruments are crucial in making alternative fuels competitive with fossil fuels in the maritime sector.

The establishment of green maritime corridors is seen as a positive initiative by all interviewees. From a state perspective, green corridors are beneficial for attracting foreign investment and EU funding. National policies can support green corridors by setting national goals based on international goals, legitimizing green corridors as projects of strategic interest for the country.

Technology neutrality was mentioned as a potential barrier to the development of green corridors. The EU Taxonomy and Renewable Energy Directive were mentioned as instruments that define which sources of carbon and alternative fuels are considered green, as well as which projects or investments can be considered as contributing to sustainable activities. These directives will significantly influence the choice of decarbonization technologies in the maritime sector and may direct the development of green corridors towards certain technologies.

Finally, many interviewees emphasized the importance of addressing the demand for decarbonized transportation, thereby validating the inclusion of the whole value chain in the framework presented in Fig. 1. Voluntary instruments such as CoZEV are already in place, and upcoming regulations such as the Corporate Sustainability Reporting Directive (CSRD) and the Green Claims Directive will further drive customers of transportation services to consider carbon-neutral transportation as a strategically important option. Some interviewees emphasized the regulation at the transportation customer and whole value chain end, which can help increase the transparency and uniformity of emission reporting and any 'green claims' based on it. This is expected to facilitate the demand for sustainable transportation.

5 Conclusions

Green maritime corridors are a 'bottom-up' solution for decarbonizing shipping in a gradual yet transformative way. Establishing such corridors requires cooperation across the entire value chain and often a fundamental shift in business logic in order to benefit from sustainable transportation. While it is difficult to pinpoint any specific policy instruments aimed at green corridor development, the role of the current instruments is to both facilitate the supply of carbon-neutral maritime transportation through regulation at shipping and alternative energy side and facilitate the demand for such transportation through ensuring that the value of carbon-neutral transportation is verifiable.

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Integrating Intra-terminal Logistics Optimization and Freight Train Scheduling

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Abstract. Intermodal freight transportation is characterized by the use of multiple different modes of transportation to transport goods from their origin to their destination. This allows freight carriers to combine the individual advantages of each mode to design an overall better route than would be possible with only a single mode. However, the use of multiple modes of transportation necessitates their synchronization to allow for the expeditious transshipment of goods at intermodal terminals. We propose an algorithmic optimization framework for planning transshipment operations within an intermodal freight train terminal that also considers the availability of connected overland railway tracks according to available railway infrastructure timetables by interfacing with the railway simulation tool OpenTrack.

Keywords: intermodal freight transportation · container logistics · terminal logistics · transport decarbonization

1 Introduction

In intermodal freight transportation, goods are carried from their origin to their destination by multiple different kinds of vehicle, such as freight trains, trucks and cargo ships. To facilitate easy switching between different modes of transportation, goods are usually packed into standardized intermodal containers that can be easily transferred between and transported by the various types of cargo vehicle that are used [3].

Intermodality allows freight carriers the opportunity to better exploit the various advantages of different modes of transportation, while at the same time compensating for their weaknesses. Freight trains, for example, can carry many more containers than trucks per vehicle, significantly reducing personnel requirements. Additionally, their ability to be directly powered by the grid allows these

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transports to be handled in a much more environmentally friendly way. Trucks, in contrast, offer greater flexibility, since they can transport containers to any place connected by the road network without any need for coordination with railway infrastructure operators. Thus, a route that combines a long-haul transport of containers by freight train with first and last mile deliveries by truck would allow the carrier to retain much of the flexibility of a truck-only route while still benefiting from a train's greater efficiencies.

However, operating such intermodal routes places an additional synchronization burden on the freight carrier, since they need to ensure that transshipment between modes happens quickly and efficiently. Therefore, optimizing the handling of containers within intermodal freight terminals is of paramount importance. Yet, considering terminal operations in isolation is insufficient. Especially in Europe, freight trains rank below passenger trains in track access priority, decreasing their opportunities to translate efficiency gains during container handling into shorter turnover times when trains have to wait in the terminal for a slot to become available along their planned route [5].

We therefore propose an integrated optimization framework that combines the railway simulation tool OpenTrack[1] with an algorithm for planning the optimal handling of containers within an intermodal freight rail terminal. To the best of our knowledge, such an integrated optimization approach has not yet been studied in the literature.

2 Intra-terminal Logistics Optimization

The principal component of our algorithmic optimization framework optimizes the movement of containers, as well as of the equipment necessary to move them, within an intermodal freight train terminal.

2.1 Problem Definition

We consider a single intermodal freight train terminal with a fixed layout, as illustrated by Fig. 1. The terminal consists of (a) a set of parallel tracks on which trains can park, (b) a set of parallel lanes alongside those tracks on which trucks can drive, and (c) a storage area (parallel to both) where a limited number of containers may be stored for some time.

Tracks, lanes and the storage area are all equally split into multiple sectors. Trucks may only traverse lanes in one direction and no two trucks may be parked in the same sector at the same time.

Trains arrive at the terminal on a fixed schedule at their assigned track and must depart there again by a given deadline. Each train is associated with a set of containers that must be *handled* before the train can depart again. We distinguish (a) *arriving* containers, which are unloaded from a train (and transported off-site), (b) *departing* containers, which are brought into the terminal and loaded onto a train, and (c) *round-trip* containers, which are unloaded, transported off-site and back and then loaded onto a train again.

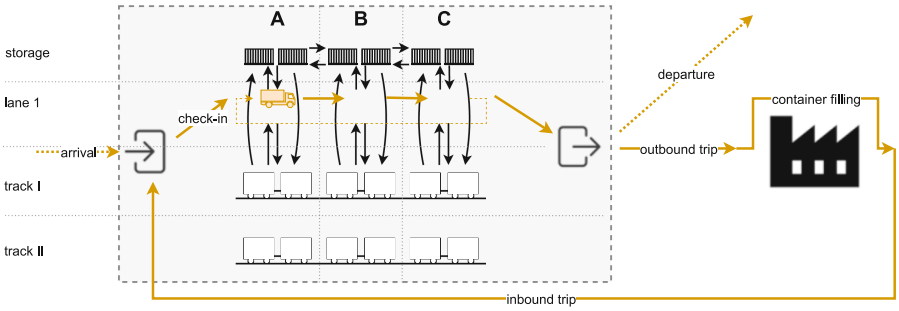


Fig. 1. Exemplary terminal layout with two tracks (I, II) and one lane (1) that are each split into three sectors (A, B, C), showing the path of a single round-trip container (and the truck that is transporting it).

The transportation of containers from and to the terminal is handled by trucks, which can carry one container each. Within each sector, containers can be transferred between trains, parked trucks and the storage area by gantry cranes, which can also move between different sectors within the storage area as long as they keep sufficient distance from each other.

Every container transport or transfer takes a predetermined amount of time, which depends on the distance the truck/crane must travel between the pickup and the dropoff location. The operator also incurs corresponding costs for each transport/transfer. Similarly, keeping a container in storage costs the operator some amount of money proportional to the time for which it is kept there.

The optimization objective is finding a cost-optimal feasible transportation plan for all containers.

2.2 Time-Expanded Network

In order to better describe the behavior of our system across the entire planning horizon, we introduce a so-called *time-expanded network* (also referred to as space-time networks) – a directed, acyclic graph where each vertex represents a specific location within the terminal (such as a particular sector within any track, lane or storage) at a specific time [2]. Every arc within the graph connects a vertex corresponding to an earlier time to one corresponding to a later time, representing the opportunity for an object (in our case, e.g., a container, truck or crane) to move between the corresponding locations within the indicated timeframe. Such graphs are frequently rendered as a two-dimensional grid of vertices, where a vertex's row denotes its spatial location and its column denotes the point in time represented by it.

In our optimization problem, we consider (a) the entry to the terminal, (b) the exit from the terminal, (c) every sector of every track, (d) every sector of every lane, (e) every sector of the storage area, as well as (f) every customer where containers are handled, to be a separate location for the purpose of constructing the time-expanded network.

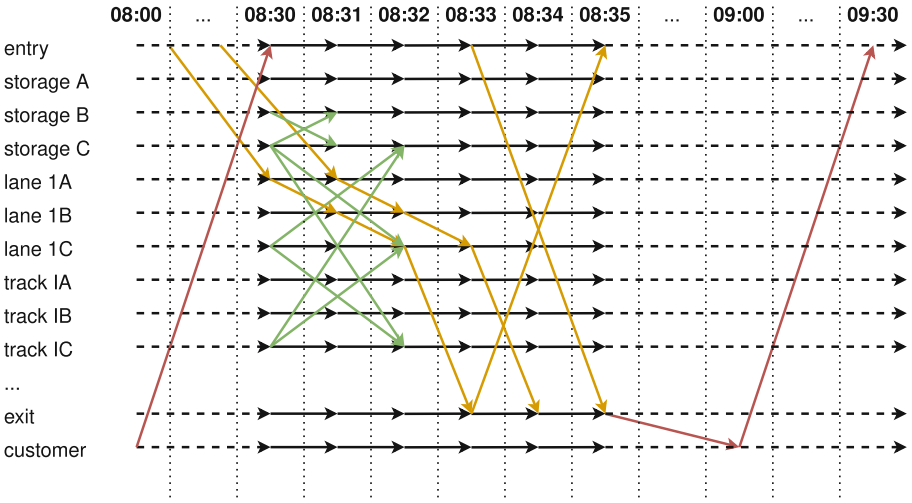


Fig. 2. Excerpt from an exemplary time-expanded network, with (some) truck (yellow, red) and crane movement arcs (green).

The set of vertices within the time-expanded network then consists of one vertex for each such location at each discrete point in time within our considered planning horizon.

These vertices are then connected by arcs as follows. First, every vertex at every location and every point in time (except the last) is connected to its immediate successor at that same location, which corresponds to remaining at that location for one time period.

Next, we consider the movement of trucks within the terminal. To this end, for all points in time where this is feasible, we connect (a) the entry vertex to every lane's first sector vertex, (b) every sector vertex (except the last) of every lane to that lane's next sector vertex, (c) every lane's final sector vertex to the exit vertex, and (d) the entry and exit vertex to each other in both directions. In each case, the difference in time between the arc's head and tail corresponds to the time required by a truck to traverse the respective part of the terminal.

Similarly, we consider the movement of gantry cranes within the terminal. As before, for all points in time where this is feasible, we connect (a) every sector vertex of every track to every lane vertex and the storage vertex in the same sector, (b) every sector vertex of every lane to every track vertex and the storage vertex in the same sector, and (c) the storage vertex in each sector to every track and lane vertex in the same sector. These arcs correspond to the *lateral* movement of a gantry crane within a sector. Again, the difference in time between the arc's head and tail corresponds to the time required by the crane to move accordingly.

For the *longitudinal* movement of gantry cranes, we connect (again, for all points in time where this is feasible) the storage vertex in each sector to the

storage vertex in the two sectors immediately preceding and succeeding it (if they exist). As always, the time difference between head and tail corresponds to the time physically required by the corresponding movement.

Finally, we connect (a) the exit vertex to every customer vertex, and (b) every customer vertex to the entry vertex, again for all those points in time where this is feasible. For the former, the time difference between head and tail corresponds to the required travel time from the terminal to the customer, whereas for the latter, it corresponds to the service time at the customer plus the required travel time back.

Each arc has an associated cost corresponding to the cost of the corresponding containers transport, transfer or storage as described above. Leaving a container on the train, in contrast, is free.

2.3 Integer Linear Programming Formulation

The previously described optimization problem can now be modeled as an integer linear program based on a multi-commodity flow formulation[4].

For every truck, gantry crane and container, we introduce a set of binary flow variables that describe the movement of the respective object through the terminal (as well as between customers) throughout the considered planning horizon. Simple flow conservation constraints for every such set of flow variables at every vertex of the time-expanded network ensure that these movements are consistent with how these objects move in real life.

Every truck flow originates at the entry vertex at the beginning of the planning horizon and ends at the exit vertex at its end. In contrast, crane flows can originate and end at any sector vertex of every track, lane or the storage area within the terminal at the beginning and end of the planning horizon, respectively. Round-trip container flows originate on the track where the train carrying them arrives, at the time of its arrival and in the sector where that container is located. Similarly, they end on the track from which their carrying train departs, at the time of its departure and in the sector where it should be placed. Arriving and departing containers behave similarly, except that their flows end at (or originate from) the customer where they are handled at the end (or beginning) of the planning horizon.

Container flow variables on all arcs (except those where they remain on a train) are linked to the corresponding flow variables of the available trucks (on truck movement arcs) and gantry cranes (on crane movement arcs) to represent the fact that containers cannot move on their own, but must always be moved by some equipment.

Storage capacity limits are enforced by in-degree constraints on each storage sector vertex at each point in time.

To ensure that trucks cannot overtake each other or share the same sector on lanes, additional constraints on temporally overlapping lane arcs (i.e., different arcs that use the same physical location at the same time – such as an arc entering a vertex from the preceding sector and one entering it from the same sector from a previous point in time) ensure that at most one of them is selected

by different trucks. Similar constraints on crane arcs ensure physical separation between these.

The objective function minimizes the total cost of the arcs selected by the various flow variables.

3 Interfacing with OpenTrack

We first use OpenTrack to compute the estimated arrival time of each freight train that will be handled by our intermodal terminal within the considered planning horizon.

Then, using the previously described intra-terminal optimization algorithm, we compute an earliest departure time for every such train.

We then use OpenTrack again to simulate the remaining part of each train's journey to determine whether any efficiency gains within the terminal (compared to the given deadline, by which we assume it would have originally departed) can be translated into an earlier arrival at the train's destination.

4 Conclusion and Outlook

We have presented an integrated algorithmic optimization framework that incorporates information about overland track availability into the optimization of container logistics processes within an intermodal freight train terminal.

Our first goal is to evaluate this framework on a set of real-world benchmark instances to both study its practical applicability and determine the impact of integrating railway simulation into the optimization of intra-terminal logistics.

Additionally, we want to investigate opportunities for further sparsifying the time-expanded network to increase the size of instances that our framework can successfully optimize.

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Critical Analysis of the Main Factors Causing Delays in Various Stages of a Supply Chain and the Relevant Machine Learning Models for Dynamic Lead Time Predictions

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Abstract. As supply chains extend geographically, the supply chain management seems crucial for improving companies' activities and enhancing their competitiveness. This global market liberalization creates an uncertain environment for fulfilling the deliveries on time based on the complex supply chain environment consisting of different companies acting in various stages of the supply chain process. In this context, lead time is one of the most critical measures for indicating a supply chain performance, as lead time forecast accuracy is a crucial factor of mitigating the bullwhip effect. Within the framework of the ESCALATOR project, a new innovative service is being developed aiming to dynamically forecast lead time variation, through the use of historical data and dynamic forecasts of lead time delays at the previous stages of a supply chain. This paper focuses on the validation and final selection of the factors causing delays in various stages of a supply chain, as well as the most suitable machine learning models in order to develop a service for dynamic lead time predictions at different stages of a supply chain.

Keywords: lead time · machine learning · supply chain · co-creation

1 Introduction

1.1 Main Factors Causing Delays in Various Stages of a Supply Chain

A key requirement for establishing a highly responsive supply chain is to decompose the total delays into delays per stage (production, processing, storage, sales - wholesale and retail - and transport), as well as per type of supply chain (cold, bulk and conventional, and dangerous cargo).

Vakharia & Yenipazarli (2009), identify as key factors of delay, the variability of production, due to production process interruption, and product demand, as well as the variability of product transportation time. Specifically, and with regard to delays in transport times, the inability to synchronize the shipment of goods with the planning of

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production and distribution operations is identified as a key factor. This factor is also identified by Abdellatif & Alsibani (2019), while they also identify as an indirect cause, the high cost of constructing facilities to store inventory levels such as those required to meet emergency orders.

A more detailed review and analysis of delay factors is presented by Macdonald & Corsi (2013), who identify the supply of products that do not meet quality standards, extreme snowfall events (Mohamed & Coutry (2015), Bandaly et al. (2016)), floods, hurricanes and wars, customs delays, as well as strikes, demand and order quantity variability, and finally, delays due to product returns. Mohamed & Coutry (2015) identify as a key cause, the variability of order fulfillment time which includes processing, production and product transport time, while Bode (2008) and Macdonald & Corsi (2013) identify as key delay factors, in addition to the variability of product production and demand, sources related to regulatory, legal and bureaucratic processes, as well as catastrophic events such as floods, earthquakes and hurricanes.

With the emergence of the COVID-19 pandemic, and the effects on global trade, pandemics are now emerging as a potential delay factor in the supply chain management. The association for supply chain management issued, in 2021, a detailed disruption report analysing the impact of pandemics on supply chains. The most important impact is related to product shortages due to increased consumer demand and the shortage of staff in international supply chains due to infection and isolation. Based on Macdonald & Corsi (2013), Lian & Erichsen (2019) and Abdellatif & Alsibani (2019) significant delays were due to the delay in customer payments and their clearance.

The main causes of lead time delays identified in the literature review were analysed through the supply chain operations reference model. The SCOR model enables users to comprehend and relate supply chain management processes (Ntabe et al. 2015). The SCOR model classifies the processes into four main categories: design/planning, procurement, production and transport (Association for supply chain management 2021).

The detailed record of the causes of delay mentioned above, served as the basis for the subsequent participatory processes conducted throughout the project. The aforementioned causes have been evaluated through questionnaire surveys and co-creation workshops by several companies with different type of activities in several levels of a supply chain in order to classify them according to frequency of occurrence and importance. The results of these process are presented at the following chapters.

1.2 Machine Learning Models for Dynamic Lead Time Predictions

With accurate order lead time prediction, companies can optimize their inventory levels, reduce overstocking, and streamline their production schedules. In recent years, machine learning algorithms have emerged as powerful tools for predicting order lead time in supply chains. By utilizing historical data, these algorithms can analyze patterns, identify relevant factors, and learn from past data to generate accurate predictions.

The issue of order lead time prediction is first addressed by Lingitz et al. (2018). The authors develop a suite of multiple machine learning algorithms that include Multivariate Adaptive Regression (MRE), Decision Tree Regression (DTR), Boosted Regression Trees (BRT), Lasso Regression (LD), Neural Networks (NNs) and Random Forest

Regression (RFN). The application of the suite of algorithms was performed on historical lead time data of semiconductor manufacturing. The method with the highest accuracy was Random Forest Regression. Gyulai et al. (2018) implemented a suite of machine learning algorithms to predict the lead time of orders in a complex environment where the complexity of lead time prediction arises from the multiple number of process parameters, and especially the high impact of customer order flow on work in progress. Similarly, Schneckenreither et al. (2021), applied a Neural Network (NN) to predict lead time. Order lead time forecasting in a pharmaceutical supply chain is reviewed by Oliveira et al. (2021). Such supply chains require low order lead times to provide efficient healthcare services. In this context, the authors develop a suite of machine learning algorithms including Linear Regression (LS), Support Vector Regression (SVR), Random Forest Regression (RFF), and Multilevel Perceptron (PPE), with RFF to have the best overall performance, with an average error lower than two days.

In a subsequent phase of the project, these algorithms will use the values of the delay factors identified as most pertinent to generate the final delay result for the customers. During this stage, the development of the algorithmic suite assisted the authors in determining the requisite variables and factors.

2 Investigation of Potential Users' Opinion

2.1 Questionnaire Survey

The questionnaire survey was conducted between March and May 2022 and a total of 47 responses were collected from representatives of companies operated in various stages of the supply chain. The supply chain was divided into five typical stages (production, processing, storage, sales (wholesale and retail) and transport) and the possible factors causing delay were classified at each stage. As it was expected, several factors are common to the different stages.

The questionnaire was structured to gather information related to:

- the stage/stages of the supply chain in which the company is involved in,
- the delay factors that are most frequently identified in house and when a third party is involved in one of the stages, and
- the company's type/activity in order to draw conclusions by type or product.

In the first part of the questionnaire, participants were asked to provide some information about their companies. The 42.6% of them has a turnover of more than €10,000,000 and in about 40.5% of them 25–99 employees exist. The companies are active in the following sectors of economic activity: trading companies with 74.5%, manufacturing with 36.2%, importing with 31.9% and exporting with 14.9%, with several companies being active in more than one sector. With regard to the type of cargo handled by each company, it was observed that the largest percentage of companies handles dry/conventional cargo (48%), followed by those handling refrigerated and/or cold cargo (34%). A smaller percentage of companies handle bulk cargo (13%), followed by companies handling dangerous goods (only 5%).

The largest proportion of companies are active in the wholesale (57%) and retail (21%) sector, with manufacturing/processing activity are following (21%). Finally, the

number of the segments of the supply chain that each company managed in house or outsourced is vital in order to identify the crucial factors causing delays. The majority of companies manage up to three stages with 30% managing one stage and 24% of companies managing two and three stages respectively. The most common stage for outsourcing is transport (78.3%), followed by warehousing (17.4%).

Regarding the factors causing delays, the rates vary depending on the stage of the supply chain at which the delay occurs. In particular, there are notable percentage variations from one stage to another. As a result, companies have to deal with several problems depending on the stage of the supply chain the product exist, which makes it even more difficult to deliver the final product on time. The final results about the factors causing delays will be analysed at the results session of this paper.

2.2 Co-Creation Workshops

Following the questionnaire survey, two workshops were held in order to bring together experts from different companies and collect experiences on the delays identified at different stages of a supply chain. The co-creation workshops were organized online through interactive sessions on the Miro platform and the participants had the opportunity to list the factors that disrupt the operation of their supply chains.

The questions focused on 3 main categories. In the first one, participants assessed the results of the previous questionnaire, confirming or updating their answers (delphi survey). The second category focused on recording quantitative results of the time of delay caused by each critical factor. Finally, in the third and last category, the outliers/special events, i.e. unforeseen and unusual events were examined. These unforeseen events are impossible to include in a prediction algorithm and therefore it was necessary to identify and exclude them from the designed service.

In general, customer payments are one of the most important factors that can delay the production, shipment or distribution of an order. Experts explained that without paying the total amount, the order cannot be sent to the final customer, and that delays both the scheduling of production and transport of the order. The import and export of raw materials and final products, especially where customs clearance procedures are involved, are processes that cause delays and are responsible for additional costs in production and transport steps. Additionally, they also affect the customer's satisfaction rate and the total reliability of the company as a whole. The interrelationships between processes and communication between departments are seamless factors that enhance more resilient and sustainable supply chains. Delays due to unexpected events and disruptions at social, political and economic levels also disrupt supply chains, however it is unrealistic to provide an approximation of the total time of delay.

3 Results - Discussion

The paper describes the work carried out in order to identify the critical factors that cause delays at different stages of multi-level supply chains. The results of the literature review were evaluated by industrial experts and potential future clients of the service to be developed, though interviews and participatory co-creation workshops. Each factor was ranked according to its appearances in the responses.

The final identification of the most important independent variables was initially carried out through their categorization into three types on the basis of the Pareto analysis. The type A refers to the most important independent variables. These variables make up approximately 20% of all variables and correspond to 50% - 80% of the frequency of responses. The results of the participatory processes and Pareto Analysis identified the most important factors, independent variables of the predictive algorithm, as presented in Table 1.

Table 1. Most important independent variables based on Pareto analysis

Production	Processing	Warehousing	Sale	Transport
Delay in the supply and delivery of raw materials/products by the supplier and the transport company	Delay in the supply and delivery of raw materials/products by the supplier and the transport company	Delay in the supply and delivery of raw materials/products by the supplier and the transport company	Delay in the supply and delivery of raw materials/products by the supplier and the transport company	Delay in order processing
Delay in order processing	Delay in order processing	Delay in order processing	Delay in customer payments	Delay due to extreme weather conditions
Delay in the replenishment process of raw materials/ products orders	Delay due to unexpected events (wars, earthquakes, flood)/political instability	Delay in customer payments	Delay in the management and sorting of raw materials/products	Delay on custom clearance

The critical analysis of the literature review for the identification of the machine learning algorithms used to dynamically forecast the order lead time in multi-level supply chain highlights the Random Forest Regression (RFF) and Decision Tree Regression (DTR) as the most commonly used ones. The RFF was identified as the most accurate method in the majority of studies, while the Linear Regression excels in terms of training speed and ease of application to problems with multiple variables. As a result, these algorithms are those included in the suite for dynamic prediction of order lead time service.

In general, the above prioritization of delay factors/ potential independent variables gives an indication of how they should be addressed and included in the prediction algorithms to be developed within the project. However, the selection process of the independent variables per stage of the supply chain will take place during the development of the service and the training of the algorithms, based also on the data availability from company's clients' datasets.

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A Satellite Image Based Eco-Routing Solution: Requirements Analysis from Industry Interviews

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Abstract. This paper presents the initial requirements of eco-routing using Earth Observation in two industrial contexts. Earth Observation (EO) is the practice of taking images of earth from space using satellites. Recent progress in EO imagery means that these images are near real time. This creates additional opportunities to leverage image data. Currently, logistics companies have used location-based data for many cases. Exploring the use of EO imagery is promising, especially in the execution of logistics operations. Eco-routing is optimising routes by some parameter improving the routes' sustainability. Eco-routing has provided value to firms by reducing the operational fuel costs and also provides value by contributing to a cleaner future. This study will focus on the investigation of the requirements of EO images to contribute to eco-friendly routes between two nodes.

Keywords: Satellite image · remote sensing · eco-routing

1 Introduction

The primary research question this paper seeks to answer is "Should logistics companies implement remote sensing enabled eco-routing?". The secondary research questions are "What is eco-routing?", "What should be optimised?" and "How do we implement this using earth observation/remote sensing data?". The structure of this paper is as follows: We first explore satellite remote sensing and eco-routing in a short literature review. Next, we introduce the methods and materials for our interviews. Then, we present the results from the interviews. We split the results into their respective areas. Lastly, we discuss and conclude this paper with the implications for further research.

2 Literature Review

The purpose of this short literature review is to define what technologies and problems we are matching in our proposed solution to logistics related industry. To understand the technologies at hand, we first need to review satellite-based remote sensing. Eco-routing itself is a complex concept, with changing definitions. Hence, we need to define for this paper how we view eco-routing. ***Satellite-based Remote Sensing:*** In this paper, we consider satellite-based remote sensing in the specific application of earth observation

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(EO). EO is the technological advancements enabling us to observe earth through satellite imagery [1]. With advancements in this technology we now have a plethora of different sensing techniques [2]. The main sensing technique that we expect to use is the one where high-quality images are taken of the earth's surface. These pictures and other relevant imagery can provide data relating both to traffic [3], as well as road characteristics [4]. However, there are other techniques that may be useful for road characteristics. For example, commercially available radar technologies are able to detect the earth's surface through foliage and clouds. These advanced radar technologies are highly precise, being able to measure differences of up to 50 cm [5]. Therefore, since the goal of this paper is to outline the requirements for improved eco-routing, we should not exclude any way to get there. Existing research also supports the use of satellite remote sensing to capture moisture levels in soil [6]; topographical applications [7]; traffic levels [3]; size of load estimates [5]; patterns - due to the ability to record data over time [8]. ***Eco-Routing:*** Eco-routing is a specific practice in logistics of optimizing routes based on an objective function that includes ecological or environmentally motivated elements [9]. The criteria that are typically looked at include: fastest route (e.g. fastest average speed), least kilometres, context specific criteria [9]. Another angle of eco-routing is fleet management and ensuring that the fleet is as environmentally friendly as possible [10].

3 Methods and Materials

The method for this paper to explore whether logistics companies should implement remote sensing enabled eco-routing is the use of semi-structured interviews for relevant logistics actors. The interviews were scheduled for 60 min. The interviews were "semi-structured" in format. This structured enabled three things. First, the structure enabled an introduction and conclusion, which are important for stakeholder relations. Second, the structure ensured that about half of the interview was dedicated to listening and understanding to the industry expert and that the second half was dedicated to mapping and brainstorming key requirements for opportunities using satellite imagery. Third, the lack of a strict structured enabled discussion to flow so that we could uncover finer details. We invited people who would be familiar enough with the high-level strategic direction of the company, but are not so far removed from the logistics process that they would not be able to tell us about it at the operational level. As a result, we ended up trying to select people who were managers close to the logistics side. This method aligns with best practices outlined by user research publications [11] and [12].

We prepared both interviews through due diligence to ensure that we had some prerequisite knowledge. This was important to focus the interviews around the research topic, rather than industrial knowledge.

The first firm interviewed was a large forestry company in Finland – Company A. Company A was represented by someone with the title of "development manager". This person had experience both in the forestry sector as well as the logistics sector. This is why we thought that their profile would be suitable for this research.

The second firm interviewed was a large organic materials recycling firm – Company B. Company B was represented by their "logistics manager". This title immediately signals that this representative has an adequate profile for this research.

4 Results

4.1 Timber Transport

The first interview exposed several facts to elucidate the current logistics set up (presented in Fig. 1) and shed light on what the forestry industry currently needs from satellite imagery. The transport set up in the forestry sector in Finland is not as centralized as we thought. Company A, despite being one of the largest operators in the Finnish forestry sector, does not own any trucks. Our interviewee explained that this set up is the cheapest way to do land transport, as it enables company A to set up calls for certain transportation areas/jobs/projects. The contracts remunerate companies based on cubic metres of timber as well as kilometres driven. Both of these are predetermined and known by company A, thus leaving the sub-contractors competing on price. This also shows that an eco-routing algorithm, should it be efficient at producing cost savings, would directly be reflected in the entrepreneurs' costs, and therefore allow entrepreneurs to compete in the market better. In terms of the existing software, both the logistics and the actual harvesting of timber is managed by a third party produced software, with appropriate packages for logistics and harvesting. Company A's representative broadly explained that this software catered mostly to the actual tracking of timber product, and that only the logistics package could be doing anything to optimise routing. Additionally, it was mentioned that company A struggles to see how any of the forestry logistics chain could be optimised as most timber products already have a pre-set destination before even being planted. However, we believe that he meant this in terms of optimising the actual transportation of the product from one node to another without taking into consideration how it is transported from one place to another. Table 1 describes the key requirements for a routing algorithm in the forestry sector, based on our discussion with company A. From this table we can begin to deduce that the primary Earth Observation techniques would be related to road characteristics and profile. Both these features are fairly static,

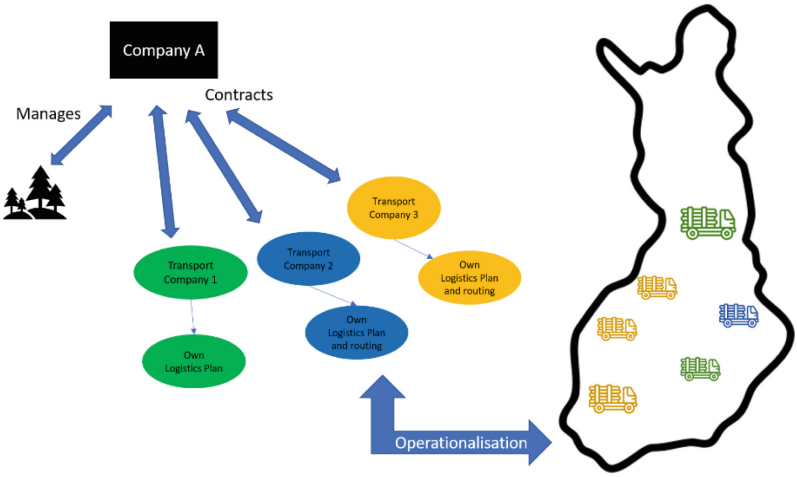


Fig. 1. Company A transportation set up

requiring maybe a single update every day to ensure that data for more sensitive items is updated.

Overall, it is intuitive that the entrepreneurs will compete on cost, and therefore the eco-routing algorithm should find a route that minimizes fuel consumption.

Table 1. Requirements from the forestry sector

Requirement	Problem Solved	Logistics Chain Link	Satellite Imagery Application
Different time windows for different plans	This is potentially addressed by company A's existing software	timber transport	Predictive monitoring
Home base routing plan ("MePa")	Most trucks operate around a home base	timber transport/routing	–
Road characteristics identification: load of tracks	Ad hoc solution exists: surveying and self-reporting	harvesting and collection to roadside storage	Predictive analysis of truck load bearing capacity of roads/tracks
Road characteristics identification: Depth of Tracks	Ad hoc solution exists	harvesting and collection to roadside storage	Potentially solvable using simple imagery from different angles
Accuracy and frequency of satellite data	predictive and informative solutions	–	Frequency of passovers needs to be checked
Precision of satellite data	This addresses the specific case in which data may autocorrelate because of limited definition	–	Different satellites have different definitions
Profile of roads	Potentially addressed by subcontractors	timber transport/routing	Topographic surveying by satellites
Strategic loading	Loading the trucks in a way that it is at its lightest when the roads are most difficult	routing	Topographic surveying by satellites

4.2 Organic Materials Transport

The organic materials recycling process of company B relies on an internally developed logistics operating system. The most interesting process for this research is the carcass collection process, as this is the one that has most room for optimization according to our interviewee. Company B has two main lines of input – the first is by product from

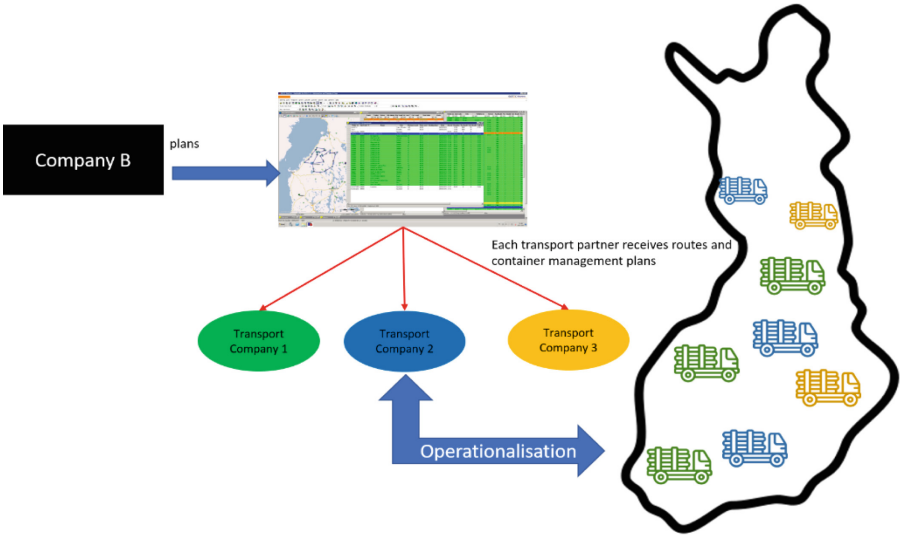


Fig. 2. Company B transportation set up

meat processing plants. The second is carcasses which are collected from around the country side. Figure 2 describes the transportation process for the carcass collection.

In terms of structure, company B does have its own logistics department, but they do not own a fleet of trucks. All of the transportation is done by subcontractors. Company B's business model revolves around containers – which they own - and are spread out over different locations. The freshness of the raw material is a critical factor in this industry. Company B's internal logistics operating system is already extremely advanced, and from the initial discussion it is already clear that they have some sort of routing algorithm for carcass collection. Company B's representative explained that the two key factors were based on the "cost" (distance) and the "retrieval time". This is because there are EU regulations dictating the time until when a carcass can be recycled. If this deadline is missed, the carcass is still collected, but is destroyed rather than recycled – therefore causing a net loss for company B. This highlights why these two were highly ranked as routing criteria. Additionally, the routing system also relies on a "home base" system, as in the timber trucking world as well. These ideas are also reflected in Table 2 which outlines some of the gleaned requirements from the discussion with company B.

Table 2. Requirements in the organic materials recycling context

Requirement	Problem Solved	Logistics Chain Link	Satellite Imagery Application
Home base + intermediate warehouses	Truck fleet subcontracting + maximising by product transportation from all of Finland to company B's production lines	Carcass and by product collection	"Live" status of containers (live tracking of containers) for: 1) moving containers, 2) stored containers at production facilities; or 3) intermediate warehouse management
Daily route planning for carcass collection and container routes	once a day is enough to set the routes	operations	
Minimise cost	Current routing algorithm minimises costs based on kms	operations/routing	
Collection Time	Current routing algorithm optimises route based on collection times for different carcasses (Most urgent first)		

5 Discussion and Conclusions

From the introduction, the main research question was defined as "Should logistics companies implement Remote Sensing Enabled Eco-Routing?". The secondary research questions were "What is eco-routing?", "What should be optimised?" and "How do we implement this using earth observation/remote sensing data?".

The first question is answered by the interviews. It is clear that in both industries – logging and organic materials recycling – the logistics aspect has been curated to be highly economically efficient. Both company A and company B do have some policies and interest with regards to sustainability, however this is not their top concern when it comes to routing. Both firms operate with a no-ownership principle in terms of trucks. It appears that company A is much less concerned as to how the transportation plans are executed, as there is a high level of clarity around what timber products should go where. According to our interviewee there is little to no room for optimisation. In company B's case, they have already spent a significant amount of resources constructing their own internal logistics system in order to fulfil their needs. The carcass collection process has potential for further optimisation using eco-routing principles, however it would still have to fulfil the minimum requirements of having a home base system, minimising

kilometre cost, and ensuring that collection times are respected. Both firms showed interest in using satellite imagery and remote sensing to solve problems. However, both problems proposed in either industry fall outside of the realm of eco-routing. In the Forestry context, a lot was discussed around the use of satellite imagery to look at moisture levels and load bearing capacity of logging tracks. Additionally, other use cases included ditch-road level comparisons, as well as rut depth in existing forestry tracks. In the context of company B they showed an interest in managing and having an overview of their containers – especially around slaughterhouses, to explore optimisation opportunities there.

In terms of the technology requirements for company A, we have precedent to believe that moisture analysis for roads, and surrounding areas is feasible through the use of Special Sensor Microwave Imager/Sounder (SSMIS) Technology and Special Sensor Microwave Imager/Sounder (SMAP) L-Band Radar Technology [13, 14].

Change detection, which is the use case for company B, can be achieved through Synthetic Aperture Radar (SAR) technology [15], and is already implemented to some extent by players in the private market [8]. Despite the existing use case, the application of change detection to land transport would be novel.

The second research question is answered by the literature review in that Eco-routing is a specific practice in logistics of optimizing routes based on some objective function that includes ecological or environmentally relevant elements [9]. What should be optimised – we argue that the movement of the trucks, rather than the goods, should be optimised. Based on our interviews this would allow for more economical and ecological logistics.

The third question is about implementation. From our interviews it was clear that neither firm had use cases that were ready to experiment with the implementation of Eco Routing and Remote Sensing. However, on a theoretical level, an existing eco-routing algorithm could modify with additional parameters. These additional parameters would be fed with additional data coming from remote sensing to optimise a route based on known eco-routing parameters – e.g. route profile and road characteristics.

The conclusions that we can draw from here are: 1) further investigation, closer to the operational level is needed to understand the forestry context more deeply to see if it is truly as closed as system as company A made it out to be. 2) Collect and present use cases more clearly for potential users of satellite imagery for eco-routing. 3) Explore other industries to see if eco-routing in industry is something that is useful. The next steps are to address at least point 2 in more depth, and continue collaborating with industry players to understand their needs and address how satellite imagery could address them. Additionally, we will continue to investigate on how to ensure that satellite imagery in eco-routing can be achieved, also towards near real-time utilization, and presented in a more concrete manner so as to show stakeholders how this could benefit them.

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The SEAMLESS Approach to Enabling Fully Automated Waterborne Freight Feeder Loop Services

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Abstract. This paper describes the approach that is developed within the EC-funded *SEAMLESS*, which is implemented by a diverse consortium of 26 organisations across Europe. The main objective is to develop and adapt the missing building blocks and enabling technologies into a fully automated, economically viable, cost-effective, and resilient waterborne freight feeder loop service for Short Sea Shipping and Inland Waterways Transport. The envisioned service will be provided 24/7 by a fleet of autonomous cargo shuttles, supported by humans-in-the-loop in Remote Operation Centres (ROCs). These centres efficiently collaborate with automated shore-side infrastructure while ensuring safe interaction with conventional systems. To enable seamless freight flows and reduce delays at intermodal nodes, the relevant logistics system will be redesigned, while a digital "bird's eye" view of the supply chain will facilitate optimized planning, reconfiguration, and resilient logistics. The building blocks for enabling this type of waterborne operation that will be developed within *SEAMLESS* include the DockNLoad port interface, which consists of automated mooring and cargo handling systems, the modular vessel concepts and operations that will be transferable to different use cases, and the ModalNET platform that will provide integrated supply chain support by acting as a "digital twin" of the physical logistics chain.

Keywords: Autonomous waterborne transport · synchro-modal logistics · modal shift · zero-emission waterborne transport · logistics · autonomous port operations

1 Introduction

The transport industry faces several challenges in the path towards sustainable operations, including congestion, and the need to minimize environmental impact through zero-emission solutions [1]. In the ever-evolving transportation landscape, the different transport modes have embraced higher levels of automation, digitalization, and connectivity as the keys to sustainability [2–4]. However, the large scale integration of

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automated and autonomous systems in waterborne freight transport is challenged by the following obstacles [5, 6]: 1) technological readiness related to the complexity and cost of vessel and automation of the port interface, 2) operational unknowns mainly related to how remote control is implemented, 3) regulatory complexity that leads to a lack of clarity and legal uncertainty with respect to deployment of solutions, and 4) stakeholder readiness in terms of general public acceptance and investment willingness.

It is within the above context that the EC-funded, Horizon Europe SEAMLESS project will address these challenges by developing and adapting missing building blocks and enablers into a fully automated, economically viable and cost-effective, waterborne freight feeder loop service for Short Sea Shipping (SSS) and Inland Waterways Transport (IWT). SEAMLESS will develop and integrate autonomous systems in a way that ensures safe, resilient, efficient, and environmentally friendly operation to shift road freight movements towards waterways and demonstrate to the transport community that autonomous feeders can solve today's transport problems and overcome any real and perceived obstacles.

2 The SEAMLESS Transport System

The scope of SEAMLESS within the supply chain includes (see Fig. 1): 1) cargo handling, from ship-shore and within the port, at maritime and inland ports that act as intermodal hubs with other maritime and hinterland connections (i.e., trucks and rail), 2) loop transportation of various cargoes (incl. Containers and bulk cargo) between maritime and inland ports, 3) information flow throughout the supply chain with respect to the transportation means, the cargoes, and the supporting shore-side infrastructure.

The SEAMLESS automated waterborne freight feeder loop service will be delivered by autonomous, modular cargo shuttles, which will operate 24/7 with humans-in-the-loop located in Remote Operations Centres (ROCs) (Building Block 2). The autonomous vessels will efficiently cooperate with automated and autonomous shore-side infrastructure and safely interact with conventional, manned systems in the supply chain (Building Block 1). The service will also be based on a redesigned logistics system that will facilitate seamless, safe, synchromodal, and resilient freight flows and minimise bottlenecks and delays at intermodal nodes (Building Block 3). This includes a digital "bird's eye" view of the supply chain, including the operating physical assets, that allows the exploitation of real-time information for planning optimisation and reconfiguration to support resilient logistics. The SEAMLESS building blocks will be developed within the project as "plug-n-play" modules, applied as required depending on the use case. By developing these building blocks and integrating them with existing results from the EC-funded, H2020 projects MOSES, AEGIS, and AUTOSHIP, SEAMLESS will introduce a fundamentally new concept for fully automated waterborne freight feeder loop service for SSS and IWT. In the following sections, the building blocks are briefly described.

2.1 Building Block 1: Automated Port Interface (DockNLoad)

SEAMLESS DockNLoad consists of the following modules: 1) a re-engineered version of an existing automated mooring solution for fully autonomous operation onboard the

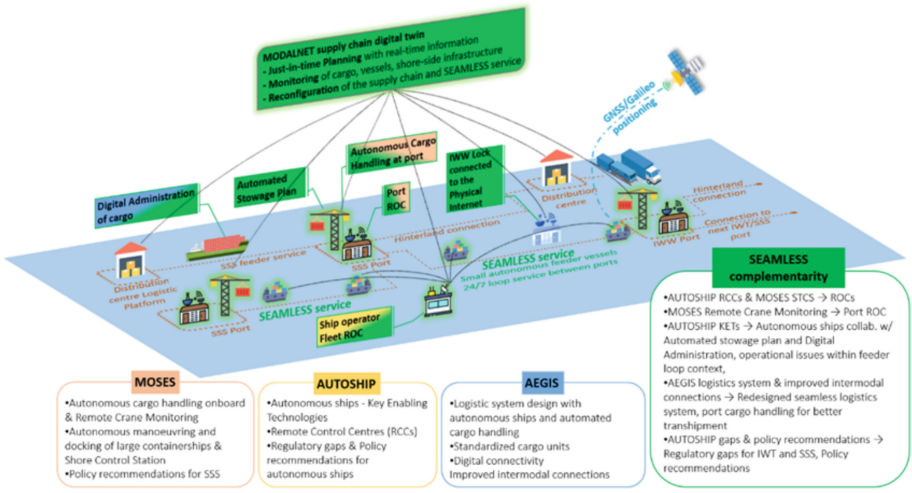


Fig. 1. SEAMLESS concept and technology building blocks for seamless and automated logistics. Image produced by Angeliki Stouraiti in Inkscape, an open source software

autonomous vessels involved in the SEAMLESS service, 2) an autonomous, innovative crane system for cargo handling at port supported by an automated stowage planning system, and 3) a system for handling automated port calls. The autonomous mooring module consists of a robotic arm that works with conventional mooring lines that maximizes the system's compatibility with legacy port infrastructure (e.g., bollards). The autonomous cargo handling module will consist of an innovative crane system designed to reduce cargo swing and rotation while exploiting the available real-time data from the autonomous mooring module regarding the vessel's relative position to the quay. The Voyage and Container Optimization Platform (VCOP) will provide the autonomous cargo handling system with the (un)loading sequence information in advance of the port call, while also interfacing with ModalNET (Building Block 3) to receive updated sequences and work orders. The Autonomous Vessels' Smart Port Manager (AVSPM) will enable automated port calls for autonomous vessels that will include negotiating port calls, monitoring safety and security and managing emergencies, and route planning optimisation.

2.2 Building Block 2: Modular Vessel and Operations Concepts

This building block addresses the design and operation phases for autonomous vessels and consists of the following modules: 1) rapid prototyping approach, 2) risk-based safety assessment, 3) a Guidance, Navigation and Control (GNC) scheme, and 4) the ROC concept. The SEAMLESS rapid prototyping approach will develop methods for quickly and easily evaluating green vessel concepts for commercial viability in specific operational contexts (incl. safety, environmental performance, and cost issues) in the early stages of design. In the context of risk-based safety assessment, SEAMLESS will develop an integrated risk assessment tool based on the principles of Operational

Envelopes [7] to construct standardised assurance cases for autonomous vessels that will enable risk-based approval with lower effort and cost. The GNC scheme will ensure safe interactions of autonomous marine and inland vessels with conventional, manned vessels by implementing COLREG-aware collision avoidance that will be supported by a monitoring module for detecting, diagnosing, and managing faults, as well as for identifying falsified sensor data (e.g. due to AIS spoofing) and will contribute towards fault-tolerant control. The SEAMLESS ROC concept will build on the technologies developed in the EC-funded, H2020 project AUTOSHIP towards the "low-attention ROC" concept, where a single operator supervises multiple vessel operations, while "high-attention" operations are maintained as a fail-safe strategy.

2.3 Building Block 3: Integrated Supply Chain Support (ModalNET)

The ModalNET logistics network "digital twin" will depend on the following modules: 1) a collaborative framework of logistics platforms, 2) digitalized administration procedures based on the requirements of relevant European regulations, and 3) voyage planning, navigational, and operational support. The functionalities of ModalNET, for example when a shipper or logistics will be planning and initiating any freight transport from a point of origin to a point of destination, include identifying the optimal combination of transports, calculating the most suitable schedule, the associated costs and predicting route performance, organizing the transport chain by generating all the booking and shipment orders and other documentation for the different modes of transport. In addition, ModalNET will monitor the fleet of small autonomous vessels involved in the seamless service throughout the transport lifecycle and evaluate how fleet the fulfils the transport needs (e.g., in case new vessel is required to meet increasing demand). The main digital assets that will be included in the ModalNET "digital twin" will be branch offices, shipments, transport units, transports, and stored items (linked with gate in and gate out operations). These will be complemented with other digital assets such as documents, services, procedures, transport means, location facilities, logistics charges and master data.

3 The SEAMLESS Methodology

For the SEAMLESS automated waterborne freight feeder loop service, the missing building blocks will be developed by following a four-phase approach: 1) Baseline/Positioning, 2) Innovation, 3) Verification, and 4) Impact Assessment. In the first phase, the system requirements for the SEAMLESS building blocks will be determined along with the baselines with which the performance of the SEAMLESS solutions will be compared and the redesigned logistics system. The Innovation phase will include determining the technical specifications and system design of the building blocks. In the Verification phase, the developed solutions will be verified and validated in full scale demonstrations in the context of the demonstration use cases and by means of simulation in the context of the transferability use cases. The Impact assessment phase will ensure the long-term sustainability and exploitation potential of the building blocks by: 1) assessing the individual and combined performance within the context of the

SEAMLESS use cases, 2) assessing the impact across the European supply chain, and 3) developing viable business models and business plans. The results will be used to document the positive effects of the new systems and to provide a roadmap for technical and policy initiatives.

The SEAMLESS Use Cases consist of the following (see Fig. 1): 1) two full-scale demonstrations that will combine the critical elements of the physical and digital assets developed in the project with existing assets in real-world conditions for SSS and IWT, and 2) five transferability use cases that cover a wide range of transport applications and geographical regions with different requirements throughout Europe.

The objective of the demonstration cases is to verify the Technological Readiness Level (TRL) achieved during the project and include a North European SSS case and a Central European IWT case. The SSS case involves a potential container feeder loop between the city of Bergen and Ågotnes in Norway demonstrated with a highly automated, fully electric RORO vessels that will be monitored by the SEAMLESS Remote Operations Centres (ROCs). The demonstration for the IWT case involves a highly automated, inland container barge and offering low to zero emission through an exchangeable battery-electric energy system.

The objective of the transferability cases is to assess the impact of the building blocks in various operational contexts and evaluate the replicability of the project results by implementing a structured methodological framework. For each use case, the performance of the SEAMLESS solutions will be benchmarked against a "reference case" that reflects existing transport solutions, including traffic flows, particulars of operating vessels, and market attributes. These cases include routes in the following regions: Western Mediterranean, Adriatic Sea, Eastern Mediterranean, the Black Sea, and the English Channel for SSS and Western and Central Europe for IWT.

4 The Expected Impact of SEAMLESS

The deployment of the SEAMLESS building blocks targets to promote maritime autonomous services on a Pan-European scale, by enabling streamlined and fast logistics via a fully automated waterborne freight feeder loop service that is integrated into the digital transport ecosystem and therefore promotes synchromodality. Operating this type of SEAMLESS service is expected to contribute to modal shift from land-based to waterborne transportation by 20% by increasing the competitiveness of the service against existing alternatives by the same percentage.

This will be achieved by effectively reducing the early movers' risks, in terms of safety, environmental performance, and required investment, of fully automated waterborne transport services. Towards this end, SEAMLESS will improve cost-effectiveness and safety of highly automated and autonomous port-side infrastructure in maritime and inland ports, simplify the deployment requirements for autonomous vessels, and develop sustainable business models for autonomous SSS and IWT. Indicatively, SEAMLESS targets a reduction of logistics services costs by 15% compared to similar existing services, while increasing the reliability of service by 40% and reducing the time for approval of autonomous vessels by 40% compared to the Yara Birkeland benchmark (i.e. 1 year for approval). In addition, SEAMLESS will reduce legal and regulatory uncertainty related to autonomous waterborne transport for both SSS and IWT by providing

a roadmap to make deployment safer, cheaper, and with a positive social impact, as well as increasing public awareness concerning the implementation of autonomous transport technologies. Indicatively, SEAMLESS targets a shift of existing jobs to higher-skilled jobs by 30% to support autonomous SSS and IWT.

These achievements will not only enable the market uptake of the SEAMLESS solutions but will also improve the European competitive advantage within global markets with respect to connected and autonomous shipping, by fostering an increase in knowledge and availability of highly-skilled jobs across several member states and associated countries.

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Establishing Living Labs for City Logistics: Scoping and Initial Outcomes

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Abstract. Living Labs (LLs) are collaborative spaces where stakeholders are offered the opportunity to address relevant challenges. In the context of city logistics, LLs promote knowledge exchange, innovation, and learning among stakeholders, while also focusing on understanding how different UFT solutions are perceived by stakeholders, and how these perceptions influence solution adoption. In this direction, the aim of this study is twofold; first to provide a framework for establishing city logistics LLs, and second, to validate this framework via showcasing the challenges and barriers of LLs of different size, purpose and scope, to elicit requirements and foster the actual implementation of the envisaged solutions and their scale up. The research contributes to the advancement of sustainable urban logistics practices to enhance the efficiency, sustainability, and resilience of Urban Freight Transport (UFT) systems.

Keywords: Urban Freight Transport · Co-creation · Stakeholder Engagement · Knowledge Exchange

1 Introduction

Living Labs (LLs) are collaborative environments where various groups of stakeholders come together to co-create and co-design solutions addressing complex urban challenges [1]. In the context of city logistics, establishing LLs provides a platform for stakeholders to collaborate and test innovative solutions that improve the efficiency, sustainability, and resilience of Urban Freight Transport (UFT) systems. They facilitate the exchange of knowledge, ideas, and resources, enabling stakeholders to learn from each other successfully without being hampered by conflicting interests and agendas [2].

Recent literature on Living Labs (LLs) for last-mile delivery innovations indicates that LLs are a pluralistic approach centered around bringing together diverse sets of stakeholders in new formations to co-create products and services in complex settings [1]. While most LLs focus on fostering interactions between end-users and private actors for technology development through a triple helix perspective, the emerging concept of urban LLs specifically emphasizes urban and civic innovation through quadruple helix co-creation. This approach facilitates spatially embodied collaboration between private entities and civil society [2, 3]. As a result, urban LLs have become a means to approach

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smart mobility or smart city futures, where multiple actors need to align to solve complex challenges [3].

The innovation of the current framework discussed in this article lies in recognizing that, while urban LLs provide a promising arena for co-creation, there is room for expanding the methodology further. Key areas for improvement include how to engage and align stakeholders throughout the innovation process [4], how to create environments where stakeholders can co-create and learn from each other successfully without conflicting interests and agendas, and how to leverage outcomes from Living Labs on a larger scale [2, 5]. Additionally, there is a need for further research on methods for citizen engagement in urban LLs to better understand how these labs could and should interact with citizens [6, 7].

In this direction, the aim of this study is twofold; first to provide an innovative framework for establishing city logistics LLs, and second, to validate this framework via showcasing the challenges and barriers of LLs of different size, purpose and scope, to elicit requirements to foster the actual implementation of the envisaged solutions and their scale up. To achieve the first objective, key stakeholders involved in the city logistics sector were identified, along with their respective roles. Then a conceptual framework for the establishment of LLs is developed. The envisaged framework outlines a process for developing a shared vision and establishing governance and management structures to promote stakeholder engagement and effective collaboration. The framework is applied to five case studies –Athens/Greece, Barcelona/Spain, Flanders/Belgium, Ispra/Italy, Oxfordshire/UK– currently deployed in the frame of the European Horizon project GREEN-LOG [8]. As per the second objective, through iterative engagement with stakeholders in the period January-June 2023, challenges and barriers for all five LL were identified.

2 Developing a Co-creative Living Lab Framework - Charting the Scoping Phase

LL co-creation has to be tailored to the local social and cultural context and organised through inclusive and iterative processes that involve engaging diverse stakeholders, fostering open dialogue, facilitating knowledge exchange, and providing opportunities for collaborative decision-making and experimentation. While many LLs primarily emphasize on enhancing interaction between end-users and private entities to drive technology development within a triple helix framework, the GREEN-LOG LL model distinguishes itself by placing a particular emphasis on urban and civic innovation. This is achieved through a quadruple helix co-creation approach that encourages collaborative efforts within physical spaces between private entities and civil society [3].

The adopted framework approach of this study is inspired by the methodology of Smith & Iversen [9]. It begins with Scoping activities, serving as a preliminary Phase Zero phase in participatory design projects; it is then followed by subsequent phases involving Developing and Scaling dimensions. Focusing on the Scoping dimension, it involves predefined stakeholders in co-design activities and timelines to initiate the development of protagonist communities within the LL. A protagonist community refers to a group of individuals or stakeholders who actively take a leading role in initiating and driving

positive change within their community. Moreover, user definition and participation configuration are also integral parts of the phase.

The Scoping phase is characterized by two distinct subphases; the introduction of the LLs, and the alignment of goals and visions. As per the former, LLs are often requested to provide two key contacts (in the frame of city logistics, these could be a city representative and a logistics service provider) to conduct initial interviews. These interviews aim to map existing activities, experiences from previous projects, expectations, collaboration visions and future activities.

3 Results of Scoping Phase

The first step of Scoping phase in the GREEN-LOG project required the identification and clustering of stakeholders whose perspectives are crucial for developing effective policies/solutions. Based on an extended literature review [10], four main clusters main clusters emerged. The corresponding stakeholder categories to these clusters can be seen in Table 1.

Table 1. GREEN-LOG stakeholder clustering.

Cluster	Stakeholder Category
Cluster A	Local government agencies, Environmental groups, Community groups/Citizens, Emergency responders
Cluster B	Researchers and academics, Financial institutions, Insurance companies
Cluster C	Businesses/Shippers, Logistics companies, Technology companies, EV manufacturers and charging infrastructure providers
Cluster D	End users/Customers

Moreover, customized "Meet-Ups" were arranged for all five LLs. These involved, inter alia, determining potential local stakeholders; developing goals' and barriers' alignment; planning potential user journeys and more.

3.1 Determining Local Stakeholders and Organizational Structure

The various LLs underwent a facilitated process to create an organizational structure that defines the roles of local stakeholders within the project. This structure delineates core team members (fully dedicated to the project), involved team members (regular contributors), and informed team members (stay updated and provide input as needed) (Fig. 1).

3.2 Goals and Barriers

The LLs within the GREEN-LOG project engaged in collaborative discussions to articulate their respective goals/visions and barriers. The discussions took place on a

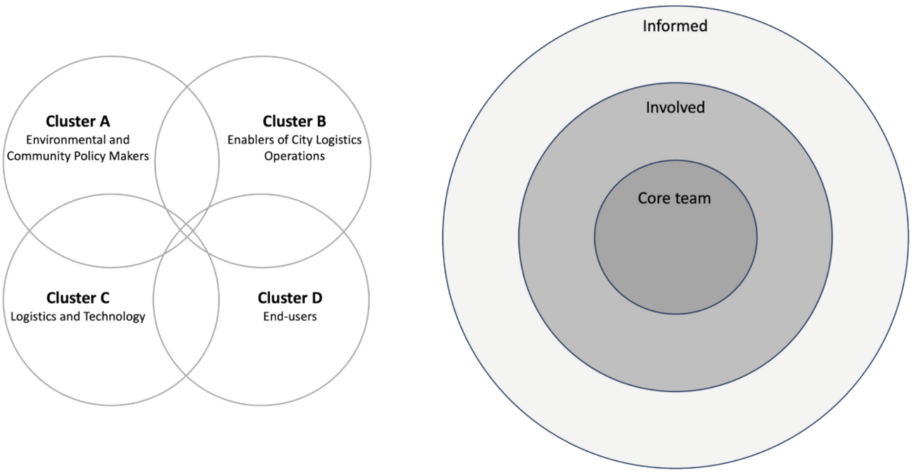


Fig. 1. LL structure to organise local stakeholders by clusters and levels of engagement.

Table 2. LL goals identified by core teams in GREEN-LOG's Living Labs.

LL	What does it want to achieve?
ATH	1. Improve citizens quality of life 2. Raise awareness on green innovative solutions 3. Promote Athens as a green tech implementation hub 4. Digitize last mile solutions
BAR	1. Public Transport participation in last mile delivery solutions 2. Greener and more efficient last mile logistics 3. More sustainable city logistics (less driven kilometres and vehicle movements, visible changes in the city)
FLA	1. Connecting supply and demand for both sender and receiver, with a technological solution that is data driven 2. Sender's and receiver's role being effectively included in the last-mile logistics Awareness of societal costs of last/first mile deliveries
ISP	1. Sustainable delivery process 2. Mixing different vehicle technologies to exploit their unique comparative advantages 3. Prototype this service and transfer it to a city-like case 4. Facilitate the promotion of innovation 5. Enable growth and economy at JRC site
OXF	1. Real world demonstration and data collection of the possibilities and benefits of using micro consolidation including simulation of CAVs 2. Understand the feasibility, potential, and societal response to micro consolidation 3. Long-term space to continue collaborative innovation and testing green logistics solutions among a wider group of stakeholders

shared digital platform using MIRO software, and the outcomes are summarized below (Table 2).

LLs identified also key barriers that challenge the realization of their objectives. These barriers span a range of logistical, regulatory, and operational challenges as follows (Table 3).

Table 3. LL barriers identified by core teams in GREEN-LOG's Living Labs.

LL	Main Barriers
ATH	1. Lack of infrastructure and regulation on micro mobility 2. In order to expand and replicate the solution, concern should be given to the implementation process of the micro consolidation centres
BAR	1. Lack of economic viability 2. Lack of alignment between stakeholders both internally and externally 3. Slow and difficult decision-making processes for public entities 4. Operators loosing clients/money during trial-phase 5. Lack of understanding of the LL trial-error approach 6. Conflicts of interests related to multiple stakeholders
FLA	1. Finding common ground for all 3 cities: overcome the differences in cities 2. Resistance to the involvement of end-receivers/shop-owners/traditional LSPs/political representatives 3. Time to bring in all stakeholders in all cities
OXF	1. Procurement issues and processes: delays, and value for money 2. Problems finding suitable site with good cycle access 3. Too slow development of technology 4. Difficulties in buy-in couriers and national parcel carriers outside of consortium 5. Social, legal and political barriers 6. Problems with involving the right partners
ISP	1. System continuity 2. Paths identification physical barriers (sidewalks, steps) 3. Final users' involvement 4. Delivery robot traveling without interfering with other road users 5. Administrative coordination between stakeholders 6. Technical integration of the solution 7. How to offer a continuative service and manage corner cases (guarantee the delivery if technical faults arise, location of logistics hubs, etc.)

3.3 Tentative User Journeys

Each of the LLs was also guided through the Scoping phase to cultivate a user-centric approach to developing delivery solutions. This involved identifying potential users and mapping their interactions with the solution through a process known as "User Journeys." A User Journey serves as a design tool that illustrates the complete sequence of interactions and experiences a user undergoes when engaging with a product or

service, starting from their initial awareness and engagement, and concluding with the desired outcome or conversion. User Journeys are invaluable for gaining insight into user perspectives, pinpointing pain points and opportunities, and guiding the design and optimization of products or services [11].

In the GREEN-LOG project, this particular activity was primarily centered around 'proto personas.' Proto personas are preliminary and generalized representations of potential users, often based on assumptions or limited research. They serve as a foundation for guiding early-stage design decisions. As a result of this activity, tentative User Journeys were created. These User Journeys played a crucial role in planning upcoming user-involved co-creation activities and defining user requirements. Moreover, these provisional User Journeys also served as effective communication tools during co-creation activities. They helped solidify the local delivery solutions, paving the way for future engagements with LL stakeholders. Figure 2 shows the tentative User Journeys of Ispra LL which is focused on the development of a delivery platform that integrates a booking system with delivery robots.

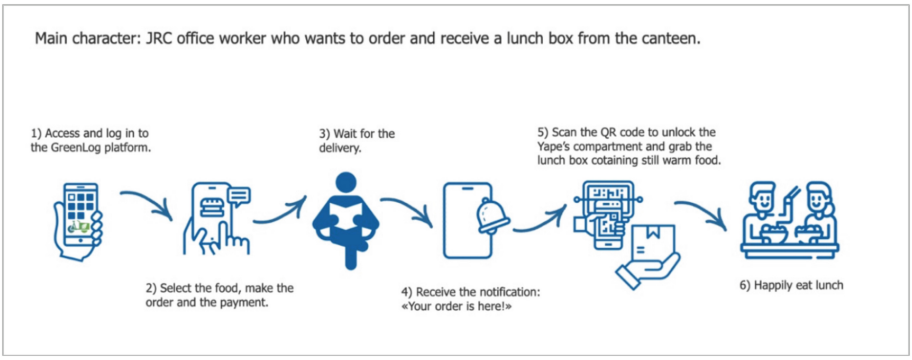


Fig. 2. LL Ispra's tentative User Journey presents how an office worker orders a lunch box from the canteen delivered by a delivery robot service.

4 Concluding Discussion

During the Scoping phase presented in this study, co-exploration was facilitated, relevant participants were identified and dialogues leading to common understandings among stakeholders and researchers were encouraged. Other key conclusions was the strong consensus on the importance of sustainable logistics solutions among stakeholders and the revealed varying perspectives and priorities of different stakeholders.

Moving forward, the next critical step is to transition the LLs into the Developing phase. In this phase, collaborative work will be undertaken with stakeholders to engage iteratively with the technological solutions, addressing various levels of abstraction. To initiate this phase, the creation of both generic and context-specific activities and frameworks, aligned with the active involvement of citizens and local stakeholders, will

be pursued. Through these measures, the aim is to encourage experimentation and co-development of their own implementation practices, fostering innovation and sustainable solutions within the GREEN-LOG project.

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Adapting MTVRPTW for Small Business: A Simplified Approach to Optimizing Food Delivery Logistics

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Abstract. This paper presents a case study of a food delivery startup, and uses Operations Research (OR) techniques to address the complex logistics challenges faced by the company. The objective is to develop an automated and optimal solution for a startup located in Montpellier, France that faces many problems with delivery operations, taking into account factors such as resource allocation and environmental impact. The study focuses on the vehicle routing problem (VRP) with Multiple Trips and Time Window (MTVRPTW), and employs a heuristic algorithm to generate a complete delivery plan based on customer orders and the company's existing infrastructure. The goal is to provide the startup with a sustainable and efficient logistics solution that can help them to reduce costs and improve their overall operations.

Keywords: food delivery startup · logistics optimization · vehicle routing problem

1 Introduction

The rise of e-commerce and on-demand delivery services has led to a significant increase in the volume of goods being transported around cities and towns [1]. This has put pressure on businesses to optimize their logistics operations in order to reduce costs and improve efficiency [2]. One key aspect of logistics management is the vehicle routing problem (VRP), which concerns the optimal selection of routes for a fleet of vehicles to service a set of customers [3]. The VRP is particularly challenging for startups, which often have limited resources and a need to quickly scale their operations in response to changing market conditions [4].

Solving the VRP requires taking into account a wide range of factors, such as the number and location of customers, the capacity and constraints of the vehicles, and the time windows for deliveries [5]. Additionally, there is the increasing concern for sustainability, to minimize the environmental impact of transportation, especially in urban areas [6]. For example, the CO2 emissions generated by delivery vehicles can contribute to air pollution and climate change [7]. As such, it is important for startups to consider

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the environmental impact of their logistics operations when developing solutions for the VRP [8].

The Multi-Trip Vehicle Routing Problem with Time Windows (MTVRPTW) is one of the variations of the classic VRPTW that arises in many real-world applications where a set of customers need to be visited by a fleet of vehicles and those vehicles can return to the depot to start a new route. In the MTVRPTW, each vehicle can make multiple trips to serve the customers within a certain time window, and the objective is to minimize the total cost while satisfying all the constraints.

Despite the challenges, the MTVRPTW has been successfully applied to various real-world applications, including waste collection, logistics, and transportation. For example, the MTVRPTW has been used to optimize the routing and scheduling of waste collection vehicles in urban areas [9], the scheduling of nurse visits to elderly patients [10], and the optimization of delivery routes for online grocery retailers [2]. In these applications, the MTVRPTW has been shown to provide significant benefits in terms of cost savings, improved efficiency, and reduced environmental impact.

2 Methodology

2.1 Problem Statement

The studied company is located in France and is specialized in delivering baskets of vegetables and fruits on a weekly basis. Deliveries are mostly made to intermediate delivery points, called “relay points”, which presents a significant logistical challenge for the startup. These locations are mostly located in city centers where congestion and emissions are already high.

Additionally, due to French rules on city congestion, there are many areas that can only be delivered by bike, as they are designated as low-emission zones (LEZ). These zones, created by the Loi d’Orientation des Mobilités (LOM) in 2019, limit or prohibit the circulation of the most polluting vehicles in order to improve air quality. This restriction to bike deliveries, which have limited capacity and require multiple roundtrips, highlights the need for a vehicle routing problem (VRP) approach that can optimize the delivery routes and resources.

2.2 Data Collection/Current Situation

The study involved mapping all company data processing procedures, starting from the moment a customer purchases a basket, including data extraction, transformation, and loading processes. In the case study, relay points were categorized into groups based on their time windows and assigned to specific work teams or shifts, each associated with a particular vehicle type, accounting for MTVRPTW constraints.

Upon comprehending the driver’s route, shift compositions, and corresponding groups of relay points, we explored commercial software to optimize delivery sequencing using the VRPTW concept. However, this software couldn’t support the complex multiple trip concept, and it’s essential to note that few user-friendly commercial solutions are available for MTVRPTW.

We utilized the predefined shifts (relay point groups with respective addresses) as inputs for the commercial software, which generated an optimal visiting sequence. To compare results, we conducted similar tests using our VRP algorithm, considering minimal distance parameters. We then compared the total distances traveled using our software's chosen route and the commercial software's recommended route. Our algorithm was evaluated under the same load and time constraints, aiming to minimize travel time across 30 previously utilized routes.

2.3 Analysis

To improve the company operations, we developed an algorithm to automate the process of gathering and organizing order data, integrating it with relay point details, including addresses. This algorithm served as a data pipeline, feeding information into our route optimization system. It takes inputs like total orders with addresses, available vehicles, and their capacities. Additionally, we utilize a file containing all deliveries for the week to create a distance matrix.

The distance matrix is a vital tool, listing distances, travel times, or costs between different locations. It plays a crucial role in logistics, helping us determine the shortest or fastest routes between various points. Leveraging the Google Distance Matrix API, we precomputed this matrix, enabling our route optimization algorithm to calculate precise road distances between all origin and destination addresses. This matrix serves as essential input for our optimizer, facilitating efficient route planning. This process was repeated for over 10 relay points, ensuring comprehensive coverage of our delivery network.

2.4 Software Optimizer and Heuristics

For our small business logistics solution, we opted for Google's route optimizer in OR-Tools, utilizing Python. This tool takes the distance matrix between all relay points, their time windows, vehicle details, and capacities, as outlined in Table 1, as its input. It efficiently computes the fastest routes between relay points, optimizing point grouping to yield the most efficient results. Table 1 shows the initial results.

Our chosen software optimizer uses our reference of time windows and score to ensure that each vehicle's route complies with the customers' time window for visits. However, when the time window is narrow, meaning that there is only a short window of time available for the vehicle to visit the customer, it becomes challenging for the algorithm to find a viable solution.

This scenario presents edge cases where the algorithm cannot balance two conflicting objectives: minimizing the total distance traveled by the vehicles and ensuring that each customer is visited within their time window. To solve this, we propose to increase the number of vehicles to find a viable solution.

The VRPTW solver in OR-Tools uses a combination of heuristics and exact algorithms to find solutions. The algorithm is based on the ideas of Clarke and Wright, and uses a combination of savings and sweep algorithms to construct initial solutions. The Sweeping Algorithm constructs initial solutions by starting at the depot and adding stops in a circular sweep around the depot. The algorithm assigns each customer to the nearest

route based on the distance from the depot. Let the set of relay points be denoted as RP, and let the coordinates of the deposit be denoted as (0,0). The Sweeping Algorithm assigns each customer to the nearest route based on the distance from the depot. This can be expressed as follows:

The algorithm starts setting the angle of the sweep be denoted as:

$$\theta = 0^{\circ} \tag{1}$$

Then it sorts the relay points by angle from the depot: RP = {rp1, rp2, …, rpn}, sorted by:

$$arctan(yi, xi) \tag{2}$$

We let the set of routes be denoted as R = {R1}, where R1 is the route containing the depot.

We add the first relay point to the route R1 = {0, rp1}.

For each remaining relay point i from 2 to n, the solver follows the steps:

a. Let Rj be the route with the closest last stop to ci
b. If adding rpi to Rj would not violate any constraints, add ci to Rj
c. Otherwise, create a new route Rk for ci: Rk = {0, ci}

Then the algorithm returns the set of routes: R = {R1, R2, ..., Rk} respecting those rules.

Finally, the distance between the depot and each customer can be calculated using the Euclidean distance formula:

$$distance = \sqrt{(x2 - x1) + (y2 - y1)^2)} \tag{3}$$

Once initial solutions are constructed, the algorithm uses a combination of local search and metaheuristics to further improve the solutions.

2.5 Scoring Algorithm

In order to create multi trips and allow the vehicle to return to the deposit respecting the time windows of the relay points and also the data of vehicles working times, a system of routes scoring is needed to be attached to the VRPTW Solver as a filter, so the complete solution can work.

The main objective of the Scoring Algorithm is to prioritize the relay points considering their time window restrictions and to divide them into the multipaths vehicles, we created a scoring system, which is the first soft restriction.

This scoring system effectively optimizes delivery routes, considering factors like vehicle capacity and time windows. In our example, with two vehicles each having a capacity of 10 baskets, we ensure that the total number of baskets doesn't exceed the combined capacity of both vehicles.

The optimizer handles relay points 1 to 4 initially, as relay 5 can't fit into the first shift due to capacity constraints. It later returns for relay 5. After supplying this relay data to the optimizer, we obtain the optimized routes and the return time to the depot for each vehicle.

3 Results

Based on the conducted experiments, the results indicated that the proposed reference model was able to achieve up to 95% improvement in terms of computational time (see Fig. 1) and 6% of average improvement in terms of the total distance traveled by the vehicles, compared to the baseline model of the commercial software.

Making a comparison of route traveled distances between the two softwares, the graph below shows the results of each software for each route. The diagonal line represents the situation in which the result of the two softwares is identical in terms of distance. Points above this line are the routes where our software has obtained a better result than the commercial software, and points below the line represent the other case. In 60% of the analyzed points, our algorithm results found better solutions for the tested routes (see Fig. 2).

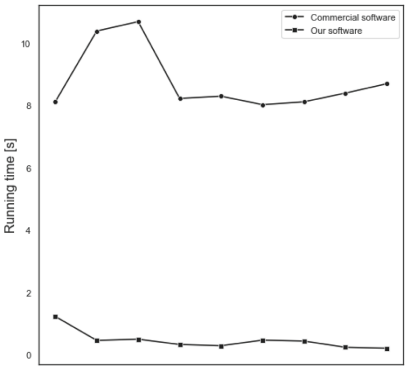


Fig. 1. Software Running Time

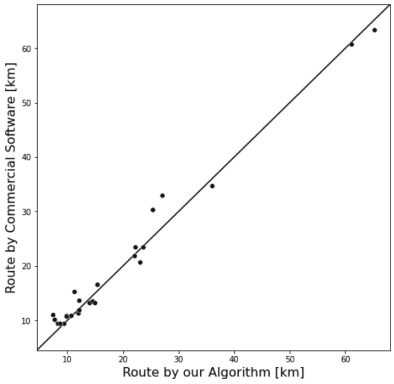


Fig. 2. Route total distance

4 Discussions and Conclusion

The study discusses the successful application of Operations Research techniques in tackling complex logistical issues faced by food delivery startups. It highlights the use of a heuristic algorithm to devise efficient delivery plans based on customer orders and the company's infrastructure, considering factors like resource allocation, environmental sustainability, and vehicle type limitations. Although the algorithm was effective, it faced limitations with existing Vehicle Routing Problem (VRP) tools, leading to the reliance on a scoring system for route sorting. Future enhancements could involve incorporating clustering algorithms and real-time data to further refine the solution.

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Data-Driven Decision-Making in Fashion Logistics: A Systemic Approach in the Greek Clothing Industry

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Abstract. In the wake of the pandemic, the fashion sector faces unparalleled challenges, marked by sustainability issues, supply chain disruptions, the diversification of customer communication channels, and an urgent demand for technological adaptation and rapid deliveries. As this landscape evolves, the essence of data-driven decision-making becomes paramount, particularly for retailers. It is an essential shift in response to evolving consumer demands and broader societal pushes for zero emissions in transportation. Central to this discussion is Logistics 4.0, which underscores the need for transitioning from conventional methods to intelligent, evidence-backed decision-making processes. Using a Greek clothing company as a case study, this paper delves into the myriad of external factors, ranging from political to environmental influences, and internal business processes that shape logistic choices. Through in-depth interviews with executives and a comprehensive survey, the research team gauged the current state of logistics management in the Greek clothing industry, with a special focus on the noticeable absence of Business Intelligence techniques in some firms. Conclusively, a novel BI Decision-Making tool will be introduced, birthed from the BI&OX project, designed to support and streamline inventory, production, and transportation planning. This tool is pivotal for decision-makers, enabling them to test various scenarios and craft strategies that cater to company-specific needs, with applications from demand forecasting to intricate supplier evaluations.

Keywords: data-driven · supply chain · fashion retail

1 Introduction

The Greek fashion sector navigates a complex web of external elements that profoundly shape its logistics and supply chain strategies. These elements cover political, legal, economic, social, technological, and environmental domains. For businesses in the Greek fashion domain, understanding these elements is crucial to maintaining competitiveness and enhancing operations. This study seeks to examine the primary external influences

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impacting logistics within this industry, utilizing a questionnaire-based survey method. The findings aim to provide valuable insights, assisting companies in enhancing their logistics and supply chain responsiveness to constantly changing external conditions. The methodology for this topic is organized as follows: It begins with an extensive literature review, highlighting the challenges faced by the Retail Fashion Sector. This is followed by a comprehensive review of insights from a study under the BI&OX project banner, emphasizing the challenges the Greek Fashion Sector faced during the pandemic. The research then delves into the external environment with the survey to identify challenges and opportunities for Greek fashion enterprises. The study concludes by emphasizing crucial aspects of the Supply Chain, highlighting the importance of flexible management techniques suitable for the dynamics of the fashion retail environment. With a thorough understanding of their external environment, Greek fashion firms can identify emerging opportunities and challenges, leading to informed decisions and effective supply chain strategies.

2 Literature Review

The fashion retail industry, in its dynamic nature, faces complex challenges that influence its supply chain and logistics. Fundamental concerns revolve around identifying trustworthy suppliers, ensuring punctual deliveries, navigating reduced lead times, and addressing broader issues such as labour disputes and subpar supplier communications (Fashinza 2023). Overlaying these are external challenges. Events like pandemics, economic shifts (McKinsey & Company 2021), climatic disruptions, and geopolitical tensions (Seara et al. 2022) compound the inherent variability and transience that define the sector (Wang et al. 2012). This fluid landscape, accentuated by the volatility stemming from fickle consumer behaviours, underscores the necessity of continuous evaluations of brand strategies and operational intricacies (Bindi et al. 2021; Newman & Foxall 2003; Ponis 2007). It's imperative to address nuances like the "Bullwhip effect", where slight demand variations amplify supply chain uncertainties (Lee et al. 1997; Christopher 2004). In response to the industry's complexities, innovative approaches have been championed, notably the adoption of technology like data analytics platforms that enhance supply chain collaboration and provide better visibility. This technological emphasis became particularly salient during the recent pandemic, which disrupted European fashion but simultaneously spotlighted the need for digital and sustainable transitions (McKinsey & Company 2022). This endeavour, aimed at heightening responsiveness to customer trends and swiftly shifting demands, seeks to boost the efficiency of the entire supply chain, from suppliers to end customers (Vona 2003). Building on this, the study evaluates the impact of these determinants on the logistics and strategies of Greek fashion companies.

3 Methodology and Key Findings

HIT/CERTH developed an in-depth methodology to assess the Greek fashion retail industry, which underwent substantial shifts from 1995 to 2022 due to both external and internal influences. As demonstrated in Fig. 1 this analytical approach involved:

1. Distilling insights from a Sectoral Study.
2. Administering a dedicated online questionnaire and workshops with business' representatives to understand real-world challenges and supply chain methodologies.
3. Employing a PEST analysis specific to the Greek Fashion Retail Sector, also using online surveys.

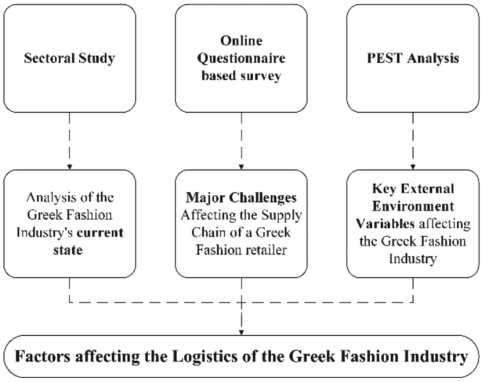


Fig. 1. Methodology

These surveys were collaboratively crafted by HIT/CERTH, Emetris S.A., and with instrumental input from SEPEE (The Association of Knitting and Ready-to-Wear Clothing Companies of Greece), grounded in an exhaustive literature exploration. They were disseminated digitally via the Google Forms platform targeting businesses within the Greek retail fashion retail landscape, operating both locally and internationally. Over a span of two months, feedback was gathered from representatives of 18 of the 25 firms identified by SEPEE as most pertinent to this investigation.

3.1 Key Sectoral Study Findings

The Association of Knitting and Ready-to-Wear Clothing Companies of Greece (SEPEE) conducted an analysis assessing the fashion retail industry's shifts in Greece over an extended period. This study revealed the industry's fluctuating state, especially during the COVID-19 pandemic. In 2020, following tourism and other sectors, the fashion-textile industry faced significant losses, including a 30% drop in turnover. Men's fashion retail suffered the most, while underwear and sports categories declined the least. Despite previous growth in exports, 2020 saw a decrease to €1.55 billion from €1.91 billion in 2019. While 83% of fashion exports targeted EU countries, the overall imports for the fashion-textile sector dropped by 19.7% in 2020. However, 2021 marked a recovery, with increased exports by 33.8% and a boost in domestic retail sales by 43.4%, signalling a rebound towards pre-pandemic levels. In the future, factors such as political support, ongoing pandemic effects, the energy crisis, and emerging industry trends like fast fashion and just-in-time inventory management will be pivotal for the Greek fashion-textile industry (SEPEE 2022).

3.2 PEST Analysis Results

The Greek fashion retail sector is shaped by political, economic, social, and technological (PEST) influences. This section presents findings from a sectoral study and survey, emphasizing external factors affecting Greek fashion retailers. The "external environment" encompasses broader forces impacting a sector, not just individual companies (Papadakis 2016). This broad analysis, called PEST Analysis, provides insight into overarching systems like political, economic, social, and technological landscapes that a business operates within but doesn't control (Economy-pedia.com 2022). After identifying the critical elements of each PEST category through literature, businesses rated their significance on a scale ranging from 'Very Unimportant' to 'Very Important'. For clarity in assessment, these ratings were converted to scores: 1 for 'Very Unimportant' up to 5 for 'Very Important'. These scores revealed the dominant factors within each PEST element. Table 1 shows the top-rated factors. Political considerations highlight government stability, taxation, and incentives. Economically, household purchasing power is paramount, with a secondary focus on energy costs and inflation. Social trends emphasize digital distribution channels influenced by social media and demographics. Technologically, e-commerce growth and IT advancements are pivotal, enabling data-driven decision-making.

Table 1. PEST Analysis highest scored factors per External Environment

PEST element	Factor	Score	%
Political External environment	Governmental Stability	4.1	82%
	Taxation	3.8	76%
	Special taxation incentives	3.4	69%
Economic External environment	Household purchasing power	4.6	91%
	Energy costs	4.3	87%
	Inflation rate/GDP	4.1	82%
Social External Environment	Shift to multiple distribution channels	3.8	77%
	Strong influence from social media Marketing (influencers' impact)	3.7	73%
	Demographics	3.5	70%
Technological External Environment	The emergence of the Internet and e-Commerce	4.1	81%
	Evolution Information Technology	3.9	78%
	Investments in infrastructure and R&D activities	3.8	76%

3.3 Major Challenges and Factors Affecting the Supply Chain

This chapter details the results of a survey of Industry experts and business representatives on challenges Greek fashion retailers face in supply chain operations, especially in inventory management and supplier relationships. Survey findings underscored the predominant challenge in inventory management: the intricate task of demand forecasting. A vast majority of businesses grapple with either an overabundance or a severe lack of inventory, both of which have profound implications. Furthermore, escalating operational costs related to storage compound these challenges, adding financial strains. While these challenges are paramount, the survey also explored the strategies that these retailers employ to navigate these issues. Most retailers rely on routine inventory checks and centralized warehouses for efficient distribution. Key data metrics like inventory turnover and item-specific costs are closely monitored. As these businesses gear up for a new season, past sales figures prominently influence their collection decisions. Interestingly, while trends are paramount for a significant proportion of businesses, other metrics like leftover inventory and production costs also weigh in. Unfulfilled orders hold considerable importance for half of the participants, with other indicators like return rates and past forecasting accuracy considered less crucial. When shifting the focus to Supply Chain Management, supplier selection emerges as a vital component for these retailers. Quality and cost of service dominate their decision-making process. Yet, it's also evident that factors like reliability and delivery speed are indispensable in this selection. While responsiveness and flexibility rank high, other aspects like the supplier's geographical location and environmental impact seem to take a backseat in priority. Overall, these findings provide an intricate understanding of the multifaceted challenges and strategies within the Greek fashion retail sector, laying the groundwork for targeted strategic interventions.

4 Conclusions

To sum up between 1995 and 2022 various internal and external factors have had an impact, on the fashion sector in Greece causing changes in its growth and operations. Despite facing challenges and undergoing adjustments this industry remains crucial to the Greek economy particularly in terms of exports. It also continues to embrace advancements. The future success of this sector relies on adopting technology implementing practices focusing on exports and effectively managing resources. Within this context the BI&OX Project by HIT/CERTH provides a decision support tool for professionals in the industry. It incorporates findings from this study to facilitate data driven decision making. The services offered by this project along, with their high-level architecture are depicted in Fig. 2.

The tool includes four main functions/services that each one can give input to the next one but can also operate independently. Each step takes into consideration the challenges the Greek Fashion Retailers face to give the optimal result. Finally, it assists the retailers with providing visibility in regard to the cost of their optimal order, based on the demand forecasting results, the optimal inventory results, how these are translated to textile needs and the supplier rankings.

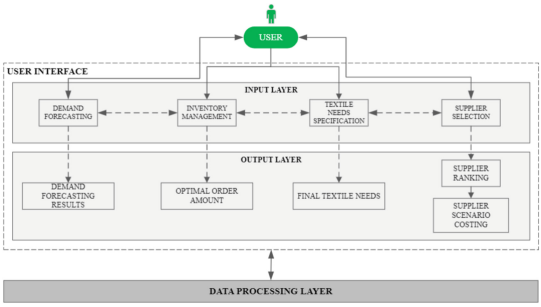


Fig. 2. Data-driven decision-making tool functions

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Decarbonising Last Mile Logistics

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Abstract. Logistics is at the core of modern society and essential to transport food and goods in the heart of cities, where most Europeans live. However, recent statistics show that only half of truckloads moved at maximised capacity in 2021 [1], and the rapid increase in the last mile deliveries - 78% by 2030 [2] - affects the economics of logistics and its externalities on the urban tissue, including high traffic, noise and air pollution. It is worth noting that last mile logistics represent 30% of the total CO2 emissions of logistics transportation. Amongst the EU Green Deal objectives, several aim to tackle this: 55% reduction of emissions from cars and 50% from vans by 2030 [3]. On a local level, there is also an increasing push for zero-emission zones in inner cities, as 26 of the world's largest cities signed up to the Green and Healthy streets pledge [4]. To foster and accelerate this transition towards economically, environmentally, and socially sustainable city logistics, systemic changes in last mile delivery ecosystems are needed. The analysis of previous collaborative urban logistics experiences shows that future urban logistics consolidation frameworks must be built on six fundamental pillars to guarantee the success and sustainability of their generalisation: collaboration, sustainable business models and added-value services, urban integration and space management optimisation, regulation, digital infrastructure, and innovation transferability enablers.

Keywords: Last-mile logistics · decarbonisation · collaboration · digitalisation · intelligent transport systems · Physical Internet · Logistics-as-a-Service · Digital Twins · Blockchain · Micro-consolidation

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1 Introduction

The rapid growth of e-commerce poses sustainability challenges, with a 25 million-tonne CO2 increase and 21% rise in traffic congestion in the last mile. This contradicts European Green Deal, Paris Agreement, and Green City Accord goals for zero-emission urban logistics by 2030. Urban logistics faces challenges like a lack of focus, coordination, and data. European Union (EU)-funded projects aim to address these by testing solutions, emphasizing the need for strategic urban logistics focus, better coordination among stakeholders, and improved data and information for operational efficiency and long-term planning, aligning with overarching sustainability objectives.

2 State of Play- Key Areas

2.1 Collaboration

The existing literature reviews highlight various forms of collaboration, each presenting distinct potentials and barriers. Vertical collaboration involves coordination across modes and service operators throughout the value chain, while horizontal collaboration focuses on multiple providers working within the same transport chain section, sharing orders and infrastructure [5]. The motivation behind such collaborations includes demonstrated effectiveness in reducing last-mile logistics costs and environmental impact, and improvements in service quality by minimizing lead times [6]. Despite these benefits, financial sustainability remains uncertain, contingent on the type of goods being delivered. Trust issues, along with competitive dynamics in the logistics sector, pose challenges, particularly in terms of data sharing. Access to data is vital to enhance knowledge, develop digital tools, and tailor hypotheses and optimization scenarios to showcase the economic advantages of collaboration. Public authorities play a crucial role in fostering a conducive environment for collaboration and solution implementation, with powerful legal frameworks to promote sustainable practices and innovative models within their local strategies. This synergy ensures a transformative ecosystem, making projects like those discussed in this paper highly promising.

2.2 Sustainable Business Models and Added-Value Services

Regarding collaboration and asset sharing, the evolving challenges in city logistics also demand innovative business models. Overcoming traditional asset management boundaries, these models create added value services. A notable example is the joint establishment and management of Urban Consolidation Centers (UCCs), where logistics players (potential competitors) implement horizontal collaboration to enhance performance and resource utilization. Recognizing each entity's contribution and role within the urban freight ecosystem and assessing each entity's contribution to value creation, paralleled by an estimation of the distribution of related benefits and costs is of utmost importance. Exploring sharing, specialization, and allocation strategies can lead to sustainable Collaborative Business Models (CBMs) in city logistics, fostering economic viability and cooperation among providers. Integrating value-added delivery models (such as urban

logistics hubs, micro-consolidation centers, etc.), together with autonomous vehicles, innovative cargo-bikes, and zero-emission transport modes optimizes urban logistics for sustainability and efficient resource allocation.

2.3 Regulation

On another note, the acceptability of low emissions zones (LEZs) may face economic and social challenges, but their demonstrated positive environmental impact, including a notable reduction in NO2 concentrations [7], provides a compelling rationale. LEZs can serve as an incentive for carriers to invest in sustainable vehicles, such as cargo bikes, prompting a fleet upgrade to continue operations in restricted-access areas [8]. Concurrently, restricting conventional delivery trucks through policies like time limits, congestion charges, noise pollution restrictions, and pedestrian zones can bolster support for alternative transport modes like cargo bikes. In addition to adapting local regulations, endorsing cycle logistics as a viable and competitive alternative in last-mile transport is crucial. Complementary support from public frameworks includes strategies such as facilitating real estate access in dense areas, incorporating urban logistics into broader planning schemes, utilizing cycle logistics in public procurement, offering financial incentives, and creating platforms for knowledge exchange among cycle logistics stakeholders. Numerous ongoing projects exemplify best practices and success factors in regulations and public policy frameworks, aiming to provide accessible, replicable, and operational guidelines for a sustainable transition across economic, environmental, and social dimensions.

2.4 Urban Integration and Space Management Optimization

Modular approaches in urban logistics involve dissecting the intricate logistics ecosystem into smaller, interoperable modules adaptable to urban needs. These modules, including electric vehicles, micro-containers, micro-fulfilment centers, and smart traffic management systems, offer flexibility for customized integration in city planning. The three primary solution categories are 1) delivery fleet modal shifts, 2) consolidation and emerging urban storage infrastructure, and 3) innovative delivery frameworks, encompassing the entire last-mile process. European Union-funded projects like URBANE (39 partners with 12 Living Labs and 6 pilots - 6 feasibility studies), DECARBOMILE (31 partners, with 4 Living Labs and 4 Satellite Cities, implementing 11 use cases), and GREEN-LOG (30 partners with 5 LLs, 10 cities implementing various use cases - at least one per city) bring together diverse partners to tackle urban logistics challenges. Through living labs and pilot studies, these initiatives aim to address congestion, emissions, and delivery costs in real-life scenarios, contributing to the evolution of sustainable urban logistics (Table 1).

2.5 Digital Infrastructure

Digital transformation has revolutionized logistics and last-mile delivery, playing a pivotal role in the transition path towards safe, efficient, and sustainable last mile transport. In

Table 1. Intervention mapping (At the time the paper is written, these are the planned interventions. As we are in preparation phase of the pilots, changes may occur.)

INTERVENTIONS	URBANE	DECABOMILE	GREEN-LOG
Alternative delivery fleet mode			
Electric Delivery Vehicles	Valladolid, Helsinki, Bologna, Karlruhe	Hamburg, Istanbul, Logrono, Nantes	Athens, Gent, Leuven, Mechelen, Oxfordshire
Drones, droids			Ispra
Autonomous vehicles, connected Autonomous vehicles, cargo-bikes and robots	Helsinki, Karlsruhe	Sarajevo	Ispra, Athens, Gent, Leuven, Mechelen, Oxfordshire
Public Transport modes for delivery fleet re-balancing (e.g. trams, trains)	Karlsruhe		Barcelona
Consolidation & emerging urban storage infrastructure			
Innovative standard micro-container for aggregation and multimodal use		Nantes, Logrono, Hamburg	
Urban consolidation centers (UCC), micro consolidation centers, mobile depot, micro logistics hub	Helsinki, Bologna, Thessaloniki, Barcelona	Nantes, Hamburg, Logrono, Istanbul, Getafe, Ghent, Tallinn	Athens, Barcelona, Oxfordshire
Connected parcel lockers for both pickup and delivery	Helsinki, Bologna, Thessaloniki	Hamburg, Logrono, Istanbul, Nantes, Getafe	Athens, Barcelona
Innovative Delivery Framework			
Delivery parking zones	Valladolid	Nantes	Athens, Barcelona, Oxfordshire
Real time assets monitoring and tracking		Istanbul, Logrono, Hamburg, Nantes	Ispra, Barcelona
Vehicle routing and crowd shipping deliveries	Bologna, Thessaloniki, Helsinki	Istanbul, Logrono, Hamburg	Oxfordshire, Ispra

(*continued*)

Table 1. (*continued*)

Innovative Delivery Framework			
New urban access regulation to LEZ & respecting loading/ unloading zones	Valladolid	Tallinn, Sarajevo	
Dynamic re-routing	Bologna, Valladolid	Hamburg, Logrono, Istanbul	Oxfordshire, Ispra
Fleet and route optimisation	Valladolid, Karlsruhe, Thessaloniki, Barcelona	Logrono Nantes, Istanbul	Oxfordshire, Ispra

this crucial phase of the supply chain, digital tools, technologies, and concepts that realize Physical Internet vision [9] through interconnected dataspaces, optimization tools, Logistics-as-a-Service (LaaS) platforms [10], the inclusion of green autonomous vehicles, Digital Twins (DT) and blockchain are the key elements to reduce traffic congestion, emissions, and energy consumption achieving efficiency and sustainability. Indicative tools for optimizing logistics include: i) LaaS marketplaces with dynamic pricing for flexible logistics services; ii) Artificial Intelligence-enabled augmented intelligence platforms for demand modeling and location planning; iii) Dynamic routing with real-time tracking and monitoring, supported by machine learning and demand prediction, to optimize deliveries and reduce congestion; iv) DT leveraging real-time data through interactive user interfaces, incorporating modern digital mapping and geographic information systems. These tools collectively enhance efficiency, reduce empty loads, and address congestion challenges in the logistics ecosystem. All these digital tools accompanied by their underlying supporting technologies and scientific knowledge can augment the planning of modern supply chains at all levels: strategic, tactical, and operational levels.

3 Innovation Transferability Enablers

EU Member States (MS) are actively working towards promoting the seamless adoption of innovative last-mile solutions across multiple European cities through the use of "Innovation Transferability Enablers" (ITE). These tools aim to facilitate the implementation of successful interventions in optimizing last-mile networks. The previous sections outlined a diverse range of interventions, spanning both physical and digital infrastructure, regulatory measures, and policy implementations. These interventions span a broad spectrum, ranging from the application of crowd shipping services [11] to fleet smart management systems [12], as well as other types of Intelligent Transport Systems enabled by enhanced connectivity [3]. Even scientific tools like mathematical programming scheduling models [13] for optimal transshipment or unloading of vessels [14] and trucks [15] constitute interventions that can offer decision support towards effective transportation and logistics networks planning. The key emphasis is on ensuring that these interventions go beyond ad-hoc solutions, requiring creators to prioritize scalability, adaptability, and robustness to meet the varied requirements of EU cities

and MS. Open-access digital platforms, known as transferability enablers, allow for the exploitation and replication of successful last-mile logistics innovations in European cities. These platforms support upscaling, re-deployment, and the identification of sustainable solutions, allowing follower cities to implement cost-effective, green logistics networks with defined Key Performance Indicators (KPIs) and efficient sustainable solutions.

4 Conclusions

Digital tools are crucial for enhancing collaboration between Public and Private sectors in European last-mile logistics. The ITEs support stakeholders, local authorities, and logistics providers in exploring collaborative schemes to benefit the city and boost private sector competitiveness. Public authorities can encourage collaboration, promote shared logistics infrastructure, and impose legislative frameworks or KPIs for improved urban community outcomes. Thus, the integration of digital tools is crucial for realizing emission-free innovative and collaborative logistics initiatives.

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Integrating Parcel Delivery Services into Public Transport Operations Through a Common ICT Platform

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Abstract. Transport organizations and local authorities are facing growing challenges due to increasing traffic within city centers caused by delivery traffic. New sustainable mobility concepts for urban logistics are therefore needed that are able to make use of the existing infrastructure in a more efficient way by decreasing the overall traffic volume. The project logIKTram focuses on shifting delivery traffic from road to rail on medium and short distances by integrating cargo tram operations into a common ICT platform, specifically on extending the public transport planning and control systems (ITCS) and the design of interfaces between public transport and logistics systems. The ICT platform follows a data broker architecture (MQTT) enabling data provision to all relevant systems including the logistics, the public transport and the tracking as well as the booking system. Existing systems in place, such as the on-board computer (OBU) of the tram, the ITCS of the public transport operator, the load carrier system of the logistics provider, as well as the booking and tracking system of the freight operator will be modified and connected via interfaces with the ICT platform allowing seamless integration of all systems.

Keywords: cargo tram · urban logistics · public transport · ICT platform

1 Introduction

Cities are facing growing challenges due to the increase in traffic within city centers. A major contributor is the growing high volume of delivery traffic in inner cities that has led to congestion and parking issues, increased emissions, notably CO2, NOx and fine particular matter, as well as noise pollution and safety issues [1]. This increase in delivery traffic in cities reflects a large increase in online shopping behavior and was recently amplified during the COVID-19 pandemic, exposing weaknesses of a transport system running at maximum capacity and lacking political regulations and guidelines [2]. As of today, many current solutions that aim at switching to electric drives within the same modal split only help reducing local emissions. However, they do not improve the overall traffic load on the road nor parking issues [3].

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Therefore, there is a need for new sustainable mobility concepts for urban logistics that make more efficient use of existing infrastructure by decreasing the overall traffic volume. Furthermore, new cross-company cooperative bundling concepts and intermodal solutions, based on existing transport corridors and infrastructure for freight transport, which defuse land conflict and, through selective additions, create a new sustainable transport system for a urban and regional selection of companies and households.

The research project logIKTram [4] focuses on shifting delivery traffic from road to rail on medium and short distances by connecting distribution centers in the urban hinterland with logistic hubs in the inner city. The cargo tram concept in this research uses the existing two-system tram and rail infrastructure of Karlsruhe, Germany, to provide electro mobility solutions for commercial inner city logistics. The cargo tram concept developed in this research thereby represents a novel vehicle concept that was not previously adapted in other applications. While freight trams have been successfully applied before, such as the cargo tram in Dresden that was exclusively used for factory logistics and the cargo tram in Zurich used for bulky waste logistics, they were operated on separate dedicated vehicles [5]. The cargo tram concept in the logIKTram project, on the other hand, is intended for combined transport of both passengers and goods in an urban and regional context, across the B2B and B2C sectors. The consolidation of goods in cross-docking (goods handling) have so far only taken road transport into account, characterized by different shipment sizes and vehicle containers. This requires a combination of an ICT-supported consolidation platform that encompasses transport planning, automatic transport handling and an integration into the public transport operations system for offering economic viable services.

The focus of this article lies on the required technical infrastructure and on the conceptualization of an integrated information and communications technology (ICT) platform for the combined transportation of goods and passengers.

2 Cargo Trams and regioKArgo

2.1 A Brief History of Cargo Trams

The concept of cargo trams is an old concept that dates back until the 1860s. One of the earliest application of cargo trams could be found in Arad, Romania where operations where based on horse carriages [6]. Following this example, cargo trams in the early years were widely used for postal, delivery, and heavy-duty construction operations, with prominent examples found for example in Frankfurt, Germany (postal tram) or in Vienna, Austria (heavy duty transport). With the introduction of individual motorized transport, cargo trams operations declined rapidly. However, some operations existed well into the 90s, such as in Timișoara, Romania (until 1993) or in Gotha, Germany (until 1988). In the early 2000s, cargo trams saw a revival in Dresden, Germany, where a dedicated cargo tram was used for industrial supply of goods to the Volkswagen car manufacture plant in the city, or in Zurich, Switzerland, where a cargo tram has been used for waste disposal since 2003 [7]. More recent projects can be found in Saint-Étienne, France, Frankfurt, Germany and Berlin, Germany where cargo trams are used as a testbed for delivery services in the frame of research projects. However, most of

these applications focus on inner city logistics and do not take the urban hinterland into account.

2.2 The regioKArgo Concept

The regioKArgo [8] concept aims at providing a holistic approach towards sustainable delivery services, by making use of the existing regional tram-train network in the Karlsruhe, Germany region. A special case of tram-train service in Karlsruhe is the "Karlsruher Model" [9], a tram-train concept making it possible for seamlessly operating a tram on the city tram and on the heavy rail network in the region combining 750V DC and 15kV AC operation into one dual mode vehicle. Due to these combined operations, the tram-train network of Karlsruhe is one of the largest tram-train networks consisting of over 500 km total track length. This makes it possible to connect the urban hinterland directly with the city center and making it favorable for cargo tram operations, as major delivery centers are generally located outside of the city. Figure 1 displays the concept behind regioKArgo and the research project logIKTram, where the tram-train will be used to connect large delivery centers located at the outskirt of the city with local distribution hubs in the city center, running the delivery service on both the heavy rail network and the tram network. Once the goods reach the delivery hubs in the citer centers, last-mile sustainable solutions such as cargo bikes will be used for final distribution to the customers.

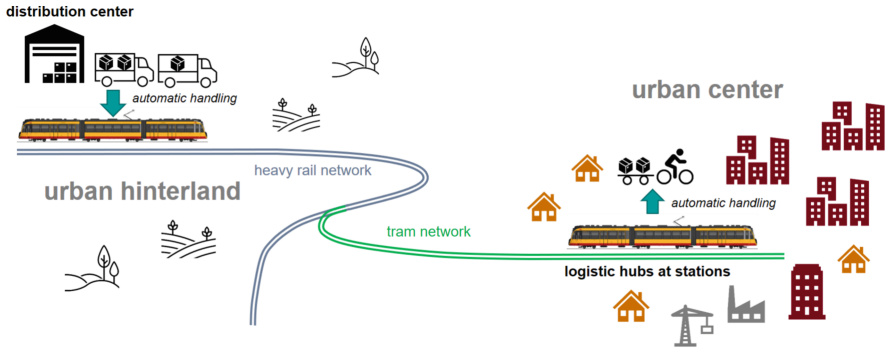


Fig. 1. The regioKArgo and logIKTram concept for integrating parcel deliveries into tram-train operations connecting delivery centers with local city hubs in the inner city

3 Development of an Integrated ICT Platform

One of the main objectives of logIKTram is the development of an integrated ICT platform combining systems from logistics and public transport. This common ICT platform will also be able to interact with the cargo tram by direct communication with relevant tram systems, such as the onboard computer (OBU), the braking assistant (relevant for precise loading and unloading) as well as with the handling carriage for

tracking the delivery services. Figure 2 depicts the scope of the ICT platform and its interaction with the physical cargo tram concept. The platform covers the whole process of the cargo tram-based transportation services, including the booking and transport planning, the handling and journey planning, the monitoring of the operations (public transport and delivery service), as well as the accounting and eco-balancing of the service. The interaction of the ICT-platform with the cargo tram systems includes the bundling process, the loading and coupling process, the operation of the tram and finally the uncoupling and unloading process.

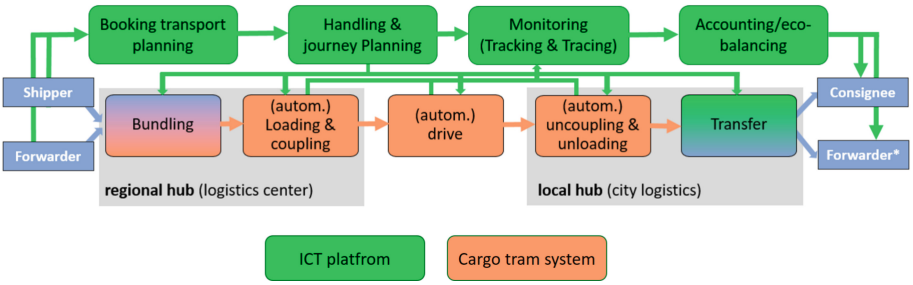


Fig. 2. Components of the integrated ICT-platform interacting with the cargo tram system.

In order to facilitate the integration of a widespread range of systems, one of the main objectives is the use of existing standards whenever possible. At the core of the ICT-platform stands a Message Queue Telemetry Transport (MQTT) broker, which functions as a central data exchange component. All components of the platform can publish data on the broker and – at the same time – subscribe to data via defined topics. VerneMQ [10], which is distributed as open source software (Apache 2.0 license), is used as MQTT broker in logIKTram, hence, it supports the ICT-platforms whole lifecycle from research to commercial service. The broker structure enables all actors to access data by using standard exchange formats:

- Communication standards defined by VDV (Association of German Transport Companies) and the General Transit Feed Specification (GTFS) on the public transport side
- Electronic Data Interchange for Administration, Commerce and Transport (EDIFACT), Global Standards (GS1) to connect logistics systems with the public transport systems.

The logistics requirements, which require planning security of 24–48 h, were implemented with the help of schedule data in the VDV and GTFS standards. This enables planning security of several days as well as short-term and current changes to upcoming planning measures that may require re-planning of the logistics service. Additionally, they integrate delays as well as GPS data in the logistics process in order to provide real time information for freight forwarders, public transport as well as last mile operators. The integrated ICT-platform includes elements from logistics (logistics back- and frontend), public transport operations (ITCS, onboard components, planning), tracking (back- and frontend, apps), simulation, and the cargo tram system (see Fig. 3).

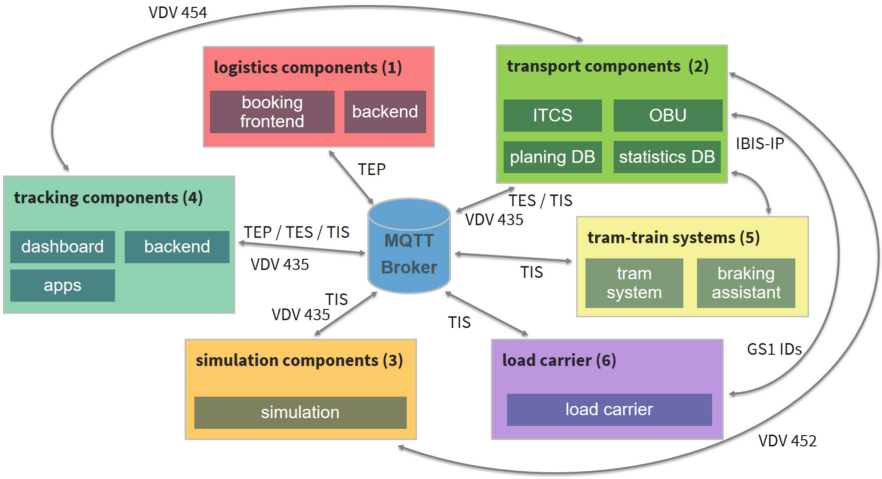


Fig. 3. The ICT platform architecture of the logIKTram cargo tram

The logistics components (1) consist of a booking frontend and backend, which allow the forwarder to access the logistic planning system and to process transport requests, while also allowing the cargo tram to access the transport offer. Alternatively, the forwarder is able to book delivery slots through the use of a frontend interface. The public transport components (2) consists of the intermodal transport control system (ITCS), the panning and statistics databases of the public transport operator, and the OBU system in the cargo tram. The public transport components provide public transport planning, dispatching and scheduling as well as real-time positioning and status updates to all components of the ITC-platform. Data provisioning is handled via the MQTT broker, with the exception of the planning data and the real-time status updates, which are directly transferred via APIs in the VDV and GTFS formats. Information from the logistics components about the deliveries and routing (Transport Execution Status (TES) and Transport Information Status (TIS)) is consumed by the public transport components via the MQTT broker. The Simulation components (3) act as a digital twin as well as an agent-based scenario simulation, allowing for running scenarios and simulating the cargo tram, together with the whole logIKTram ICT-platform system. The tracking components (4) consisting of front- and backend, are processing the Transport Execution Plan (TEP) form the logistics component as well as the real-time data from the public transport and the simulation components. The data is exchanged via the MQTT broker and via standardized VDV APIs for real-time status updates of the cargo tram. Besides the position of the tram, information about delays, vehicle, and scheduling is provided and distilled in a graphical user interface (GUI) for the customer to track the status and expected arrival time of the delivery. The interaction with the physical systems, including the tram systems (5) and the load carrier (6), is managed via the public transport components (OBU) using IBIS-IP protocols. The information exchanged include details about the stopping position, loading and unloading station, as well as

shipping information that is transmitted from the logistics components via the MQTT broker and OBU of the cargo tram.

4 Conclusion and Discussion

Enabling delivery services into combined passenger and goods tram-train operations is a challenging task from both an operational and an information technology perspective. The work presented here focuses on the integration of multiple systems from multiple domains that are required to offer a holistic ICT platform for cargo tram operations. A major challenge next to the lack of standards between the different systems is the fundamental difference in planning and operation of logistic and public transport services. Information on the capacity and status of the cargo tram running on scheduled series is needed to serve the highly dynamic nature of delivery services. The broker architecture provided sufficient scalability and adaptability in order to interface the different components. After the successful testing of the ICT-platform in a virtual environment through by means of simulation (digital twin), a real world demonstration is planned in the frame of the regioKArargo initiative.

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Customer and Retailer Expectations from City Logistics: Comparative Analysis of the Market in Thessaloniki, GR

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Abstract. City logistics operations are significantly affected by the rapid expansion of electronic commerce (e-commerce). The pressure of the demand is being transferred to the last-mile distribution, disproportionately increasing the workload of service providers, while affecting the overall cost and fulfillment times for the entire supply chain. In this study, the expectations and demands of consumers and online retailers concerning city logistics provision are captured. A questionnaire survey carried out, addressing independently the two target groups focusing on the market routines in Thessaloniki, Greece. The purpose is to record and analyze the market needs to identify niche areas that are under-served, and their service will maximize sustainability and the overall benefit for the local users and the society. In general, it was recorded that delivery speed, reliability and flexibility are essential for both user categories. Service providers should focus on under-served market segments to gain competitive advantages and benefit the overall city logistics system. Specific suggestions for researchers and practitioners are also provided.

Keywords: City logistics · e-commerce · customers

1 Introduction

City logistics operations are significantly affected by the rapid expansion of electronic commerce (e-commerce), which has experienced unprecedented growth in recent years. Online sales in 2019 reached levels that were, approximately, 3 times higher than the corresponding of 2014 [1]. Due to the COVID-19 pandemic, the percentage of online sales to the total sales increased even more between 2020–2022. Customer demand and the promise of operational cost reductions prompted retailers to increasingly use online channels for their sales; a strategic move that could grant them significant competitive advantages and contribute to their expansion [2]. Predictions for last-mile delivery in the forthcoming years surpass the figures of the pandemic, with a forecasted annual growth rate of 9.29% in USD billion projected until 2027 [3].

The pressure of the unforeseen growth, however, is being transferred to the last-mile distribution, disproportionately increasing the workload of service providers, while

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affecting the overall cost and fulfillment times for the entire supply chain [4]. This negatively impacts the overall shopping experience of the consumers and damages the credibility of retailers to execute their orders on time.

This study analyses the dynamics of the online retail market at the city of Thessaloniki, Greece, aiming to comprehend the expectations and demands of consumers and retailers concerning city logistic services. It comparatively analyzes user expectations and requirements to propose measures that maximize the overall system sustainability. A questionnaire survey is carried out addressing independently the two target groups. The two questionnaires were developed based on extant city logistics typologies, covering parameters like storage, transport, delivery, product and time. Results analysis identified points of conflict and areas of convergence between the two user types. As a general conclusion, it was recorded that delivery speed, reliability and flexibility are essential for both categories of users of a city logistics network.

In Sect. 2 city logistics characteristics are defined, in Sect. 3 the study methodology is presented, in Sect. 4 the city logistics and e-commerce landscape in Greece. Section 5 analyzes the survey results and Sect. 6 summarizes the main outcomes, proposing insights for practitioners and researchers.

2 Theoretical Background

City logistics consists of functions necessary to serve the demand for the distribution of goods in urban environments; starting from the moment an order enters the last mile until reaching the customer [5], crucially influencing the daily life of cities and citizens [6]. It entails activities spanning from order delivery to store replenishment, construction, and the reverse chain (waste, recycling, returns). These activities aim to serve specific market segments (e.g., prepared food, groceries, clothing, pharmaceuticals, homewares, pet supplies, electronics, books, office supplies) that require different transport types (e.g., courier, general cargo, temperature-controlled, waste).

Given the growing urban population, expected to reach 68% of the total world population by 2050, from 55% currently [7], cities will face serious consequences from logistics operations soon. City logistics contribute to greenhouse gas (GHG) emissions with 23% of the total transport and logistics GHG [8]. Due to its composition of various components (e.g., equipment, products, infrastructure, stakeholders, etc.), the business model used to transport goods within urban areas is shaping the quality of city logistics services. Establishing and maintaining effective city logistics operations is a formidable challenge, with the swift growth of e-commerce further amplifying it.

A city logistics system is described based on [5]: (1) the type of storage (e.g., urban distribution center, micro-consolidation), (2) the means of transport (e.g., bicycles, trucks, drones, etc.), and (3) the type of delivery (e.g., home delivery, self-service with or without supervision). [9] present 11 models that are classified according to: (1) type of goods (e.g., refrigerated, postal, waste), (2) type of change (i.e., means and supply chain configurations), and (3) means of transport (e.g., trucks, bicycles, buses, boats, trams). [10] recognizes three types of end-user service: (1) pickup from distribution point or store, (2) grouping for collection from designated point (e.g., post office, etc.) and (3) house delivery. [1] suggest that cargo size and delivery urgency dictate the utilized transport methods. Combining the above categorizations, last mile systems could

differentiate according to the following properties: (1) *type of city logistics activity*; (2) *type of storage* (3) *means of transport*; (4) *type of delivery*; (5) *delivery time*; (6) *type of products*; (7) *package size*.

3 Methodology

A questionnaire survey has been employed for data collection addressing two types of city logistics services users: the end consumers and the online retailers. Questionnaire research is often used in research that studies business and operational functions, especially when the focus is the analysis of habits [11]. In conjunction with the questionnaire survey, an analysis of existing literature and good practices was carried out. This helped understanding the research context (i.e., the Greek market) and shape the structural framework of the questions. The questionnaires employed structured closed and open questions to include motionless answers as well as flexibility and richness [12]. The questionnaires aimed to (1) record what city logistics characteristics are considered important, (2) record the intentions of users. The study was carried out between 01.06.2022–31.07.2022 in the city of Thessaloniki, Greece, using Google Forms to develop and distribute the questionnaires. The Consumer Questionnaire collected 110 responses (50.9% male, 46.4% female, 86.4% of them in the 18–44 age group). The Business Questionnaire preceded a market analysis identifying 300 online retailers, mostly related to food services and thus excluded. The survey was sent to 100 companies (response rate 35%), predominantly small (77%) with physical/online presence (94%), mainly active in clothing (34.29%), household (20%), and office supplies (20%).

4 City Logistics and E-Commerce: The Situation in Greece

The total e-commerce value in Greece for 2021 was estimated at €14b (2019 and 2020, €9b and €11.5b, respectively) [13]. A consistent upward trajectory is evident, bolstered notably by the COVID-19 pandemic. The trend shows stabilization tendencies, with e-commerce purchases accounting for over 10% of the overall expenditure. The pandemic's lasting effect is clear in e-commerce growth, even after the "reopening" of the economy. Since 2020, Greek consumers turned to e-commerce increasing the sector's turnover by 77% (base 2019) and overall purchases to 59% (51% in 2019) [14]. The pattern persisted in 2021, with 95% of major Greek urban centers residents making at least one online purchase per year [15]. 52% of the total annual transactions refer to food, clothing, pharmacy or electronics, with electronics and food having the highest penetration. During 2021, all product categories recorded a 6–12% sales increase [17].

Amidst the swift e-commerce expansion in Greece, the courier industry found itself compelled to adjust and cater to the evolving demand. The pandemic exposed the sector's pain-points, which proved unprepared. Due to insufficient resources, low service levels were the main challenge, leading to extreme delivery times (from 3–5 days before to almost a month). This gave rise to customer discontent and placed considerable stress on retailers. City logistics providers operated amidst intense competition, rapidly evolving technology, intricate operations, and an urgent necessity for greater sustainability. The Greek e-commerce and last-mile delivery landscape poses a formidable challenge to the

involved actors. Hence, persistent efforts are required to enhance efficiency, focusing on aspects like shorter times and ecological impact, increased reliability, flexibility, tracking, and resource utilization. 95% of consumers surveyed state that transport costs and delivery times are factors that hinder their purchases [17].

5 Analysis and Discussion

Key to the study was to understand the online purchasing routines of the consumers and retailers in the city. Purchasing frequency and product type are indicators of the demand for city logistics services (deliveries) that could dictate the requirements for an efficient city logistics system. Most consumers (58.2%) order online at least once per week or every two weeks, with the rest ordering a few times or once per year. 74.5% of them usually buy clothing, while 60.9% appliances and 30% pharmaceuticals or books. Significantly, the highest share (82.7%) refers to purchases of prepared food, however, this type of product is not in scope in this study. To fulfill their orders, 9/10 consumers choose to have them delivered to a place of their choice (e.g., home or work, etc.); the rest pick up the products from designated points. The consumer preference distribution reveals significant opportunities in under-served market segments that lack specialized express delivery services (e.g., apparel, pharmaceuticals, pet supplies, books, etc.).

Corresponding to the analysis of consumer expectations, the relative importance of delivery factors that influence overall shopping experience was analyzed. Results analysis show that consumers expect accurate (66.4%), flexible (64.5%) and speedy (57.3%) deliveries. Accuracy refers to both deliver-to-promise, as well as the reduction of failed delivery attempts; flexibility reflects the choice of pick-u/drop-off points at the chosen place and timeframe; and shipping speed is the required time from order placement to drop-off (with 75.3% preferring same day shipping). Return policy scored lower (40%), while on-demand options and the overall delivery cost are not considered as important. The cost of transportation is another important aspect, as it could determine the city logistics provider choice. When asked what influences most their overall purchasing experience delivery-wise, the consumers responded to the delivery costs and timeframe. As mentioned earlier, most companies that participated in the survey facilitate both physical and online sales; most of them (88%) sell exclusively one product type (e.g., clothing). On average, companies ship 4–10 orders daily; single-order deliveries (40%) or combined up to three (28.6%) and more than three (14%). 74% of them deliver at least 25% of the total online sales ‘to the door’ of customers, while 31.4% deliver at least half. The rest of the orders are usually picked up at a local pick-up point. The orders are primarily shipped directly from the store (69%) (distribution center 3%, local warehouse 17%, supplier’s warehouse 11%).

As stated by the retailers, the shipping timeframe that they offer to their customers varies between same day delivery (31%), 1–2 (31%), and 3–5 days (26%). Delivery in one day is an important milestone, as the options for delivery in a time greater than or less than one day gather percentages of 49% and 51%, respectively. However, this is a finding that is not supported by the consumer side. The study identified that 1 in 2 consumers state that they usually receive their products within 3–5 days and 86.7% need at least 2 days to receive them. Only 5.5% receive within 24 h, 1.8% on the same day and

6.4% within 2 h. Consumers' demand for speed is not met by the existing options in the market, as only 8.2% state that they usually receive within the day at the latest. Therefore, the delivery timeframe can be identified as an element with potential to become a strong differentiator among city logistics providers and their competition.

6 Conclusions

In this study, the expectations and demands of consumers and online retailers concerning city logistics provision were captured. A questionnaire survey was carried out, addressing independently the two target groups focusing on the market routines in Thessaloniki, Greece. The purpose was to record and analyze the market needs to identify niche areas that are under-served, and their service will maximize sustainability and the overall benefit for the local users and the society.

The comparative examination of the findings revealed areas of disagreement as well as points of agreement between the user categories. It was recorded that delivery speed, reliability and flexibility are essential for both categories. Domestic competition is a particularly important decision criterion and competition differentiator, able to determine the services that are provided in a market (e.g., under-served segments like pharmaceuticals, delivery less than same day). For each aspect, the following are suggested to city logistics practitioners and researchers: Speed (1) Delivery within day or even hours; (2) Integration to business ERPs for real-time inventory management; (3) Cargo bundling and delivery routing using technology (AI/ML). Reliability (1) Real-time tracking to eliminate unsuccessful deliveries; (2) Constant customer communication (e.g., messages, calls); (3) Electronic proof of receipt/delivery/payment. Flexibility (1) Delivery timeframe selected by end users; (2) Drop-off point selected by end users using geofences; (3) Bundle shipments from various sources (consumers, inventory replenishment, etc.); (4) Fully functional reverse supply chain to cover returns.

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A New Concept for Resilient and Green Freight Transport and Logistics Networks Against Disruptive Events

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Abstract. In 2021, economic losses due to supply chain disruptions in the Eurozone amounted to €112.7 billion Euro: Natural catastrophes (e.g., hurricanes, earthquakes, floods, and wildfires) multiply in the wake of climate change. The risks of pandemics, trade restrictions, cyber-attacks, and geopolitical conflicts are omnipresent. Hence, the threat of disruptive events to the European transport network grows ever greater. Additionally, GHG emissions can drastically increase by up to 50% if disruptions are not treated efficiently. Here, the project "Resilient multimodal freight transport network" (ReMuNet) comes into play: ReMuNet will enable the multimodal freight network to react and respond 20% more quickly to disruptive events and help to reduce European inland transport emissions on the main run by over 50% by 2026.

As a trailblazer for the Physical Internet, the project pursues the vision to enable and incentivize synchro-modal relay-transport on European rail, road, and inland waterways to increase holistic network resilience. ReMuNet can identify and signal disruptive events and assess their impact on multimodal transport corridors. It reacts quickly to disruptive events in real time. It supports TMS providers to improve route planning resilience by communicating alternative, pre-defined, multimodal transport routes. ReMuNet orchestrates route utilization, suggests transshipment points, and optimizes capacity allocation, minimizing damage and shortening the recovery time. This paper introduces ReMuNet and its vision, objectives, and expected results.

Keywords: supply chain disruptions · resilient networks and operations · synchromodality · Reinforcement Learning

1 ReMuNet's Vision

1.1 Introduction

ReMuNet is a research and innovation action project, funded by the European Commission in Horizon Europe, that aims to enhance European freight transport resilience through synchromodal routing and event-based relay-transportation. Synchromodal

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transportation is defined as a multimodal approach that uses multiple modes of transport to move goods efficiently by using live data to provide demand-driven transport services, combining several transport modes [1]. In a synchromodal context different modes of transport can be used in relay models, e. g. railway or inland waterways [5]. Relay-transportation originally describes the process of two truck drivers swapping trailers at a transshipment point and carrying the new loads back to their home terminals, subsequently closing the distance to the cargo's final destinations [3, 4]. Within ReMuNet the concept of event-based synchromodal relay transport is used as a swift response to disruptive infrastructure failures increasing holistic network resilience while significantly reducing emissions.

ReMuNet identifies and signals disruptive events, such as natural disasters, traffic jams, and strikes, and assesses their impact on multimodal transport corridors. It then reacts quickly and seamlessly to disruptive events in real-time and supports TMS providers[1] to improve route planning resilience. ReMuNet communicates alternative, pre-defined, multimodal transport routes to logistics operators and subsequently to truck drivers, locomotive drivers, and barge captains, enabling a faster and more adaptive multimodal network response. Moreover, ReMuNet orchestrates route utilization, suggests exchange nodes for multimodal transport modes, and optimizes capacity allocation, minimizing damage and shortening the recovery time. This leads to more sustainable responses to disruptive events in the Eurozone.

1.2 Core Functionalities

ReMuNet's four core functionalities comprise:

1) A **standardized methodology to describe multimodal transport networks**. This standard is based on existing approaches and has been developed with various stakeholders to ensure practicability and acceptability across Europe. It can be easily transferred into appropriate regulatory frameworks and ensures better operational stakeholder interconnectivity. The standard will simplify communication and information-sharing between actors in the freight transport ecosystem.
2) An **algorithm to calculate multimodal route alternatives and capacity utilization** in the face of disruptive events to keep the freight transport network running smoothly. It uses real-time data to dynamically plan synchromodal alternative routes. Disruptive events can include pandemics, natural disasters, geopolitical conflicts, and construction sites.
3) A **collaborative platform that connects relevant logistics operators and enables them to manage disruptions.** This platform provides secure and resilient digital logistic and network management tools, including alternative route planning and orchestration of event-based synchromodal relay transportation. Easy data exchange enables efficient collaboration to keep the supply chain moving.
4) The use of **AI (Reinforcement Learning) to model and evaluate alternative courses of action.** This provides the basis for a self-learning, adaptive multimodal European freight transport and logistics network that strengthens the resilience of

[1] Transport management system.

European trade. Thus, ReMuNet can learn and adapt to changing conditions, making it even more effective in transport orchestration.

2 ReMuNet's Objectives

The concept of the Physical Internet foresees a seamless network where resources and assets can be shared openly and efficiently. ReMuNet's **main objective is to support the achievement of this vision by giving the transport network the ability to prepare, respond, and adapt to disruptive events**.

In practice, ReMuNet uses digital technologies to holistically improve the resilience of the logistics and freight transport network. This includes making planning more robust and secure, reducing response times, and speeding up system recovery. ReMuNet also takes environmental aspects into account and aims to provide synchromodal transport options with the lowest emissions. This contributes to the implementation of the Physical Internet and helps to reduce the environmental impact of freight transport.

Hence, ReMuNet identifies and signals disruptive events while assessing their impact on transport corridors. To enable a faster network response, ReMuNet orchestrates route and capacity utilization. It communicates alternative multimodal transport routes to logistics operators and subsequently to truck drivers, train drivers, and barge captains.

3 ReMuNet's Methodology

ReMuNet's methodology centers on fostering the evolution of a finely tuned multimodal transport infrastructure capable of withstanding conflicts. These conflicts typically manifest during route planning, particularly when disruptive events occur (see Fig. 1). For this, we propose synchromodal relay transport to ensure resilience by design.

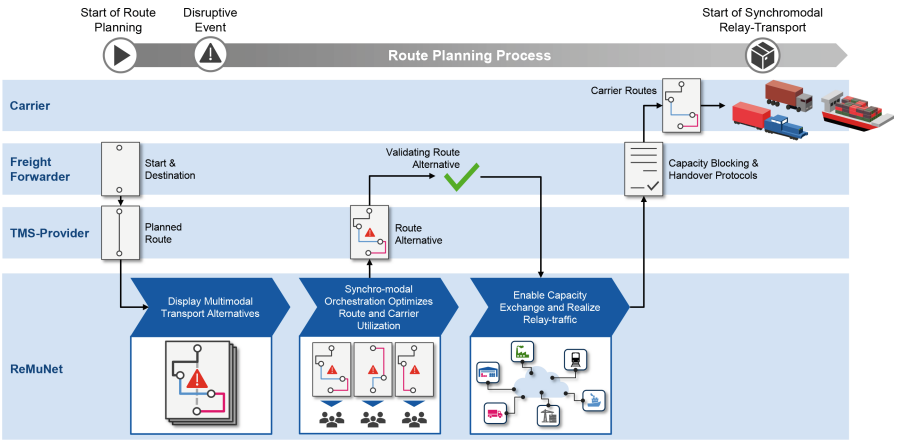


Fig. 1. ReMuNet thrives on collaboration of multiple logistics stakeholders

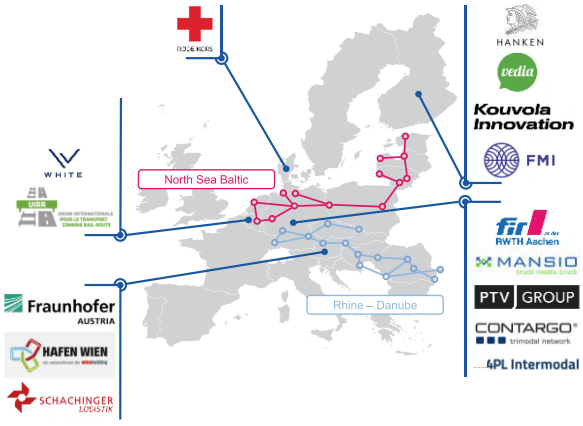
Within its open framework, the collaborative ReMuNet platform will effortlessly assimilate into the European concept of the Physical Internet. Presently, freight transport networks are fragmented and predominantly overseen by forwarders, shippers, or

logistics service providers, lacking a cohesive operational transport network. Synchromodal transport emerges as a facilitator for such a unified transport network, constituting a pivotal element of the overarching "Physical Internet" vision. As a foundational component for synchromodal, resilient, and capacity-optimized transport routing, ReMuNet assumes a significant role within the framework of the Physical Internet.

The ReMuNet's idea starts off with a freight forwarder, delivering goods from point A to point B uses modern TMS-software to calculate the most efficient route and mode of transportation,

1. when an unforeseen event disrupts his/her planning process.
2. Classical TMS-systems offer alternative routes that require longer times, but do not consider the disruption impact, emissions, costs, or synchromodal potentials.
3. NOW: The ReMuNet platform displays multimodal transport alternatives that offer higher resilience (e.g., switching from road-based to rail-based) and are more sustainable by design. The information is communicated to the driver/means of transport via navigation system interface and messaging.
4. In a second step, ReMuNet anticipates the predicted impact of disruption and orchestrates route and carrier utilization by offering system-optimized route-based alternatives for each stakeholder.
5. As effect, ReMuNet enables synchromodal capacity exchange and realizes cross-actor relay-transport.

We defined two pilot corridors, each with distinct objectives. The North Sea Baltic pilot endeavors to establish a resilient and sustainable route for supplying goods to Ukraine, while the Rhine-Danube pilot emphasizes an ecological multimodal approach. Consequently, ReMuNet's use cases concentrate on addressing geopolitical concerns in the North Sea Baltic region and ecological, climate-resilient disruptive events along the Rhine-Danube corridor. Lessons gleaned from the COVID-19 pandemic are pertinent to both scenarios. Unlike disasters and conflicts that directly impact transport and communication infrastructure, the pandemic disrupted transport networks due to workforce shortages, leading to the closure of critical facilities such as warehouses, manufacturing plants, ports, and airports. Additionally, political decisions resulted in the shutdown of national borders and transportation modes, including air traffic.



Regarding the development and implementation of ReMuNet's four core functionalities, three constitutive technological work streams have been defined (see Fig. 2).

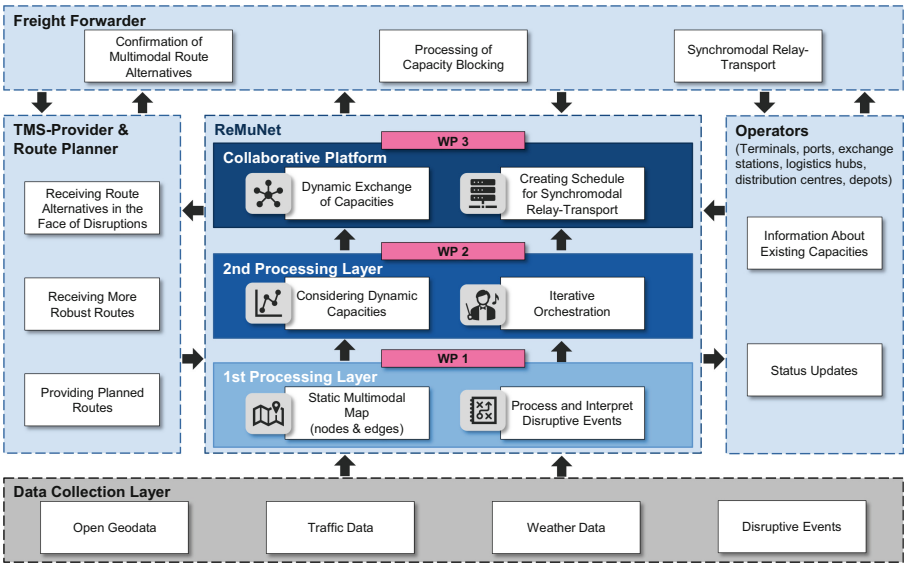


Fig. 2. Conceptual and simplified architecture of ReMuNet

Firstly, we amalgamate existing standards detailing multimodal transport nodes and edges with data on disruptive events. This fusion facilitates the creation of a cohesive data repository serving as input for the initial processing layer. The outcome is a consolidated description standard integrated into a static multimodal map. Additionally, we formulate a typology discerning various disruptive events affecting multimodal freight transport. Secondly, we construct a reference model delineating multimodal transport networks and devise an algorithm for presenting alternative transport options during disruptive events. This reference model displays the impacts of disruptive events, establishes the groundwork for intelligent routing algorithms, and thereby supports the collaborative platform. By enabling an examination of disruptions based on events and their effects on transportation chains, genuine resilience is instilled into the system through intelligent route planning and dynamic capacity allocation. These capabilities will be unified within the collaborative ReMuNet platform. The comprehensive suite of functionalities is underpinned by a foundational data layer that amalgamates data from operators across various levels.

Initially, ReMuNet relies on four distinct data sources: static, dynamic, disruptive, and operator data, each contributing to various functionalities. Static data encompasses infrastructure and multimodal transfer points, while dynamic data expands upon this by incorporating transport capacity, weather conditions, and traffic data. Complementary to these, disruptive data includes information about natural disasters and sudden shifts

in demand, while operator data, such as that from ports and freight forwarders, further enriches the database, ensuring its robustness.

Simultaneously, the system undergoes continual enhancement through the establishment of a reinforced learning environment. This environment involves an AI-based simulation of disruptive events and a model for orchestrating routes and capacities.

4 Conclusion

The ReMuNet system is rooted in the principle of developing an optimized multimodal transport network that is resilient to conflicts. Conflicts can arise in the route planning and transport process due to disruptive events. To address this challenge, ReMuNet proposes synchromodal relay transport, which is designed to be resilient by design. The open and collaborative ReMuNet platform will seamlessly integrate into the European vision of the Physical Internet.

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Estimating a Detailed Trans-European Origin-Destination Matrix of Road Freight Transport

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Abstract. Detailed data regarding the types and quantities of goods transported, both regionally and internationally, plays a pivotal role in developing sustainable freight transport strategies. However, such data is currently lacking. This paper presents a method based on Iterative Proportional Fitting for creating comprehensive Origin-Destination (OD) matrices representing European road freight transport flows. The approach integrates publicly available statistical data on freight transport, including international transport flows between countries, the total volumes of goods loaded and unloaded in all NUTS 3 regions, the distribution of transport distances and the shares of different types of cargo. The proposed methodology addresses data inconsistencies and missing information. The resulting demand matrices provide detailed insights into the volumes and types of freight exchanged via road transport between NUTS-3 regions throughout Europe.

Keywords: Road freight transport · Transport demand · Iterative Proportional Fitting

1 Introduction

In Europe, road transport stands as the primary source of emissions within the transportation sector, with heavy-duty vehicles (HDVs) accounting for approximately a quarter of these emissions[4]. To devise strategies for more efficient and sustainable freight transport, e.g., shifting transport to more efficient modes or optimizing the trans-European transport network (TEN-T), it is essential to have detailed knowledge of the quantities of solid and liquid bulk goods, palletized goods, and freight containers being transported. This information needs to encompass both international and regional transports with the highest possible level of precision. However, such data is currently not readily available. Existing methods use toll data and traffic counts to estimate freight transport

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demand [1] but don't include details about the origin, destination, and types of goods. The statistical office of the European Union (EuroStat) collects data on the quantities of goods transported between countries, which can be accessed through an online database[5]. Additionally, data is available on loaded and unloaded goods at the NUTS-3 regional level, the distribution of transport distances, and the proportions of various cargo types. However, this data only offers a limited perspective on freight traffic flows, corresponding to marginal totals in the origin-destination (OD) matrix. Iterative Proportional Fitting (IPF) is a method employed in economics and survey statistics for aligning a distribution provided in one dataset with the totals reported in various other datasets. It serves to refine data tables in situations where information is either incomplete, erroneous, outdated, or based on a sample [6]. For instance, IPF finds applications in determining passenger origin-destination flows on bus routes using boarding and alighting data [7], and in generating socioeconomic attributes for a synthetic population in Activity-Based travel demand modeling, leveraging a sample of cross-tabulated attributes from one zone and marginals of other zones[2].

In this paper, we present a method based on IPF for creating a detailed tabulation of European road freight transport flow volumes (OD matrices) by using publicly available freight transport statistics. The proposed approach reconciles the available data into a coherent result and handles potential inconsistencies between the data sources by minimizing the error. The resulting demand matrices provide insights into the volume of goods transported nationally and internationally between NUTS-3 regions, while also distinguishing between different types of cargo.

This paper is organized as follows: Sect. 2 describes the data sources used in this study, Sect. 3 explains the algorithm for creating the OD matrices, Sect. 4 presents the results, and Sect. 5 concludes this study.

2 Data Sources

EuroStat collects road transport statistics on the transport of goods with heavy goods vehicles [5]. Data collection consists of annual and quarterly datasets from each member state on vehicles registered within their borders, capturing loaded journeys and information about the transported goods, typically over a one-week observation period. The collected information includes metrics such as tons, tonne-kilometres, vehicle-kilometres, and the number of journeys. Cargo types are classified into: liquid bulk goods, solid bulk goods, large freight containers, other freight containers, palletized, pre-slung, mobile self-propelled units, other mobile units, and other cargo types.

For our study, we use the following Eurostat data: International road freight transport by country of loading and unloading (table *road_go_ia_rc*), Total road freight transport by region of loading (table *road_go_ta_rl*), Total road freight transport by region of unloading (table *road_go_ta_ru*), Total road freight transport by type of cargo and distance class (table *road_go_ta_tcrg*), and the Distance matrix between NUTS-3 regions [3].

In this study we focus on the annual amount of transported goods in thousand tons and we only extract the corresponding variable. However, the methods described here can also be applied using the number of journeys instead.

It is important to note that these data stem from sample surveys and are subject to sampling errors and bias. Moreover, detailed breakdowns reduce sample sizes and amplify errors. In the Eurostat tables, a specific code is used to indicate that the micro-data observations are fewer than 10. These codes can be replaced with zeros for estimation purposes, which will, however, introduce disparities between aggregated and disaggregated data. Another code is used to indicate that data is missing. Data imputation approaches, such as extrapolation from previous years, can generate additional inconsistencies in the data, which have to be reconciled, when computing the OD matrix.

3 Method

The method employed to estimate a detailed road freight OD matrix relies on an approach known as Iterative Proportional Fitting (IPF). IPF is a mathematical technique used to adjust a matrix to align with predefined totals (marginals). This adjustment process consists of scaling along different dimensions, typically rows and columns, to match the desired marginals. Since each adjustment step may disrupt the alignment achieved in the previous step, IPF iteratively repeats these adjustments in cycles until all specified marginal totals are satisfactorily approximated.

To describe the available and desired data in a formal way, we first introduce the following definitions:

C_R is the set of reporting countries.
C is the set of countries of loading (origin) or unloading (destination).
R is the set of NUTS-3 regions of loading (origin) or unloading (destination).
$R_c \subset R$ is the set of NUTS-3 regions of country $c \in C$.
T is the set of cargo types.
L is the set of distance classes ($<$ 50km, 50km$-$149km, 150km$-$299km, 300km$-$499km, $>$ 500km).

The desired OD matrix can be written as a function $m : R \times R \times C_R \times T \to \mathbb{R}$ such that $m(o, d, c_r, t)$ is the amount of cargo of type t that is transported by road from origin o to destination d using a vehicle registered in country c_r.

The distance matrix is a function $\delta : R \times R \to L$.

Table *road_go_ta_rl* (total road freight transport by region of loading) is a function $f_l : K_l \subseteq R \times C_R \to \mathbb{R}$ defined by

$$f_l(o, c_r) = \sum_{(d,t) \in R \times T} m(o, d, c_r, t). \tag{1}$$

Table *road_go_ta_ru* (total road freight transport by region of unloading) is a function $f_u : K_u \subseteq R \times C_R \to \mathbb{R}$ defined by

$$f_u(d, c_r) = \sum_{(o,t) \in R \times T} m(o, d, c_r, t). \tag{2}$$

Table *road_go_ia_rc* (international road freight transport by country of loading and unloading) is a function $f_{lu} : K_{lu} \subseteq C \times C \times C_R \to \mathbb{R}$ defined by

$$f_{lu}(c_o, c_d, c_r) = \sum_{(o,d,t) \in R_{c_o} \times R_{c_d} \times T} m(o, d, c_r, t). \tag{3}$$

This table only contains international transport and cabotage such that $K_{lu} \subseteq \{(c_o, c_d, c_r) \in C \times C \times C_R \mid c_o \neq c_d \vee c_o \neq c_r \vee c_d \neq c_r\}$.

Table *road_go_ta_tcrg* (total road freight transport by type of cargo and distance class) is a function $f_{td} : K_{td} \subseteq T \times L \times C_R \to \mathbb{R}$ defined by

$$f_{td}(t, l, c_r) = \sum_{(o,d) \in R \times R:\ \delta(o,d) = l} m(o, d, c_r, t). \tag{4}$$

The goal is to align $m(o, d, c_r, t)$ with the aggregate functions defined in Eqs. (1) to (4). To this end, we generalize IPF to scaling arbitrary parts (subdomains) of m instead of just scaling rows and columns. The domains K_l, K_u, K_{lu}, and K_{td} of the functions define the available marginals. Note that the domain definitions address missing data by allowing the domains to be subsets of the complete domains. For instance, $K_l \subseteq R \times C_R$ means that for some regions and reporting countries the information on the quantity of goods loaded might be missing. To prevent oscillations in the presence of inconsistencies in the input data, we introduce a *learning rate* $\alpha_i \in [0, 1]$ to control the size of adjustments made by IPF. To balance rapid convergence and stability, the learning rate can be gradually reduced throughout the iterations.

The procedure for calculating an estimate for m is as follows:

Initialize $m^{(0)}$ with small positive numbers and repeat the following steps for $i = 0, 1, 2, \ldots$ until convergence:

1: $\hat{f}_l^{(i)}(o, c_r) := \sum_{(d',t') \in R \times T} m^{(4i)}(o, d', c_r, t')$

$$s_l^{(i)}(o, c_r) := \begin{cases} f_l(o, c_r) \div \hat{f}_l^{(i)}(o, c_r) & \text{if } (o, c_r) \in K_l; \\ 1 & \text{if } (o, c_r) \notin K_l. \end{cases}$$

$$m^{(4i+1)}(o, d, c_r, t) := m^{(4i)}(o, d, c_r, t)(\alpha_i(s_l^{(i)}(o, c_r) - 1) + 1)$$

2: $\hat{f}_u^{(i)}(d, c_r) := \sum_{(o',t') \in R \times T} m^{(4i+1)}(o', d, c_r, t')$

$$s_u^{(i)}(d, c_r) := \begin{cases} f_u(d, c_r) \div \hat{f}_u^{(i)}(d, c_r) & \text{if } (d, c_r) \in K_u; \\ 1 & \text{if } (d, c_r) \notin K_u. \end{cases}$$

$$m^{(4i+2)}(o, d, c_r, t) := m^{(4i+1)}(o, d, c_r, t)(\alpha_i(s_u^{(i)}(o, c_r) - 1) + 1)$$

3: $\hat{f}_{lu}^{(i)}(c_o, c_d, c_r) := \sum_{(o',d',t') \in R_{c_o} \times R_{c_d} \times T} m(o', d', c_r, t')$

$$s_{lu}^{(i)}(c_o, c_d, c_r) := \begin{cases} f_{lu}(c_o, c_d, c_r) \div \hat{f}_{lu}^{(i)}(c_o, c_d, c_r) & \text{if } (c_o, c_d, c_r) \in K_{lu}; \\ 1 & \text{if } (c_o, c_d, c_r) \notin K_{lu}. \end{cases}$$

$$m^{(4i+3)}(o, d, c_r, t) := m^{(4i+2)}(o, d, c_r, t)(\alpha_i(s_{lu}^{(i)}(c_o, c_d, c_r) - 1) + 1)$$

4: $\hat{f}_{td}^{(i)}(t, l, c_r) := \sum_{(o',d') \in R \times R:\ \delta(o',d') = l} m(o', d', c_r, t)$

$$s_{td}^{(i)}(t, l, c_r) := \begin{cases} f_{td}(t, l, c_r) \div \hat{f}_{td}^{(i)}(t, l, c_r) & \text{if } (t, l, c_r) \in K_{td}; \\ 1 & \text{if } (t, l, c_r) \notin K_{td}. \end{cases}$$

$$m^{(4i+4)}(o, d, c_r, t) := m^{(4i+3)}(o, d, c_r, t)(\alpha_i(s_{td}^{(i)}(t, \delta(o, d), c_r) - 1) + 1)$$

The initialization acts as a 'prior,' guiding IPF to a solution close to $m^{(0)}$ that aligns with available marginals while resolving discrepancies. Assuming that missing information likely suggests minimal goods flow, in particular for cross-trade and cabotage, we employ very low priors: 10^{-6} for cross-trade and cabotage, and 10^{-3} for all other transport operations.

4 Results and Discussion

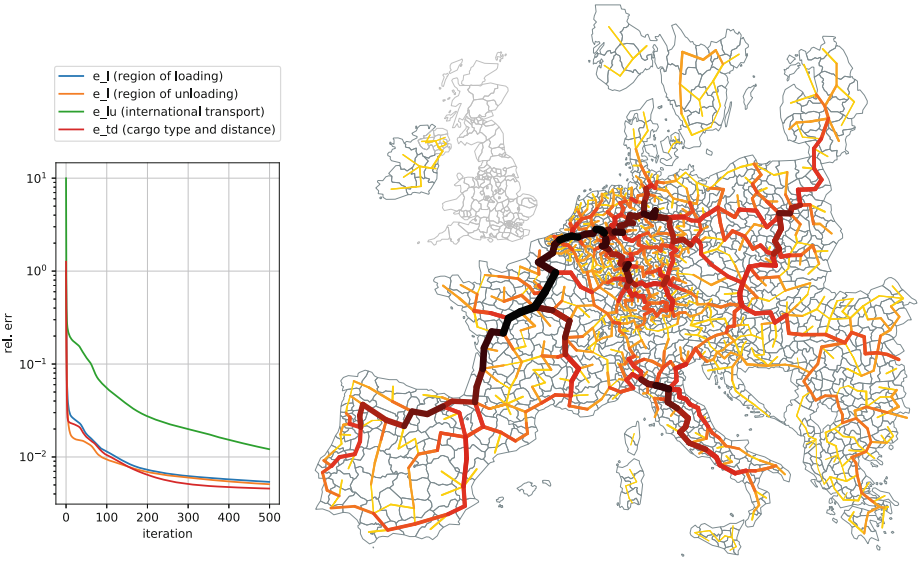


Fig. 1. Evolution of the relative errors over iterations of IPF (a), and the resulting road freight flows visualized as paths along neighbouring regions (b).

We applied the method to data of the year 2022. The evolution of the relative marginal errors $e_{\cdot}^{(i)} = \frac{\sum_{K_{\cdot}} |\hat{f}_{\cdot}^{(i)} - f_{\cdot}|}{\sum_{K_{\cdot}} f_{\cdot}}$ over the IPF iterations are shown in Fig. 1(a). After 500 iterations, the errors are $e_l = 0.5\%$, $e_u = 0.5\%$, $e_l u = 1.2\%$, and $e_t d = 0.4\%$. The resulting road freight flows are visualized as paths along neighbouring NUTS-3 regions in Fig. 1(b).

It is important to note that the available statistical data used in this study do not fully determine the OD matrix. For example, cargo type information is limited to the reporting country and distance. However, there may be dependencies on specific origin and destination regions, currently addressed only through statistical relationships between reporting countries and regions. Nonetheless, the methodology is expandable, and incorporating more data sources can reduce ambiguities and enhance result reliability. One approach is to include tonne-kilometers in addition to transported tonnes for loaded and unloaded goods,

providing a new aggregate as input for the estimation: dividing tonne-kilometers by tonnage yields total distances traveled for each source or destination region. Another improvement approach involves reassigning current origin-destination flow estimates on the road network in each iteration, adjusting traffic volumes using data from traffic sensors or toll systems.

5 Conclusion

We presented an IPF-based method to estimate a comprehensive OD matrix for road freight transport at the NUTS-3 level across Europe. The resulting matrix aligns with all existing aggregate statistics and reconciles potential disparities among data sources. These outcomes provide a solid basis for developing strategies aimed at improving the efficiency and sustainability of freight transport.

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Data-Driven and Dynamic Land Use for Physical Internet-Led Urban Logistics and Planning

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Abstract. DISCO is an innovation action project co-funded by the European Commission, focused on upscaling urban logistics and smart planning, accelerating the transition to decarbonized and digital cities by changing the logistics paradigm using a Physical Internet (PI) led approach. DISCO leverages the PI and Urban Cloud concepts to demonstrate the value of dynamic allocation of city infrastructures. The 5 DISCO-X measures employ sensor enabled infrastructures using PI collaboration protocols and an Urban Cloud model to enable the efficient and effective allocation of city infrastructures to users. In order to guide the cities towards the digital transformation and thus allowing them to build an ecosystem of logistics players that are willing to stay interconnected, three actions are necessary: (i) Influential market players register last-mile delivery capacities in an Urban Freight (UF) Data Space and establish trusted data sharing with planners for smarter, effective, functional, and real-time planning; (ii) The Meta Model Suite delineates optimal paths to achieve concrete transformation in Living Labs acting as PI networks; (iii) all involved actors comply with certain IT standards and protocols. In UF Data Space, DISCO will know all freight transport capabilities and space available in the city, in real-time and in advance and will support operational efficiency, dynamic planning, optimal use of available infrastructures, network and asset and better user experience. DISCO will deploy a demonstration involving 4 Starring Living Labs + 4 Twinning Living Labs and a package of 23 innovation measures, along 5 DISCO-X innovations, layered as digital, physical and business.

Keywords: Urban Logistics · Physical Internet · Data Space

1 Introduction: The DISCO Vision

Priorities of the EU Green Deal [1] to reduce climate emissions by 55% by 2030 and for cities to become climate-neutral by 2050 cannot be met only by setting vehicles' decarbonisation targets. To achieve these goals, urban space, logistics services and transportation systems need to be re-designed, adopting a dynamic and optimal space allocation

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approach that integrates urban freight within an efficiently operated network-of-networks that exploits underused land based on throughput demands. Cities are complex entities composed of multiple interacting networks of actors, systems, technologies, and regulations [2]. As a structure built from the interaction of multiple networks, a city is not a planned construct, but an emergent concept reflecting the multitude of interactions between its underlying components (e.g., [3]). Historically, the approach cities have taken to managing this complexity has been to organize functionally and, within function, to focus on either technical or geographic components of the function [4]. Unfortunately, such a structure has encouraged the development of "silo" thinking, which ignores the interconnections of the various networks that operate within a city. As cities have grown, the services that they are expected to deliver to their citizens have also grown. These services, provided by numerous city functional departments and external commercial entities, intersect, facilitate, and constrain the various recipients of the services in an emergent manner that no individual city department or company can foresee or control. Given the city's inability to systemically control or understand what is happening at the operational level means that the efficient and effective use of city infrastructures is not possible resulting in user frustration, loss of good will, and fair allocation. Another approach to managing the operations of the city's infrastructure is required. One such approach uses the Internet as an example of how intelligent objects and resources might be managed. If every physical entity is instrumented with a real time sensing and communications device, why can't these physical entities be managed like resources on the Internet? A "Physical Internet" concept [5–8] is a particularly useful model for thinking of city infrastructures like computing resources that can be provisioned "on demand" through cloud like "Infrastructure as a Service" (IaaS) concepts [9]. It is also a useful approach to managing freight and mobility services, which resemble the flow of packets over the Internet [10]. By abstracting its infrastructure through an "Urban Cloud" model, the city would provide convenience to its citizens and businesses. These users would no longer have to seek out open areas for parking, dropping off, or picking up items. They could schedule the abstract space through applications built on top of the city's IaaS services and be assured that they could use the space for the duration that they have scheduled it.

DISCO leverages the PI and Urban Cloud concepts to demonstrate the value of dynamic allocation of city infrastructures. The DISCO-X (X = Curb, Proxi, Bay, Estate, and Collection) measures employ sensor enabled infrastructures using Physical Internet collaboration protocols and an Urban Cloud model (city infrastructure managed as a service and a digital twin platform connecting to the infrastructure, linking federated dataspaces, and providing modeling and analytic tools to predict behavior and build additional services as a Platform as a Service) to enable the efficient and effective allocation of city infrastructures to users.

2 Methodology: The DISCO Approach

The DISCO relies on four subsequent methodological steps of a journey to scale up and accelerate to a climate-neutral data-driven value destination to 2030. This route is with the following methodological paths (Fig. 1):

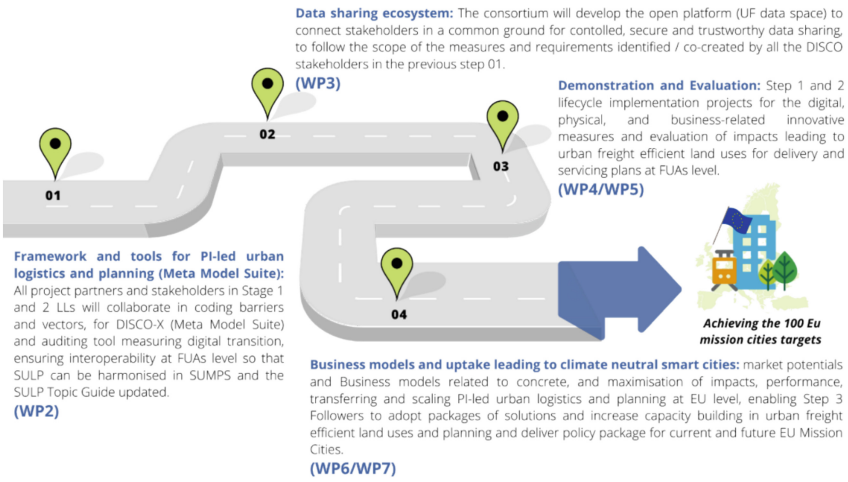


Fig. 1. Route to digital transformation in urban logistics and planning

In order to guide the cities towards the digital transformation and thus allowing them to build an ecosystem of logistics players that are willing to stay interconnected, three actions are necessary:

Action 1: Influential market players, from big carriers to cargo-bike couriers, register last-mile delivery capacities in an Urban Freight (UF) Data Space (IT platform) and establish trusted data sharing with planners for smarter, effective, functional, and real-time planning. Operators can benefit of dynamic (on-demand) and optimal use of (underexploited or strategically positioned) lands/space and adoption of zero-emission vehicles (e.g., e-bike to LEFV) and roll out of sustainable modes (waterborne / rail).

Action 2: The Meta Model Suite delineates optimal paths to achieve concrete transformation in Living Labs (LL) acting as PI networks, running packages of innovative digital, physical, and business measures, co-designed and enabled by multi-stakeholders' connectivity. Digital maturity is measured by Assessment Toolkit so that measures are widely accepted, scaled and to be considered in SULPs.

Action 3: All involved actors comply with certain IT standards and protocols, and ideally also on shipment sizes that are modular enough so that they can be flexibly and dynamically combined to allow a certain interconnection of the different parties to perform efficiently. In UF Data Space, DISCO will know (stream) all freight transport capabilities and space available in the city (e.g., freight hotels), in real-time and in advance and will support operational efficiency, dynamic planning, optimal use of available infrastructures, network and asset and better user experience. DISCO will be at the service of cities and operators, co-designing, simulating, monitoring, evaluating and scaling-up the DISCO innovative measures, belonging to different DISCO-X. These measures will be demonstrated by adopting the Meta Model Suite, enabled by the UF Data Space, empowering uptake, and replicability at different phases of design and implementation, and ensuring stakeholder's participation.

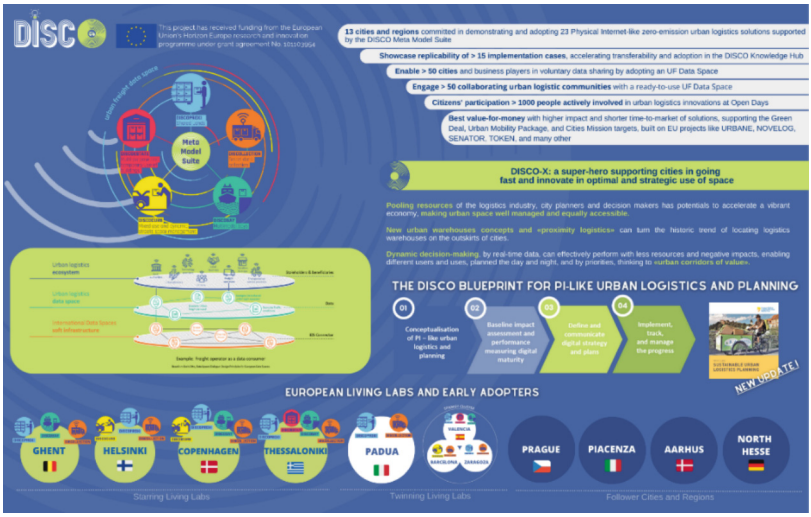


Fig. 2. DISCO overall approach

Meta Model Suite: The Meta Model Suite is a novel framework that supports the implementation and adoption of green last-mile delivery solutions in urban areas, based on the PI-led DISCO-X innovations listed below:

DISCOCURB - ***Mixed use and dynamic streets space management*** **-** Smart and flexible use of curb side, for parking slots, pick up points and network management.

DISCOPROXI - ***Shared Lands*** **-** Urban corners or lockers for nearby deliveries and omnichannel shipments, to optimise multiple collection and delivery solutions.

DISCOESTATE - ***Multi-purpose, flexible and temporary use of building space*** **-** Retrofitting building space for multi-tenant and temporary logistics use and enhance the reliability of last mile deliveries.

DISCOBAY - ***Multimodal bays*** **-** Mutualised and multimodal (e.g., rail/waterborne) distribution centres pooling green last mile delivery.

DISCOLLECTION - ***Smart data collection methods*** **-** Advanced access control and real time routing for optimised and prioritized, incentivised and dynamic access permission enabling smart network management upon priorities and functional areas.

These innovations aim to promote the adoption of shared green last mile solutions by considering physical, digital, and operational aspects. The suite consists of four main functionalities: (1) guidance to cities on the different DISCO innovations and their requirements, (2) definition of the transition path for each DISCO city to achieve a smooth transition to PI-led innovations and incorporate them into their SULP, (3) planning and operational tools for designing and implementing the different DISCO-X solutions, and (4) guidance to cities on the data requirements of each DISCO-X and how to develop their own dataspaces.

Urban Freight Data Space: The DISCO UF Data Space is the underlying digital enabler for the deployment of data-driven collaborative planning services. It provides a trustworthy framework for sharing data related to transportation, delivery, space use, and

supply chain operations in urban areas across decentralised networks, whilst introducing semantic interoperability. The latter is particularly critical for establishing a common understanding of data meaning and context across diverse sources and the DISCO-X applications. Through the DISCO UF Data Space data sovereignty, transparency and fairness are ensured, creating the ground for stakeholders' onboarding. Data connectors will facilitate seamless data exchange services while incorporating robust data security enforcement mechanisms. A catalogue of key reusable services will further support the development of sustainable urban logistics strategies.

The Adaptive Blueprint for PI-Like Urban Logistics and Planning: The Adaptive Blueprint process will run across 4-Phases that will help cities and communities in undertaking a successful digital transformation with a simple stepwise approach, as initially planned in the Fig. 2. It will intensify the dialogue on SULPs and will provide insight in relation to urban logistics system of the future, the main planning requirements for promoting the shift towards PI-led solutions.

3 Preliminary Results and Discussion

At the final submission stage of this paper, the project hasn't reached yet one year of life. However, preliminary results showed: (i) Cities are confronted with a vast array of data types, originating from various platforms and in different formats. This heterogeneity, stemming from the unique requirements of the five DISCO-X categories, underscores the need for a specialized data aggregation tool or add-on within the urban dataspace; (ii) A preliminary version of the Meta Model Suite was introduced. This tool is envisioned as a comprehensive resource for cities embarking on the journey towards PI-enabled infrastructure management, offering a unified framework for the effective implementation of PI principles in urban logistics and infrastructure planning.

The DISCO impact domain underpinning PI-led urban logistics land use and planning in which innovation must be placed at the service of cities are: ***Shared Solutions***: Ability to create asset-less solutions by crowdsourcing platforms bringing various stakeholders under a common platform and creating value in terms of the economy of scale expected to generate. They can collaborate around technology to provide on-demand deliveries when it comes to their last-mile logistics. ***Connected logistics***: Ability to leverage key trends towards a data-centric approach and use analytics to manage fleets and regroup deliveries to take critical decisions pertaining to key logistics functions. Incorporating analytics to optimise routes and fuel usage, control emissions and monitor operational efficiency and performance, as well as for predictive deliveries to understand where an order would be. ***Smart logistics***: Ability to offer authorities opportunities to improve dynamic traffic management and improve enforcement of local rules, e.g., in terms of accessibility of a city centre. Smart logistics offer business opportunities to logistics companies and customers, improve efficient transport and warehousing, and facilitate (inter)connectivity among logistics networks, e.g., exchange of transport orders between different parties and/or modalities. Equal sharing costs / benefits models remain a hot topic. The exchange of traffic and logistics trip data between companies / authorities enables parties to improve operations. Smart logistics solutions create new connections and enable LSP's to collaborate. ***Urban network management***: Ability to adopt flexible

and smart use of networks, dynamic access regulation, low emission zones regulation and monitoring, parking space management, dynamic routing. ***Agile storage and last-mile distribution:*** Ability to improve the delivery process and manage loading and unloading areas (scarce space management, in a flexible and integrated way, and of the contested curb side); to improve consolidation of goods and management of flows; to introduce new technologies that can make the freight distribution process more efficient through automation and data analysis.

4 Future Research

DISCO project will run for a total of four years, being yet at the first year only the initial phase of DISCO-X innovation in urban areas has been delineated together with a PI-operational paradigm offering a guidance for cities in implementing DISCO-X strategies effectively. In the next months/years for each DISCO-X, specific tools will be developed to enable the operation of the DISCO-X solutions to each city. The Urban Freight Data Space will facilitate the tools deployment by providing the good organization of the data needed for the implementation of each DISCO-X in the cities and utilize the meta data flows of the Urban Freight Data Space to obtain information sufficiently covering their needs.

Disclaimer DISCO is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them."

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Food Delivery Services Influence on Urban Mobility – A Systematic Literature Review

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Abstract. Food delivery services have more than tripled since 2017, further driven by the implications of the COVID-19 pandemic. This increase and digitalization have paved the way towards a new urban mobility and logistics scenario. This research investigated the recent impact of food purchase/delivery on mobility, such as the replacement of individual private mobility to physical stores by the use of online platforms and delivery transport modes. A systematic literature review was carried out to identify how business operations affect urban mobility and the challenges behind these changes, by understanding the effects that food delivery can have on urban mobility and the transport system. The study was based on a PRISMA analysis, selecting papers from SCOPUS and Web of Science between 2012 to 2022. The review concluded a knowledge gap with only 20 papers, highlighting the implications of food delivery services on traffic congestion, road safety, policies, and infrastructure. The study concluded the need for changes on the urban planning perspectives by offering insights to the academic environment and outlining directions to future research. It also underlines planning deficiency between urban mobility and urban logistics under the umbrella of food delivery.

Keywords: Food delivery · transport · urban mobility · logistics · delivery route · on-demand transport services

1 Introduction

The food delivery services have become viral worldwide, particularly the online food delivery, which has altered the last-mile segment with substantial impacts on the transport and logistics network by a demand that is extremely dynamic in space and time [1]. Every year, especially in the wake of the COVID-19 pandemic, more consumers use delivery services for a variety of reasons, which highlights questions about the impact of these types of work on physical spaces and mobility practices, which can range from security, traffic, to carbon-footprint and beyond [2].

Although over 160 research papers have focused on consumer behaviour/experience, food delivery platform workers (couriers), and new technologies to improve the food delivery apps, such as route optimization, few papers have addressed current research

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and trends towards the impact of this segment on the urban mobility, but not one focused on it entirely. Thus, this study offers opportunity to contribute to the literature on a less-explored domain of food delivery services, by reviewing the literature published from 2012 to 2022, to analyse the extent of the impacts on urban mobility caused by food delivery, and the change in food purchase behaviour. For this, the following questions will be answered: to what extent is the food delivery service affecting the urban mobility? What can be learned from the research that have taken place? Focusing on the opportunities and challenges these impacts pose.

2 Methodology

This research follows the PRISMA guidelines, to ensure a transparent search, which will focus on a clearly defined topic, following pre-determined criteria, to achieve scientific accuracy. The search for documents was carried out until May 2023, with the strategy of using two different database, SCOPUS and Web of Science, and analysing documents from 2012 to 2022 in English and in Portuguese (Table 1). These two databases provide high-quality documents and are widely used. The searching strategy was based on the terms "food AND delivery AND transport", three strings separated by proper Boolean operators, and was later refined by title, abstract and keywords related considerations. This resulted in 290 documents, being 28 from SCOPUS and 262 from Web of Science.

Table 1. Paper selection criteria.

Items	Description
Database	Scopus and Web of Science
Language	English and Portuguese
Time interval	2012 - 2022
Inclusion criteria	Food AND delivery AND transport; Open access; SCImago Q1 and Q2

The next phase was to remove the duplicated documents (11), papers with journals ranked at SCImago as Q3 and Q4 (17 documents), and with no open access (12 documents), resulting in 250 documents. An eligibility criterion was made by the examination of the abstracts focusing on the relationship and impacts that the food delivery service is imposing on the urban mobility transportation system. This culminated on the classification between relevant and not relevant documents to this study, excluding 217, as many of them focused mainly on delivery app platforms (67), customer behaviour (54), route optimization (21), and drones as the goal for the future (23). The remaining 33 documents were then analysed one by one in their full text, from which another 13 documents were also excluded, since they did not add direct value to the subject by not covering the impacts of food delivery on urban mobility, leaving 20 documents at the end (Fig. 1).

The final step was the analysis of the selected papers for their categorization and scope examination. The categorization was made in 10 areas of study based on: platform-based

delivery personnel, mobility practices of the couriers, road safety, traffic regulations, traffic, conditions, sustainability, pollution, urban mobility plan/infrastructure, parking/loading, and KPI/new technology. The studies were carried out in China, Canada, France, India, Colombia, Malaysia, Taiwan, Italy, and Australia.

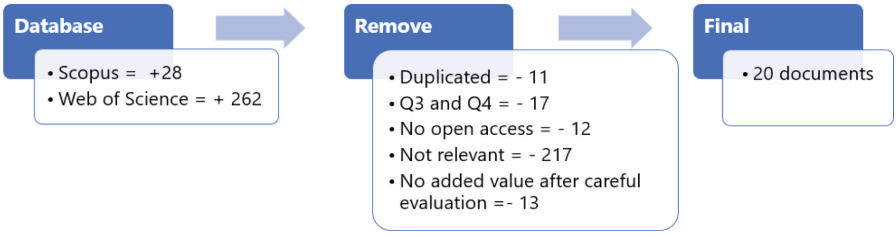


Fig. 1. PRISMA analysis

3 Results

It is possible to observe a growing trend in the publication of articles per year in this segment, as 80% of them were published in 2020–2022 (Fig. 2). Nevertheless, to accommodate the current and future delivery configuration, the articles still maintain the impacts of deliveries and the need for solutions and changes, within the scope of mobility, as a supporting actor in studies, and not as the lead protagonist. They highlight problems with the platform-base delivery personnel (9), their behaviour on traffic (16), road safety (15) and traffic conditions as the main objective, which may set the scene to point out vaguely about the urban mobility constraints in the document (Fig. 3).

The working personnel profile, behaviour and perspective is highlighted in some of the papers [2, 3], as a segment dominated by young males, who may be facing problems accessing the labour market, they usually are independent contractors paid by delivery and seeking to have the freedom to choose the day and time of work. Nevertheless, the idea behind platform workers having freedom and malleability during their work has been proven as fictitious, as companies are increasing daily control over their labour and dodging their employer obligations [2, 4, 5], especially when there is an algorithm management system which promotes lack of transparency, invisible managers, and limited control over work process, increasing the pressure over the workers and consequently their willingness of risk-taking actions, putting their lives and others in danger.

Based on the mobility practices of workers in the food delivery segment, the articles mentioned that they tend to prefer the use of bicycles and two-wheeled motorized vehicles around the world due to their speed, carrying out long hours of work on the roads using smartphones, finding themselves distracted when driving, and violating traffic regulations to meet their demands on time, by speeding, changing lines illegally, and driving in the opposite direction [2–8]. Understanding traffic conditions, driver behaviour and the environments they are subjected to is important for business success [9–13] and can implicate in more safety and efficiency.

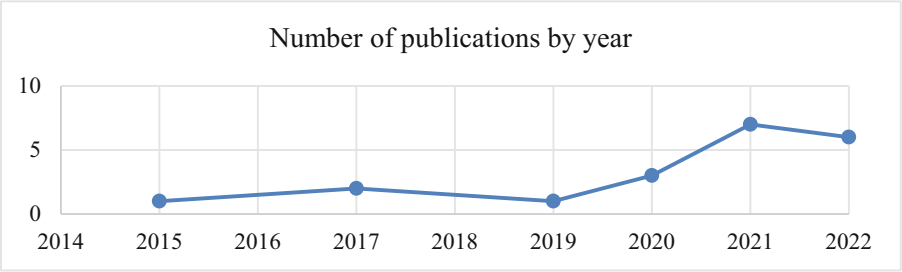


Fig. 2. Number of publications by year

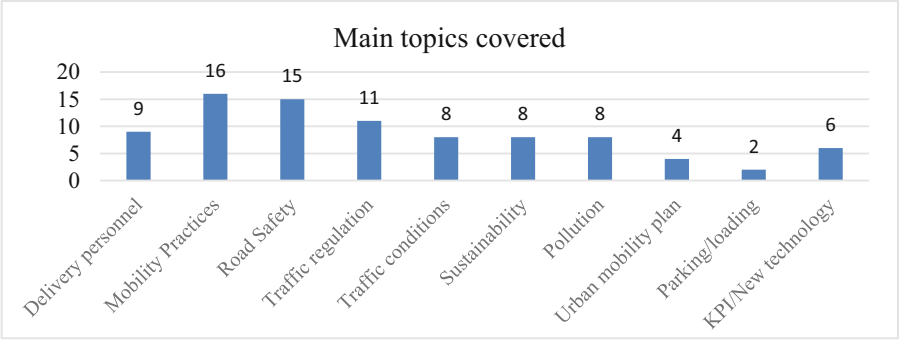


Fig. 3. Categorization of papers by topics covered.

Sustainability and pollution are stated as consequences of this work modality, as it is generating more congestion and pollution due to the increase on the number of workers and use of motor vehicles to speed the process [2].

A few studies indicate the linkage between food delivery services practices and demand with urban policies and plan. Regarding the policies, "city logistics measures are not easy implemented by local authorities, and readily accepted by stakeholders" [14], as there are different needs and expectations. It is essential to propose government traffic regulations to improve the safety of drivers and control delivery services business, as policymakers are not considering all the stakeholders (specially the delivery personnel) in their city decision-making [4, 5, 15–17]. It also highlights that the streets and cycling network can improve the delivery activity and make it less dangerous [2], by safeguarding the cycle lanes and adding advanced stop lines which will reduce the negative behaviour towards bicycle riders [3].

4 Discussion

Getting to know the profile, perspectives, and behaviour of the working personnel of these delivery services helps understand and research solutions for the problems caused by this sector. The consequences of lack of training and high life-threatening situations due to couriers working conditions, together with the carbon-footprint increase, endorses the

exploration of new solutions such as bicycles and electric bikes, cargo-bikes and drones [6, 18, 19], assuming in great number as the answer for the mobility problems. Although, research about the urban mobility impact and consideration is left aside by many.

Thinking on a different scale, another actor involved in this process are the companies responsible for providing delivery services, which can help with the safety of their employees and road users, relieving time pressure on workers by reducing their burden on number of deliveries, making them more efficient, providing more human work and, consequently, helping the traffic system, as drivers can act less recklessly.

The inherent externalities of this last-mile logistic influences on the reduction of logistics spaces and road safety, increases the traffic congestions and carbon-footprint, and alter the urban mobility planning scope. It is important to bear in mind that the urban mobility infrastructure providing good traffic conditions, policies and regulations can act positively towards a more ideal scenario. For example, thinking on a cyclist perspective, it is crucial to have adequate regulation for road sharing and road safety, education on how to share streets, a positive attitude towards cyclists, and an infrastructure that prioritize the cyclists [7]. People's willingness to change consumption behaviour [20] and the practice of workers in carrying out their tasks plays an important role in achieving an urban planning that entails this boom in food delivery.

There is a need to focus on studies and attitudes that can bring changes to planning and regulating cities, assuming last-mile delivery is one of the most crucial logistic segments, the improved fit of food delivery trend in the mobility system is paramount.

5 Conclusion

Although this study contributes to the food delivery and urban mobility literature, it suffers from a few limitations, as we have used specific inclusion and exclusion criteria to select the academic literature for the review, limiting the generalisation of findings. Whilst we endorse interventions developed by researchers with the urban mobility in mind, it is time to contemplate urban mobility planning more holistically, avoiding the technological solutions and pillared approach that ignores the broader dimensions of urban mobility and its rebounds. As the research trend is leading us to solutions such as drones and route optimization, it is more urgent to focus on the mobility aspects (e.g. lack of infrastructure, improvement of green modes of transport), and logistic challenges (e.g. how to make it more effective and sustainable, in a regulated manner).

The extent impacts on urban mobility caused by food delivery remain uncertain, opening an array of unresolved research questions. To move forward, stakeholders must evaluate how best can the negative aspects be mitigated and the positive promoted, ensuring a good urban mobility environment. Researchers may investigate solutions that will be best suitable for this gig economy in a planning aspect, and the challenges behind implementing technologies on the urban mobility environment. Also, governments must take actions based on studies and data collection, to improve their regulation in a sense that includes and restricts the delivery personnel, promote learning channels, and implement good infrastructure to their cities.

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Monitoring and Assessing Heavy Traffic Loads: Feedback from French Initiative and Data Analysis

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Abstract. The usage of road networks by road freight transport has grown since the first generation of pavements and structures, it is still growing, and regulations concerning weights and dimensions have widely evolved. These developments might accelerate the wear of infrastructure, therefore costs for infrastructure maintenance, repair and strengthening increases. For a National Road Authority or road manager, these effects are obvious, although not easily monetized. To be able to make effective policy, it is very important that the information about these effects is understandable for policymakers, contains the correct details and that the costs are transparent with a certain degree of reliability.

To deal with this issue, Cerema -which is the French national institute for road maintenance and assessment- has proposed a new service for road managers, which is the comprehensive monitoring of traffic loads and/or structures. Depending on the needs of the infrastructure managers, the traffic loads are being recorded and analyzed, and some vulnerable infrastructure elements (bridge or pavements) can be instrumented for better assessment and residual life estimation.

This paper will detail this innovative technical solution, by focusing on the sensing techniques that are being used and the processed information that is provided to the NRAs. For that, the implementation on an existing, integral, concrete bridge will be described.

Keywords: Heavy traffic loads · Weigh-in-Motion · data analysis · re-assessment of structures

1 Introduction: Problem Statement and Proposed Solution

The usage of road networks by road freight transport has grown since the first generation of pavements and structures, and is still growing, and regulations concerning weights and dimensions have widely evolved [1]. For example, the transport sector has to reduce emissions to contribute to the reduction of global warming, which led in some countries to larger vehicles that carry more goods with relatively less fuel. But other measures to reduce emissions and measures to meet the shortage of truck drivers can also lead to an average higher vehicle weight, such as powertrains for alternative fuels or better

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loading to reduce the number of journeys. These developments might accelerate the wear of infrastructure [2], there-fore costs for infrastructure maintenance, repair and strengthening increases. For a National Road Authority or road manager, these effects are obvious, although not easily monetized. To be able to make effective policy, it is very important that the information about these effects is understandable for policymakers, contains the correct details and that the costs are transparent with a certain degree of reliability.

Numerous sensitive structures and infrastructures, which may be off-limits to the heaviest vehicles, are subject to conditions that exceed the conditions of use. These overloads are not without consequences: premature aging, inability to use, even collapse. By implementing preventive measures, infrastructure managers can considerably reduce risks and impacts.

With the help of traffic analysis and hazardous vehicle identification tools, guidance in decision-making on monitoring and protection measures is proposed:

- **Establish a diagnosis of the traffic using the (infra)structure:** identification of data and its caracteristics to be processed according to the structure and its condition, inventory of existing (traffic) data, initial analysis of the structure's situation,
- **Design a device for monitoring and measuring overload:** Proposal of a device adapted to the technical context and environment, definition of relevant indicators for maintenance of the structure, design of infrastructure instrumentation to quantify and/or anticipate disorders, proposal of an intervention program if disorders appear,
- **Assisting the road owner or manager in its management strategy, both of the infrastructure and the monitoring solutions:** support in defining the monitoring and protection strategy (information, education, repression, etc.), purchase and deployment of monitoring and operating equipment (installation, initialization control, maintenance), monitoring and analysis of indicators, capitalization of results and definition of a traffic monitoring policy, training for the usage of these monitoring tools.

It is in fact very important to provide both information and indicators on the traffic and its agressivity to the infrastructure (as it is the only possibility for traffic management and it is what road managers often work with) and information and indictors on the structural health of the infrastructure and its evolution (as it is the real, measured time-dependent impact of the traffic and other actions on the structure).

In the following, we will briefly describe the implementation of this technical solution on an existing, concrete bridge.

2 Example of Traffic and Structural Response Monitoring

The example which is presented here is linked to an issue encountered by the public road manager, Alsace Collectivité européenne: Indeed, they need to weigh and monitor the abnormal loads and their effects, which carry gas turbines from Belfort to the harbours of Alsace [3]. Indeed, Alstom and General Electric manufacture and export gas turbines, which represent a high economic value. Despite the measures taken in terms of passage of the abnormal loads, surrounding traffic management procedures and the reinforcement of bridges, the frequency and weight of these convoys (800 tons) have led to track deterioration.

It has therefore been proposed to identify and weigh the most aggressive convoys (which are generally those with more than 25.5 tons per axle) on a weighing station at Herrlisheim-près-Colmar.

On the basis of these analyses, and with a view to anticipating maintenance operations, an ageing rule for structures as a function of actual traffic, has been proposed, based on traffic and structural measures at a concrete bridge (Fig. 1).



Fig. 1. Bridge monitored in both loadings and structural effects.

This bridge, whose structural type is quite usual in France (over 5000 bridges of this type) shows a certain number of defects: extensive transverse cracking and discontinuous longitudinal cracks on the underside of the slab, inclined cracks on the intrados in the corners, presence of moisture, longitudinal cracks and "hollow-sounding" areas on the lower surface at free edges, cracking of abutments with presence of moisture, water seepage between cornice and slab flanks, east and west, and even through cornices, characterized by active calcite concretions and detachment or flaking of repair plaster, etc.

Therefore, the main recommendations during the periodic inspection has been to monitor the evolution of the cracks on the intrados and abutments (length and width), but also to monitor the opening of longitudinal and transverse cracks during the passage of an abnormal load.

To implement that dynamic weigh-in-motion stations have been installed both on the bridge and on the pavement ouside of it (Fig. 2), and several cracks are monitored by displacement sensors.

3 Traffic-Induced Damage Detection: Some Elements of Assessment and Prediction

Traffic monitoring has been proved to be quite a challenge, as current, commercial weighing systems are not supposed to deal with such high loads. Therefore the accuracy was not as good as expected (for "normal" traffic, the accuracy of conventional WIM systems is traditionally around $\pm$ 10% for GVW).



Fig. 2. Layout and installation of weigh-in-motion stations.

Nevertheless, it could be noticed that there is quite a disparity in terms of measured Gross Vehicle Weight (Fig. 3), axle loads and distance to the closest axle (Fig. 4).

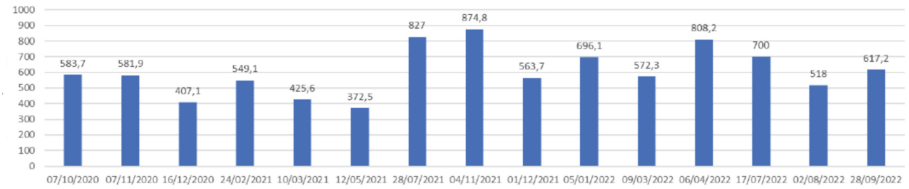


Fig. 3. Measured GVWs for individual abnormal loads.

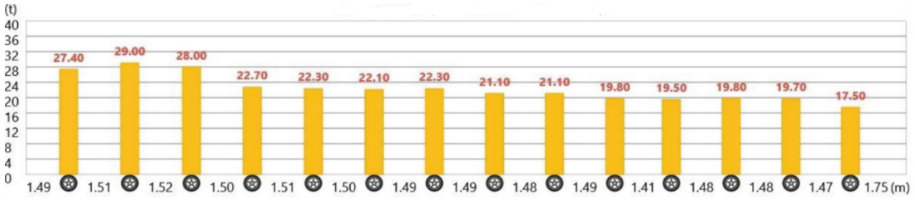


Fig. 4. Measured axle loads with correspond axle distances (distance to teh closest axle).

When considering the opening of the cracks, it has been found, quite obviously that the effect of the temperature is the major component and needs to be removed (Fig. 5).

Moreover, after removing the effect of the temperature, the exponential effect of these abnormal loads is visible (Fig. 6): in fact, it has been shown that after some passages of abnormal loads, some cracks do not close anymore which means that the structure has reached its plastic limit.

The work is ongoing, and is dealing with in-time data analysis for abnormal load effect assessment and time series prediction, for guidance in terms of traffic and infrastructure management.

From a practical perspective, a link between the measured damage sign (crack width) and characteristics of the vehicle (GVW, axle loads, travel speed) has been assessed: as expected for this type of short-span structure, the GVW has little impact, but axle loads

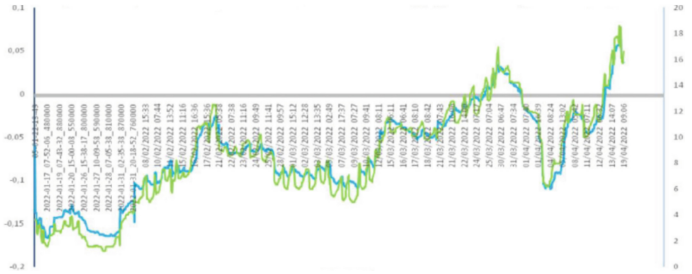


Fig. 5. Evolution of crack width (blue line) and temperature (green line) with time.

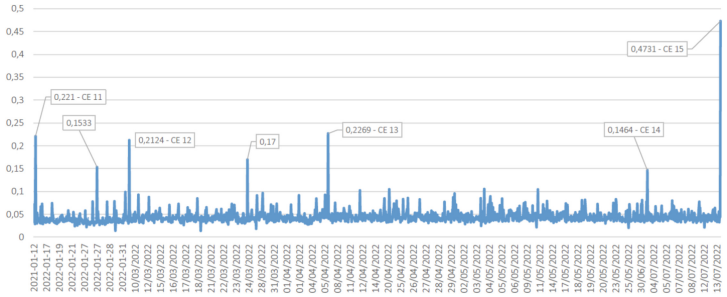


Fig. 6. Crack evolution in link with traffic loads

and travel speeds are important parameters to be monitored for global assessment of the wear of the structure (Fig. 7).

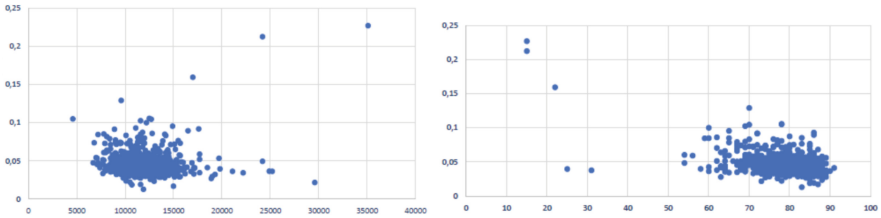


Fig. 7. Measured crack width as a fonction of the highest axle load of the vehicle (on the left, in kg) and the speed of the vehicle (on the right, in km/h).

4 Conclusion

Monitoring traffic and its influences on infrastructures is more and more needed today, because of the evolution of traffic loads and the ageing of the infrastructure. This paper has presented a technical solution, and some major conclusions that have been drawn.

Current works are linked to voluminous data analysis and time series prediction.

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Road Freight Models to Accelerate Green Transition in Europe

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Abstract. Finland's aim is to halve transport emissions by 2030 and eliminating them completely by 2045. One of the ways to reduce freight transport emissions is by linking and analyzing characteristics, like general freight transport volumes, time management and energy generation and use, to generate a road freight model as a policy support tool to assess development towards the zero-emission goals. The purpose of this study is to understand how to integrate electric freight vehicles in the future national road freight model of Finland. The study answers questions on identifying the current road freight transport models, methods of road freight transport model development, their purposes, and including electric freight vehicles in road freight transport models. Through literature review, we found out that there are number of studies providing overviews about the freight transport modelling, but only a few, which consider the electric freight vehicles as a part of modelling. Freight transport models are mainly used to provide support for decision-making at national or regional levels, and model to understand the relationship between transportation and economic activity and connecting the traffic flows with the networks.

Keywords: Road Freight Transport · Electric Freight Vehicles · Green Transition · Freight Demand · Freight Transport Model

1 Introduction

There is now a sense of urgency to decarbonize the transportation sector. The transportation sector is the second highest greenhouse gas-producing area with a 24% share of CO2 emissions in year 2017 [13]. About 5.5% of the global GHG emissions come from logistics activity. 90% of this is generated by freight transport, of which two-thirds are produced by trucks and vans [14].

Transportation planning plays an important role in an economy, especially using macro-level planning techniques. For example, by including population figures, proper capacity planning can be conducted [13]. Additionally, modelling of the road freight transport is necessary, and is a part of future studies since it is about prediction and planning [13]. Some of the variables that can be included in modelling road freight transport are the average cost and distance of freight transportation, population, area, number of cities and villages, average household income, and GDP of the province [13].

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Through the method of literature review, our purpose is to understand how to integrate electric freight vehicles in the future national road freight model of Finland. We aim to identify and describe the existing road freight transport models and road freight traffic flows in different European countries. The study answers the following research questions: 1) What are the current road freight transport models? 2) How are the road freight transport models developed and for what purposes are they used? 3) How can electrified road freight transport be modelled to strengthen the green transition by adoption of electric freight vehicles?

2 Freight Models

Freight transport is a necessary part of the economic development of a region due to its role of moving goods [1]. Additionally, planning of road freight transport is very crucial in a country, and should include traffic flow on the roadway networks, as proper planning can lead to operational flexibility and availability [13]. It must be noted that inefficient logistics operations cause high costs to be incurred, which would in turn limit the growth and the competitiveness of an economy [7]. Furthermore, increase in traffic causes road congestions, which reduces the productivity of freight transport operations and also deteriorates the reliability of deliveries. The "sequential four-step model" for passenger transport planning was redefined for freight demand modelling as supply-demand (monitoring the economic activities), distribution (modelling freight flows from origin to destination), modal split (assigning the freight flows on different modes), and assignment (change freight flows to vehicle units and assigning them to networks) [6]. Freight transport modelling is associated with the following actors: producers make the goods to move, shippers manage the movement, carriers haul the goods on the roads, hauling companies handle their fleet on the roads, and consumers create demand for goods and thereby causing transportation demand [11]. Moreno-Quintero [10] argues that the road planner, who provides road repair and maintenance services, is also a significant actor.

3 Methodology

This research compiles studies on road freight transport models and gathers data to understand the current models, how they are developed, their purposes and how electrified road freight transport can be modelled to strengthen the green transition by adoption of electric freight vehicles. Using Scopus database, 52 papers were found through the use of the following keywords "Road freight", "transport", "traffic", "modelling", "model", "flow" and "density". This number of papers were narrowed to 15 when selecting the most relevant articles for this study.

4 Results

4.1 Road Freight Transport Models

Havenga, J. H [6] said that there are many national freight demand models that have been developed in Europe, and they are being recognized and used for different purposes. SAMGODS (the Swedish model) and the Norwegian model are the most famous ones [6].

The National Freight Model or NFM for Norway is a strategic transport network model [12] that optimizes shipment sizes, "transport chains (number of legs, selection of modes and vehicle types)" [12] and transit points to reduce associated costs. The model is composed of the following components [12]: Transport Demand (the commodity flow matrices, which is the total commodity flows between suppliers and end users, between municipalities), Network Model (infrastructure of all transport modes, showing transport distance, time, and location of terminals), Cost Functions (costs associated with transport distance, time, and functions for all transport modes), and Optimization (best possible choice based on shipment size, frequency, and mode to reduce associated costs).

The national transport model Austria (Verkehrsmodell Österreich, VMÖ) is examined by Grebe et el. [5]. This new VMÖ model consists of both passenger and freight parts, and it aims to model all the transport that is relevant for transport flows on Austrian infrastructure. The freight part of the model is an Aggregated - Disaggregated - Aggregated (ADA) model with following steps: the results of an input-output-model are transformed into firm-to-firm flows, the choice of shipment size and transport chain is modelled, and the origin-destination (OD) relations are aggregated for the individual modes and assignment to the networks. The ADA model has been implemented for Sweden, Norway, and Denmark as well. The resulting model outputs are generated trips (distinct OD-matrices for each mode, travel purpose, population group, etc.), the distribution of different key variables (time, distance, cost, etc.) and transport performance both for freight and passenger transport (tonne-kilometres, passenger-kilometres).

Stock-flow model (BIG) of the Norwegian vehicle fleet differentiates vehicles into 7 types, does not consider two-wheelers, considers only vehicles that drive on roads, and further classifies vehicles based on their powertrain technologies. The values that are input into the model are the vehicle class, powertrain technology and weight of the new vehicles from the base year until year 2050. The model generates the "annual vehicle stocks, vehicle kilometres driven, tonne kilometres hauled, energy consumption by powertrain" [12] and emissions.

In the European Union (EU), an integrated transport policy analysis tool, TRANS-TOOLS, was developed in 2004, which considered the Trans-European Transport Networks (TEN-T) development and policies related to sustainability, intermodality and decoupling. The use of this tool is to support transport forecasting, infrastructure planning and policy analysis. In 2015, the HIGH-TOOL was developed as a strategic high-level transport policy assessment instrument to analyze policy scenarios and is being supported by the TRANS-TOOLS [6].

4.2 Development and Uses of Road Freight Transport Models

The classic road freight transport model, which was redefined by De Jong et al. [6], is combined with spatial general computable equilibrium models, supply chain choice models, and hypernetwork models, in recent times [1]. In France, there is a domestic road freight survey (TRM) consisting of a poll on French trucks. Three types of information are asked: targeted information (location of loading, location of unloading, category of good transported, reported tonnes, reported tonne-kilometers), sampling information (statistical weight of each truck), and contextual information (age of the vehicle, the type of vehicle, activity of the transporter and region of registration) [2]. Havenga and Pienaar [8] proposed a methodology to create and apply national freight flow model for South Africa. The proposed methodology develops a comprehensive description of South Africa's surface freight flow market space based on the definition of four definitive freight flow market segments, and these segments are used to develop national road freight flows using the annual traffic counts.

Havenga [6] lists the purpose of national freight demand modelling as: to assess the impact of different transport policies, to form policies to use multi-modal network for freight transport optimally, to develop transport infrastructure and related policies, to conduct a cost-benefit analysis on decisions regarding transport infrastructure development, and to understand spatial location demand patterns. The road freight transport model helps to understand the schedule of the goods vehicle fleet, to solve logistics challenges, to conduct integrated planning for national infrastructure development, to assess the complete transport of goods and commodity flows, to improve vehicle utilization and fuel efficiency, and to shift to alternative transport modes and lower use of carbon fuels [7]. The future vehicle fleet requirements can also be estimated, which would allow better freight transport and environmental policy development, congestion planning, fuel demand- and oil-price estimation [7]. The model also helps the authorities to make informed decisions on investments in certain transport modes [7]. In South Africa, the annually gathered freight-flow information could be used to infrastructure planning, optimal network development and market structuring. The new South African model gives the total surface freight transport flows, which defines the trends in movement in various metropolitan areas and rural areas [8]. Gallo and Marinelli [3] used the road freight transport simulation model, to evaluate the impact on CO_2 emissions and fuel consumption of the introduction and development of fuel cell electric vehicles (FCEVs) for long-haul freight transport. The results highlight that the simulation model could be useful to identify the optimal locations for refueling stations, which require a detailed analysis of traffic flows and should be made at a regional level and with national coordination. Loder et al. [9] studied urban traffic modelling using the unique pNEUMA drone data set from Athens, Greece, to describe and shed light on urban freight operations. The data covered vehicle stopping frequency and loading and unloading stops. One of the aims was to provide information for decision-making processes in municipalities.

4.3 Green Transition by Modelling of Electric Freight Vehicles as Road Freight Transport

Studies have shown that a system level decarbonization of road freight is possible, but it requires many initiatives and time [12]. According to Rosenberg et al. [12], GHG

emissions can be reduced by electrification and by using hydrogen as fuel for long-haul freight vehicles. This can be achieved by introducing strong policies (e.g., high CO_2-taxes), and developing new technologies in the field of batteries and hydrogen. Unfortunately, battery cost, it's gravimetric energy density and lifetime are the major disadvantages for battery electric trucks (BET) [12]. The disadvantages for fuel cell electric trucks are the fuel cell costs, hydrogen tank volumes and hydrogen prices [12]. Nevertheless, many vehicle manufacturers have planned manufacture of electric heavy-duty trucks [12]. Additionally, a good charging/ refueling infrastructure is also required to function the transport fleet. González Palencia et al. [4] studied the role of powertrain electrification in achieving deep decarbonization in road freight transport in Japan as a case study, using a vehicle stock turnover model and a scenario-based approach. The results of the study can help policymakers to understand powertrain electrification to reduce CO_2 emissions from road freight transport and consequently, help them to design policies to reach environmental targets and emissions reductions in the transport sector. They highlighted the requirement of cost and supply of electricity and hydrogen to achieve powertrain electrification in road freight transport.

5 Discussion and Conclusions

In this paper, we understand the current state of road freight transport models for the integration of electric freight vehicles. Firstly, the study examined the current road freight transport models, some of which we found from literature, are: the National Freight Model or NFM for Norway (a strategic transport network model to optimize transport operations and reduce costs), the national transport model of Austria called VMÖ, (to generate trip-related factors, variables, and transport performance), the Stock-Flow Model (BIG) from Norway (to generate annual vehicle stock, vehicle kilometers driven, tonne-kilometers hauled, energy consumption by powertrain, and emissions), EU's TRANS-TOOLS (an integrated transport policy analysis tool), and EU's HIGH-TOOL (a strategic high-level transport policy assessment tool to analyze policy scenarios). Secondly, the study explored the development of road freight transport models and found that the classic road freight transport model has been redesigned to combine spatial general computable equilibrium models, supply chain choice models, and hyper-network models. Thirdly, we investigated the purpose of road freight transport models to find that they are developed to assess the impact of policies, make decisions on transport infrastructure development, assess goods and commodity flows, estimate future vehicle fleet requirements, and plan to avoid congestions. Lastly, we delved into integration of electric freight vehicles in road freight transport to know that road freight transport models can be used for designing policies, planning for green technologies, calculating emission reduction, and estimating the cost- and planning the supply of electricity and hydrogen for the transport fleet.

The practical implication of this paper is that it gives information to authorities and other transport industry stakeholders, to plan the transition to electric freight vehicles. However, a limitation of this study is that there were only a few journal articles on integration of electric freight vehicles and road freight transport models. In the future, our aim is to create a national road freight transport model in Finland to facilitate green

transition. This paper is part of the research project SIX HOVE (Sustainable industry X – Heavy on-road vehicles ecosystem), which is being conducted in Finland. The aim of the research project is to produce a roadmap for the promotion of electrification of trucks in Finland.

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Understanding the Success of Road Freight Decarbonization Strategies. A Case-Study from Spain

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Abstract. Road freight transport decarbonization is an important element in the global agenda. There is a large body of literature addressing operational research solutions and optimization. However, it is not clear whether the actual sector can be reactive to policies to promote its decarbonization. Even more when the sector is pressured by its clients and upstream supply chain trends, and seems not to have any room for enhancement. In order to further understand the sector's potential to improve its productivity, a system's dynamics diagram is developed. Moreover, an analysis of the Spanish road freight sector with quarterly data from 2000 to 2023 is carried out using a vector error correction model. Results suggest that the sector's productivity, in ton-km, is reactive in the long-term to diesel prices, by producing a lasting reduction ton-km. However, the long-term response to an increase in transport prices might increase the total ton-km.

Keywords: Road freight · system dynamics · error correction model · econometrics

1 Introduction

Road freight transport is both a contributor to GDP as well as to GHG emissions and climate change, making its decarbonization an important element in the global agenda. It has been largely researched and operational solutions to improve its productivity have been produced. However, it seems that it faces many barriers for it to improve its productivity. As [1] puts it, transport demand is described as having a derived nature in that the client does not receive any benefit from the transport itself. It is complementary, and necessary, to the economic activity it serves (connecting geographically separated economic agents).

The logistic efficiency and the energy efficiency improved, especially in the 1990s due to the allowance of heavier trucks. Since then, no major efficiency gains have been realized (according to [2]). In relation to that, based on literature review, 6 main challenges have been identified: asset utilization ([3, 4]) consolidation, the pressure of lead time and other supply chain trends ([3, 5, 6] and [7]) backhaul, fuel efficiency and its rebound effect ([8]) and incentives ([2] and [9]).

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The sector's performance being subordinate to the demands of its clients arises the question of what transport policies can help decarbonize road freight. To analyze this, this article first, using system dynamics, depicts the whole picture of the sector and derive conclusions the potential of pricing. Second, it carries out a Vector Error Correction Model (VECM) using time-series analysis for the Spanish sector quarterly data from 2000 to 2023 in order to assess the potential impacts of transport price and diesel price on productivity (ton-km), hence aid in decarbonization.

2 System Dynamics to Capture the Complexity of the Sector and Policy Implications

In view of the intricate position of the sector, system dynamics (SD) approach is suitable for investigating the effects of policies and strategies in complex systems ([10]). Figure 1 expands on the work of ([11, 12]) in SD in freight. In general, five big lines of causalities are found towards the sector's decarbonization. These are because of demand; because of infrastructure and road freight mode share; consolidation (optimization and load matching); and fleet engine efficiency; fleet sizing; and costs (marked loops 1 to 9).

For the purposes of this conference paper, loops 1, 1' and 1'', all describe the balancing loops affecting the system's fuel consumption though consolidation and reduction of total distance travelled (either ton-km or veh-km), yet each channels ton-km decline through either empty running, average distance travelled and number of shipments, respectively.

Related to that, loops 3 and 4 help understand that demand is not affected through price. First, because it can be absorbed by the carrier (freight operator's profit margin) or because (loop 4) transport costs are balanced through an optimization of the system (consolidation, decline of empty mileage, etc.). These mechanisms are important to understand whether, through the subsequent econometric analysis, it is found that the sector's output indicators are not reactive to prices.

3 Time Series Analysis of Road Freight Productivity in Spain

Stemming from the system dynamics diagram an increase in the transport costs (variable), would result in a short-term decrease in the productivity indicator. In the light of this, the question is whether such decline lasts in the long-term. That is the long-term effects of consolidation through pricing mechanisms.

For this purpose, the observatories of road freight transport from the Spanish Ministry of Transport, Mobility and Urban Agenda (MITMA, [13]) provide the necessary data in quarterly periods since 2000. Relevant indicators have been plotted in Fig. 6. Ton-km, ton transported and ton supplied (fleet size indicator) fluctuated according to the 2007 crisis. On the other hand, productivity indicators decreased (ton/ton-supply) or remain constant over time (ton-km/ton-supply). With that, it can be concluded that in term of productivity per asset, the system has resulted in a loss of efficiency or productivity. Finally, both diesel and distribution price have been increasing steadily, diesel being more volatile. That is another indication of the system's ability to absorb price variations and not pass it to the customers (see 2008–2021 period) (Fig. 2).

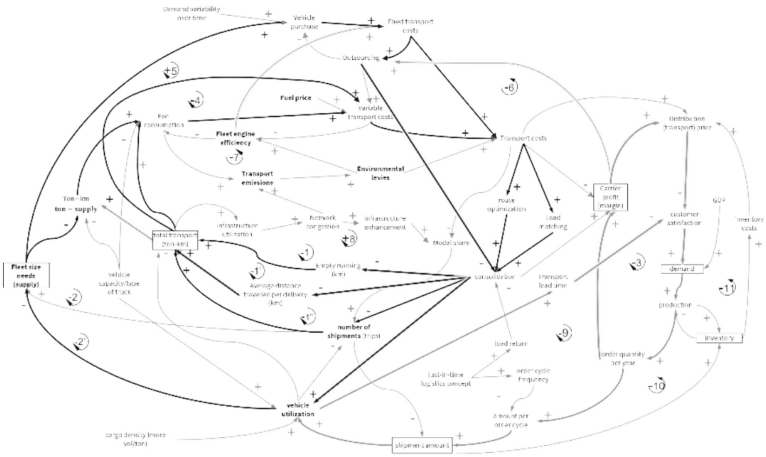


Fig. 1. System dynamics of road freight transport. Reinforcing loops marked with numbered circled arrows with positive sign, likewise for balancing loops market with a negative sign.

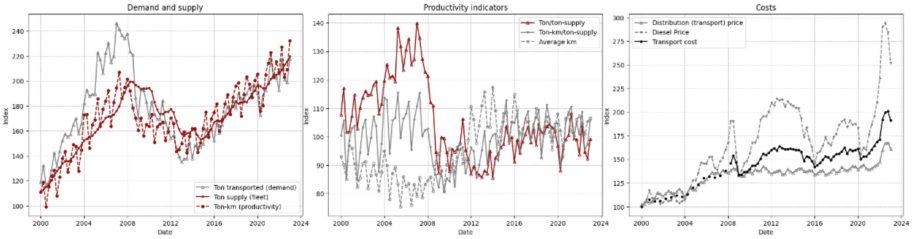


Fig. 2. Evolution of quarterly data of road freight indicators in Spain.

3.1 Vector Error Correction Model

In view of the above, this section will develop an error correction model to study the long-term relationship between variables. In particular, between ton-km, transported tons (as a demand indicator), diesel price and distribution (transport) price. Examples of ECM models are found in the literature for freight time series analysis ([1, 14–16]).

The Vector Error Correction model follows the formula in Eq. (1). In this case, it has a restricted trend with dummy variables correction for 2007 crisis (2007–2009), pos-crisis period (2009–2019) and COVID-19 period (2020–2023), given that the range of data is quarterly from 2000 Q1 to 2023 Q2. Vector $\boldsymbol{y}$ is composed of the variables mentioned above, and the error correction term is represented by the bracket component pre-multiplied by the adjustment coefficient $\boldsymbol{\alpha}$.

$$\Delta \boldsymbol{y}_t = \theta_0 + \phi t + \sum_{i=1}^{n} \theta_i \Delta \boldsymbol{y}_{t-i} + \sum_{i=0}^{n} \delta_i \Delta \mathbf{x}_{t-i} + \boldsymbol{\alpha}(\boldsymbol{\beta}' \boldsymbol{y}_{t-1} + \varepsilon + \tau t) + \mu_t \quad (1)$$

3.2 Results

All series are stationary of order I(1), the lag order is selected to 1 and the cointegration order is selected to be 3. With this specification the model passes the autocorrelation, heteroskedasticity, and residual normality tests.

Table 1 (model fit) shows that despite the beta coefficients of the three ECTs being significant, no alpha adjustment coefficient, neither for diesel price in the first equation, nor ton transported for the second or ton-km for the third long-term relationships are significant nor with correct sign (the product of $\alpha \cdot \beta$ must be negative, [17]).

This is important as it suggests that the 3 cointegration equations expected cannot be found between solely ton-km and the rest of the variables. This could suggest that (in the 2000–2023 period), in the long-term, ton-km has not been affected neither by transport price nor diesel price. What this might suggest is that the equilibrium changes when there is a deviation from the equilibrium. This fact can be checked with the subsequent analysis of impulse response functions.

Table 1. Results and significance of the coefficients of the ECM $\boldsymbol{\beta}$ and adjustment vector α coefficients (p-value in brackets, *** < 1%, ** < 5%, * < 10% and - > 10%).

	$\beta 1$	$\beta 2$	$\beta 3$
Ton-km	1	1	1
Ton transported	0	−0.55448(***)	0
Transport price	0	0	6.4776 (***)
Diesel price	0.35075(***)	0	0
Trend t_0	−0.011089(***)	−0.0029422(***)	−0.0345(***)
θ_1(constant 2007–2008)	−0.60167(***)	0.031388(-)	−2.2168(***)
Trend t_1 2007–2008	0.020205(***)	−0.00079838(-)	0.071446(***)
θ_2(constant 2009–2019)	−0.10667(***)	−0.016675(-)	−0.67722(***)
Trend t_2 2009–2019	0.0081310(***)	0.0013156(**)	0.029408(***)
θ_3(constant 2020–2023)	0.95696(***)	0.031896(-)	4.1499(***)
Trend t_3 2020–2023	−0.0044372(-)	0.00079930(-)	-0.028618(***)
	$\boldsymbol{\alpha}1$	$\boldsymbol{\alpha}2$	$\boldsymbol{\alpha}3$
Ton-km	−0.30633(***)	−0.75212(***)	−0.032087(-)
Ton transported	-	0.38082(-)	-
Transport price	-	-	−0.061016(***)
Diesel price	0.21746(-)	-	-

First, Fig. 8 shows how after an initial drop in ton-km when transport price increases, the long-term equilibrium shift to an eventual rise in the total ton-km. This might be explained because of the low effect of transport prices in the long-term that are overrun by the exogenous transport demand. Figure 10 might support that, showing that a rise

in the transport prices has no effect on the demand of freight transport, but may even increase. Note, however, that the 90% confidence interval is close to zero implying that in reality there might be no effect (uncoupling of the two variables).

On the other hand, after a positive shock in diesel price, ton-km experience a rise that is quickly compensated for by a decrease in ton-km, presumably because of the pressure of truck operators to consolidate their operations (Fig. 3).

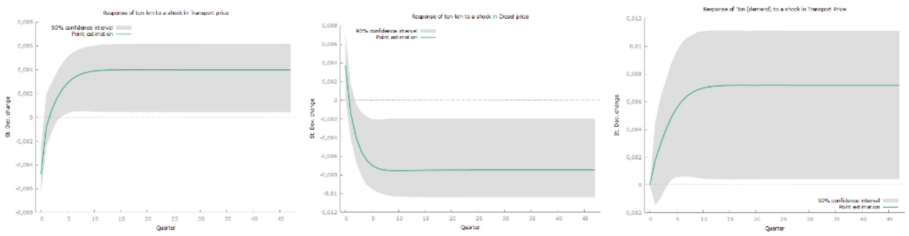


Fig. 3. IRF of productivity (ton-km) to a positive shock in transport price (left) and diesel price (middle). IRF of a positive shock in transport price upon ton transported (demand)

4 Conclusions and Policy Recommendations

This research has evaluated, through a vector error correction model (VECM), the impact of diesel and transport prices in the whole trucking industry (road freight) in Spain, from 2000 to 2023. From the statistical description of the sector's productivity indices, both mass occupancy (ton/ton-supply) and ton-km/ton-transported suggest that not only the productivity has not increased but it has decreased. This is in line with the literature position on the sector's subordination to its clients or upstream and downstream supply chain trends. Despite this, the VECM might indicate that the system's total production can be reactive to diesel price and transport prices.

Results suggest that changes in distribution (transport of cargo) prices and diesel prices might have a long-lasting response, as shown by the Impulse Response Functions analyzed. For instance, a positive shock in diesel price, after a short-term increase there is a shift to a new equilibrium where total ton-km are reduced. That is aligned with the system dynamics diagram developed where the trucking companies compensate for an increase in the transport cost by optimizing their operations under balancing loops. Secondly, an increase in transport prices, after an initial decrease in ton-km (perhaps due to a decrease in demand), demand might recover due to the exogenous economic conjuncture, carriers do not face pressure to consolidate the operations resulting in an eventual rise in ton-km.

In view of the above, it may be concluded that pricing policies on Diesel do have a positive effect because of the reduction of ton-km in the long-term. The consideration of such pricing policies must be taken with care, as the profitability of carriers must be ensured so that the sector does not become precarious. In particular, given that diesel prices are not passed to the clients as it is clear from the evolution of prices.

On the other hand, distribution (transport) prices do not turn out to be aligned with the reduction of ton-km. It means that the system dynamics of the sector and the other economic activity precursors do not have the power to transmit information to the clients and change their cargo requirements. It could be suggested that freight activity is, to some extent, uncoupled from transport prices. Consequently, demand management through pricing seems to have limited reach.

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Implementing Sustainable Micro-Logistics Hubs for Innovative Physical Internet Urban Delivery Methods: The Bologna Case

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Abstract. Within the HORIZON EUROPE project URBANE, the Bologna Living Lab is implementing a measure listed in the Sustainable Urban Mobility Plan (SUMP): Nearby Delivery Area (NDAs), combined with a collaborative approach among logistics operators and the utilization of zero-emission vehicles. The NDA serves as a micro consolidation centre for the transhipment of goods from conventional vans to cargo bikes and/or light electric vehicles. The ultimate goal of this pilot project is to define guidelines for implementing low-impact and sustainable micro-logistics hubs for urban deliveries.

The paper provides an update on the ongoing implementation, with a description of the current state of the art and the incoming data from the deliveries operations.

Keywords: Sustainable urban logistics · Micro-logistics hubs · Nearby Delivery Area · physical internet · Collaborative logistics · Freight as a Service (FaaS)

1 Introduction

Microhubs play a crucial role in re-designing the last-mile delivery chains and enabling the use of light electric vehicles. These vehicles, while having shorter travel ranges compared to traditional diesel and petrol trucks, are well-suited for circulating in high-density city centres with narrow streets and limited space for loading and unloading activities [1]. Many pilot projects indicate that urban cycle logistics and microhubs concepts can be successfully implemented. These initiatives seems to offer a more viable alternative to Urban Consolidation Centres, but they might still face similar issues like low profitability and high dependence on public subsidies [2, 3].

As part of the HORIZON EUROPE project URBANE, the Bologna Living Lab is working towards implementing a measure outlined in the Sustainable Urban Mobility Plan (SUMP). This measure involves the establishment of Nearby Delivery Areas (NDAs) combined with a collaborative approach among logistics operators and the deployment of zero-emission vehicles. The primary objective is to create a low-impact solution that restructures last-mile deliveries by integrating the use of electric cargo tricycles and lockers as microhubs.

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The ultimate goal of this pilot case is to define guidelines for implementing sustainable, low-impact, and innovative micro-logistics hubs for urban delivery methods. These guidelines have the potential for significant replicability in other contexts due to the modular approach that allows for the activation of various services as needed.

This paper aims at the implementation of the pilot project in order to contribute to the lack of specific knowledge about the diversity of functions and special features of cycle logistics and related transshipment hubs, extensive urban planning regulations, and scaling of cycle logistics systems beyond pilot status.

2 Methodology

The pilot project in Bologna is analyzed as a case study, with two main phases. The first phase of the pilot deals with designing and planning the implementation. It has been running from December 2022 until January 2024.

To describe the main characteristics for the phase 1, the framework proposed by Katsela et al. in 2022 [2] is adopted. This framework focuses on microhubs typologies, and their distinctive features. It includes the following seven elements:

1. Microhub definition
2. Infrastructure and location
3. Last-Mile Fleet Composition
4. Operational Typology- focus on Shared Infrastructure
5. Stakeholder Partnerships
6. Public Support
7. Key and Value-Added Activities

2.1 Data Source

The second phase, focused the actual test of the microhubs and final deliveries, will run from February 2024 until August 2024 and it will provide a dataset with information such as the details of routes for deliveries, trip distances, and the use of the lockers. These data are not presented in the paper, however a presentation of the preliminary data will be available for the conference.

3 The Pilot Project in Bologna, Italy

The Living Lab will be implemented in the historical centre of the municipality of Bologna, with an area of about 4 km^2. The coordinates of the most important square (Piazza Maggiore) are 44.493889°, 11.342778°.

Bologna (387,842 inhabitants) is the regional capital of Emilia-Romagna region, located north-central Italy. The city is one of the main nodes of national and international transportation networks. Indeed, it has a direct access with the main motorways (A1 Milan-Naples, A14 Bologna-Bari, A13 Bologna-Padua) and with the regional and national rail networks (including high-speed one). The Bologna International Airport

(Marconi) and the railroad terminal (Bologna Freight Village, that is located in the territory of Bologna Metropolitan City) are classified as Core Nodes of three European Transport Corridors (Baltic Adriatic, Scandinavian Mediterranean, Mediterranean).

The municipality of Bologna has 387,842 inhabitants, of which 53,737 residents in the historical centre, namely the oldest part of the city that is included in the ring road system. Almost the entire road traffic in the historical centre is regulated by limited traffic areas. In the municipality of Bologna there are 6,866 active commercial businesses. Almost the 40% of the total amount of these businesses (2,656) are in the historical centre and 2.312 are included in the limited traffic areas.

The city aims to promote Freight as a Service (FaaS) and the physical internet approach in urban freight distribution, utilizing cargo bikes and vehicles with modular units to facilitate flexible, fast, and sustainable transhipment. For this pilot test, the city of Bologna adopts an omnichannel approach, enabling the flexible, shared, and optimized use of infrastructures primarily located in public spaces.

City planners are exploring the introduction of physical internet delivery methods and the potential future application of crowd shipping. The URBANE Project also supports the development of a Digital Twin of the micro-logistics hub network, using real-time data, which will aid in planning for public administrations and enable resilient and sustainable deliveries for operators.

The following subsections describe the pilot case based on the seven elements identified by Katsela et al. [2].

3.1 Microhub Definition

The microhubs are identified as part of the NDAs, where installing an automated parcel locker, remotely managed and monitored. Each locker has 45 slots, 135 in total for the three lockers.

3.2 Infrastructure and Location

The municipality has conducted the difficult task of identifying suitable locations considering the spatial constraints in dense urban environments. The medieval city's morphology posed limitations for logistics operations, characterized by limited curb space and a lack of available parking and loading facilities.

In determining the chosen locations, factors such as the site for loading/unloading and transhipment activities, whether at the curb, in public or private parking lots, had to be taken into account. These selected locations needed to allocate the required space while also ensuring minimal conflicts with nearby residents, institutions and shops, and adhering to efficiency criteria for optimizing last-mile operations.

As a result, three NDAs have been identified, indicated by a blue star is the microhub, for deliveries within the historic centre (Fig. 1).

3.3 Last Mile Fleet Composition

The final deliveries are carried out with electric pedal-assisted cargo tricycles, a 90 cm wide rear-wheeled tricycle with a carrying capacity of 90 kilos, a maximum battery

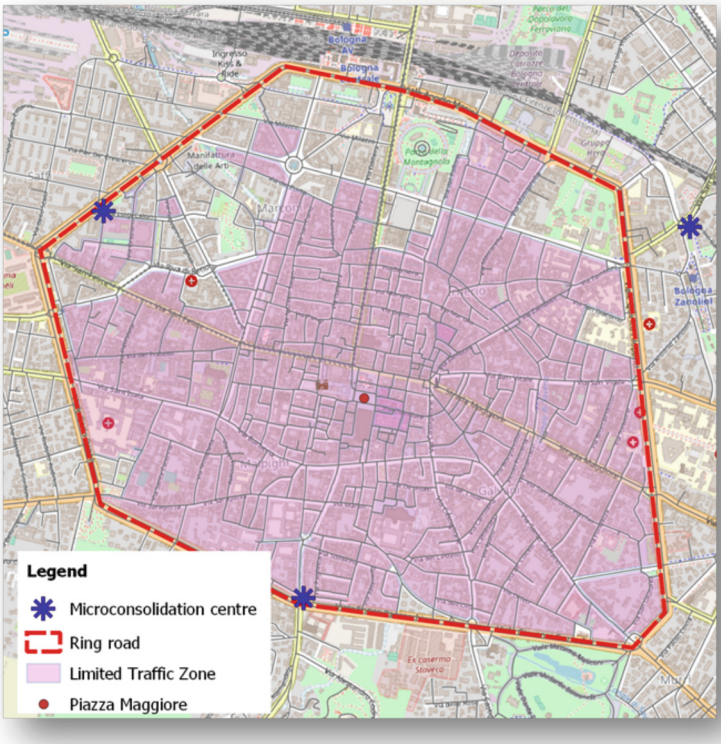


Fig. 1. Bologna's three microhubs. Image courtesy of the Horizon Europe project URBANE (grant no 101069782), reproduced with permission.

operating range of 100 kms, and the maximum speed for pedal assistance capped at 32 km/h. The vehicle provides real time tracking.

3.4 Operational Typology- Focus on Shared Infrastructure

The city of Bologna opted for a shared infrastructure for logistics operations. For the pilot project, the local authority has started the lease for three lockers, accessible to the three carriers involved in the test. The lockers are located in public land. The public authority has contracted private transport providers via tender for the final deliveries.

3.5 Stakeholder Partnerships

The strategy at city and metropolitan levels includes various stakeholders from the public, private sector, and civil society. In practice retailers, transport providers, society, residents, and end-receivers have been involved in the process of urban planning over the years. The SULP of Bologna already identified a permanent table for the development of the freight activities which is the Freight Quality Partnership (FQP). This working

group is led by the City of Bologna and all the trade associations for shops and transport operators are members.

The partners involved For the pilot project, selected stakeholders have been involved, including the Institute for Transport and Logistics (ITL) to coordinate the technical activities; and Gel Proximity, the facilitator of data exchange between lockers (or delivery points). Its task is to provide the access to the NDA to the different transport operators and to the different last milers. This is done by using API which allows to connect different services to an open network of logistics deliveries. The transport operators involved are TYP and 2 Torri.

The partnership includes the Emilia-Romagna Region, OPEN ENLoCC, Trade associations, AICAI (Italian Air freight forwarders associations), DHL, FedEX, UPS, Etc., the Metropolitan City of Bologna, Enel X for the potential use of NDAs as recharging stations for electric vehicles. Moreover links to other cities of the region (e.g.: Ravenna, Piacenza, Modena, Reggio Emilia, Rimini) are established.

3.6 Public Support

The pilot project receives public financial support for operations at the startup phase, with the intention of phasing out subsidies as the centre generates enough market volume to create self-sustaining operations.

Moreover the city of Bologna has designed restricted access areas and emissions-based restrictions, with deliveries time windows.

3.7 Key and Value-Added Activities

The key activity linked to the pilot project is the opportunity to digitalize the NDAs use and to implement a booking system for the transhipment activities, which could be linked to the routing system to optimize trips. Moreover real time information on flows and quantity of freight will be available, combined with geolocalization of vehicles. This information is particularly important for the city in order to take decisions on the time windows of the Limited Traffic Zone and for the implementation of other urban freight related measures (e.g. night deliveries). The digitalization process must be accompanied by a relevant and detailed study on GDPR.

The identification of these areas and the use of EGNSS systems will also allow a more optimal use of the infrastructures, passing over the traditional booking system and using more innovative IT tools based on artificial intelligence.

The digitalization of the service can be done by using the digital solutions like as Blockchain technology or APIs: Indeed, considering that most deliveries are expected to be done through a cargo bike, it is important to consider also the social situation of riders. Bologna is the first EU city which implemented the “Carta dei diritti fondamentali dei lavoratori digitali nel contesto urbano” (Chart of the fundamental rights of digital urban workers, signed by the city of Bologna on gig economy) to which some web platform already joined. In this perspective, the aim is to protect the riders right by using digital registers which preserve the information and log all the pick ups and drop off from the NDA. This digital solution will also allow the unattended deliveries and pick ups to and from the NDA.

4 Final Remarks

Consolidation centers have typically encountered challenges such as low profitability and a strong reliance on government subsidies due to stringent regulations. The emerging trend of transitioning towards smaller hubs, like microhubs, represents an attempt to address these issues. This ongoing pilot project in Bologna aligns with the current trends and it has the goal to test a low-impact solution combining NDAs with automated lockers and light electric vehicles.

Various challenges are faced including the development and establishment of a business model for innovative delivery methods in urban areas [2]. In similar initiatives in European cities, players of the last mile deliveries have experienced the greatest levels of disruption and might have not financially benefitted from additional and costly transshipment operations in the urban core. Therefore it is even more crucial to foster collaboration among various logistics operators, including potential competitors in the sector, as promoted in Bologna.

Moreover reducing the distance travelled by traditional vehicles is crucial to mitigate negative externalities such as road congestion, noise, CO2, and pollutant emissions. This approach will enhance road safety and improve the quality of urban spaces. Furthermore,

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Freight Demand Modeling for Green and Digital Logistics

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Abstract. Freight transport demand modelling (FTDM) from dispatch logs and partial observations play a key role in providing realistic expectations of freight transport needs and in assessing the environmental impacts of new policies. Shaping freight transport to answer the current challenges of green logistics – decarbonization, energy consumption optimization, intelligent and sustainable management – requires a continuous assessment and adaptation of the whole logistic system. Demand-centric models may support these ends. Understanding advances in freight modelling is thus crucial to overcoming FTDM challenges, including data scarcity. This paper provides two major contributions: i) a review of the state-of-the-art models on freight transport demand modelling, and ii) an integrated overview of how these models can support decision-making aligned with sustainability goals towards green (zero emissions) and digital logistics.

Keywords: Freight demand modeling · Green logistics · Digital logistics

1 Introduction

Freight demand models aim to provide a representation of how vehicles, goods, commodities (or other units of reference) move within a spatial network. Understanding these patterns involves the development of models that simulate the demand and supply for various transportation services, such as road, rail, air or sea. In the literature, two types of freight demand modelling are prevalent: Origin-destination and tour-based models [1, 2]. Origin-destination (OD) models aim to represent the flow between an origin and the final destination, while tour-based models estimate trip chains starting and ending at the same location (e.g., a single truck departs from a warehouse, distributes goods to a number of sites, and then heads back to the same warehouse). Regardless of the unit trip formulation, these approaches are a specialized aspect of transportation planning and analysis, crucial for providing valuable insights into the movement of vehicles/goods (e.g., supplier to consumer or supplier to warehouse), optimizing supply chains, and making informed decisions related to freight operations, logistics, and transportation policy. This paper aims to contribute with: i) a review of state-of-the-art freight demand models ii) their applications in aiding decision-making that aligns with sustainability objectives (Sect. 2) and discussion of future challenges associated with demand modelling in the context of decarbonization and digitalization (Sect. 3).

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2 Freight Transport Demand Models Applications: Insights from the Literature Review

2.1 Freight Origin-Destination Models

In the context of aggregate freight demand analysis, the four-step approach is still largely used for freight OD demand modelling [1, 4]. Due to the challenges in acquiring disaggregated trip data, including the fact that individual trip data is private, this method is still used in research [4]. By combining input assumptions and aggregated data (e.g. Direct survey of demand and supply), this model generates a set of trip tables that describe the major flows within a study area (by zone). Conventionally, the model is iteratively refined along the following four stages: i) trip generation, ii) trip distribution, iii) mode choice and, iv) trip assignment. The trip generation model estimates trips generated in each zone using socio-economic and land use variables as its first step [1–3]. Having attraction and production volumes, the trip distribution model disaggregates the data by assigning trips (or another reference unit) for zone-to-zone links. To this end, gravity models are a prevalent approach [1, 4, 6]. This model establishes trip frequency between i and j as proportional to the product of attraction in zone i and generation in zone j, adjusted by the distance or impedance function. For instance, Kalahasthi et al., (2022) include the weight of cargo transported from zones i to zone j. The mode choice model aims to distribute the trip flows between modes (e.g., private car, truck, rail), considering for instance market shares and shipment level [1, 3]. Holguín-Veras et al., (2021) provide qualitative insights by interviewing industry experts and found that freight rates and reliability are the primary determinants for mode choice. Although road mode was preferred, those interviewed were willing to switch to more sustainable modes. Furthermore, the research emphasizes the importance of using precise commodity information in the mode choice model. Consistent with this idea, Jensen et al. (2019) introduce a discrete model designed to estimate how freight transport chains are chosen in Europe, considering a multimodal transport chain (rail, sea and road) and different commodity groups (dry bulk, liquid bulk, containers and general cargo). Finally, the trip assignment model aims to assign the flows on each road or transit route based on the mode choice and trip distribution results. OD models can be also applied for commodity flow estimation. In this context, Kalahasthi et al., (2022) highlight that due to network asymmetry in commodity flow distribution, estimating empty trips is necessary. The commonly used approach for this estimation is the Noortman and van es' empty trips model [8].

2.2 Freight Tour-Based Models

In the context of freight transport and logistics, a tour-based model is a type of modelling approach that focuses on the representation and simulation of the movement of goods, shipments or vehicles in the form of "tours" [9]. Freight tour-based modelling is especially applied to urban freight transport systems where the vehicle needs to perform a sequence of activities and stops (e.g., last-mile delivery). Research has increasingly adopted tour-based modelling in transportation and logistics due to its ability to better simulate real-world scenarios [10–13]. By accounting for the complexities of multi-stop and multimodal trips, this shift allows researchers and decision-makers to effectively

provide optimal planning (e.g., optimize routes, minimize cost, and reduce environmental impacts). To this end, GPS traces are collected and combined with survey data with activity information. For instance, Alho et al., (2019) and Venkadavarahan et al., (2020) acquired activity data through driver surveys, encompassing information like stop purpose, location, duration, and the amount of cargo handled. Indeed, tour-based models require higher data and computational capacity. However, as technology, sensorization initiatives, and data integration protocols advance, the advantages of employing tour-based models surpass these obstacles. Despite the limited data, advanced approaches have been proposed with the aim of effectively and comprehensively representing tour demand by considering several factors [10–13]. Venkadavarahan et al., (2020) focus on understanding and modelling complex tour-based freight movements of vehicles. It identifies driver and vehicle characteristics, estimates tour numbers and employs non-linear and soft computing models for predictions. Amongst these, neural networks outperform the peer machine learning models, offering valuable insights for transport planners and researchers. Moreno-Palacio et al., (2023) improve freight tour synthesis with fuzzy logic, addressing the variability of human behaviour that is overlooked in traditional entropy-based models. Fuzzy logic allows for a more flexible modelling approach, accommodating variations while nearing expected values. Alho et al., (2019) assess different model specifications for urban freight simulation, focusing on trip- and tour-based models for converting shipments into vehicle flows, using Singapore's vehicle operations data. Comi et al., (2021) provide a framework for simulating delivery tours, to demonstrate its effectiveness in generating freight distribution O-D matrices. The authors calibrated the model using GPS trajectory data from light goods vehicles in Italy. Within tour-based models, agent-based models have gained presence offering advantages when compared to the analytical demand models mentioned earlier [14]. Shippers, carriers, receivers and other actors in the freight transport and logistics ecosystem are modelled as agents that interact with each other, enabling them to simulate movements or actions in alternative policy scenarios. Besides the ability of each agent to learn and adapt, it is possible to evaluate spatio-temporal dynamics [15].

2.3 Transport Modeling for Green and Digital Logistics

OD models or tour-based models are indispensable tools that provide and guide decision-making processes for achieving environmentally responsible and technologically advanced supply chains [15–20]. In this context, we now provide a view of recent research that hinges on demand modelling and contributes towards green and digital logistics. Homayouni et al. (2022) introduce a sustainable logistics model that considers vehicle types and emissions in commodity transportation, favouring cap-and trade policies over carbon tax policies for more effective emissions reduction. Given the uncertainty of product demand, the previously mentioned authors provide a probabilistic approach that considers pessimistic, expected and optimal scenarios, along with assumptions such as a fixed carbon capacity and price during the time horizon. In a more dynamic spatial and temporal approach, Anand et al. (2021) simulate the delivery cap and price policy using an agent-based model, showcasing its potential to reduce vehicle travel and generate revenue for municipalities. Recent studies have focused on optimizing modal shift, route planning, and capacity allocation while considering sustainability

goals. For example, Guo et al., (2022) calculate the carbon emission estimation considering the Well-to-Wheel and the Tank-to-Wheel perspectives for the hinterland-based container intermodal network (roads, inland waterways, railways, and sea). Two models are employed, i) an energy computation model that considers vehicle features during transportation and transfers, ii) a freight flow model that uses the gravity approach but assumes shortest routes and does not consider traffic congestion. Among the practical insights, Guo et al. (2022) advise optimizing container capacity, considering the cargo and multimodal network constraints. In this scope, effective commodity-based models are vital since they allow for the ahead planning of cargo combinations, reducing transportation resources and consequently, minimizing environmental impact and providing cost reductions. The vehicle routing problem (VRP) has been extensively studied, and emerging research is now integrating environmental considerations, advanced vehicles such as drones and autonomous robots, and multimodal options [17]. Another application of VRP appears in reverse logistics (RL) operations. In the scope of e-commerce, Lamba et al., (2019) identify the uncertainty of demand as one of the three topmost barriers for RL. Sar et al., (2023) emphasize the need for future research to integrate VRP with Industry 4.0 tools to mitigate demand uncertainty. With the introduction of greener fuel energy (e.g., electric, hydrogen, biofuel), freight demand modelling becomes pivotal, along with route optimization, infrastructure planning and energy provision. In the scope of electric vehicles, Vazifeh et al., (2019) contribute a novel data-driven approach to optimize the placement of EV charging stations in urban areas. The demand model estimates vehicle flows using "Call Detail Records" over 4 months. Spatiotemporal demand dynamics are crucial for strategically siting hubs for smart electric charging (or other green energy sources), accounting for freight vehicle constraints and power grid limitations.

3 Digital and Decarbonization Challenges

Table 1 serves as an overview of the referenced works, assessing their contributions to two key aspects: i) digitalization, which involves enhancing organizational and network efficiency and productivity through the integration of technology, and ii) addressing sustainability goals, particularly decarbonization [5]. In this literature review, we utilize the review by Kalahasthi et al. (2022) as a key reference while also incorporating the most noteworthy studies from the past three years (2019–2023) in the field. "Partial" category means that the work touches upon these topics but primarily suggests them as areas for future research. In the context of this analysis, ensuring the quality and availability of data emerges as a crucial concern [1–4, 6–8]. This entails the acquisition or estimation of crucial data points, such as trip details, energy consumption, and transportation modes used between attraction and generation zones. Efforts have been made to overcome the data limitations by developing algorithms that seamlessly integrate various data sources. The second significant challenge pertains to demand uncertainty. There is a need for dynamic demand modelling to accommodate both spatial and temporal variability. Despite the complexity of the freight transport and logistics ecosystems, agent-based modelling shows to be a promising approach in capturing complex interactions among stakeholders and dynamic variables in transportation systems [9, 10, 15]. Table 1 seems

to indicate the need for multimodal models to accommodate interactions of stakeholders in transport markets while accounting for fuel emissions and other externalities across the whole supply chain, which will require collaborative approaches in logistics. As environmental-related concerns and policies evolve, freight demand models need to be adaptable and open to new socioeconomic dynamics. Several studies outline the need to tackle challenges related to green vehicle routing, reverse logistics, and optimizing supply chains in line with sustainability goals [18–20]. Further research is being conducted within the EU funded project ADMIRAL to assess needs of companies/stakeholders for greener approaches to logistics with enhanced models to support decision making.

Table 1. Reviewed studies: decarbonisation and digital logistics issues addressed (yes/no).

Studies	Freight transport mode (road/rail/maritime)	Model or Problem type	Digital logistics Yes/No/Partial	Decarbonisation Yes/No/Partial
[18]	Road	VRP	Partial	Yes
[1]	Road/Rail	GM and DC	No	No
[6]	Road/Rail/Sea	GM	Yes	Yes
[4]	Road	GM	Yes	Partial
[16]	Road	OP	Yes	Yes
[3]	Road/Rail	DCM	Yes	Yes
[8]	Road	ETM	Partial	Partial
[15]	Road	ABM	Yes	Yes
[11]	Road	SCM	Partial	No
[20]	Road	OP	Yes	Yes
[10]	Road	ABM	Partial	No
[7]	Road/Rail/Sea	DCM	No	No
[2]	Road	EMM	Partial	No
[9]	Road	ABM	No	No

VRP: Vehicle Routing Problem; GM: Gravity model; DCM: Discrete-choice Model; EMM: Entropy maximization model; SCM: Soft computing models; OP: Optimization Problem; ETM: Empty trips model; ABM: Agent-based model; SCM: Soft computing models.

4 Conclusion

This work explores advances in freight OD models and freight tour-based models (FTDM) and their alignment with sustainability goals in decision-making. Among the advancements in demand modeling, agent-based models are promising, as they may integrate real-world data, support sustainability and simulate interactions between agents (e.g. suppliers, carriers). With the integration of Industry 5.0, demand models can be enhanced and integrated with social and environmental sustainability aspects (e.g.,

low/zero emissions) and promote self-adaptive and collaborative logistics, while optimising supply chains. Algorithms to reduce demand uncertainty will prospect future research on current challenges related to sustainability in freight logistics.

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Road Freight Electrification: Digital Model for Fleet Depot Electric HGV Charging Infrastructure

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Abstract. Charging infrastructure is a significant investment on top of the purchase cost of electric HGVs, therefore decisions to minimise the charging infrastructure requirements, meanwhile future proofing options for maturing technology, need to be informed by computer simulation that will build confidence and facilitate the evaluation of various options.

This paper describes the investment challenges and use of a new digital model for computer simulation of fleet depot based electric HGV charging infrastructure. This enables the evaluation of fleet and infrastructure technical options, provides costs for investment decisions, and guides operational planning.

Keywords: Sustainable freight and logistics · Electric HGV · Charging infrastructure · Depot operations · TCO · Digital model · Simulation

1 Background

1.1 Challenging Business Case

The environmental imperative for HGV electrification is established, with European governments moving to ban the sale of new non-zero emission goods vehicles [e.g., 1, 2]. However, there is unclear economic and operational viability making the business case for HGV electrification particularly challenging for fleet operators.

Electric HGVs are approximately three times the cost of equivalent diesel vehicles. Meanwhile, fleet operators also need to plan electric HGV recharging facilities at depots, adding significant infrastructure investment cost.

1.2 Prior TCO Research

Prior total cost of ownership (TCO) studies suggest electric HGVs can reach parity with diesel HGVs by end of life, but recharging infrastructure costs are often skipped.

Ledna et al. [3] explored long-term scenarios for total cost of driving (TCD), on the basis that public access recharging infrastructure will develop to meet demand. Wang, Z. et al. [4] addressed vehicle rather than recharging infrastructure cost. Wang, G. et al. [5] also studied TCD, introducing penalty costs for dwell time lost to recharging.

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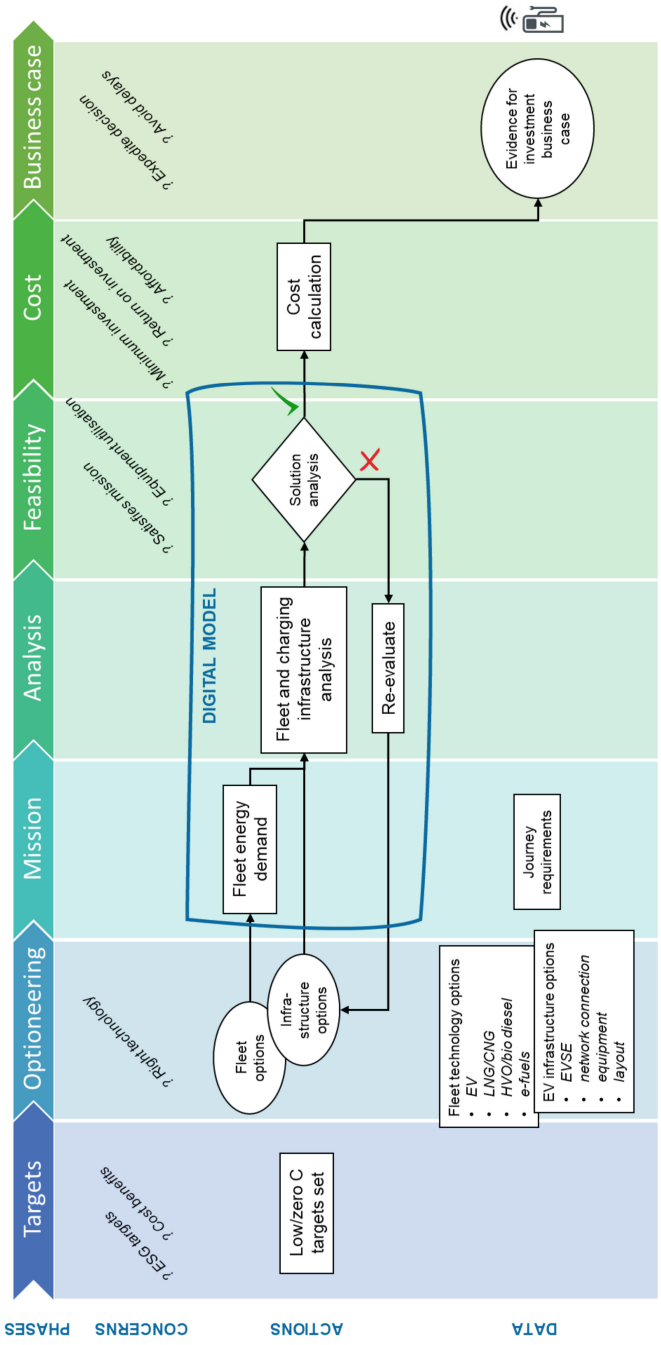


Fig. 1. Infrastructure investment decision journey.

Quak et al. [6] validated electric HGV economics, but with low power overnight chargers. Drake et al. [7] examined electric HGVs' cost effectiveness using depot and destination charging up to 250kW and example network connection cost. Basma et al. [8] included equipment cost for 100kW and 350kW chargers, and service and maintenance in the TCO calculation, but without installation civils, electricals, nor financing.

1.3 Technical and Operational Challenges

Charging Speed and Time. Electric HGVs have battery sizes of 500kWh and larger [9]. Fast recharging is necessary to minimise dwell time, with a technical standard for megawatt charging (MCS) to be published shortly by CharIN [10].

Infrastructure Availability. Electric HGV recharging infrastructure is scarce. Investment will focus on key freight routes [11], leaving fleet operators to plan electric HGV recharging at depots.

Electricity Distribution Network Capacity. Recharging multiple vehicles concurrently requires to import substantial power from the electricity distribution network. For most locations, a connection reinforcement request is needed to the distribution network operator (DNO), which incurs complex costs and lead times [7].

1.4 Investment Decisions

The flow diagram in Fig. 1 describes the decision journey of a Fleet Director (or a Facilities or Finance Director), to arrive at a business case for charging infrastructure. Identifying both the fleet and infrastructure options requires experience but the analysis of the fleet mission, and the potential for each fleet and infrastructure option to satisfy the fleet mission, are too complex and require computer simulation.

2 Digital Model

2.1 State-of-the-Art

Digital models of public recharging infrastructure offer operational benefits to drivers and CPOs, and support urban planners to optimise investments [12]. Digital models also enable grid edge management for peak demands and flexibility/off-peak recharging [13].

Francisco et al. [14] used a MATLAB digital model to optimise charging process management for EV fleets through time window allocation. Korotunov et al. [15] introduced a virtual prototype to support charger predictive maintenance.

A new digital model will assess the feasibility of fleet and infrastructure options.

2.2 Methodology

A new digital model has been developed with MATLAB/Simulink Simscape Electrical [16], using input data including the following:

- Fleet vehicle operations, therefore calculating fleet energy consumption (demand),
- Charging infrastructure options,
- Depot site power equipment and/or energy storage options (depot energy network),
- Electricity distribution network connection and reinforcement options.

The new digital model calculations determine the feasibility of options to satisfy the fleet mission, the equipment utilisation, and the profile for energy imported from the electricity distribution network from which the energy consumption costs can be calculated. The overall capital and operational cost outputs then support the investment calculations and the business case for fleet and infrastructure decisions.

2.3 Depot Energy Network

Together, the recharging infrastructure power equipment and further infrastructure, such as new local energy storage or local generation, create a new energy network at the depot. Modelling recharging infrastructure options involves:

Integration of Renewable Energy Sources. With rising energy costs, local renewable generation is attractive to reduce electricity import from the distribution network [17]. Integration involves historical data and advanced forecasting (e.g., [18]) to predict the intermittent generation (location, season, weather) for energy planning.

Energy Storage for Operational Resilience. Local energy storage aids integration of local renewable generation, by peak shaving and load shifting. Local energy storage also provides network stability during supply and demand dynamics, and will ensure uninterrupted recharging service during supply disruption, improving overall operational resilience [19, 20]. Local energy storage may also mitigate reinforcement [21].

Commercial Opportunities. Local energy storage offers economic opportunities through energy price arbitrage and flexibility services to the distribution network [17].

Bidirectional charging vehicle-to-grid is a promising additional network flexibility service (exporting vehicle energy to the distribution network). Predicable usage patterns of electric HGVs make this an attractive future possibility.

Site Consumption and Energy Management. Existing depot loads to balance with the electric HGV recharging demand include for example lighting, heating, ventilation, industrial plant, material handling equipment, security systems, and offices.

Figure 2 illustrates charging and depot energy network management strategies for the above listed considerations.

2.4 Fleet Operator Findings

The new digital model supported evaluation of depot sites with electric HGV fleets up to 50 vehicles, including both shuttle and multi-drop operation, with either dockside or remote recharging. The optimum number of chargers per vehicle and the potential for local energy storage (investment) varies from depot to depot, often depending on the distribution network connection and reinforcement cost.

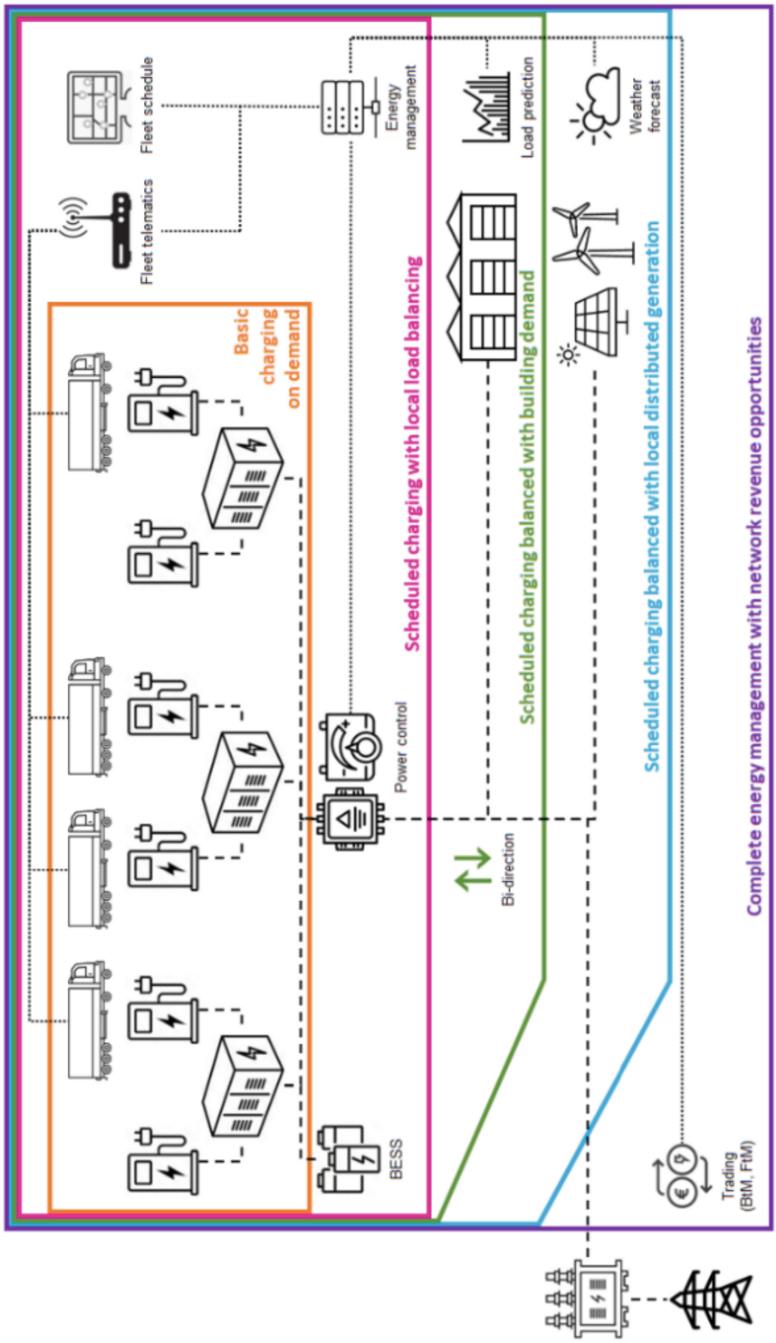


Fig. 2. Depot energy network schema including electric HGV charging and strategies.

The new digital model helped to understand daily profiles for energy import (costs). Fleet consumption costs dominate the cost calculation, highlighting the critical importance of fleet operation and recharging regime according to tariff. A positive return on local energy storage investment has been shown [22].

3 Conclusion

Prior TCO research for electric HGVs has focused on vehicle and energy costs rather than recharging infrastructure, but this investment is significant. Computer simulation is needed to evaluate the fleet and infrastructure options facing Fleet Directors.

The new digital model described facilitates this evaluation of options, and feeds into an overall infrastructure investment decision journey to arrive at a business case. Cost assumptions and forward-looking statements cannot be avoided, so care must be taken in applying results. All HGV fleets and depots are unique.

Suggested future work should look at how key costs will reduce with adoption, and the role of public funding for depot and destination recharging.

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Business Model Implications of Innovative Solutions for Sustainable Urban Freight Transport

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Abstract. Urban freight transport faces significant environmental and societal challenges, necessitating innovative solutions. This paper explores the business model implications of such solutions, drawing insights from research trials conducted in Bremen, Mechelen, and Groningen as part of the "Urban Logistics as an on-Demand Service" (ULaaDS) project. While many proposed solutions are technologically ready, their integration into existing business practices and scaling for impact remains challenged. Key findings highlight the tension between innovative solutions and entrenched business-as-usual models. The interplay between private business and public authorities emerges as an important factor, with mutual expectations shaping the trajectory of these solutions. The research underscores the need for a holistic approach, integrating technological, business, and regulatory facets, to ensure sustainable urban freight transport solutions can compete effectively.

Keywords: Urban Freight Transport · Sustainability · Scalability · Public Policy · Commercial Viability

1 Introduction

The urban freight transport research community has proposed and studied a wide array of innovative solutions over recent decades [1–3]. These solutions strive for different ends: some primarily address environmental concerns while others focus on the impact of urban freight transport on public space, noise pollution, and safety. The means to meet these ends are diverse. Broad strategies include decarbonization, consolidation, and the spatial or temporal separation of freight transport from people living, working, or visiting the city. Solutions target the vehicles and the logistics facilities involved in urban freight transport, through technological innovation, the introduction of novel business models, and changes in regulations. Some are driven by private enterprises; others find their genesis in public organizations or in public-private partnerships.

Given the scope of urban freight transport and the magnitude of the environmental and societal challenges, innovative solutions must be deployed at scale to make considerable impact and be viable in the long term. Yet, scale and long-term viability have been

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challenging. Pilot tests with urban consolidation centers, for example, often handle shipments of only a few suppliers, carriers, or receivers [4] and seldom make it past the pilot stage [5]. And, despite broad attention and long-term testing, the use of cargo cycles remains challenging [6]. These, and other, innovative solutions in urban freight transport typically rely on proven technology, maybe except for autonomous freight transport vehicles. The real challenge for deployment at scale, then, lies not in the technological readiness, but rather in the way the solution is integrated into existing business practice.

This paper explores the business model implications of innovative solutions for sustainable urban freight transport. Insights are drawn from research trials in Bremen, Mechelen and Groningen, as part of "Urban Logistics as an on-Demand Service" (ULaaDS), a project within the European Union's Horizon 2020 research and innovation programme. The research trials provided critical lessons learned about the integration of innovative solutions into existing operational processes, competition with business-as-usual, and the role of rigorous regulations to ensure long-term viability.

2 Research Trial Descriptions

The ULaaDS project focused on five innovations in on-demand and sustainable urban freight solutions, namely the integration of (1) containerization and (2) cargo bikes into last-mile delivery, the development of platforms for (3) the integrated management of urban freight transport and (4) vehicle sharing, and (5) the sharing of location and infrastructure for passenger and urban freight transport.

Different innovations were trialed across three lighthouse cities involved in the project: Groningen (the Netherlands), Mechelen (Belgium), and Bremen (Germany). While different in aspects such as population size and regulatory context, these three European cities have in common a historic city center and a bike-friendly infrastructure and attitude. The three research trials focused on different solutions and are described below.

2.1 Groningen Research Trials

The Groningen research trials focused on the implementation of a platform for shared zero-emission urban freight vehicles and the placement of parcel lockers on public transit hubs.

The platform for shared zero-emission urban freight vehicles was aimed at providing shopkeepers in the city center of Groningen with access to zero-emission vehicles for the on-demand supply of their shops and delivery to consumers in and around Groningen. Different vehicle types—a cargo bike, a light electric freight vehicle, and an electric van—and their use by entrepreneurs with a different urban freight transport demand were tested. Shopkeepers in need of a zero-emission vehicle can reserve one via an app, pick the vehicle up from its parking location, use it, and afterwards return it to the same parking location. During the trial, vehicle reservation and use was possible for a select group of shopkeepers and free of charge, but with the explicit purpose of gaining insight into the business model of the platform. Reservations and vehicle use were closely monitored and discussed with the shopkeepers during several sessions.

The scope of the parcel locker research trial was changed and expanded from placing a few parcel lockers to developing a policy framework for parcel locker placement in public spaces in general. As the ULaaDS project was being developed and initiated, parcel lockers had become a mature solution, deployed at scale by many logistics service providers across Europe. While being actively involved in the placement of a locker proved challenging, an increasing number of actors sought permission to place parcel lockers in public spaces without financial support. The trial therefore shifted its focus to better facilitating parcel locker placement requests through the development of a policy framework [7]. The process included several public-private dialogues, a benchmark of solutions across Europe potentially relevant for the framework, and a spatial analysis.

2.2 Mechelen Research Trials

The Mechelen research trials focused on setting up a platform for collaborative urban freight transport and the piloting of an autonomous vehicle sharing passenger and freight transport services.

The collaborative urban freight transport platform was aimed at consolidating parcel pickups at local shops in the inner city of Mechelen. The fragmented nature of these pickups, with few parcels per stop for each logistics service provider and few stops in relation to the size of the area, leaves ample room for improved cost-effectiveness through consolidation. Under the proposed platform, parcels from several well-known logistics service providers would be picked up by a third-party cargo bike company and transported to a hub for sorting and further transport and delivery by the logistics service providers. Using cargo bikes for pickups, combined with the benefits of consolidation, aligns well with the city's sustainability goals. Ultimately, the research trial did not reach full deployment, mainly due to the complexity involved with clearly outlining the business processes as well as the sharing of costs and benefits across the partners involved.

The pilot testing of an autonomous vehicle with shared passenger and freight transport services included a preparation phase and an operational trial with the vehicle. In the preparation phase, several scenarios were considered to integrate passenger and freight transport, and the final solution included an autonomous shuttle for passenger transport on a business park with a small parcel locker being installed in the vehicle for freight transport. The vehicle, with a capacity for nine passengers, traversed a 2-km route with six stops operating between 11 AM and 6 PM. From June 2022, the operational trial ran for one month with passengers only and then for one month with the parcel locker installed. The parcel locker that was installed had three small and three medium-sized compartments, and functioned like a traditional parcel locker in that customers could simply select it as delivery location during checkout at a web shop.

2.3 Bremen Research Trials

The Bremen research trials focused on scaling up containerized urban freight transport and exploring solutions for integrating passenger and urban freight transport.

Containerized urban freight transport relies on the "Physical Internet" metaphor [8]. Here, seamless material handling because of standardized containers should lower the

cost of transshipment and hence facilitate transshipment to smaller-sized vehicles in an urban context. In the research trial, the notion of containerized transport included two container sizes: The smallest container fits exactly on the back of a cargo bike and can be loaded onto the bike in one go; the larger one fits exactly nine of the smaller ones. By pre-loading the smaller containers at an upstream facility based on their last-mile delivery sequence and then loading these into the larger container in the same order, the time spent on downstream material handling is minimized, which enhances the efficiency of using cargo bikes for the final stages of development. After successful pilot tests with smaller, mostly B2C parcels, the trial expanded the scope of the containerized solution to larger B2B shipments. The goal was to study if the solution fits this broader scope.

The integration of passenger and urban freight transport was pursued in two ways. First, a community-based cargo bike lending scheme was rolled out with the aim to introduce cargo bikes to citizens in Bremen. Each cargo bike is assigned a "host", typically a local shop or coffee bar. The host provides a parking spot, manages reservations, and assists with maintenance. Users can reserve a bike online—free of charge—and use it for transporting goods for which they would otherwise use a car. Second, a digital pilot explored the potential for combining parcel pickup and delivery with on-demand passenger transport services. Based on real-world data from reference cities, a digital environment was created to test different ways in which parcel transport could best be integrated in the on-demand passenger transport services. The final solution that was tested aimed at picking up parcels from local businesses and delivering them to locations nearby, and utilizing vehicles needed for passenger transport in that same area whenever idling.

3 Business Model Implications

The ULaaDS research trials in Groningen, Mechelen, and Bremen provide valuable insights into the challenges and opportunities of implementing sustainable urban freight transport solutions.

Like many of its sister EU projects, the ULaaDS research trials mostly deployed and studied innovative solutions at a relatively small scale. Achieve meaningful environmental and social impact, however, requires scaling these solutions to city-wide or regional levels. While the technology underlying many solutions is, in essence, ready for large-scale deployment, taking them from 'proof-of-concept' to widespread application remains a key obstacle in the journey towards sustainable urban freight transport. Scaling up raises complex questions around infrastructure investment, operational feasibility, and commercial viability.

A notable observation across the trials is the relationship between private businesses and public authorities. When deploying sustainable solutions, private businesses often expect public support—either implicitly or explicitly—through resource allocation or regulatory adjustments. In Bremen, for example, the containerized urban freight transport solution involved public support for the micro-hub operations in terms of finding suitable locations and enabling space on a private parking lot. The cessation of this support led to a halt in activities, raising concerns about the long-term viability of these solutions in the absence of continuous public support.

Another challenge emerges from the juxtaposition of these innovative solutions against business-as-usual. Existing urban freight transport models are characterized by externalized negative environmental and societal impacts. While these negative impacts are widely recognized, this recognition alone does not impede actors in this sector to continue with their operations as they have done for a long time. Indeed, time has allowed business as usual to evolve into a highly cost-effective way of operating, and the business models of innovative, more sustainable solution will likely have a hard time competing on cost—especially before they reach deployment at scale. The challenge for urban planners lies in creating an environment where sustainable alternatives can compete fairly.

The Groningen research trial with shared vehicles highlights the importance of a supportive regulatory environment in influencing business decisions. The introduction of the time-access restriction zone, combined with the launch of the shared vehicle platform, created a unique situation where shopkeepers were more inclined to explore sustainable urban freight transport options. This suggests that policy measures can act as catalysts, nudging businesses towards sustainable practices. This may entail reassessing regulatory frameworks and economic instruments to ensure they encourage sustainability and do not inadvertently sustain harmful practices.

4 Discussion and Conclusions

Each of the innovative solutions tested in Bremen, Mechelen, and Groningen have been the focus of prior academic studies [9–12]. In the ULaaDS project, the aim was to gain insights into the scalability and business model implications when innovative sustainable urban freight transport solutions are deployed in medium-sized European cities.

Insights from the ULaaDS research trials offer a roadmap for sustainable urban freight transport. They underscore that the transition to sustainable urban freight transport requires more than just technological advancement and reveal important challenges when scaling innovative solutions for meaningful environmental and social impact. Notably, these challenges lie in the competition from business-as-usual and the interplay between private business and public authorities, each with mutual expectations about the trajectory towards deployment of innovative solutions at scale. A successful transition hence calls for collaboration among businesses, public authorities, and other stakeholders—creating a comprehensive approach that encompasses technological, business, and regulatory considerations, ensuring that sustainable solutions can compete with business-as-usual on a level playing field. This calls for a reevaluation of regulatory frameworks and economic instruments, ensuring they foster sustainability and do not perpetuate unsustainable urban freight transport practices.

Acknowledgements. This paper summarizes three deliverables related to business and operating models of the ULaaDS trials (D3.1, D3.3, D3.5) published on https://ulaads.eu/. ULaaDS is a project under the CIVITAS initiative and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 861833.

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Performance Assessment of Multi-articulated Flexible Vehicle Platforms in Realistic Road Infrastructure Models

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Abstract. This paper explores the application of modeling and simulation techniques to evaluate the performance of multi-articulated vehicle combinations in real-world scenarios within the context of the ZEFES (Zero-emission flexible vehicle platforms with modular powertrains serving the long-haul freight ecosystem) project. ZEFES aims to address transport sector emissions, by pioneering zero-emission vehicle technologies. Assessing the capabilities of these vehicles in challenging real-world conditions, such as roundabouts and sharp turns is necessary, since long vehicle combinations (up to 33.5 m) require large road width for maneuvering. Rollover tendencies in highway entry and exits are also considered. This assessment aides in determining the right vehicle in the right duty for cross border operation. An automated workflow identifies critical road sections using GPS data and constructs digital road models using the OpenCRG framework. GPS data is interpolated for feature extraction, focusing on analyzing heading angle changes. To perform swept path analysis, the available road-width is extracted using computer vision and known road design standards. Realistic vehicle reference trajectories are generated, and driver behavior is modelled to simulate maneuvering, considering the unique characteristics of multi-articulated vehicles, based on empirical methods.

Keywords: Digital Twin · Vehicle Infrastructure Interaction · Computer Vision

1 Introduction

1.1 ZEFES Digital Twin Architecture

As part of the Green Deal, Europe aims for carbon-neutrality by 2050, with a 55% CO2 reduction by 2030 [1]. The road transport sector targets a 30% reduction, requiring efficient heavy-duty vehicles like Battery Electric Vehicles and Fuel Cell Electric Vehicles. Advances in battery technology, ZEV (Zero Emission Vehicle) allowances, and falling battery costs aid emissions reduction. However, widespread adoption relies on a robust charging infrastructure, which introduces route optimization challenges. The ZEFES project explores real-world ZEV adoption and efficiency enhancements through demonstrators.

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An objective of the ZEFES project is to develop a digital twin platform (in the form of a user interface), with tools for logistics operations, including buying decision, mission planning, right vehicle in the right duty (RVRD), predictive maintenance, etc. The HAN University of Applied Sciences is developing a sub-tool in the RVRD tool to assess the feasibility of using a particular vehicle combination in an arbitrary route/mission. These vehicles suffer from maneuverability and stability constraints, startability and gradeability issues during reduced friction conditions.

1.2 Vehicle-Infrastructure Interaction Simulation

In the sub-tool, Global Positioning System (GPS) data from a mapping/routing Application Programming Interface (API) is analyzed with respect to the performance of ZEVs. Critical sections in routes are classified as roundabouts, sharp turns, highway entry/exits, and steep slopes. Roundabouts and sharp turns are challenging due to the need for large turning radius, while highway entry/exits pose rollover risks. Steep slopes are dangerous due to vehicle gradeability limitations at particular loading conditions. PTV API is used for ZEV charging-optimized routes [2]. These critical sections are simulated with the user's vehicle combination with the following workflow:

1. Perform multi-body simulations using known ZEV parameters and European road infrastructure specifications.
2. Create a simulation result database, with each result signifying a Key Performance Indicator (KPI) for specific infrastructure elements like roundabouts and sharp turns (requiring swept path analysis), highway entry/exits (requiring rollover analysis), and steep gradients (requiring gradeability analysis).
3. The sub-tool running in a Docker environment will obtain the route data, detect critical sections in the route and use the results database for assessing the safety.
4. Safety is then categorized into three levels: green, orange, and red according to the KPI results and this is published back to the API which can possibly replan.

The results database is formulated as a multi-dimensional look-up table of KPIs in order to assess the safety. In [3], the authors present a complete methodology for multi-body modelling and performance assessment. This methodology was then used in [4] to assess the performance of longer and heavier vehicles. With this, the highway entry/exits and sharp slopes can be assessed. However, simulating a ZEV, especially a multi-articulated ZEV with real-world infrastructure conditions has not been achieved in published literature. In [5] and [6] for instance, software such as Autodesk® Vehicle Tracking© and AutoTURN© were used to perform swept path analysis on known roundabouts. These software packages use kinematic models of various vehicle combinations to estimate trajectories. While offering comprehensive customization, these software can only be used manually, and not programmatically, which is required in ZEFES since:

– Simulating every possible ZEV combination, in every possible roundabout size and exit can result in 1000s of simulations, which would be extremely time consuming to perform manually in the kinematic software packages.
– Although kinematic models can provide accurate results in low acceleration, low steering angle simulations, multiple studies have shown that the trajectory errors

increase when highly dynamic maneuvers are performed. In [7], a kinematic model of a car, a 9 degree of freedom (DoF) model and actual test vehicle are compared using a combination of curves and straight line driving. The results indicate that the errors increase with the length of the maneuver. The mean error was 32.5% lower in the 9 DoF model compared to the kinematic model. In conclusion, for a 4 wheeled vehicle, the more turns executed, the higher the errors will be. When considering a multi-articulated ZEV such as an A-Double (tractor-semitrailer-dolly-semitrailer) consisting of tens of wheels, the errors will be significantly higher if kinematic models are used for swept path analysis. Hence, purely kinematic models used in the aforementioned software are not feasible for this methodology.

– Weather conditions significantly influence the road grip. Such tools do not take this into account.

Furthermore, automating the process of determining locations of critical sections along a route is an open problem. Services such as Google Maps provide turn-by-turn directions in their APIs, but lack the ZEV focused logistics optimization.

1.3 Research Objectives

Existing swept path analysis methodologies are unsuitable and hence this paper explores on the following research questions:

– How can specific road infrastructure features such as roundabouts, highway entries and exits be detected in GPS route data?
– What methodologies can be used to extract the usable road width and perform swept path analysis?

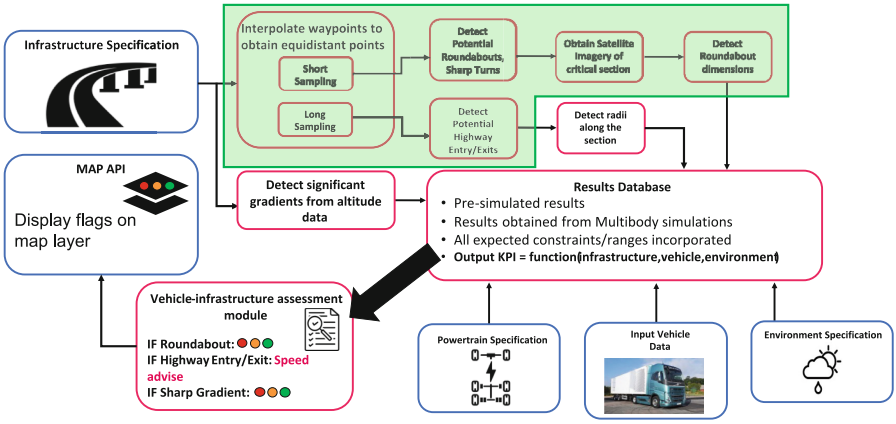


Fig. 1. Methodology to identify critical sections, extract road boundaries and perform vehicle-infrastructure assessment.

Section 2 describes the sub-tool workflow and the detection of critical sections in GPS data, Sect. 3 explores empirical and analytical techniques to extract usable road width.

2 Methodology

The methodology for detecting critical sections in GPS data (see Fig. 1, green portion) involves interpolating the route data, since GPS coordinates along a route are logged as a function of speed and not distance. Equidistant data points are essential for the application of identification algorithms consistently across diverse regions. Data at equidistant query points are interpolated linearly (due to fast computation time).

Two datasets are generated during interpolation, one sampled in 10 [m] steps and another with 50 [m] steps. Shorter steps capture sharp direction changes, while longer steps are ideal for detecting large curve radii. A detection algorithm assesses heading changes between consecutive points. Detecting sharp turns and roundabouts is straightforward, but highway entry/exit detection is complex due to diverse designs. European guidelines specify road section dimensions [8], with motorways having 750–900 [m] radius curves and expressways as low as 35 [m]. Interpolating in 50 [m] steps ensures the presence of at least 2 data points in the sharpest curves, making it suitable for highway entry/exit detection. To detecting highway entry/exits:

- Group consecutive large heading ($>10^{\circ}$) changes data points
- Compute radius of curvature for every 3 points along the group:
  - If the group's mean radius of curvature is < 1000 [m] & length of group is > 250 [m], save as highway entry/exit
  - Else, ignore outlier radii (due to imperfect GPS data) and recompute

Similarly, the algorithm for detecting sharp turns and possible roundabouts:

- Group consecutive large heading ($>20^{\circ}$) changes
- Compute length of the group:
  - If length of the group is $<= 40$ [m] & difference between initial and final heading in the group is $> 60^{\circ}$, save as sharp turn
  - Else, compute radius of curvature for every 3 points along the group:
    - If the group's mean radius of curvature is < 200 [m], perform image detection for detecting a possible roundabout

3 Satellite Image Analysis

After grouping critical sections and identifying possible roundabouts, their satellite images are analyzed to extract the road sections by segmentation. A generalized vision artificial intelligence model OpenGVLab [9], and K-means clustering are considered. While the latter method is simpler, both are sensitive to the image resolution available. To detect a roundabout, as shown in Fig. 2, where the original image (a) is segmented (b), and in its gray scaled image (c), MATLAB's *imfindcircles()* is used to detect circles. This uses Hough's transform, which looks for certain shapes in the image. Using the detected circle's radius, the roundabout boundaries are reconstructed due to known design regulations.

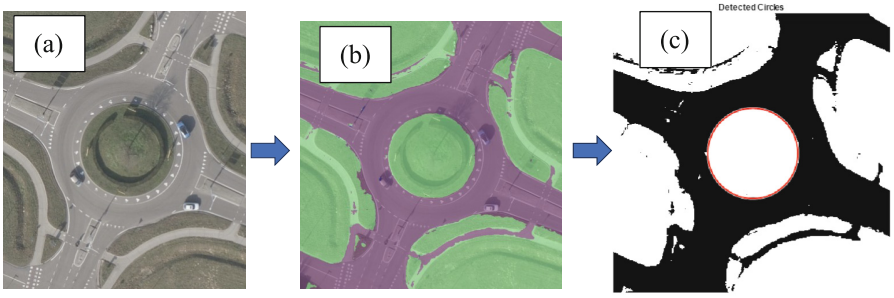


Fig. 2. Extraction of road and non-road pixels and detection of circles. Original image (a); Segmented image (b); Detected circle in red (c). Original image retrieved from MATLAB's Mapping Toolbox [10].

3.1 Swept Path Analysis

After extracting road features, the next step involves simulating a high-fidelity multi-body model on the road surface for swept path analysis. These models use the Magic Formula tire force and torque equations, which implement the combined slip steady-state, and the optionally the turn slip effects [11]. These tire models require a compatible road model. OpenCRG, a widely used road surface file format framework is used to build a road models for each critical section, considering the detected road features. Truck driver behavior at sharp turns and roundabouts indicate that as much of the available road width is to be utilized, see Fig. 3(a), that needs to be reflected in simulations. Hence, a reference path that represents realistic trajectories are created (see e.g., Fig. 3(b)).

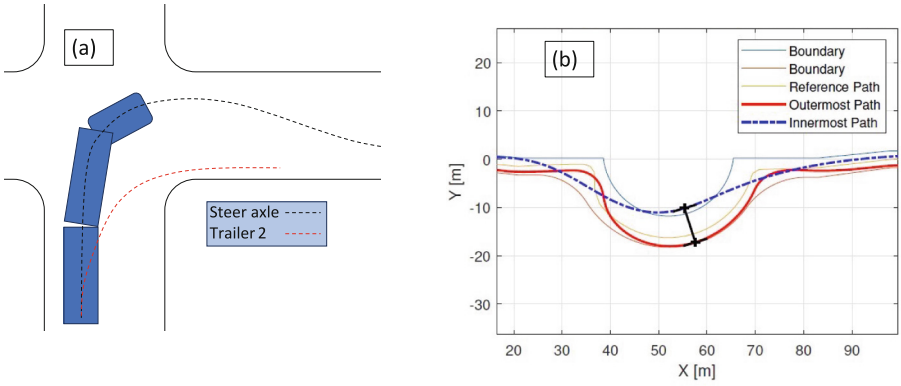


Fig. 3. Truck driver behavior and simulation results. Overshooting the curve [12] (a); Simulation results of an A-Double in a roundabout (b).

With these set of models, numerous model (vehicle and road) parameter permutations are taken into account and the results database is populated for every possible critical section.

4 Conclusions

This paper presented analytical techniques based on heading angles and curvature to detect critical road sections due to the need for programmatic analysis. Road features segmentation was explored using computer vision and data techniques. Additional techniques are required to improve the robustness of circle detection with varying image quality. The results database can be populated with the developed methodology of multi-body simulations which utilize the actual infrastructure information. Although the empirical method to define reference paths in critical sections provide a solution, the path is not optimized for each specific vehicle combination. In future work, a model predictive control based path optimization technique will be pursued.

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Circularity of Reusable Packaging

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Abstract. As part of circular economy, reusable packaging is a key to reduce waste. In order not to ruin the intended sustainability impacts one must take care on the return transport of the reusable packaging and the according logistic concepts. This paper takes a first step in defining a catalogue of use cases to structure the different opportunities of the trip back of reusable packaging to senders. This catalogue is the base terminology to design, optimize and compare concepts regarding their impacts and to derive the according consequences for the entire logistic chain.

Keywords: Circular Economy · Reusable Packaging · Transport Chains · Logistic Concepts · Environmental Footprint

1 Motivation

Packaging, especially for the delivery of goods in the CEP (courier, express and parcel services) domain, results in a lot of waste. It is estimated that packaging accounts for approximately 46% of global plastic waste [1], which is especially true if the parcel's packaging is used just one time. The EC defined several targets for reducing waste in its Directive 94/62/EC of 20 December 1994 on packaging and packaging waste [2]: 65% by 2025, 70% by 2030. To further prevent packaging waste, the European Commission published a proposal for a revision of EU legislation on Packaging and Packaging Waste on 30 November 2022.

Circular economy, and especially reusable packaging, like reusable cardboards, plastic boxes, etc. may constitute a solution. But more stable and robust materials and constructions are needed, which results in a higher environmental footprint for production and maintenance than for single-use packaging. Furthermore, there is an additional transport demand if the packages go back to the sender. This paper focusses on this perspective and contributes to find clever logistics solutions to integrate returns into delivery processes.

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As part of the national research project ReKEP [3], this study structures the opportunities how delivery of goods and the return of packaging can be combined. So far, there is no terminology or catalogue of these options for combined package/goods transport available in the literature. Therefore this paper provides this contribution and build this important first step to a common terminology to enable the selection and optimization of solutions for sustainability logistics with reusable packaging.

2 Definition Process

The first step to structure use cases of trips of reusable packaging was inspired by a more general principle in the priorization of measures for sustainable mobility. Like in Austria's 2030 Mobility Master Plan [4] the highest priority 1 is to **_avoid_** transport entirely wherever possible. As priority 2, the transport that is left should be **_shifted_** to the most sustainable mode of transport. And as priority 3, within each mode, traffic should be **_improved_** to reduce energy consumption.

The translation of this priority concept to classes of use cases of trips of reusable packaging is as follows:

Class 1: No additional trip / transport. In this class, the reusable package is only transported with a good in it.

Class 2: Existing transport, without goods. In this class, the empty reusable packaging is taken along by an already existing trip.

Class 3: Additional transport. In this class, additional trips are performed to return the reusable package into further delivery processes. Especially these use cases need investigation to minimize the additional transport milage.

With this first classification in mind an iterative process on exploration / brainstorming and feedback sessions within the research team have been performed to come up with a first set of use cases. Each use case has been enriched with a description, one or more examples, comments for clarification and potential variations that are covered in the use case category. This edited collection has been revised in a project workshop by experts and practitioners in logistics and reusable packaging. With this feedback the final catalogue of use cases of trips of reusable packaging was created.

3 Resulting Categories

To visualize the different use cases small figures according to the legend presented in Fig. 1 are attached.Due to text limitations the identified variations are not described in this paper. Such variations are regarding the point in time and the location between the delivery of the good and the start of the return transport of the reusable packaging, the type of packaging as well as the actors involved. Exemplary, the return transport could be performed via a return station.

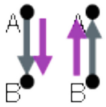
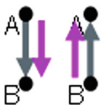


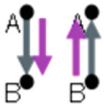
Fig. 1. Legend for the visualizations of the use cases.

3.1 Class 1: No Additional Trip / Transport



[UC 1a] Returns (from the delivery spot). *Description:* Goods delivered in reusable packaging are sent back in reusable packaging without having been used.

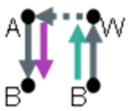
Example: The customer buys clothes from a mail-order-company and sends unsuitable items back to the retailer in the original packaging.



[UC 1b] Sharing of goods. *Description:* When sharing goods, the goods are picked up from a warehouse in reusable packaging and brought to the place of use. After a limited period of use, the goods are returned to the warehouse in a reusable packaging.

Example: The customer receives a tool for use for a limited amount of time and sends it back in a reusable packaging after use.

Comment: In terms of transport, this use case is the same as [UC 1a].



[UC 1c] Waste. *Description:* After delivering a good, rubbish is transported away in the reusable packaging of the delivery.

Example: After a good has been delivered, the reusable packaging is used to transport pre-sorted plastic waste.

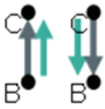
Comment: The destination of the removal is very diverse and depends heavily on the type of waste (e.g. organic waste, batteries) and the corresponding recycling strategy (reuse, recycling, composting, waste incineration,…).



[UC 1d] Second-hand goods. *Description:* A good is transported after it is used for a longer time from a consumer to the next consumer in a reusable packaging.

Example: To transport goods sold via an online marketplace, reusable packaging that is available at the private seller is used.

Comment: The Use Case does not pre-define, where the seller takes the reusable packaging from.



[UC 1e] Repairs. *Description:* An item is sent by the user for repair in reusable packaging. After repair it is sent back to the user in reusable packaging.

Example: A laptop is sent by the customer for repair to the dealer in reusable packaging, who then sends the repaired laptop back to the customer a reusable packaging.

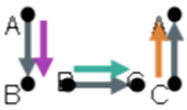
Comment: The difference to [UC 1a/b] is that the starting point for repairs is with the user.



[UC 1f] Onward transport / transport chain. *Description:* The same reusable packaging is used for the delivery of raw materials as well as for shipping the refined product.

Example: The housing of an electronic product is delivered, and the assembled product is sent to retailers in the same reusable packaging.

Comment: When reusing reusable packaging, attention must be paid to the suitability of the packaging for both transport trips (purity, weight, size,…).



[UC 1g] Real circular systems. *Description:* At real circular systems, the reusable packaging is reused in a continuous chain of transport, always filled by the same or different goods.

Example: A company receives intermediate products in reusable packaging, which it reuses when transporting waste products to a processing point. There the reusable packaging can be used to send the processed materials back to the producer of the intermediate products.

Comment: There are hardly such cycles in traditional product life cycles that allow such a closed chain of transports with the same reusable packaging. This will change soon as circular economy progresses.

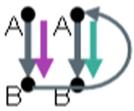
3.2 Class 2: Existing Transport, Without Goods



[UC 2a] Unpack and return straight away. *Description:* The goods delivered in reusable packaging are unpacked immediately and the reusable packaging is returned to the supplier.

Example: When receiving the delivery, the customer removes the goods directly from the reusable packaging, which remains with the supplier.

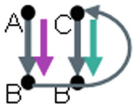
Comment: This is only possible in the case of a personal hand-over.



[UC 2b] Return next time. *Description:* A good is delivered in reusable packaging. With the next delivery from this supplier, this reusable packaging will be given back to the supplier.

Example: The customer hands over to the supplier reusable packaging from a previous delivery from this supplier.

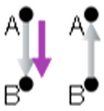
Comment: Of course, starting from the second delivery onwards the reusable packaging from the previous delivery(s) can be returned.



[UC 2c] Give back to someone. *Description:* A good is delivered in reusable packaging. The next time a supplier delivers, this reusable packaging is given back to the supplier.

Example: The customer gives the supplier reusable packaging from an earlier delivery from (any) supplier.

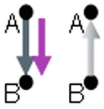
Comment: The difference to [UC 2b is that the supplier of the different deliveries doesn't need to be identical. This asks for standardization of the reusable packaging.



[UC 2d] Return on their own. *Description:* The reusable packaging of a delivery is returned to the sender by the recipient himself.

Example: Filled deposit bottles are returned by the recipient to the sender (e.g. department store) after they have been used/emptied.

Comment: In this use case, there is no CEP like return/onward transport of the reusable packaging.

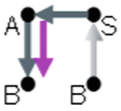


[UC 2e] Shopping Street concept. *Description:* The reusable packaging of a home delivery of a shopping street is returned by the recipient himself.

Example: After purchasing products all goods of all shops of a single customer are collected (e.g. in a delivery center of a shopping street) and delivered to the customer's home in reusable packaging. The customer takes the reusable packaging(s) with them the next time they visit the shopping street.

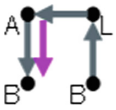
Comment: This is a special version of [UC 2d or UC 2f].

3.3 Class 3: Additional Transport



[UC 3a] Via collection points. *Description:* The return transport of the reusable packaging always takes place via a dedicated collection point. The transport from the recipient to the collection point is carried out by the recipient himself.

Example: The customer transports the reusable packaging received at a delivery to a collection point (e.g. a department store).



[UC 3b] Collection by reusable packaging logistics provider. *Description:* The reusable packaging is collected from the recipient by a reusable-packaging-logistics-provider, bundled and transported to the senders of goods.

Example: Pallet logistics – eg. EUR-pallet [5].

Comment 1: This Use Case is a special case of [UC 2a/b/c]. The main difference is that the return transport of the reusable packaging is coordinated centrally by the reusable packaging logistics provider and can return to the any sender. A pool of predefined reusable packaging is made available if required and collected from the recipient.

Comment 2: In this use case the standardization of reusable packaging, including the qualities necessary for return, is essential.

Comment 3: The role of the reusable packaging logistics provider is usually taken over by a transport company.



[UC 3c] Broker/matchmaker for reusable packaging. *Description:* The demand for reusable packaging from senders as well as offers of no longer used reusable packaging from recipients are coordinated from an intermediary office (exchange/matchmaker). Also, the corresponding transports are organized by this agent.

Example: Company A receives many preliminary products in reusable packaging, but they cannot reuse this packaging any further. The brokerage office now links this offer with a company B that needs this reusable packaging for sending goods.

Comment 1: In this use case, too, the standardization of reusable packaging, including the qualities necessary for return, is essential.

Comment 2: The role of the matchmaking agency can be performed by very different players, from a central, possibly even public, body to a free competition at an (online) stock exchange.

4 Outlook

This paper is just the first step to enable future investigations in the selection and optimization of solutions to achieve the intended sustainability goals originally intended by reusable packaging. Based on this catalogue of trip use cases of reusable packaging, optimization concepts can be developed. In doing so, the established common terminology enables to compare different logistic concepts and their impact on transport mileages, payload-distances as well as energy demand and CO2 emissions.

To take effect it is important to make it known in the research as well as operator and governance community. This paper as well as dissemination activities of the underlying project ReKEP [3] will undertake this task.

From a scientific point of view there is potential to generalize the catalogue beyond the CEP sector and extend it to all applications of reusable packaging. In this way it will create an important contribution to speed up of the introduction of circular economy and the success of the physical internet.

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Circular Economy and Life Cycle Assessments

Laboratory and Field Study of High-Rate Recycled Asphalt Pavement Rejuvenated with Waste Cooking Oil

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Abstract. Europe generates a large amount of site-won asphalt annually. European Union (EU) promised to increase circular economy policies, considering the concerns related to the efficient use of non-renewable resources and the struggle against climate change. Innovative technique's contribution to those goals is of primary importance.

This paper summarises the results of the CoolAsphalt project, aiming to study an innovative process to reuse RAP – reclaimed asphalt pavement – with a high incorporation proportion, up to 100%. High rates of RAP in new asphalt mixtures for pavements require a rejuvenating agent to recover the lost bitumen's volatile components. This study involved the addition of waste cooking oil (WCO) collected from restaurants, canteens and collecting points around municipal territories. Vegetable oil consumption is growing annually worldwide, resulting in a large amount of WCO that needs to be valorised.

The laboratory studies consisted of designing the asphalt concrete blends to apply in real-scale trial sections and assessing their mechanical and functional properties because resistance to ageing could be an issue for the lifecycle of these asphalt mixtures. An accelerated long-term ageing procedure simulated a five-year in-service period for Lisbon's climatic conditions.

The results show that the mechanical and surface properties of the hot (HMA) and warm mixtures (WMA) are suitable for low/medium traffic pavements. During the blends' manufacturing in a conventional drum plant, some issues related to the RAP's water content and the mixing temperature arose. These events allow the authors to highlight some recommendations on producing high RAP content asphalt mixtures with WCO as a rejuvenating agent.

Keywords: waste cooking oil · RAP · mechanical performance · long-term ageing · surface properties

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1 Introduction

Placing value on non-renewable materials has become a critical priority within public policy to attain specific goals related to a circular economy and the sustainable utilization of natural resources. Given the growing emphasis on these societal issues within the construction and maintenance of transport infrastructure, there is a pressing requirement to study and reuse materials for consecutive lifecycles in road pavements to minimize their environmental impact. Reusing of RAP – reclaimed asphalt pavement - has been widely used, but the ratio between manufacturing asphalt mixtures from virgin raw materials and those incorporating RAP is still low in Europe [1]. Hence, practitioners must intensify the incorporation rate of RAP in daily operations to align practice with the ongoing policies. Rising the RAP rate into new asphalt mixtures requires restoring the aged binder properties, such as reducing hardness and the propensity to cracking, and enhancing the capacity to bond to aggregates [2]. In this context, waste cooking oil (WCO) as a rejuvenator for the RAP's aged bitumen emerges as an opportunity to value another waste whose production is increasing globally [3]. This technique diminishes the improper disposal of waste materials like RAP and WCO in unsuitable locations, such as landfills and sewage systems, and reduces energy consumption.

Many relevant papers on the use of WCO to produce bio-bitumen have been published over the last decade [3]. Since most of these studies available mainly involved characterising the resulting bio-bitumen from mixing WCO and bitumen with promising results [3], it is advisable to conduct additional performance assessments on asphalt mixtures manufactured with a high content of RAP and WCO as a rejuvenating agent added during the mix blending process (dry method). This paper exposes the findings on the properties of asphalt mixtures produced in the laboratory and at an industrial scale regarding the recycling of up to 100% RAP while employing WCO as a rejuvenator.

2 Materials and Methods

2.1 Materials

The studied mixtures were based on a typical asphalt concrete for pavement surface layers, AC 14 surf 35/50, considered as reference, with 5% of 35/50 penetration grade bitumen content by mass of the total mixture. The blends with 60 and 80% of RAP and WCO were developed to the same type of layers. Because the asphalt plant could not produce 100% RAP mixes, the study considered 80% RAP for WMA and 60% for HMA as the practicable maximum. The RAP was milled in a 14-year-old pavement with 4.5% aged bitumen content. Figure 1 shows the gradations of RAP and the blends with 60 and 80% RAP superposed to the grading envelope generally used in Portugal.

As the project focuses on investigating cost-effective asphalt mixtures with high RAP rates, the gradation of the blend with 100% RAP had no adjustments to fulfil the gradation specification limits. After some initial studies [4], the results focused in this paper refer to different compositions: a hot-mix AC with 60% RAP, 10% WCO and 1% virgin bitumen (H-60RAP); a warm-mix AC with 80% RAP, 10% WCO, 1% virgin bitumen and 1.5% of organic wax (melting point of 100–110 ºC) as warm-mix additive (W-80RAP). The WCO content was selected based on previous studies [4].

The percentages of RAP and virgin bitumen refer to the blend's total mass, whilst the proportions of WCO and organic wax indicate values by the mass of the total binder. The WCO for the laboratory studies was domestic waste with acidity values between 0.359 and 0.426 mg KOH/g and a 919 kg/m^3 density. The WCO used in the plant at a real scale was collected from urban containers and had acidity values between 3.8 and 4 mg KOH/g.

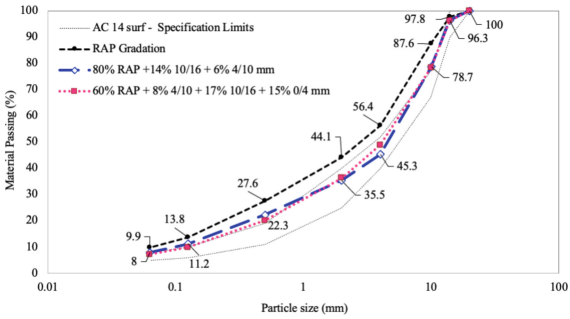


Fig. 1. Gradation of RAP and blends with 60 and 80% RAP

2.2 Methods

In the laboratory, the blends' components were preheated in an oven before mixing at 150ºC for the hot mixes and 130ºC for the warm mixes. After the mixing phase, the blends were placed in an oven at the mixing temperature for 30 min to allow the WCO to interact with the binder. Testing on cylindrical specimens with 102 mm in diameter and 64 mm in height, compacted with 75 blows per face, delivered the volumetric properties and Marshall properties of the studied blends used to determine the initial blend's compositions [4] considering Marshall values of 26.5 kN and 5.0 mm for stability and flow, respectively. These thresholds considered an increase of 25% over the maximum values currently applied for Portuguese specifications for virgin raw materials. The same type of specimens compacted with 50 blows per face supplied the results for water sensitivity in indirect tensile strength (ITS) tests conducted at 15 °C. The indirect tensile strength ratio (ITSR), as specified in EN 12697–12, was considered to evaluate the water sensitivity. Roller compacter moulded slabs to cut prismatic beams with 410 × 50 × 50 mm^3 to evaluate stiffness (EN 12697–26) and fatigue resistance by conducting the four-point bending (4PB) test, performed under controlled strain conditions at 20 °C (EN 12697–26). These tests were performed before and after an accelerated ageing procedure of specimens on TEAGE [5] to simulate a 5-year in-service time. Similar slabs with 40 mm thickness were moulded to assess rutting resistance in wheel-tracking tests according to EN 12697–22 by applying 10,000 loading cycles of a wheel at 50 °C.

The British pendulum test evaluated skid resistance using EN 13036–4 to measure the surface's PTV (pendulum test value). The measurement of texture depth (MTD) was conducted by the volumetric patch method by EN 13036–1.

Cylindrical cores and slabs taken from the pavement prototypes were also tested: cores for water sensitivity, beams from slabs for stiffness and fatigue resistance. Tests conducted directly on the pavement surface evaluated the surface's skid resistance and texture depth.

3 Results and Discussion

3.1 Water Sensitivity

Figure 2 presents the results of ITS and ITSR obtained for laboratory specimens and field cores.

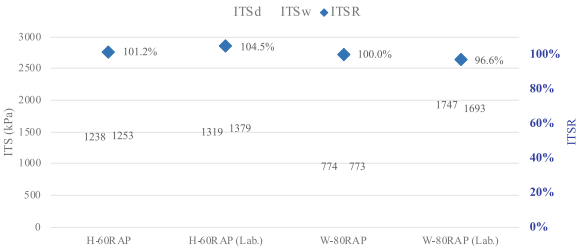


Fig. 2. Water sensitivity in indirect tensile strength tests.

The results obtained for the laboratory and field mixtures tested show low sensitivity to water because the ITSR values are higher than the 80% usually required. However, the ITS values were relatively low for the cores taken from trial sections with W-80RAP. The higher void content (5.7%) measured for field cores for W-80RAP may explain the lower ITS values for these compared with those from laboratory specimens (air voids of 0.2%).

3.2 Rutting Resistance

Figure 3 presents the variation of rut depth with the number of wheel passes for the slabs taken from the pavement trial sections. These curves allowed us to determine RDair (rut depth) and WTSair (slope of the wheel tracking curve in the quasi-linear region), comparing them with similar tests on the laboratory moulded slabs. The results show that the specimens revealed suitable resistance to rutting, notwithstanding the specimens from the field resist less than the compacted in the laboratory (ratio above 1.0). This tendency is verified for RDair and WTSair. In the case of the 80 RAP blend, the highest air void in the field justifies the more significant deformation observed. The mix with 60% RAP exhibited better resistance to rutting regarding RDair and the worst for WTSair. Despite having similar volumetric properties in the field and the laboratory, the different aggregate structures in both situations are likely to explain the worse behaviour shown by the slabs from the field.

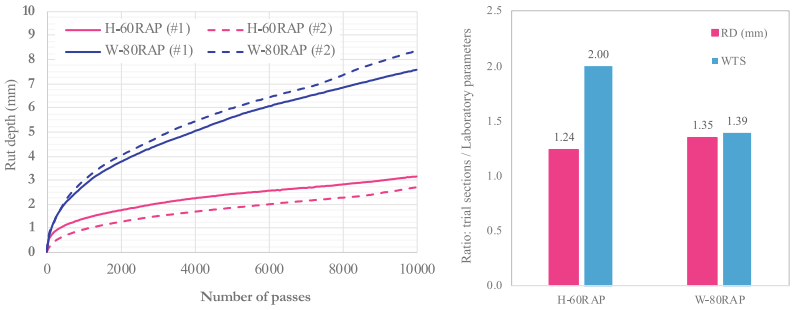


Fig. 3. Rutting resistance of field specimens (left) and ratio between trial sections and laboratory resistance (right).

3.3 Stiffness and Fatigue Resistance

The stiffness moduli measured to field specimens were 2250 MPa and 3770 MPa, at 10 Hz, respectively, for the warm mix W-80RAP and hot mix H-60RAP. These values are approximately 10% less than those of laboratory specimens. Therefore, it seems that the differences mentioned above regarding air voids of the specimens from the field and the laboratory had low influence on the stiffness results.

In what ageing is concerned (simulation of 5 years of exposition to in-service conditions), for the blend W-80RAP, the field mixtures were more sensitive to ageing than those from the laboratory. The "aged stiffness / unaged stiffness" ratio varied from 2 to 2.9 (frequencies from 30 to 1 Hz) for the field specimens, while this variation was from 1.4 to 2 for the laboratory mixture. The higher potential of water and UV radiation access into the specimens through the voids for the field specimens may be the reason behind the observed behaviour.

Fatigue resistance results revealed suitable behaviour for laboratory and field specimens. The results for ε6 – strain needed to attain fatigue failure of specimens after 1 million loading cycles – rising from the fatigue laws of the studied blends revealed the results presented in Table 1.

Table 1. Fatigue resistance of the blends based on the ε6 (μm/m) parameter.

Blend designation	Laboratory specimens	Aged laboratory specimens	Field specimens
H-60RAP	234	179	268
W-80RAP	198	132	251

The results show that the fatigue resistance of the mixtures obtained in the trial sections is adequate and even considerably higher than that observed for the laboratory samples. Moreover, the hot-mix asphalt (H-60RAP) performed better than the W-80RAP, revealing less ageing sensitivity.

3.4 Surface Properties

The surface characteristics of laboratory slabs and the trial sections' surface are summarised in Table 2.

Table 2. Surface properties.

Blend designation	Laboratory specimens	Field specimens	Laboratory specimens	Field specimens
	Skid resistance (PTV)		Texture depth (MTD)	
H-60RAP	80	85	0.91	0.77
W-80RAP	77	85	1.78	1.12

All blends met the standard requirements for texture depth (typically 0.7 mm in Portugal) and skid resistance with a minimum PTV of 60. H-60RAP exhibited a lower texture depth compared to W-80RAP. It should be noted that the surfaces of the slabs produced in the laboratory did not undergo any action to remove the surface bitumen film, which impairs skid resistance. On the contrary, vehicles circulated on the field pavement before skidding resistance was assessed. This situation explains the slightly higher PTV in the field.

4 Conclusions

The results presented in this paper allow the following main conclusions on warm- and hot-mix asphalt with high rate of RAP and WCO as a rejuvenator: 1) low sensitivity to water; 2) Adequate resistance to rutting, with the hot mix showing better behaviour than the warm mix; 3) Suitable stiffness and fatigue resistance, even after being subjected to a long-term ageing process; excellent surface characteristics (skid resistance and texture depth).

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Rejuvenation of High-Content Reclaimed Asphalt Mixtures with Bio-Heating Oil: Laboratory and Plant-Produced Experience

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Abstract. Habitually, bio heating oil – BHO – is valorised to generate energy as fuel for boilers. This matter is a by-product derived from biodiesel production containing mainly volatile elements. These compounds could be beneficial to recover the lighter fractions of aged bitumen of RAP – reclaimed asphalt pavement – to be added in high-rate incorporation in new asphalt mixtures. Although RAP has excellent potential to be reused in pavement construction and rehabilitation actions, the available data for Europe shows that there is a need for additional efforts to achieve higher levels of RAP reuse.

This paper presents results from the project CoolAsphalt, which aims to develop low-cost asphalt concrete on an industrial scale with up to 100% of RAP reuse, meeting appropriate requirements for medium / low-traffic roads. This 30-month ongoing project was funded by the European Union and the Portugal 2020 programme. It involved the study of different hot and warm asphalt blends in the laboratory in terms of empirical, mechanical, and functional properties. Since most of the binder within the blends suffered ageing due to solar radiation and climate exposure, the effect of secondary long-term ageing on mechanical and functional properties was assessed on asphalt mixtures specimens moulded with a high proportion of RAP and BHO as a rejuvenator.

The laboratory results revealed that BHO effectively contributed to recovering the aged binder's properties, considering the results obtained for water sensitivity, rutting resistance, stiffness, and fatigue cracking resistance. Even though practically no gradation adjustment was performed for the resulting asphalt mixtures, the surface and mechanical properties of the asphalt mixtures were suitable. Moreover, the production, laydown and compaction on an industrial scale to build the necessary pavement prototypes allow us to propose some relevant recommendations for using this type of mixture.

Keywords: bio heating oil · RAP · mechanical properties · accelerated ageing · surface properties

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1 Introduction

Despite policies to increase the circular economy in transport infrastructures, available figures indicate further efforts are needed to increase the reclaimed asphalt pavement (RAP) reuse in European road pavements [1]. As RAP is a valuable end-of-life material and its use reduces the consumption of non-renewable virgin raw materials, many authors have been testing it [2]. However, a high content of RAP requires a suitable quantity of a rejuvenating agent to restore the aged bitumen [3]. The literature uses several bio-oils [4], such as those obtained from a biodiesel production plant, where waste cooking oil and animal fats are used as the primary raw materials. The production process involves esterifying the free fatty acids, followed by transesterification. Bio Heating Oil (BHO) is a low-viscosity black oily liquid from biodiesel distillation. This residue mainly comprises less volatile organic compounds and residual Fatty Acid Methyl Ester (FAME).

Several authors have been evaluating the effect of bio-oil on binder's properties and rheology performance [4, 5]. By incorporating bio-oil, the binder's rotational viscosity and softening point generally decrease while the penetration and ductility increase. It also decreases the complex modulus and increases the phase angle. In terms of mixture, the literature mentions that the laboratory mixing time to add bio-oil to virgin binder varies from 10 to 40 min, and the temperature range is 130 to 180ºC [6]. A study using bio-bitumen produced with BHO in asphalt mixtures [7] showed that although the materials' resistance to water damage was suitable, it slightly decreased as the percentage of BHO increased. The same tendency was observed in the wheel tracking test at 60ºC. Results for fatigue revealed some inconsistency because the blend with the bio-bitumen with the highest content of BHO revealed the best fatigue performance. However, the resistance for lower BHO contents blends was lower than that made with the virgin binder.

Despite existing studies, additional laboratory tests should be carried out to assess the behaviour of asphalt mixtures (warm and hot) with a high proportion of RAP and BHO as a rejuvenating agent, even after long-term ageing. This paper presents the findings of a study conducted as part of the ongoing CoolAsphalt project that aims to create an economical paving material for medium to low-traffic roadways while minimising changes to the original properties of RAP and BHO.

2 Materials and Methods

2.1 Materials

The studied mixtures were based on a typical asphalt concrete for pavement surface layers, AC 14 surf 35/50, used as a reference, with 5% of 35/50 penetration grade bitumen content by mass of the total mixture. The blends with 60 and 80% of RAP and BHO were developed to the same type of layers. The RAP was milled in a surface layer with 4.5% aged bitumen content. The gradations of the RAP's aggregates, the blends with 60 and 80% RAP, and the gradation limits generally used in Portugal are presented in Fig. 1.

As the project's primary focus centres on the exploration of cost-effective asphalt mixtures featuring high RAP rates, it's worth noting that the gradation of the blend containing 100% RAP required no adjustments to meet the specified gradation limits.

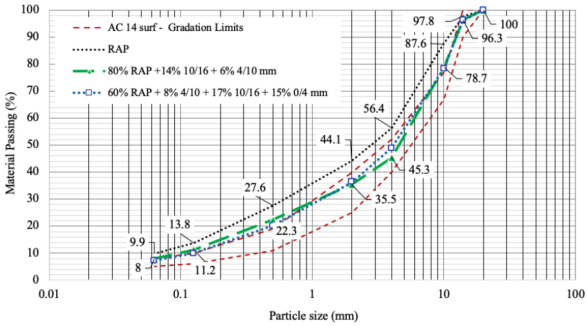


Fig. 1. Gradation of RAP and blends with 60 and 80% RAP.

The compositions evaluated in this paper include a hot-mix asphalt concrete (AC) with 60% RAP, 10% BHO, and 1% neat bitumen (referred to as H-60RAP), as well as a warm-mix AC featuring 80% RAP, 10% BHO, 1% neat bitumen, and 1.5% of organic wax serving as a warm-mix additive (designated as W-80RAP). The contents of RAP and neat bitumen are expressed as a fraction of the total blend weight, whereas the contents of BHO and organic wax are indicated as a percentage of the total binder weight.

2.2 Methods

An oven heated the blends's constituents to allow mixing them at temperatures of 150ºC and 130ºC for hot- and warm-mix asphalt, respectively. Afterwards, the blends were kept in an oven at the mixing temperature for 30 min to allow the contact between the binder and the BHO.

Cylindrical specimens with 102 mm in diameter and 64 mm in height, compacted with 50 blows per face, were tested in indirect tensile strength (ITS) tests at 15 °C, before and after water conditioning to assess water sensitivity, as defined in EN 12697–12. Similar cylindrical cores delivered these results taken from pavement prototypes.

Tests applying 10,000 passes of a wheel at 50 °C (recommended temperature in Portugal [8]) on slabs assessed permanent deformation resistance in wheel tracking tests following EN 12697–22. This type of roller-compacted slabs was sawed to obtain prismatic samples with 410 × 50 × 50 mm^3 to measure the blends' stiffness (EN 12697–26) and fatigue resistance based on four-point bending tests conducted under controlled strain conditions at 20 °C (EN 12697–24). These tests were repeated after subjecting the specimens to an accelerated ageing procedure to reproduce a long-term period of in-service conditions, with UV radiation and moisture. Cut slabs from the pavement provided results for the pavement prototypes. The pavement surface was evaluated regarding skid resistance with the British Pendulum (EN 13036–4) and texture depth using a volumetric patch method (EN 13036–1).

3 Results and Discussion

3.1 Water Sensitivity

Results of ITS and indirect tensile strength ratio (ITSR) obtained for laboratory specimens and field cores are summarized in Fig. 2. No results are available for W-80RAP from the pavement prototypes.

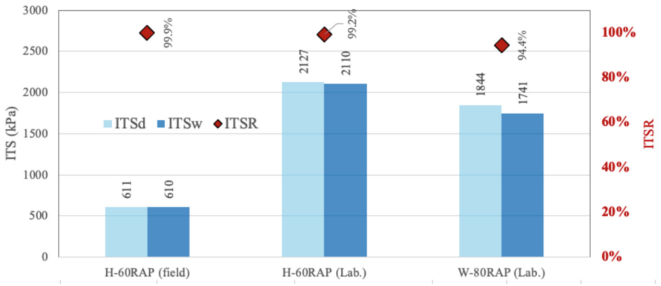


Fig. 2. Water sensitivity in indirect tensile strength tests.

The results show that the studied blends revealed limited susceptibility to water, as evidenced by ITSR values exceeding the typical 80% requirement. However, it's worth noting that the ITS values were comparatively lower for cores extracted from trial sections. This disparity in ITS values may be attributed to the higher void content observed in the field cores, measuring at 3.7%, in contrast to the laboratory specimens with significantly lower air voids (around 0.5%).

3.2 Permanent Deformation Resistance

The wheel tracking tests conducted on slabs of the different compositions provided curves that represent the growth of rut depth with the number of loads. RDair is the rut depth at 10,000 cycles, and WTSair represents the mean curve's slope between cycles 5,000th and 10,000th (Fig. 3). Additional results of H-80RAP-0.6NB are also presented to show that the resistance increases by reducing the neat bitumen content from 1.0% to 0.6%. No results are available for W-80RAP from the pavement prototypes.

Although the observed resistance is suitable, i.e., all the blends achieved low rut depth values), the slabs sawed from the pavement prototype (60% RAP) revealed less resistance than the corresponding slabs moulded in the laboratory. The higher void content achieved in the field may explain the difference. As expected, warm-mix asphalt blends with 80% RAP performed worse than hot-mix.

3.3 Stiffness and Fatigue Behaviour

The hot mix H-60RAP blends and specimens produced in the laboratory achieved stiffness values of 5,287 MPa (10 Hz, 20 °C) before accelerated ageing and 6,370 MPa

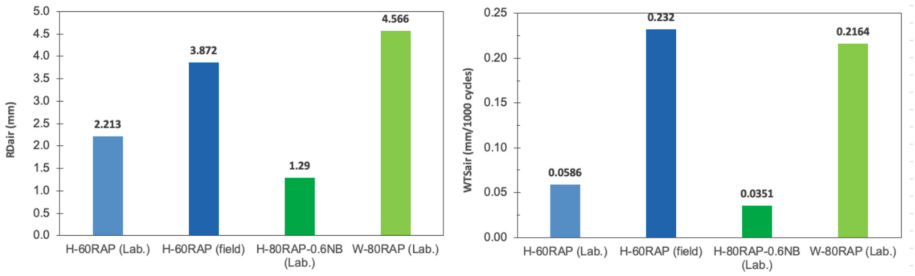


Fig. 3. Permanent deformation resistance of laboratory and field specimens: RDair (left); WTSair (right).

after being subjected to this conditioning procedure. Nevertheless, specimens cut from the pavement prototype only reached 1,290 MPa. The voids obtained for the pavement trial sections were probably responsible for the low performance obtained for the field specimens. For the same temperature and frequency conditions, the laboratory-produced warm-mix W-80RAP attained 3,192 MPa and 4,159 MPa, respectively, before and after ageing. No field specimens were available for this blend. Although the H-60RAP blend exhibits a comparatively higher level of rigidity when compared to the W-80RAP, both are suitable for use as a pavement surface layer. The better aggregate structure of H-60RAP and the presence of organic wax in the W-80RAP likely explain those results.

Regarding fatigue resistance measured in four-point bending tests, the material's showed suitable behaviour. Table 1 summarizes the regression equations parameters a and b ($\varepsilon = a.N^b$), the determination coefficient (R^2) and the values for ε_6 (μm/m) – strain needed to get specimens failure at 10^6 loading cycles.

Table 1. Fatigue resistance performance of blends.

Mixture name	Laboratory specimens			Laboratory specimens after ageing			Field specimens		
	a	b	R^2 (%)	a	b	R^2 (%)	a	b	R^2 (%)
H-60RAP	1799.0	−0.152	91.8	1504.7	−0.171	87.7	1773.8	−0.134	78.6
	$\varepsilon_6 = 220$			$\varepsilon_6 = 140$			$\varepsilon_6 = 279$		
W-80RAP	3773.3	−0.215	95.3	1303.1	−0.141	88.5	---	---	---
	$\varepsilon_6 = 194$			$\varepsilon_6 = 186$			---		

Despite the slight decrease in fatigue performance after ageing, the blends revealed suitable behaviour. The mixture with 60% RAP also showed adequate fatigue performance. As generally occurs, the hot-mix asphalt (H-60RAP) better-resisted fatigue than the warm-mix, W-80RAP, but revealed higher ageing sensitivity regarding fatigue behaviour.

3.4 Texture Depth and Skid Resistance

The mean texture depth (MTD) and the skid resistance (PTV) of the pavement prototypes' surface are presented in Table 2.

Table 2. Surface properties (laboratory / field).

Mixture name	Skid resistance (PTV)	Texture depth (MTD) (mm)
H-60RAP	80 / 79	0.79 / 0.90
W-80RAP	77 / 83	1.09 / 1.71

The results adhered to the standard criteria in Portugal, with minimum values of 0.7 mm and 60 for MTD and PTV, respectively. H-60RAP had a shallower texture depth when compared to W-80RAP. Although there is no significant difference in PTV results for the laboratory and pavement surfaces, MTD was higher for the latter, considering its higher void content, resulting in a more textured surface than the laboratory compacted slabs.

4 Conclusions

The findings presented in this paper lead to the following critical conclusions regarding warm- and hot-mix asphalt that incorporates a high percentage of RAP (Recycled Asphalt Pavement) and utilises BHO (bio-heating oil) as a rejuvenator: a) low susceptibility to water damage; b) sufficient resistance to permanent deformation, with the hot mix displaying superior performance compared to the warm mix; c) appropriate stiffness and fatigue resistance even after undergoing an extended ageing process; d) outstanding surface attributes, including skid resistance and texture depth.

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Towards a Sustainable Design and Circular Economy for Hybrid EV Batteries

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Abstract. The HELIOS European project, funded by the H2020 Programme, aims to develop lighter, modular hybrid Li-ion battery packs for EVs that combine same-size modules with high-power and high-energy cells to meet customer demands for fast charging and long-range capabilities. Nevertheless, it is important to consider the potential environmental impacts associated with the disposal of such hybrid batteries. This includes the consumption of a wider range of raw materials, the release of hazardous substances, and the emission of greenhouse gases. To address these concerns, the HELIOS project also focuses on improving the sustainability of the battery pack by creating designs for easy reuse in second-life applications and by developing recycling strategies at the End-of-Life (EoL) of the battery pack. The project has progressed in three key research areas: 1) Designing the battery pack to incorporate possible second-life scenarios using a modular configuration and enhanced dismantling techniques. 2) Froth flotation experiments were carried out to study whether graphite could be recovered in a reusable form and to create data for future LCA calculations. 3) Parallel to the froth flotation experiments, LCA methodology supported by the ISO 14040 series was used to create a baseline to evaluate the environmental impacts of the hydrometallurgical recycling of the NMC811-graphite cells. This baseline could be used later to assess the impact of graphite recovery by froth flotation, as the current LCA baseline excludes the recovery of anode materials (graphite and LTO).

Keywords: Hybrid EV Battery · Recycling · 2nd Life · Dismantling · Refurbishment · Life Cycle Assessment · Environmental Impacts

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1 Introduction

The growing electric vehicle (EV) markets have increased the demand for raw materials needed in the production of lithium-ion batteries (LIBs) to power the transition towards transportation sector electrification [1]. Furthermore, this fast-growing rate of raw material consumption also raises concerns regarding material availability, for which recycling offers a potential solution to narrow the gap between the supply and demand of lithium-ion battery (LIBs) raw materials. Consequently, the European Union has imposed new stricter recycling requirements for critical materials and from 2030 onwards, 70% of LIBs materials need to be recovered to reduce impacts due to mining [2]. However, the efficient separation of the active components and their recovery from battery wastes remains a challenge.

In addition to the regulations encompassing a wide array of requirements designed to encourage the recycling of key battery raw materials [3, 4], the European Union has introduced new targets aimed at promoting sustainability [5]. These include carbon footprint performance class requirements, applicable from 1 July 2025, for electric vehicle batteries and the reduction of battery weights [6]. The new EU laws underscore the importance of designing batteries for easy reuse in second-life applications, thereby paving the way for a more sustainable future in energy storage. Compared to directly recycling lithium-ion batteries after their electric vehicle use, the carbon footprint and energy use of batteries recycled after their second life can be reduced by 8 to 17% and 2 to 6%, respectively.

Utilizing Second-Life batteries can provide numerous advantages that contribute to their overall sustainability. Firstly, they extend the useful life of EV batteries, delaying their disposal and reducing waste [7]. Moreover, they can offset the need for new battery production and its associated environmental impact [8]. Finally, they can provide affordable energy storage solutions that support the integration of renewable energy into the grid [9]. At the European level, the potential for Second-Life batteries is significant. With millions of EVs expected to be on the roads in the coming years, a vast number of batteries will eventually reach their End-of-Life (EoL) [10]. These batteries often retain a substantial portion of their original capacity and can still provide valuable service in second-life applications prior to the final EoL recycling [11].

Currently, lithium-ion batteries are constantly undergoing development to improve EVs performance requirements for higher power density, fast charging, and longer cycle life. Therefore, a large variety of cell chemistries as well as pack, module and cell designs have entered the market to meet these demands [12]. Nonetheless, designs that are being developed to offer improved LIBs performance and longer lifetimes often result in new material selections and combinations that may not have established recycling strategies. For example, material selection can include raw materials with low economic value, which can create challenges for their separation within existing metallurgical recycling infrastructures. The wide variety of cell chemistries and module and cell designs in the market means that pyrometallurgical treatment is currently the only economically viable option, as it offers enough flexibility in terms of process feed, although with the caveat that materials such as graphite or Li are lost. [13–15].

The HELIOS project, funded by the European Union's Horizon 2020 program, has developed a series of modular and lightweight hybrid Li-ion battery packs. These packs

combine high-power cells comprised of NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) cathode and a $Li_4Ti_5O_{12}$ (LTO) anode, with high-energy cells featuring an NMC811 cathode and graphite anode. The aim of the project is to explore suitable solutions for recycling these battery modules at their EoL, as well as dismantling and refurbishment approaches to promote second-life usage and recycling. The outcomes of these efforts will be integrated into Life Cycle Assessment (LCA) models to support a sustainable and circular design for hybrid batteries.

2 Methodology

Three approaches are outlined in this study following strategies that are being developed in HELIOS project to improve the sustainability of the hybrid battery pack:

- Novel manufacturing and dismantling processes enable second life use and new methodologies for recycling and metal recovery.
- Graphite recovery from mixed NMC811-graphite-LTO chemistries is studied experimentally by froth flotation. The experiments simulate the behaviour of a perfectly liberated model NMC811-graphite-LTO system in the froth flotation process without the effect of binder, electrolyte, solid electrolyte interphase (SEI), current collector pieces and plastics to test froth flotation's potential for inclusion as part of battery recycling strategies.
- The environmental impacts of recovering Co, Ni, Mn, and Li from NMC811-graphite cells by hydrometallurgical processes were simulated and an LCA was performed to obtain an overview of the environmental impact of recovering these elements.

The outcomes of these three approaches are planned to be included in more detailed cradle-to-grave LCA models. Furthermore, an additional LCA focused on a process to recover the nickel by using a hydrometallurgy process is also to be undertaken.

3 Novel Manufacturing and Dismantling Processes for Hybrid Battery Packs

This section explains the methodological strategies to enhance the efficiency and safety of recycling processes, with an emphasis on circular design principles. The principles of the circular economy revolve around designing out waste and pollution whilst maximizing the useful life of products and materials. The main principles where the HELIOS actions are focused are as follows:

- Design Out Waste and Pollution [16]: In a circular economy, resources are used efficiently, and waste is designed out of the system from the beginning. This means that products are designed and optimized for a cycle of disassembly and reuse, which can significantly reduce waste and pollution.
- Keep Products and Materials in Use [16]: The focus is on creating a "closed loop" system where resources are not just consumed and discarded but are reused, repaired, or refurbished to extend their life. This includes considering second-life applications for products or components that can no longer serve their primary purpose.

- Rethinking of Business Models [16]: Companies are encouraged to rethink their business models to support longer product lifetimes, modular design, product sharing, leasing or take-back schemes that can help keep products and materials in use for longer. By aiming to improve the efficiency of each stage, new methods to design products via a holistic approach are applied, taking into consideration their entire lifecycle, from disassembly to manufacturing and (re)assembly - the main methods are described as follows:

The new procedures are based on a thorough Analysis of Existing Techniques used in the industry that include:

Robotic Battery Disassembly: currently battery packs are manually dismantled, which requires skilled labour and specialized tools. The introduction of robotic disassembly based on current approaches will improve the performance of the process, reduce the risk of harm to workers and decrease costs, making recycling more economically viable. Another advantage is that robots can perform tasks with extremely high precision, which will reduce the risk of damaging valuable components and will ensure that valuable battery cells are handled carefully. During the disassembly process valuable data about aging, and reliability. Etc. could be collected and analyzed.

Process Optimization: development of new procedures for dismantling and refurbishment to streamline and automate the recycling process. by involving deconstruction planning where CAD design is used for pre-planning the disassembly process where the robot follows a predefined plan to remove components in a specific order. This approach includes also exploiting the modular design where the process is simplified because robots remove not only components but entire modules. Another advancement in process optimization is that the design is done in such a way that at almost all steps disassembled components are designed to be manufactured from the same material. This will facilitate second life use and introduce new methodologies for recycling and metal recovery.

The HELIOS battery pack prototypes represent a significant advancement in battery technology, a unique combination of performance, flexibility, and cost-effectiveness through the combination of high-energy (HE) cells for increased range and high-power (HP) cells for faster charging in separate modules. By utilizing a modular design with the same size and shape plastic housings or "egg-box" (each cell inside is separated like eggs in a cardboard box), these battery packs provide a versatile solution that can be seamlessly integrated into different EV models to accommodate various power and energy demands (Figs. 1 and 2).

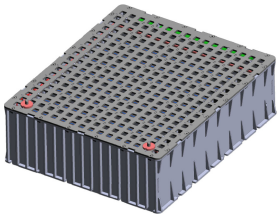


Fig. 1. HE module in "egg-box"

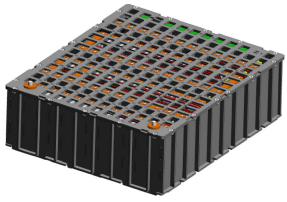


Fig. 2. HP module in "egg-box"

Either four HE or HP modules are then packaged into the so-called "subpack" that contains its own cooling circuit (Fig. 3).

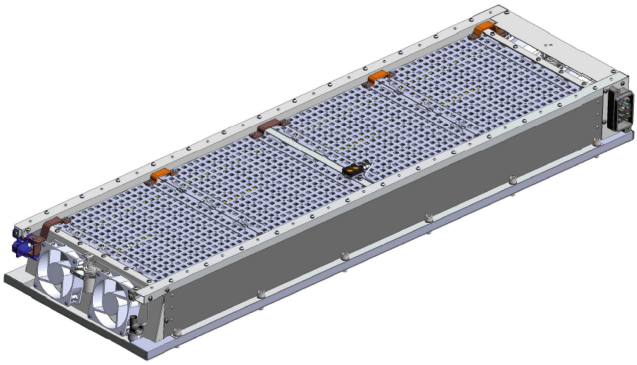


Fig. 3. Helios subpack with 4 identical modules inside

According to the needs of the original equipment manufacturer (OEM) and end-users, these subpacks can be combined in any way to meet the demands of a specific application, hence they are customizable to drivers' requirements and scale-up for different size of EVs. The interconnections between the subpacks inside a full HELIOS battery pack are quite simple and based on high voltage (HV) copper busbars and wires, which allows easy removal of individual subpacks for reuse in second-life applications like energy storage.

Furthermore, at the ultimate EoL, the complete dismantling of a subpack for the final recycling of all materials inside the "egg-box" modules is planned to be a straightforward and mainly automated process.

4 Froth Flotation as a Potential Strategy for Graphite Recovery from NMC811-Graphite-LTO Chemistries

The recycling of LIBs is primarily linked to the economic worth of the metals they hold. At present, only the most valuable metals, including Cobalt, Nickel, and Copper, are commonly extracted. [15]. From the HELIOS battery cells, Ni and Cu are predicted to face future supply risks [17] whereas Co, natural graphite and – more recently - Li, Ti, Mn and Al are also categorized as critical raw materials by the EU [2] highlighting the importance of developing strategies for the optimal recycling of these elements.

The material selection of the HELIOS battery pack poses challenges for critical raw materials recovery based on the industrial-scale extractive options currently employed for recycling spent LIBs. Pyrometallurgical processes, widely used for their high reaction rates and lack of requirement for passivation or dismantling, produce a metal alloy and a slag that contains the various oxides from Li-ion battery modules. However, this approach significantly loses critical battery materials and graphite, which is reduced to CO_2. [12, 14, 18]. Furthermore, the loss of these components will make it difficult to reach the future EU battery recycling requirements.

Consequently, research has shifted more towards hydrometallurgical recycling as a larger number of elements can be recovered, often with high selectivity [19]. Traditional hydrometallurgical recycling uses acidic media to leach metals from waste Li-ion battery electrodes, producing a solution for purification and recovery through precipitation and solvent extraction. These processes can be complex, yielding high-purity metals, but also significant secondary pollution [20, 21]. In addition, hydrometallurgical recycling is not an optimal method to recover graphite spent LIB mixtures. Graphite is porous and adds volume to the feed material, increasing water and acid consumption and producing a viscous slurry that is difficult to filter and wash [22]. Graphite particles may also get damaged during leaching, preventing its reuse it as an anode material [23, 24].

Although graphite recovery has not been the focus of most recycling processes so far, anodic graphite represents 14 – 22% of a LIBs weight and can help to satisfy the future EU recycling requirements [17]. Thus, froth flotation has recently attracted the attention for use in graphite recycling, since it is a physical separation method in which the graphite structure can be maintained, thereby allowing the direct reuse in new batteries manufacturing [17, 23, 25, 26]. Froth floatation is able to separate lithium metal oxide powder from the graphite in Li-ion batteries, by exploitation of their different wettability characteristics. Bubbles introduced into a stirred vessel containing the black mass collect hydrophobic materials, producing a graphite-rich froth. Additional reagents can enhance froth stability and promote wettability differences [27]. Direct recycling of graphite could be economically attractive if its structure were preserved and if it could be recovered with battery grade purity (> 99%). [26].

Material and methods, discussion, and preliminary results by application of this novel method in the HELIOS context are described in the following sections.

4.1 Materials and Methods

Pure battery-grade graphite, NMC811 and LTO particles were mixed according to the expected active material composition of the HELIOS battery modules, i.e., 50% of NMC811—as cathodes in both cell types contain this active material—25% of LTO and 25% of spherodized graphite particles. The particle size distributions of these model materials (shown in Fig. 4) were measured with a laser diffraction particle size analyser (Malvern Panalytical Mastersizer 3000, Malvern, UK) and the sources of chemicals used are listed in Table 1.

A laboratory-scale, 1 L flotation cell (Lab Cell-60mm FloatForce mechanism, Outotec, Espoo, Finland) was used for the flotation experiments. 40 g of the active particle mixture (50% NMC811; 25% graphite; 25% LTO) was added to 1 L of ion exchanged water and mixed by impeller at 1000 rpm for 3 min, after which the rotation speed was reduced to 850 rpm and 8 ppm of MIBC frother was added to the cell. The pulp was conditioned with MIBC for 2 min, and then air was introduced to the cell through the impeller at a flowrate of 2 l/min, to create bubbles and initiate the flotation experiment. Collection of the froth started when the froth rose to a suitable level and it was then sampled at time intervals of 0–1 min, 1–3 min, and 3–8-min to study the flotation process kinetics. The collected concentrate samples and the remaining pulp in the flotation cell were filtered and dried in a convection oven.

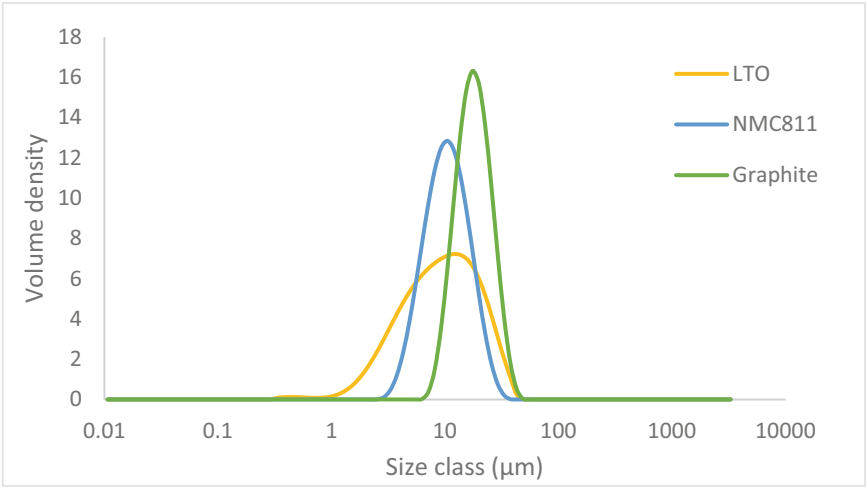


Fig. 4. Particle size distributions of model black mass.

Table 1. Materials and reagents used in froth flotation experiments of model black mass.

Distributor	Chemical	Purity [%]
MSE Supplies, Tuscon, AZ, USA	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	Battery grade
MSE Supplies, Tuscon, AZ, USA	$Li_4Ti_5O_{12}$	Battery grade
ProGraphite GmbH, Untergriesbach, Germany	Spherodized graphite	99.95
Sigma-Aldrich, St. Louis, MO, USA	Methyl isobutyl carbinol	98

These dried samples were subsequently weighed, and their composition analysed by XRF (Oxford Instruments, X-MET 5000, Abingdon, UK) and SEM-EDS (Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy) (MIRA3 SEM, Tescan, Brno, Czech Republic and UltraDry Silicon Drift Energy Dispersive X-Ray Spectrometer combined with NSS Microanalysis Software (Thermo Fisher Scientific, Waltham, MA, USA)). A schematic representation of the froth flotation experimental procedure is presented in Fig. 5.

4.2 Findings and Analysis

The hydrophobic graphite particles are collected in the froth phase, while the hydrophilic lithium metal oxides remain in the tailings. Nevertheless, with increased flotation time, the grade of the recovered graphite was found to decline - as shown in the SEM images presented in Fig. 6.

Rinne et al. [28] and Vanderbruggen et al. [17] have attributed this lowering of graphite grades to entrainment, which occurs as lithium metal oxide particles are carried with process water to the froth layer. Entrainment is an unselective recovery mechanism

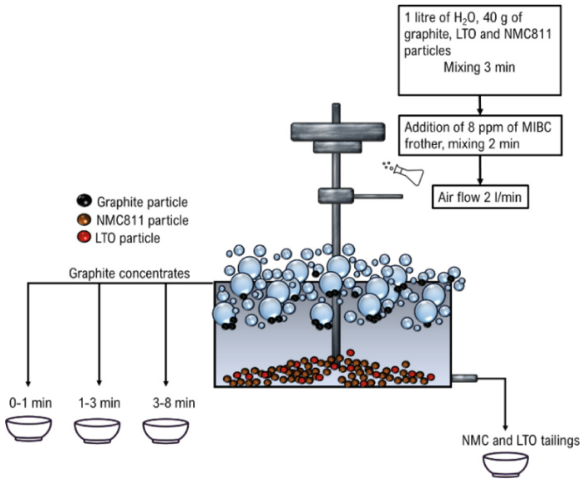


Fig. 5. Flowsheet of the froth flotation experiments.

and fine particles are more prone to be recovered by this mechanism since their settling rate is slower cf. Large particles [27]. Vanderbruggen et al. [17] measured a linear correlation between NMC111 contamination in the recovered graphite and water pulled from the flotation cell, indicating that graphite grade declines due to entrainment of particles below 10–15 μm size range. Interestingly, Vanderbruggen et al. [17] also measured significant amounts of pure NMC111 particles attaching to air bubbles in their captive bubble experiments. It is therefore possible that NMC811 and LTO particles exhibit both entrainment and true flotation behavior. The improvement of graphite grade therefore depends on the prevention of lithium metal oxide recovery by any of these mechanisms. For example, Rinne et al. [26] improved the grades of recovered graphite by increasing LCO particle sizes with selective flocculation.

Use of selective depressants targeting the LTO and NMC811 particles could also improve the graphite grades by reducing true flotation [17]. Lithium is known to leach to the process water and Li^+ ions have been shown to stabilize froths, thereby increasing water recovery and entrainment. Therefore, washing the black mass before flotation has resulted in improved graphite grades. [26, 28] Other options for reducing entrainment include lowering solid-liquid ratios [29] and selectively flocculating lithium metal oxides into larger particle clusters [26].

Figure 7 shows the cumulative grade vs. cumulative recovery curves and flotation kinetics of the 50% NMC811–25% LTO-25% graphite mixture. The data points represent the arithmetic mean from four repeated experiments under identical conditions and the standard deviations of the results. The large experimental variation can be partly attributed to the manual froth collection. On average 87.8% of the graphite could be recovered with 94.8% grade and 50% of the graphite can be recovered with 98% grade. These results show that froth flotation has the potential to be used for the direct recycling of LIBs, although further research to optimize the froth flotation process is needed to achieve consistently $> 99\%$ grades.

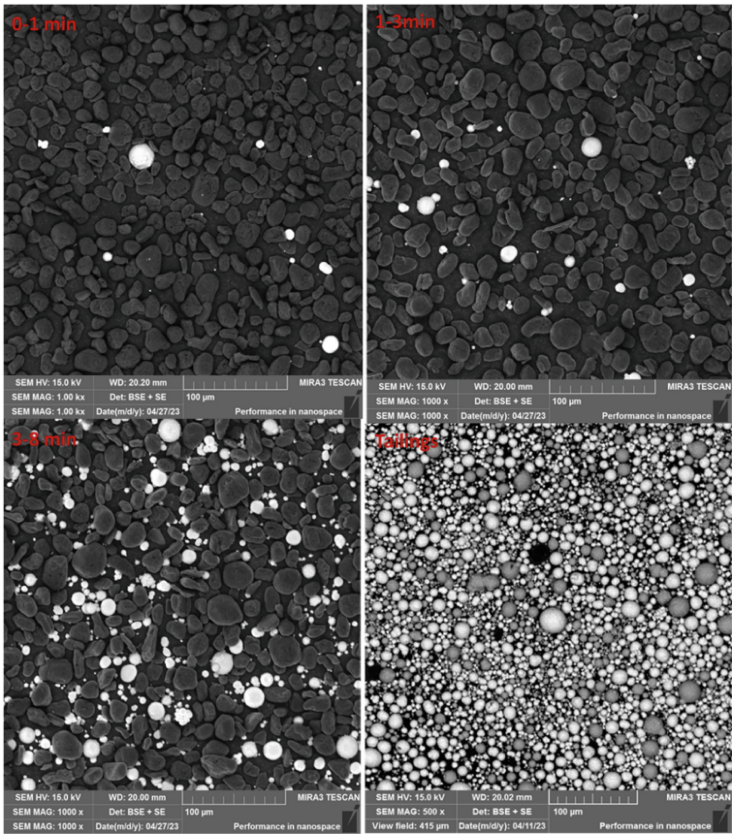


Fig. 6. Comparison of the graphite concentrates collected during 0–1 min, 1–3 min and 3–8 min flotation times and the remaining tailings. Black particles are graphite, grey particles are LTO, and white particles are NMC811.

The kinetics of graphite flotation were determined by fitting the graphite recoveries collected at different time intervals to the classical first order kinetic model according to Eq. (1) [27, 28] to obtain the rate constant k = 0.85 for the electrode mixture studied.

$$R(t) = R_{max}\left(1 - e^{-kt}\right) \tag{1}$$

where, R(t) is the recovery of graphite at time (t), Rmax is the maximum recovery after the experiment and k is the rate constant.

Such kinetic data, graphite grades information and recoveries could be utilized in the HSC simulations and LCA calculations related to the recycling of HELIOS modules.

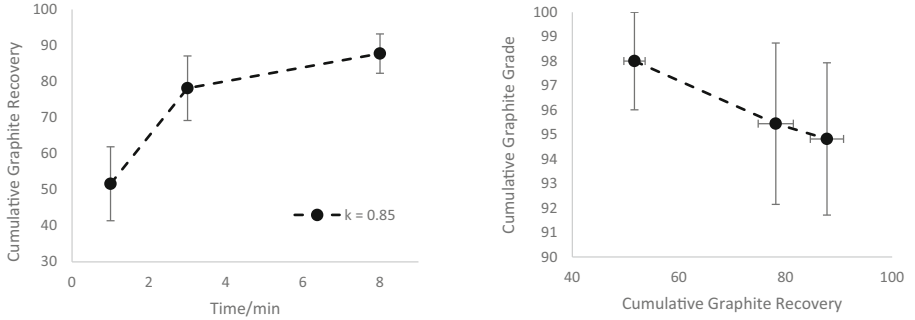


Fig. 7. Cumulative grade of graphite as a function of graphite recovery and graphite recovery as a function of flotation time during froth flotation of model black mass composed of 50% NMC811, 25% graphite and 25% LTO. The curves represent repeated experiments under identical conditions.

5 Environmental Impacts of Recovering Co, Ni, Mn, and Li from NMC811-Graphite Cells by Hydrometallurgical Processes: A Simulation and LCA Study

Process simulation is a useful tool when reliable industrial data is unable be obtained. In this case, the HSC Chemistry® Sim software module (METSO, Pori, Finland) was utilized to obtain the life cycle inventory (LCI) of the emerging hydrometallurgy recycling process. An extensive literature review was carried out to obtain the parameters for the process simulation and chemical reactions. Open LCA software by Green Delta was utilized to generate the life cycle analysis with the support of the Ecoivent 3.6 database developed by the Swiss Centre for Life Cycle Inventories.

5.1 Goal and Scope

The goal of the study was to understand the environmental impacts of recycling black mass with a high content of nickel. The functional unit selected is 1 kg of recycled black mass. For the environmental impacts it was planned that the LCA-related work undertaken as part of HELIOS would not only cover the carbon footprint of the EV batteries, but also consider additional impact categories of relevance for the actors involved in their mining, manufacture, and use by a grave to gate study. Preliminary treatment of the black mass by crushing, magnetic separation, and sieving is not included in the scope of this study along with the binder and electrolyte effects on the system.

5.2 System Boundary

The system under study is shown in Fig. 8 and depicts the hydrometallurgy process for battery recycling proposed for the black mass with high nickel content. The study boundary is composed of leaching, copper cementation, iron and aluminium removal by hydrolysis, manganese solvent extraction and precipitation, cobalt and nickel solvent extraction and crystallization, and lithium precipitation. The effluents from the system are

collected and treated via a neutralization step. Nonetheless, the environmental impacts associated with waste management and further wastewater treatment associated with the overall process were beyond the scope of this work.

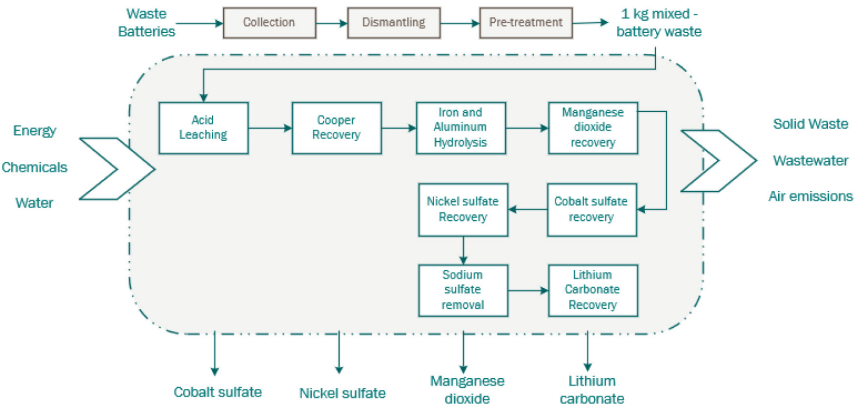


Fig. 8. System boundary and flowsheet diagram of the battery recycling process to study.

5.3 Impact Assessment Methods and Indicators

An LCA was carried out using Open LCA software, and the Ecoinvent database 3.6, with three different impact methods selected to analyse the impact categories. Under this context and aligned with the recommendations in ISO 14044 [29], the Environmental Product Declaration, EPD® system [30] and the PEF method [31], the impact categories shown in Table 2. Are suggested to study the environmental behaviour of the battery solutions. Table describes the environmental category analysed the method used and its description.

5.4 Process Descriptions

The black mass underwent preliminary treatment involving crushing, magnetic separation, and sieving, to achieve a particle size smaller than 0.125 mm. The material that was taken as a reference was investigated previously by Roy et al. (2019) who studied NMC 111 [32]. Nonetheless, the mass percentage of the LCO, LNO, and LMO were modified to stoichiometrically increase the LNO content to match the NMC811 composition. The chemical composition of the black mass fed to the system is outlined in Table (Table 3).

The black mass was fed to a leaching system that comprised of 2M H2SO4 and 4% of H2O2. The pregnant leaching solution (PLS) was further treated in a complex battery recycling circuit to recover copper as metallic copper powder through cementation, manganese recovery as oxide (MnO2), through solvent extraction and oxidative precipitation, recovery of cobalt and nickel respectively as nickel sulphate (NiSO4·6H2O), and cobalt sulphate (CoSO4·7H2O) through solvent extraction and crystallization, and

Table 2. Impact categories analysed, the method used, and units.

Abbreviation	Impact category	Unit (Method)
GWP	Global Warming Potential	kg CO_2-eq (CML)
ADP	Abiotic depletion (elements)	kg Sb-eq (CML)
ADPf	Abiotic depletion (fossil)	MJ (CML)
AP	Acidification potential	kg SO_2-eq (CML)
EP	Eutrophication potential	kg PO_4 3—eq (CML)
FW-AE	Fresh water aquatic ecotoxicity	kg-DCB-eq (CML)
MA-EX	Marine aquatic ecotoxicity	kg-DCB-eq (CML
ODP	Ozone depletion	kg CFC-11-eq (CML)
POCP	Photochemical ozone creation potential	kg ethene-eq (CML)
T-EX	Terrestrial ecotoxicity	kg-DCB-eq (CML)
FPM	Particulate matter	kg PM2.5 eq (ReCiPe)
LU	Land use	m^2 x yr annual crop land (Recipe)
HT-C	Human toxicity potential – Cancer	CTUh (USEtox 2.01)
HT-NC	Human toxicity potential – Non-Cancer	CTUh (USEtox 2.01)

Table 3. Chemical composition of the black mass fed to the system.

Component	$LiNiO_2$	$LiCoO_2$	$LiMnO_2$	Cu	Al	Fe	C	Total
wt%	54.66%	6.57%	6.85%	3.56%	0.78%	1.23%	26.35%	100%

lithium carbonate (Li2CO3). After every stage, all effluents collected and subject to a simple neutralization step were metals (except lithium, calcium, and sodium) which were removed at pH 7. Additionally, the flowsheet removes Glauber salt by increasing the concentration of Li through evaporation to remove (Na2SO4·10H2O) through crystallization, whereas aluminium and iron are taken out of the system as oxides via hydrolyzation (Table 4).

5.5 Process Performance

The selected mass flow for the study was 7000-ton of black mass/year as Rinne et al. (2021) previously proposed in their study where a LIBs and NIMH battery recycling system was investigated [21]. The flowsheet simulation was successfully recovered. ∼92% Li, 95% Co, 94% Ni, and 94% Mn. The estimated purity of the recovered materials is shown in Table 5.

Table 4. Simulation parameters for flowsheet simulation in HSC-Sim

Leaching	Unit	Value	Reference
H_2O_2	%	5	[33] [5]
H_2SO_4 concentration	gr/L	196	[33]
S/L ratio	g/L	100	[34]
Mn solvent extraction	Unit	Value	Reference
pH	-	4	[35]
O/A ratio in extraction	vol/vol	1:1	[35]
O/A in stripping	vol/vol	8:1	[35]
H_2SO_4 concentration in stripping	mol/L	0.5	[35]
$MnSO_4$ concentration in scrubbing	g/L	4	[35]
O/A ratio in scrubbing	vol/vol	10	[35]
Mn precipitation	Unit	Value	Reference
SO_2 partial pressure in SO_2/O_2	p.%	6	[36]
pH	-	3–4	[36]
O_2 utilization efficiency	%	33	Estimate
Al and Fe removal	Unit	Value	Reference
pH in neutralization	-	4	[20]
Co solvent extraction	Unit	Value	Reference
pH	-	5.4	[20]
Co loading in extractant	g/L	~17	[37]
O/A in extraction	vol/vol	1:1	[20]
O/A in stripping	vol/vol	1:4	Estimated
H_2SO_4 concentration in stripping	g/L	10	[20]
O/A scrubbing	vol/vol	10:1	Estimated
$CoSO_4$ concentration in stripping	g/L	10	[20]
Ni solvent extraction	Unit	Value	Reference
pH	-	6.5	[20]
O:A in extraction	vol/vol	1:2	Estimate
O:A in stripping	vol/vol	4:1	Estimate
H_2SO_4 concentration in stripping	g/L	10	[20]
O:A in scrubbing	vol/vol	10	[20]
$NiSO_4$ concentration in scrubbing	mol/L	0.3	[20]
Sodium sulphate crystallization	Unit	Value	Reference

(*continued*)

Table 4. (*continued*)

Leaching	Unit	Value	Reference
Li concentration	g/L	20 g/L	[38]
Na_2SO_4 solubility	g/L	12	[38]
Lithium carbonate crystallization	Unit	Value	Reference
Li concentration	g/L	1	[38]
pH	-	12	[38]

Table 5. Material recovered from the software simulations and their purities (%)

Material	Purity	Unit
MnO_2	98.41	%
Li_2CO_3	97.79	%
$NiSO_4$	99.61	%
$CoSO_4$	99.34	%

5.6 Life Cycle Inventory

A comprehensive life cycle inventory is presented in Table 6. It must be noted that even though life cycle assessment using Ecoinvent 3.6 is an optimal tool to understand the environmental impacts of a process when industrial data is not available it has its limitations. For example, solvent extraction chemicals (D2EHPA, Cyanex 272, TBP) were not included in the LCI, moreover, cobalt sulphate had to be replaced stoichiometrically with metallic cooper and oxygen gas was excluded from the LCI due to lack of data availability in the Ecoinvent data 3.6. Due to these reasons, no results related to the excluded materials were generated to analyse a more comprehensive life cycle assessment, nevertheless, this investigation was conducted using the most up-to-date information accessible during the period of this study.

5.7 Impact Analysis

The total environmental impacts are summarized in Table 7, while the contribution of every material to each category is depicted in Fig. 9. It is interesting to observe that through the impact categories nickel sulphate, sodium hydroxide, and sulfuric acid had the highest contribution to the environmental impacts. Nickel sulphate is used in minimum amounts for the purification of the recovered nickel while sodium hydroxide and sulfuric acid are used in several different steps of the flowsheet.

For GWP, the more important contributors were associated to the use of sodium hydroxide (35%), nickel sulphate(20%), hydroxide peroxide and the generation of steam (∼11%). ADP contributions were nickel sulphate 50% and sodium hydroxide and sulfuric acid with ∼19%. For ADPf contributions were related to the use of sulfuric acid

Table 6. Life cycle Inventory (LCI)

Input			Output		
Leaching					
Black mass	1.00	kg/kg	Leaching Residue	0.22	kg/kg
Sulfuric acid	1.49	kg/kg	$O_{2(g)}$	0.12	Nm^3/kg
Hydrogen peroxide	0.29	kg/kg	$H_{2(g)}$	0.01	Nm^3/kg
			H_2O(g)	2.86	Nm^3/kg
Cu Cementation					
Iron scrap	0.02	kg/kg	Cu	0.03	kg/kg
Iron-Aluminum removal					
$O_{2(g)}$	0.01	Kg/kg	O2(g)	0.01	Nm^3/h
NaOH	0.56	kg/kg	$Fe(OH)_3$	0.06	kg/kg
			$Al(OH)_3$	0.02	kg/kg
Mn Recovery					
Manganese sulphate	0.01	kg/kg	MnO_2	0.07	kg/kg
Sulfuric acid	0.10	kg/kg	$O_{2(g)}$	0.01	Nm^3/h
NaOH	0.14	kg/kg			
$O_{2(g)}$	0.03	kg/kg			
$SO_{2(g)}$	0.00	kg/kg			
Co Recovery					
Cobalt Sulphate	0.01	kg/kg	Cobalt Sulphate	0.15	kg/kg
Sulfuric acid	0.11	kg/kg			
NaOH	0.09	kg/kg			
Ni Recovery					
Ni	0.12	Kg/kg	Nickel sulphate	1.25	kg/kg
Sulfuric acid	0.76	kg/kg			
NaOH	0.62	kg/kg			
Lithium Recovery and Na_2SO_4 Removal					
Na_2CO_3	0.27	kg/kg	Lithium carbonate	0.19	kg/kg
NaOH	0.00	kg/kg	Sodium sulphate(anhydrite)	3.16	kg/kg
Effluent Treatment					
Lime	0.01	kg/kg	Wastewater	8.41	kg/kg
			Solid Waste	0.04	kg/kg

Table 7. Life cycle assessment impact categories with total results

Impact category	Unit	Value
GWP	kg CO_2 eq	3.66
ADP	kg Sb eq	2.14×10^{-4}
ADPf	MJ	50.40
AP	kg SO_2 eq	0.19
EP	kg PO_4-eq	1.15×10^{-2}
FW-AE	kg 1.4-DB eq	15.80
MA-EX	kg 1.4-DB eq	17458.86
ODP	kg CFC-11 eq	1.39×10^{-6}
POCP	kg C_2H_4 eq	7.69×10^{-3}
T-EX	kg 1.4-DB eq	1.78×10^{-2}
FPM	kg $PM_{2.5}$ eq	4.91×10^{-2}
LU	m^2a crop eq	3.04
HT-C	cases	3.43×10^{-10}
HT-NC	cases	2.72×10^{-10}

(21%), sodium hydroxide (28%), steam and hydrogen peroxide (∼11%). AP contributions were primarily the result of nickel sulphate usage (80%) and sulfuric acid (13%). EP contributions were related to nickel sulphate and sodium hydroxide usage (∼36%). For the FW-AE category, 81% is associated with nickel sulphate and 9% with sodium hydroxide. While, for MA-EX nickel sulphate(66%), sodium hydroxide (17%), and sulfuric acid (7%) are the primary associations. ODP contributions are associated to the usage of nickel sulphate 85%. POCP contributors were associated to nickel sulphate80%, and 13% of sulfuric acid. T-EX contributions were nickel sulphate 50%, sodium hydroxide at 25%, and sulfuric acid at 8%. FPM impacts were associated with the usage of nickel sulphate with 78% and sulfuric acid with 13%. In contrast, LU associated impacts were nickel sulphate(70%), and sodium hydroxide and cobalt production (∼11%) each.

It was observed in the results of the environmental impacts related to toxicity (HT-C and HT-NC) the main contributors were sodium hydroxide, hydrogen peroxide and nickel sulphate use throughout the categories. It must be highlighted that the units of these categories are quantified in several cases. For HT-C Sodium hydroxide 23%, hydrogen peroxide 27%, nickel sulphate 19%, steam, soda ash and sulfuric acid ∼8%. For HT-NC the biggest contributors were sodium hydroxide 32%, nickel sulphate 16% production and sulfuric acid 35%. Additionally, soda ash contributions through the categories were $> 7\%$ except for HT-C. Electricity contributions were $> 5\%$ in every category, therefore, it can be concluded that the battery recycling system is not highly energy dependent.

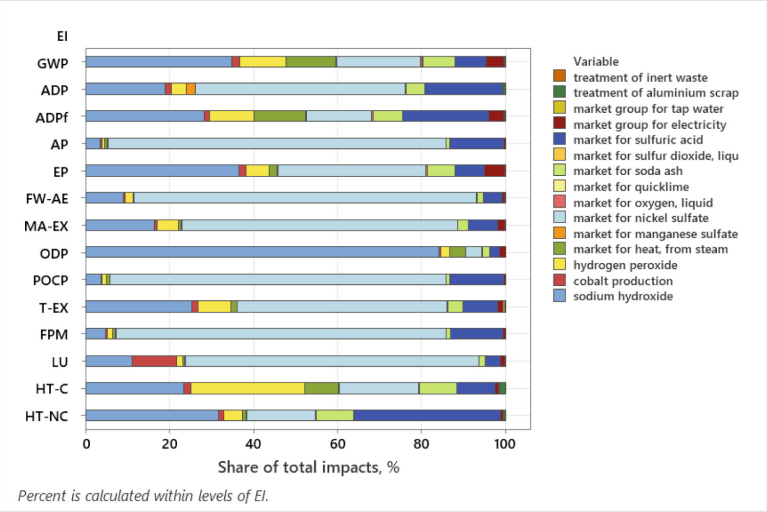


Fig. 9. Depicts the environmental impacts of every impact category assessed by Recipe hierarchy (H), CML IA baseline and USEtox

6 Conclusions

This study presents a preliminary comprehensive approach towards enhancing the efficiency of battery recycling processes within the HELIOS project. The study focuses on a set of integrated strategies that consist of three distinct actions to improve the environmental sustainability of hybrid batteries. The findings and main conclusions are outlined below:

1. The design for Disassembly/Manufacturing/Assembly focuses on creating efficient and safe methods for each stage of the battery lifecycle. This includes an analysis of existing techniques, the introduction of robotic disassembly, and the optimization of recycling processes. These methods are expected to reduce waste, lower costs, and increase worker safety.
2. Results of the froth flotation experiments demonstrate good separation between fully liberated graphite-NMC811-LTO electrode mixture. 88% of the graphite could be recovered with 94.8% purity and approximately 50% of the recovered graphite was recovered with a 98% grade. The kinetic flotation data aids in simulating the HELIOS battery pack recycling process. Removing graphite reduces environmental impact and acid use, and recovered graphite can be reused. Optimization of flotation parameters and pretreatment steps are needed to increase graphite grade. This process also enables TiO_2 recovery.
3. The results show that HSC sim process simulation baseline for recycling NMC811 cathodes provides an optimal basis for future LCA calculations for designing a recycling flowsheet for the HELIOS battery modules. It successfully recovered battery-grade lithium, cobalt, nickel, and manganese. LCA results suggest that most of the environmental impacts come from the use of nickel and sodium hydroxide. The results

from the froth flotation experiments can be incorporated into the baseline to broaden the scope of the flowsheet.

In conclusion, the integrated strategies proposed in this study have the potential to enhance the efficiency and sustainability of battery recycling processes. The findings suggest that the design for Disassembly/Manufacturing/Assembly, froth flotation experiments, and HSC sim process simulation baseline can significantly reduce waste, lower costs, and increase worker safety while recovering valuable materials from hybrid batteries while providing the basis to develop the further cradle-to-grave LCA models.

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List of abbreviations

ADP	Abiotic depletion (elements)
ADPf	Abiotic depletion (fossil)
AP	Acidification potential
EoL	End-of-Life
EP	Eutrophication potential
EV	Electric vehicle
FPM	Particulate matter
FW-AE	Fresh water aquatic ecotoxicity
GWP	Global Warming Potential
HE	High-energy
HP	High-power
HSC	H (enthalpy), S (entropy), and Cp (heat capacity)
HT-C	Human toxicity potential – Cancer
HT-NC	Human toxicity potential – Non-Cancer
HV	High voltage
LCA	Life Cycle Assessment
LIB	Lithium-ion batteries
LTO	Lithium, titanium and oxygen
LU	Land use
MA-EX	Marine aquatic ecotoxicity
NMC	Nickel, Manganese and Cobalt
ODP	Ozone depletion
OEM	Original equipment manufacturer
POCP	Photochemical ozone creation potential
SEI	Solid electrolyte interphase
SEM-EDS	Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy
T-EX	Terrestrial ecotoxicity

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Life Cycle Environmental Performance of Diesel, Fuel Cell, and Battery Electric Long-Haul Heavy-Duty Trucks

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Abstract. This study provides an environmental performance evaluation of heavy-duty 40-ton semi-trailer trucks from a life cycle perspective. The life cycle assessment (LCA) study was conducted as a hypothetical case study of semi-trailer trucks used in Norway. The life cycle impacts of diesel, fuel cell, and battery electric semi-trailer trucks are assessed in a cradle-to-grave attributional LCA study in terms of greenhouse gas (GHG) emissions as well as five other impact categories. Overall, we find that battery electric and fuel cell trucks offer GHG benefits compared to diesel trucks. However, across five other environmental impact categories, results are less clear-cut, with the diesel and battery trucks offering the lowest impact and the fuel cell truck having higher impacts. However, due to lower technological maturity and limited primary industry data available higher uncertainty exists for modelling of fuel cell systems. This should be taken into consideration in further studies. The preliminary results in this study offer environmental insights of electric powertrains and demonstrate the importance of holistic environmental impact understanding, beyond direct emissions and GHG assessment.

Keywords: LCA · Li-ion Battery · PEM fuel cells · heavy-duty vehicles

1 Introduction

Both fuel cell and battery electric powertrains are currently under consideration for heavy-duty vehicles and while the choice for electrification of city buses has fallen on batteries in Norway, it is still uncertain whether fuel cells or batteries offer the best alternative for heavy-duty trucks. Thus, the purpose of this study was to investigate and provide understanding of the environmental performance of different electric powertrain technologies that may be used to power long-haul heavy-duty freight trucks, and to compare against a conventional diesel powertrain.

While both fuel cell and battery powered trucks offer zero tailpipe emissions, their overall life cycle environmental performance is more complex and unclear as indirect emissions occur both upstream and downstream of operation. Thus, a holistic systems perspective is required when comparing the environmental performance of the different

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powertrain technologies. To evaluate and compare the environmental performance of long-haul diesel, fuel cell, and battery electric trucks in a holistic manner, we used the life cycle assessment (LCA) method. For this purpose, we compiled cradle-to-grave inventories to assess the environmental impacts of 40-ton semi-trailer trucks, which consists of a tractor unit and one semi-trailer used to carry freight. The powertrain technologies considered in the study includes diesel internal combustion engine (ICE), proton exchange membrane fuel cell (PEMFC), and Li-ion battery (LIB) electric.

2 Method

The goal of this paper is to evaluate and compare the environmental performance of diesel, PEMFC, and LIB electric long-haul semi-trailer trucks across various environmental impact categories. A process-based attributional and comparative approach was used to estimate the cradle-to-grave performance across six environmental impact potential categories of the diesel, PEMFC, and LIB semi-trailers trucks. Impacts in terms of global warming potential (GWP), photochemical oxidant formation potential (POFP), eutrophication potential (EP), ozone layer depletion potential (ODP), acidification potential (AP), and freshwater ecotoxicity potential (FETP) were estimated using the CML-IA baseline characterization method. The LCA is conducted as a hypothetical case study considering use of 40-ton semi-trailer trucks in Norway. The system boundaries included the energy carrier from well-to-wheel (WTW) and the vehicle equipment from cradle-to-grave as well as the energy use and efficiency of the hydrogen fueling and battery charging stations (but not the production or EOL of the shared infrastructure itself). The functional unit was set to "the use of a 40-ton semi-trailer truck per ton-kilometer (tkm)", where impacts were estimated based on a 16 ton payload and total mileage of 800 000 km. The total mileage was derived based on an assumed truck lifetime of eight years and a yearly mileage of 100 000 km.

2.1 Inventory Modelling

For production (cradle-to-gate) of the semi-trailer trucks, we relied on data from published [1–9] studies and ecoinvent 3.8 process data as well as original inventory data compiled for the study. For diesel trucks, we considered auto diesel sold on the Norwegian market in 2021, which is a blend of fossil diesel, fatty acid methyl ester (FAME), and hydrotreated vegetable oil (HVO). Based on statistics from the Norwegian Environment Agency, we estimated a biodiesel content of about 14%. For hydrogen used in fuel cell trucks, we considered green hydrogen produced via electrolysis using wind-based electricity. For battery electric trucks, we assumed use of the Norwegian consumption mix. To evaluate the sensitivity and for wider transferability of study results, we considered blue and grey hydrogen for the fuel cell truck as well average European electricity mix for battery trucks. Use of energy carriers were estimated to be 0.37 l diesel/km, 66 g hydrogen/km, and 1.35 kWh/km (including 5% losses in charger). To evaluate anticipated technology performance improvement in the electric powertrains, we performed uncertainty analyses considering how improvements in energy efficiency affect life cycle GHG emissions of the electric powertrains. Inventory data for wear emissions

from breaks, tyre, and road were adapted from the *ecoinvent* database to account for differences in gross vehicle weight (GVW) of each of the semi-trailer trucks as well as regenerative breaking. Break wear was assumed to be 20% lower for electric trucks due to regenerative breaking. For maintenance we considered annual replacements for tires and fluids. For the PEMFCs, we estimated one stack replacement as the estimated operation. In an uncertainty analysis, we considered both one additional (2) and one fewer (0) stack replacements. For batteries, replacements were deemed unnecessary as the use did not exceed expectations regarding calendar life or cycle life. Even so, in an uncertainty analysis, we consider how one replacement of battery modules affects the life cycle GHG emissions of battery trucks. End-of-life (EOL) modelling was done in line with the cut-off approach, where no burden is allocated to the recycled materials (i.e., downstream products) and instead, raw material input upstream of component and vehicle production has a recycled content.

3 Results

3.1 Global Warming Potential

The total cradle-to-grave GWP emissions from the semi-trailer trucks are provided in Fig. 1, where contribution to production (cradle-to-gate) is denoted green, WTT energy carrier in a darker shade of grey, TTW energy carrier in a lighter shade of grey, maintenance in blue-grey, and EOL in yellow.

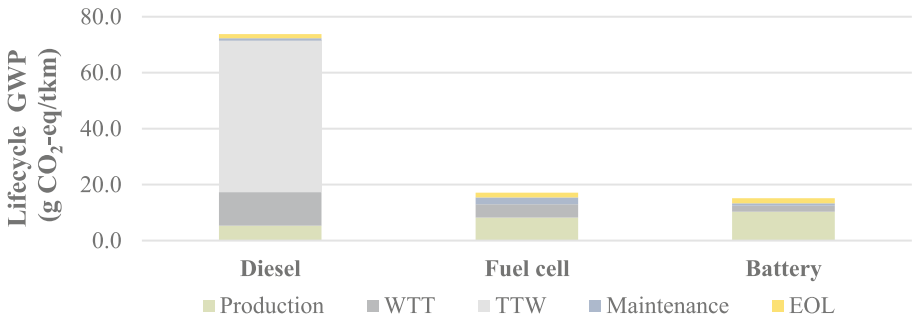


Fig. 1. Total life cycle GWP of 40-ton semi-trailer trucks with a 16 ton payload.

While the production emissions from the trailer and glider are the same for all three alternatives due to model assumptions, production emissions of the electric powertrains are significantly higher than the diesel-based powertrain. For the fuel cell truck, the higher powertrain emissions derive from the PEMFC system and hydrogen tank, which are similar in size. For the battery truck, the high powertrain emissions stem primarily from the LIB, where the modules make up about 80% of battery production emissions. For the diesel truck, the ICE contributes to approximately 65% of the powertrain emissions. Despite higher production emissions, both the electric trucks offer life cycle GHG emissions benefits compared to the diesel truck as use phase emissions are significantly

lower. WTT emissions of the fuel cell truck are higher than that of the battery truck because the hydrogen production through electrolysis is energy demanding and because the fuel cell powertrain (40%) is not as efficient as the battery powertrain (70%). The fuel cell stack replacement adds to maintenance emissions for the fuel cell truck, making its maintenance emissions significantly higher compared to the diesel and battery trucks. While the battery truck has the highest EOL emissions due to battery recycling, EOL emission contributions to total life cycle emissions are low for all powertrain technologies.

3.2 Other Environmental Impact Potentials

Figure 2 presents the relative environmental performance in terms of POFP, EP, ODP, AP, and FETP. Contribution towards life cycle impact from semi-trailer truck production (cradle-to-gate) is denoted green, WTW is grey, maintenance is blue-grey, wear is red, and EOL is yellow.



Fig. 2. Relative impact results from cradle-to-grave across multiple impact categories. Impacts are reported relative to the highest result.

When looking across multiple impact categories, we find that none of the powertrain technologies outperform the others. Generally, we find that the electric powertrains have higher production impacts. The diesel truck offers the lowest life cycle impact in terms EP and FETP; the extraction and refining processes related to battery metals tend to have particularly high contributions to toxicity impacts as well as eutrophication. It is perhaps more surprising that in terms of toxicity, the WTW impact of the battery truck is also higher than the diesel truck. The high upstream (WTT) toxicity impacts from electricity use stems primarily from copper used in the electrical distribution network. Note that because toxicity and eutrophication impacts depend on local background concentrations and chemical interactions between pollutants, caution should be applied when

interpreting the results; toxicity and eutrophication results may be viewed as indications of potentially problematic aspects of the electric powertrains, rather than providing an absolute environmental ranking of powertrains. Much of the impact from fuel cell replacements is caused by the platinum loading in the catalyst, due to upstream impacts form platinum extraction and refinery operations.

3.3 Robustness Analyses

To evaluate particularly sensitive and uncertain parameters, we performed a range of sensitivity and uncertainty analyses for the electric trucks. In Fig. 3, results from the main analysis are shown in grey (diesel), turquoise (fuel cell), and orange (battery) lines, while results from the robustness analyses are shown in the lighter turquoise (fuel cell) and orange (battery) columns.

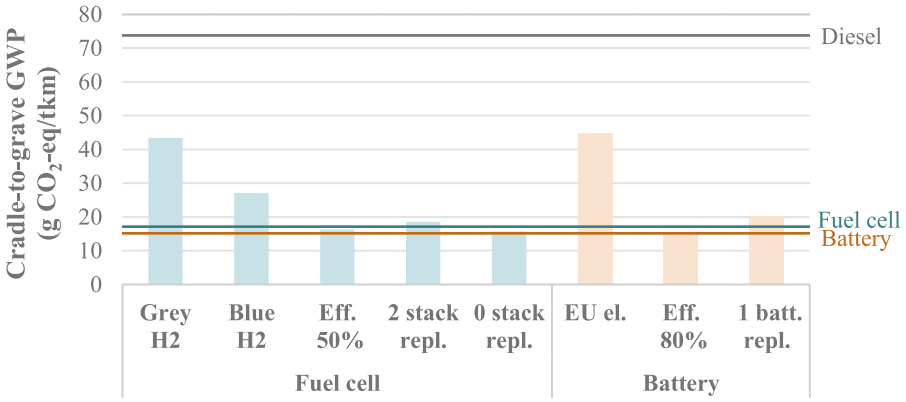


Fig. 3. Robustness analyses considering parameters for electric semi-trailer trucks.

Both electric trucks offer lower life cycle GWP than diesel trucks. Use of energy carriers from production pathways with higher carbon footprints was found to have the highest effect on life cycle emissions for both the fuel cell and battery trucks. In contrast, change in efficiency and replacement of fuel cells and batteries had less significant effects. An increase in efficiency does not offer much improvement because the carbon footprints of the green hydrogen and the Norwegian electricity used for charging are very low. With higher carbon footprints, increase in efficiency would have provided a larger relative improvement.

4 Discussion and Conclusion

Across six impact categories, we find that the different technologies offer both environmental benefits and disadvantages with no one powertrain technology outperforming the others. The results illustrate that in terms of GWP, accessibility to low carbon footprint energy carriers is more important than higher powertrain efficiency and even lifetime of

fuel cells and batteries. In terms of impacts more affected by metal use (e.g., EP, AP, and FETP), it is more important ensure high lifetime to avoid or reduce replacements of fuel cell stacks and battery modules.

The results from this LCA illustrate the importance of considering all life cycle stages and numerous impact categories to obtain a more holistic understanding of the environmental performance of different powertrain alternatives. A narrower focus limited to TTW and GHG emissions, would not have identified how important the powertrain components in the electric powertrains are to their overall environmental performance. Perhaps most importantly, a TTW focus would not have captured that in Norway, battery electric trucks appear to be more environmentally friendly than fuel cell trucks. That said, there is uncertainty associated with the results of both the battery electric truck and (particularly) the fuel cell truck, mainly due to lifetime aspects of LIBs and PEMFCs as well as data quality for modelling. In particular, the fuel cell Pt loading – which is a key contributor to many impacts for the fuel cell stack – is a parameter still under high development, meaning that impacts will likely reduce as this is optimized. Further studies should seek to minimize these uncertainties, with primary industry data for PEMFC and hydrogen tank modelling, and accounting for future technological developments.

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Irish Automotive Sector Considerations for Recycling Electric Vehicle Lithium-Ion Batteries

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Abstract. The Irish transport sector has been targeted by the government as a key area where greenhouse gases (GHG) can be drastically reduced and a fundamental plan within the government's strategy is the electrification of the private car fleet.

Electric vehicles (EV) extensively use lithium-ion batteries (LIB) as an energy source, however LIBs have a limited lifespan. LIBs are subject to a chemical and physical process known collectively as battery degradation, which limits the batteries capacity to hold a charge with time.

This characteristic will bring new and unprecedented challenges for end-of-life (EoL) vehicle waste management. As well as environmental concerns, there are significant personal health and safety risks associated with EV high-voltage LIBs. This raises important questions on how the automotive sector can safely process this additional hazardous waste stream.

This study investigates the value chain surrounding EoL EV LIBs and accentuates a best practice approach for the pre-recycling phases of; battery safety, disassembly, storage, and transportation, within the context of the Irish automotive aftersales landscape.

The research findings highlight the dangers surrounding EV LIBs, and present a best practice methodology regarding the safety aspects encompassing the pre-recycling operations. They are of particular importance to businesses, operatives, technicians and transporters, who will be directly involved in the pre-recycling phases of EV LIBs here in Ireland.

Keywords: electric vehicles · lithium-ion battery · end-of-life · safety · recycling · waste management

1 Ireland's Automotive Marketplace, the Current State of Play

Transport is a key driver in the Irish economy and while gross national income increased steadily since the 1990's, a simultaneous increase in transport associated harmful emissions has ensued [1].

The Irish government have pledged to halve GHG emissions by 2030 and achieve a climate neutral economy by 2050 [2]. Transport is a crucial area where GHGs can be radically reduced, and a central plan within the government's policy is the electrification

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of 30% of the private car fleet by 2030, thereafter only permitting the sales of EVs cars in the ensuing years [3].

The LIB will underpin this strategy as they are used as an energy source for EVs [4], however LIBs have a limited lifespan [5, 6]. LIBs are subject to a chemical and physical process known collectively as battery degradation, which limits the batteries capacity to hold a charge with time [7].

The global transition to EVs has advanced exponentially over the last number of years. Worldwide the number of EVs on the road exceeded 10 million in 2020 [8]. While in Ireland EV sales surpassed diesel vehicle sales in the first quarter 2023 for the first time [9].

This growth will translate into a proliferation of EoL EV LIBs which will require waste management. Modelling predicts that globally a million spent EV LIBs will require treatment by 2030 with the number doubling by 2040 [10].

2 Lithium-Ion Battery Degradation

The life expectancy of an EV will be largely determined by its battery. Due to the chemical and physical characteristics of LIBs, they degrade naturally with age [11, 12]. LIB degradation is a complex issue affected by multiple factors such as chemical composition, calendar ageing, usage and charge-discharges cycles [13].

The degradation process is not obvious physically as it occurs within the battery cell, however its most noticeable effects are realised when the usable capacity and power of the battery diminish. Literature varies, however most research suggests that EV LIBs reach their EoL when the state-of-health (SoH) drops to below 80% [14, 16, 17]. At this point, the battery can no longer propel a vehicle efficiently.

The time taken for an EV LIB to reach EoL is difficult to predict, as competing factors will influence the SoH degradation. Studies suggests an estimated lifespan of between 8 to 13 years [12, 15].

2.1 Electric Vehicle Battery Waste Management

Current EU directives ensure EoL vehicles and their batteries enter the appropriate recycling stream. However, new regulation on waste batteries will ensure a truly circular economy.

The new EU battery regulation which emanated from the European Green Deal [18], will impose mandatory requirements for sustainability, safety, labelling, EoL management and material recovery, while assigning additional responsibility to battery manufacturers [19–21].

2.2 Electric Vehicle Lithium-Ion Battery Recycling Processes

EV LIB recycling processes can be broadly classified into the four main areas off; pre-processing (disassembly and categorisation), pyrometallurgical (smelting), hydrometallurgical (leaching) and direct recycling (physical processes).

Any process that does not alter the battery's cell structure is considered **pre-processing**. This key step may include deactivation and powering down of the vehicle's high voltage electrical system before battery pack removal. Discharging the LIB after removal and disassembly of battery pack [22, 23].

Pyrometallurgical recycling is the most straight forward process commercialised today. However, it is not selective and the recovery of specific metals is extremely difficult [24], while lithium and other cathode elements are generally lost in this process [25].

Hydrometallurgical recycling is an exceptionally selective process which can recover large amounts of the batteries elements with high purity rates. Companies such as Duesenfeld, Northvolt and Lithion maintain they can recover up to 95% of a battery's components including its black mass (lithium, manganese, cobalt and nickel) using this method [26, 27, 28].

Direct recycling promises to be the most sustainable approach because recovered materials can be used directly in new battery production [29]. However, this process has yet to be commercialised [30].

2.3 Electric Vehicle Lithium-Ion Battery Hazards

LIBs are generally considered safe, however as with any component containing an electrical power source, hazards exist.

A fire in a LIB generally stems from a process known as **thermal runaway**, which under certain conditions can lead to a build-up of pressure, causing the rupturing of the battery pack, the release of toxic gases, fire and explosion [31, 32].

The **high voltage**[1] contained within an EV LIB presents the obvious hazards such as electric shock, electrical burns, arc flash, and fatal electrocution [31, 33]. Manufactures design their EVs and allied high voltage technologies to operate safely. However extreme care is required when working on EVs, as the high voltage risk is ever-present in the battery itself, even if the vehicle is powered down.

Associated risks of EVs include electromagnetic forces that can interrupt the operation of personal medical devices and manual handling risks with battery removal, as some battery packs weigh more than 500 kg [34].

2.4 Ireland's Role in Electric Vehicle Battery Recycling

From Ireland's perspective, the pre-processing phases of the EV recycling, such as powering down and removal of the battery pack from the vehicle will be carried out onsite by an automotive dealership, repairer or Authorised Treatment Facility (ATF - commonly known as a scrap yard).

Presently the pre-processing of EV LIBs is highly manual that requires specialist tools, equipment and trained operators who are practiced to work on EV high voltage

[1] UN and EU regulation ECE R100 classifies automotive EV high voltage as; > 60 V direct current (DC) and > 30 V alternating current (AC). EV batteries operate at a typical range of 400 V DC. However, manufacturers may work at significantly higher ranges, for example Porsche [38] and Hyundai [39] uses an 800-V DC battery.

systems. The LIB will then be transported to mainland Europe to continue its journey along the recycling value chain.

Although EVs are not new to the Irish market, they are not yet widespread and few have reached EoL. Therefore, it may be assumed that a skills gap surrounding the technology and hazards posed by EV LIBs currently exists.

3 Research Methodology

Due to the technical nature of the study, a mixed-methods pragmatic paradigm action research approach was employed. To gain a full understanding of the entire LIB value chain, a series of interviews, site visits and a convenience survey, across a diverse array of stakeholders within the electric vehicle domain were undertaken.

3.1 Qualitative Research Results

Qualitative research consisted of 14 semi-structured interviews with national and international actors. The stakeholders were categorised as public state bodies, vehicle importers and distributors, ATFs, economic actors, non-profit companies and industry experts.

543 statements relevant to this research were identified and coded using a semantic approach. Analysis of reoccurring codes led to nine key themes emerging;

1) *Transport.* Research confirmed that legislation is effective, and manufacturers are adhering to the LIB transport regulations. Concern was raised surrounding LIB transport costs to Europe ensued by Ireland's geographical nature as an island.
2) *Safety.* Stakeholders are acutely aware of the health and safety implications associated with EV LIBs. Irish actors are training and equipping their networks to work safely on EVs. Restricted access to manufacturer repair data is a concern for ATFs. A disconnect between academic study (thermal runaway) and industry (high-voltage) on the topic of safety was revealed.
3) *Knowledge.* Businesses reiterated their continued efforts to alleviate potential knowledge gaps with staff training to ensure workplace health and safety standards. The general public's ambiguous understanding concerning the second-hand market of EV LIBs was stressed as a concern.
4) *Legislation and regulations.* Current regulations are ensuring LIBs are recycled correctly. A secondary matter particular to the Irish market entails UK imported EVs which have not contributed to a central waste management fund because of a registration loophole.
5) *Recycling.* There is no standard workflow established for the EV LIB pre-recycling steps in Ireland, with different approaches being employed by organisations.
6) *Storage.* Irish stakeholders do not yet consider the storage of EV LIBs as an issue, as batteries are generally shipped from and returned to Europe on the same day.
7) *Battery removal.* Access to valid repair methods, special tooling and addressing the technician skills gap, are possible barriers for industry.
8) *Miscellaneous.* Stakeholders emphasised the new workload created in all areas of their businesses incurred by new EV operational standards. Inadequacies surrounding online training were also proffered, as working with high voltage PPE requires actual practice to achieve dexterity.

9) *Battery characteristics.* The LIB cathode type currently determines the recycling process. However, this issue is not considered during pre-recycling steps in Ireland.

3.2 Quantitative Research Results

A convenience survey among 58 light-vehicle automotive apprentice students from Technical University Dublin was undertaken, to gain an understanding of the level of awareness of front-line workers in the field.

Key findings to emerge from the apprentice survey;

1. There is a lack of understanding surrounding the electrocution threshold current.
2. Apprentices employed by a franchised dealership are more likely to have been exposed to EVs and their safe working practices when compared to those working for independent repairers.

4 Discussion

Legislation has ensured that EoL EV LIBs in Ireland are recycled correctly. However, conflicts within the different regulatory frameworks concerning EV and LIBs were cited as barriers to a correctly functioning recycling market. The EU's new regulatory framework for batteries will negate the issues raised.

The upskilling currently ongoing by stakeholders within the Irish EV field and the willingness from people to learn new skills was seen as a key enabler from an Irish perspective to bring about a safe working environment.

The financial costs of training, equipping staff with PPE and tooling is significant, which has led to different standards being employed by organisations. This is an area for concern as the hazards presented by EV LIBs are largely the same.

There is a clear knowledge divide between employees of franchised networks when compared to those from independent repairers and ATFs, suggesting a skills shortfall in the sector. The research did not reveal if this shortfall is due to under investment or an unwillingness to accept technologies that are not yet ubiquitous.

Restricted access to manufacturer specific repair documentation is a major issue for non-franchised organisations. This is of particular importance for ATFs who will be largely responsible for dismantling EoL EVs for recycling.

5 Conclusion and Recommendations

The contextual understanding gained during this research helped form the author's concept, that an industry wide standard for technicians working on EVs should be adopted and mandated by regulations.

There is currently no international standard framework for technicians who work on EVs post production [35, 36].

The author believes that a certified industry standard complying with EU regulation 1025/2012 on standardisation, is necessary to ensure all actors working with EVs are expert and fully aware of the associated personal and environmental risks to mitigate potential accidents.

The author recommends that stakeholders within the Irish EV field develop an industry-based standard in conjunction with the National Standards Authority of Ireland for technicians working on EVs. This standard should become compulsory through a statutory regulatory scheme or legislation.

The author suggests following the *Safe Electric* framework already in existence in Ireland, which is a statutory regulatory scheme for electrical contractors [37].

Such a scheme for the automotive sector would ensure only competent technicians would be eligible to work on EVs, which will lessen the possibility of serious accidents occurring while also highlighting the dangers of EVs and their batteries to the general public.

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Simulation-Based Optimization for Sustainable Textile Waste Collection Routes

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Abstract. Textile waste is all textiles and products that are dropped away. This waste comes from various sources: households, factories, and the fashion industry and significantly challenges the environmental and economic potential for sustainable waste management. This paper proposes a simulation-based optimization of textile waste collection routes, focusing on efficiency and sustainability. The model considers vehicle characteristics, collection demand, and environmental aspects. Also, it examines vehicle routes, container, and sensor technology scenarios. The results show that efficient, sustainable solutions with strategic container placement and dynamic routes can reduce travel costs and environmental impacts. As a case study, the Huesca region of Spain confirms the effectiveness of dynamic route planning and sensor technology. This method allows waste management authorities to optimize resource allocation and reduce emissions and costs, as the simulation-based method for optimizing routes can reduce costs and environmental impacts while maximizing efficiency. It highlights the urgency for waste management stakeholders to conform with recent Spanish legislation mandating. This study provides valuable insights to meet legal obligations while ensuring operational efficiency and sustainability.

Keywords: Textile Waste Collection · Circular Economy · Sustainable Logistics · Route Optimization · Agent-Based Simulation

1 Introduction

Textile waste indicates unused materials and products from the textile industry. It is a wide range of items, clothing, and other textile-based products, that are no longer needed or have gone the end of their useful life. In recent years, textile waste management has become a significant issue in the tension between environmental responsibility, regulatory compliance, and operational efficiency. These challenges highlight the urgent need for sustainable solutions in the fashion and textile industries. Waste managers now face the daunting task of complying with the new regulations in their operations to meet the operational, economic, and environmental criteria. A new Spanish law that mandates the separate collection of textile waste has highlighted the urgency of addressing this issue. This legislative reform is compelling waste management authorities to adapt their operations to the changing legal landscape. It sets the stage for a fundamental challenge:

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How can waste managers effectively manage the complexity of textile waste collection while complying with legal requirements and optimizing operational processes?

Key operational parts required by this regulatory change include understanding the waste generation profile of sites within their jurisdiction, accurately sizing collection containers, and efficiently planning collection routes. Significantly, these operational decisions must be based on more than intuition or historical practices. Instead, they must be based on data-driven insights; simulation and optimization techniques are critical. This paper addresses the demanding need for a systematic and data-driven approach to changing regulatory landscape.

Section 2 of this paper provides an overview. Following that, the methodology employed in this study is outlined. Section 4 is a description of a case study. Section 5 is discussion. Finally, in Sect. 6, conclusions are offered.

2 Literature Review

Global textile production has surged due to population growth and fast fashion trends, increasing textile demand. However, this consumption is predicted to lead to a 70% increase in global municipal solid waste by 2025, underscoring the urgent need for textile waste management, particularly in developing nations [1]. Textile waste management significantly impacts all three sustainability pillars: environmental, social, and economic [2]. A review of textile recycling technologies highlights the importance of leading economies adopting a circular approach to holistic technologies [3]. This approach is underpinned by the environmental benefits of textile reuse over incineration and landfill, with literature highlighting the superiority of reuse in reducing environmental impacts [4]. The European Union recognizes the importance of transitioning to a circular economy, highlighting trends such as digitalization and sustainability models [5]. Also, the Waste Framework Directive requires Member States to establish textile waste collection systems by 2025 [6, 7].

In response, the Guimarães municipality in Portugal conducted a comprehensive analysis of textile waste generation to prioritize separate collection routes in compliance with EU directives [8]. Furthermore, a critical aspect highlighted in the literature is the need to gather data on residents' waste generation profiles, including textile waste, to inform more effective strategies [9]. The efficiency of these systems must consider cost factors. The study introduced a management tool to calculate costs across different schemes, utilizing waste quantity and collection logistics, to optimize cost-effectiveness [10]. Studies have focused on optimizing routes using advanced algorithms, notably reducing travel distances and operational costs [11]. In the UAE, a system of smart waste collection could have a 19% reduction in operational costs [12].

Several studies have looked at innovative solutions to optimize these processes. A study presented a software system, BIN-CT, that uses computerized learning algorithms to plan optimal routes, resulting in routes that are 33.2% shorter than conventional ones [13]. Another highlighted the role of sensor technologies in dynamic route optimization, which resulted in a 7.4% reduction in pickup costs and a 10.2% reduction in CO_2 emissions [14]. In addition, the integration of ultrasonic transducers was investigated for the development of a LoRa-based smart bin architecture in the context of smart cities.

They used waterproof ultrasonic sensors to measure waste volumes in trash garbage cans [15].

This paper presents a holistic approach that combines simulation and optimization. This research seeks to provide waste management authorities with a comprehensive toolkit to address the challenges of textile waste collection while optimizing operational processes in compliance with regulatory requirements.

3 Methodology

This section provides research findings with real-world solutions. It combines data collection, optimization, and simulation components.

The first step of the methodology is obtaining relevant data from two critical sources: the locations and the available resources. The location data includes key information necessary for route planning. This includes coordinates and generation rates, measured in cubic meters per day, with the potential to be correlated with population statistics or predictive models derived from historical data. Moreover, resource data provides essential awareness for authorities and covers some aspects, including vehicle availability and economic factors such as fuel costs, labor expenses, and maintenance. It also includes vehicle details such as capacity, speed, and automation capabilities. In addition, it involves evaluating options for container sizes and exploring technologies like occupancy sensors.

The next step is route optimization. The optimization algorithm utilized is a Capacitated Vehicle Routing Problem (CVRP) algorithm, which leverages heuristic techniques to determine optimal routes. This algorithm seeks to minimize criteria, such as cost or distance, while following restrictions: including vehicle capacity limitations and other operation-specific restrictions.

To create a dynamic and flexible decision-support framework, a multi-agent simulation model has been developed using AnyLogic software. This data-driven model easily incorporates the optimization process while using the above data. The simulation allows running "what-if" scenarios based on various inputs, including location, available vehicles, container sizes, and optimization criteria. It also offers a visualization layer that dynamically represents the results. This dynamic representation gives the decision-support tool more credibility and makes it easier to visually evaluate how various factors affect the system for collecting textile waste. This comprehensive methodology is highlighted in a real-world case study, showing how it addresses problems with textile waste collection and improves operations. This illustration demonstrates the real advantages of managing textile waste. The methodology's usefulness in streamlining operations despite complex real-world situations is shown in the following section's exploration of numerous "what-if" scenarios within the textile waste collection problem.

4 Case Study

This section presents the results of a comprehensive case study conducted in the province of Huesca, Spain. Huesca is in the northeast of the country and has over 200,000 inhabitants. The case study considered 84 localities in the province that generate an estimated

0.25 cubic meters of textile waste per inhabitant per year. The map of this area is presented in Annex I.

A fundamental aspect of the case study was the simulation of diverse scenarios, characterized by distinct parameters. Notable variables included: *1-Vehicle Selection*: **The conventional van** ($12m^3$ capacity), while faster and more accessible to specific locations, requires manual container emptying. The van is prepared for servicing small ($2m^3$) containers. **The automated truck** ($28m^3$ capacity) is slower but operated by a single driver (compared to the van's requirement of two) and features automated container emptying. The truck can handle larger ($3.7m^3$) containers.

2-Route Typology: **Fixed Routes:** designed based on clustering locations, considering distance and road connectivity criteria. Suitable for weekly collection. **Dynamic Routes:** assuming the containers are equipped with IoT devices sensing occupancy levels, dynamic routes were optimized daily. The simulation detected locations requiring visits and initiated route optimization to generate optimal daily routes. **Mixed Routes:** like fixed routes, mixed routes were employed, assuming containers were equipped with occupancy sensors and executed weekly, visiting locations with containers surpassing a specified occupancy threshold.

Considering these variables, and parameters such as container occupancy thresholds and the number of containers to be placed at each site, various scenario combinations were created. Each scenario was subjected to a simulation that produced a range of results. While the system suggests the best solution in terms of distance, cost, or emissions, all scenarios remain amenable to comprehensive analysis. The following section provides an in-depth analysis of the results obtained in selected scenarios, providing valuable insight into the real-world applicability of the method and its ability to address the complexity of textile waste collection while optimizing operations.

5 Results and Discussion

Results presented in Table 1 provide a rich data set for understanding the dynamics of waste collection networks under different scenarios. These scenarios were made for several variables, including vehicle type and route typology, and to methodically assess their impact on key performance indicators such as distance traveled, costs, and emissions. The main objective was identifying the configurations that most efficiently align with the twin goals of operational efficiency and sustainability.

One significant pattern is that traditional delivery vans consistently outperform automated container loading trucks in terms of economic effectiveness and environmental impact. This pattern faces the assumption that automated technologies are always better than conventional ones. The advantages of the conventional delivery van are its maneuverability, ability to reach specific locations more efficiently, lower fuel consumption and emissions.

The mixed route typology is a favorable approach to optimize waste collection operations. This strategy mixed cluster-based route planning with the container occupancy sensors and optimized resource allocation by considering variables like distance and road accessibility, leading to decreased distances, costs, and emissions. Finding highlights the importance of using technology, data, and intelligent routing for modern waste collection.

Furthermore, selecting a scenario shouldn't be a one-size-fits-all process. The decision should allow for the specifics of the situation, the available infrastructure, and the objectives. An automated container-loading vehicle may be more advantageous in locations with vast highways and high container volumes. However, a regular delivery van may be more efficient in densely populated urban areas with little room to maneuver.

Table 1. Simulation scenarios results (three-month period of waste collection).

Scenario	Route Type	Vehicle	Distance (km)	Cost (€)	Emissions (kg CO_2)
1	Fixed	Van	14,929	25,330	4,229
2	Dynamic	Van	24,644	28,114	6,982
3	Mixed	Van	11,869	21,741	3,363
4	Fixed	Truck	14,929	52,868	11,361
5	Dynamic	Truck	16,952	56,812	12,900
6	Mixed	Truck	11,011	42,398	8,397

6 Conclusions

This paper has presented an inclusive approach to the challenges of textile waste collection, which needs to align operations with evolving regulations. The methodology integrates data collection, optimization, and simulation techniques. Through a case study in the province of Huesca, Spain, this study has demonstrated the tangible benefits of this integrated approach. By simulating different scenarios over three months, important lessons have emerged.

In addition, this study validates the value of simulation as a powerful decision-support tool. Waste management authorities can use simulation to identify necessary investments in vehicle fleets, optimal route planning, and the strategic integration of container occupancy sensors. This ensures regulatory agreement and promotes operational excellence, resource efficiency, and environmental stewardship. This research highlights the potential of data-driven, simulation-based optimization and provides practical solutions to pressing environmental challenges. As waste management stakeholders adapt to ever-changing regulations and societal demands, this study provides a roadmap for improving efficiency and sustainability while considering circular economy principles and sustainable transportation. In conclusion, integrating simulation, optimization, and data-driven decision-making in textile waste collection provides immediate benefits and positions waste management agencies for a more sustainable and responsible future. As a future line of research, the physical implementation of sensors to measure the occupancy level of the containers in the localities under study is proposed, which, in addition to serving as a lever to optimize the collection routes, will allow a better estimation of the waste generation profile of the inhabitants.

Annex I. Simulated Huesca Waste Collection Network

Annex I features a visual representation of the geographical area studied in the case, illustrating the province of Huesca, Spain (see Fig. 1). This figure, an integral part of the simulation tool's interface, displays the specific locations considered in the study, along with container placements. Notably, it utilizes a color-coded system to represent the varying occupancy levels of the containers, indicating when they exceed predefined thresholds. Additionally, the image showcases the optimized routes generated by algorithms and visually depicts the waste collection vehicles efficiently traversing these routes, offering a comprehensive visual insight into the study's waste management strategies.

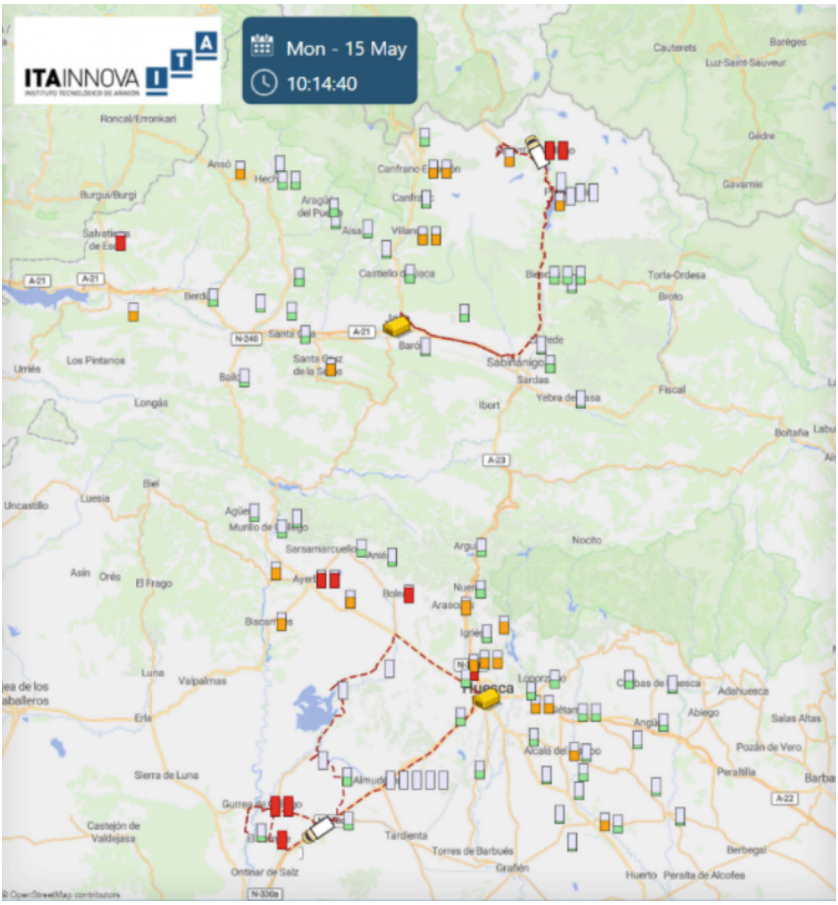


Fig. 1. Simulation visualization of Huesca's textile waste collection network. Image produced using AnyLogic simulation software and maps provided by OpenStreetMap contributors. Source: author.

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Integrating TCO and Sustainability Requirements: ESCALATE Pro-Active Design and Manufacturing Approach for Enhanced Electric Fleets

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Abstract. The European Union's plan to reduce EU-wide transport-related CO_2 emissions from heavy-duty vehicles cannot be realized without considering the GHG emissions generated during the manufacturing and electricity production phases of EVs. The European Union Funded Horizon Europe ESCALATE project approach is proposed as a proactive strategy to optimize resource utilization, minimize environmental impacts, and enhance the overall sustainability and circularity of electric vehicles (EVs) while meeting the financial aspects. ESCALATE develops solutions for 3 types of electrified vehicles (battery, fuel cell, and range extender) including the charging or refuelling infrastructure. By integrating TCO and sustainability considerations into the vehicle's design, architecture, and manufacturing processes, EV manufacturers can identify the most suitable solutions for business needs and budgets, ensuring long-term success in the competitive EV market. This paper presents the Total Cost of Ownership (TCO) and Life-cycle Assessment (LCA) approach formulated by the ESCALATE project to reveal lifetime-extended environmental and economic aspects of electrified trucks and emphasizes the importance of considering the TCO and sustainability requirements, namely life-cycle, early in the project planning phase for electric freight vehicles.

Keywords: Total cost of ownership · Electric fleets · Life-cycle Analysis · Sustainability

1 Introduction

The transportation sector significantly contributes to global greenhouse gas (GHG) emissions, accounting for 20.2% in 2021 [1]. Europe, the third largest emitter after the Asia-Pacific region and North America, contributed 16% [1]. In 2021, road transport was the main source of EU emissions, making up 26% of the total [2]. Despite constituting only 13% of the global road freight market, heavy-duty trucks (HDTs) are responsible for

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50% of worldwide road freight carbon dioxide emissions [3]. In the EU, road transportation accounted for 71.5% of all transportation GHG emissions in 2019, with passenger vehicles at 60.6% and HDTs and buses at 27.1% [4, 5].

Transitioning to electric powertrains for long-distance haul vehicles is crucial for reducing carbon emissions in the heavy-duty transportation sector, which heavily relies on fossil fuels. Over 95% of road freight trucks currently operate on fossil fuels, posing a challenge for reducing carbon intensity. The International Energy Agency (IEA) predicts that by 2050, the share of diesel and petrol vehicles could fall to 33%, replaced by alternative fuels [6]. The European Union aims to lead global emission reduction efforts in transportation, with the European Commission setting stricter targets for HDTs and buses: 45% reduction by 2030, 65% by 2035, and 90% by 2040 [7]. Battery electric trucks could significantly aid the EU's goals, potentially reducing GHGs by up to 92% if powered entirely by renewable energy [8]. The global electric truck market is expected to grow substantially, especially in the Asia-Pacific region, nearly six-fold between 2023 and 2026, and around five-fold in Europe [9].

Despite the positive outlook, a comprehensive approach to the design and operational framework of battery electric trucks, especially for heavy-duty fleets, is essential for meeting the EU's emission reduction targets. Existing literature extensively discusses electric vehicle (EV) design, life-cycle assessments (LCA), and total cost of ownership (TCO) calculations but lacks focus on the specific challenges of zero-emission heavy-duty fleet design. These fleets face unique demands and economic constraints, necessitating dedicated research. A cohesive framework addressing the lifecycle, cost, and performance complexities specific to heavy-duty vehicles is notably absent. Thus, a tailored solution for zero-emission heavy-duty fleets is essential.

The LifeCostDrive strategy addresses this gap by integrating sustainability, economic considerations, and vehicle performance, focusing on zero-emission heavy-duty fleets. Informed by the ESCALATE project's findings, this research offers detailed insights for fleet operators and manufacturers, shifting from broad EV discussions to a focused, actionable strategy for zero-emission fleets.

This paper is structured as follows: Sect. 2 examines the environmental impacts of electric heavy-duty fleets across their lifecycle. Section 3 elucidates the financial implications of electric vehicle ownership and usage. Section 4 introduces the LifeCostDrive strategy, detailing its methodologies and emphasizing its role in sustainable fleet management within the ESCALATE project. The concluding section synthesizes key findings, discusses their implications, and considers future research directions in zero-emission heavy-duty fleets.

2 Life-Cycle Assessment (LCA) Framework –Fleet Level

The International Standards Organisation (2006) defines Life Cycle Assessment (LCA) as a method to evaluate the direct and indirect environmental, social, and economic impacts of processes and products [10] and [11]. LCA quantifies resource use, greenhouse gas emissions, environmental and health impacts, and resource depletion, facilitating direct comparisons of products and technologies based on quantitative functional

performance. This is particularly important for electrified trucks, addressing sustainability challenges in transitioning from traditional to electrified heavy-duty transportation. While LCA principles are typically applied to single products, fleet-level LCA for electrified trucks necessitates a detailed exploration of sustainability across multiple vehicles. Our LCA concept considers the fleet of vehicles as the product, supported by recent studies which suggest introducing time when calculating lifecycle emissions due to changing fleet impacts over time [12], [13] and [14]. We present LCA output as total fleet emissions over a period, considering on-road energy consumption (Tank-to-Wheel) and expanding this to the fleet level by factoring in mileage and fleet composition. This dynamic approach includes future projections for energy efficiency, fleet growth, and mileage evolution (Fig. 1).

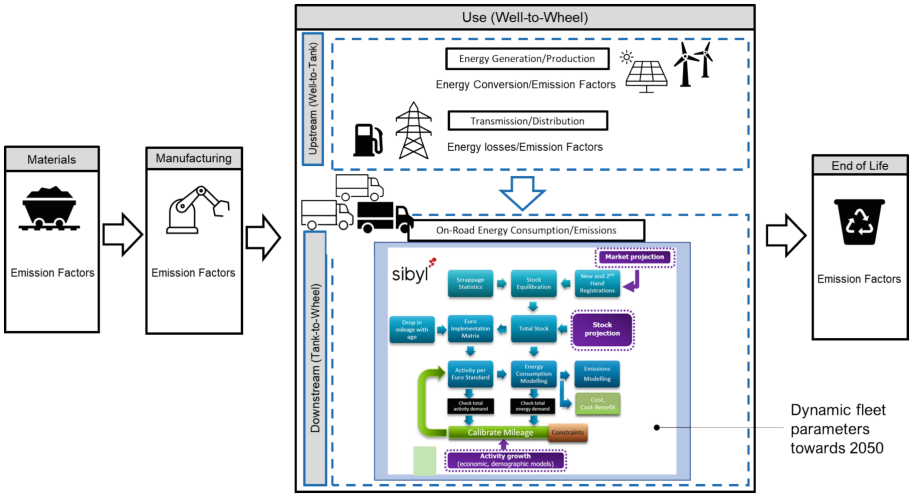


Fig. 1. ESCALATE dynamic LCA framework

Upstream impacts for energy (Well-to-Tank) include stages before on-road consumption, such as resource extraction, electricity generation, and fuel production, with emission factors accounting for the electricity mix and the efficiency of electricity transmission and fuel distribution. Vehicle manufacturing and disposal impacts are assessed from production to end-of-life, considering electrified truck components like batteries, motors, chassis, and body parts. Production country influences are also considered due to varying energy mixes and transportation distances.

Life-Cycle Costing (LCC) includes all expenses during a product's lifespan, such as purchase, operational, and end-of-life costs. Environmental-LCC assesses costs throughout the lifecycle, while Total Cost of Ownership (TCO) focuses on economic viability and performance, often excluding use and end-of-life phases unless internalised. Integrating TCO and LCC within LCA ensures a comprehensive understanding of economic and environmental impacts across the lifespan of electrified trucks, facilitating informed, sustainable decision-making in fleet management.

3 Total Cost of Ownership

As OEMs boost production and policymakers enforce new regulations, fleet owners require tools to assess the financial impact and profitability of this transition. Total Cost of Ownership (TCO) is crucial, providing insights into fleet modernisation effects. TCO facilitates comparisons with traditional ICE vehicles and identifies opportunities to enhance zero-emission heavy-duty vehicles (z-HDV) efficiency, refine powertrains, and assess economic viability. This analysis will show how TCO can be integrated into the LifeCostDrive strategy for managing zero-emission fleets. Five primary categories influence TCO: application and technical specifications, and financial parameters, including Net Present Value (NPV).

NCF (Net Cash Flow) is computed in Eq. (1) by aggregating all future costs including cost of taxes and levies ($C_{T\text{-}L}$), cost of insurance (C_I), cost of maintenance and repairs (C_M), cost of energy (C_E), cost of driver wages (C_{DW}), Cost of infrastructure (C_{In}) for year n and subtracting the residual value of the truck at the end of ownership period (RV_{Truck}).

$$\mathrm{NCF} = \sum_{n=0}^{n} NCF_{Year\,n}(NCF) = depreciation_{Year\,n} + C_{T-L_{Year\,n}} + C_{I_{Year\,n}} + C_{M_{Year\,n}} + C_{E_{Year\,n}} + C_{DW_{Year\,n}} + C_{In_{Year\,n}} - RV_{Truck} \quad (1)$$

Present Value (PV) is calculated by using Eq. (2) where NCF is the Net Cash Flow and R is the Rate of Return.

$$(PV)_{Year\,n} = \frac{\mathrm{NCF}}{(1+R)^n} \quad (2)$$

The cumulative total present value of all future payments (TPV) is calculated by using below Eq. (3).

$$TPV = \sum_{n=0}^{n} (PV)_{Year\,n} \quad (3)$$

Net Present Value of Total Cost of Ownership is calculated by combining the truck's purchase cost (C_{Truck}) with the TPV of all future payments, as shown in Eq. (4).

$$NPV = TPV + C_{Truck} \quad (4)$$

4 The ESCALATE Proactive Strategy: An Overview of LifeCostDrive Strategy

The proactive LifeCostDrive (LCD) strategy integrates Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and vehicle performance. LCA evaluates environmental impacts throughout a vehicle's lifecycle, crucial for identifying and reducing emissions in zero-emission heavy-duty vehicles (Z-HDVs). TCO examines financial aspects over the vehicle's lifespan, including long-term costs, important for stakeholders like fleet operators. Vehicle performance affects user acceptance and operational efficiency.

The ESCALATE approach analyses TCO and sustainability throughout the EV life-cycle, aiding businesses and policymakers in making informed decisions to achieve economic and sustainability goals for road transport. The framework advocates for standardised guidelines to incorporate these factors into Z-HDVs' design and manufacturing (Fig. 2).

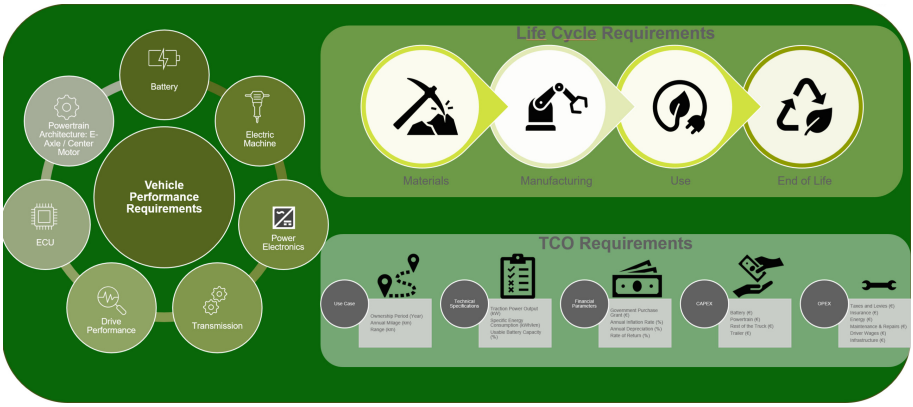


Fig. 2. ESCALATE: LifeCostDrive Framework

5 Conclusion and Future Implications

Integrating TCO and sustainability requirements early in project planning is essential for EV market success. This ensures EVs support environmental goals by reducing GHG emissions, lowering resource consumption, and promoting circular economy principles. The ESCALATE project provides a comprehensive framework to help EV manufacturers incorporate TCO and sustainability into design, architecture, and manufacturing. This proactive approach optimizes resource use, minimizes environmental impacts, enhances sustainability and circularity, and improves end-user acceptance. This research contributes to EV development literature, underscoring the importance of integrating TCO and sustainability for a greener transportation future.

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Uncertainty Sources in the Life Cycle Sustainability Assessment of Transport Infrastructure in the Context of Asset Management

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Abstract. Transport infrastructure, crucial for societal functionality and well-being, has important sustainability considerations throughout its life cycle, including resource use, emissions, and socio-economic impacts. Widely adopted life cycle thinking methodologies like LCC, LCA, and S-LCA aim to quantify these impacts, seeking to enhance the positive contributions of infrastructure while mitigating negatives. However, the reliability of these methodologies is often questioned due to the insufficient systematic consideration of uncertainties in the analyses, with deterministic assessments potentially leading to misleading conclusions. While research has progressed, with some LCC and LCA studies incorporating uncertainties, the application in the transport infrastructure field remains constrained and methodologically uneven. This paper seeks to advance the validity of sustainability assessment methodologies in transport infrastructure by reviewing sources, types, and specific triggers of uncertainty in infrastructure LCT studies, providing the reader with relevant descriptions and examples, as well as linking them across different categorizations. This research aims to advance the applicability of uncertainty analysis in the infrastructure LCT field as well as offer recommendations for future research.

Keywords: Life Cycle Sustainability Assessment · Transport Infrastructure · Uncertainty analysis

1 Introduction

Transport infrastructure forms the backbone of modern societies, facilitating global movement of people and goods. These infrastructures deteriorate over time, and as such, require interventions to restore and maintain their operational status. Today, the focus of infrastructure asset management (IAM) goes beyond merely implementing robust and safe engineering solutions, it also entails adopting and prioritizing sustainable approaches that address the negative economic, environmental, and social impacts associated with infrastructure interventions.

Life cycle costing (LCC), life cycle assessment (LCA) and social life cycle assessment (S-LCA) are life cycle thinking (LCT) methodologies developed to evaluate the

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economic, environmental, and social dimensions of sustainability [1]. In IAM, LCC enables the calculation of all agency and user costs throughout the life cycle of infrastructure networks and assets, unveiling long-term financial implications and key areas of expenditure [2]. Similarly, LCA tracks the environmental impacts of infrastructure across the asset life cycle, including the energy and resources required to carry out production, construction, demolition and waste processing tasks, as well as the emissions generated [3]. S-LCA extends this approach to the social impacts of infrastructure, covering multiple stakeholders perspectives, including workers, local community, value chain actors, consumer and overall society [4, 5].

Worldwide, transportation agencies resort to LCT methodologies to assess the performance of infrastructure interventions across the multiple dimensions of sustainability, highlighting key impacts and potential areas for improvement, and to execute comparative analysis between different options [6]. However, these methodologies are not without challenges, notably in managing the uncertainty that arises from issues related to data quality, methodological choices, or inherent variability [7, 8].

While a subset of existing studies has factored in the effects of uncertainty on infrastructure LCA and LCC analyses, this practice is far from standard. Research delivering a more comprehensive view on the subject is available, providing insights into the identification and management of uncertainties in infrastructure LCT evaluations. However, these studies tend to discuss uncertainty types and sources within a broader, more generalized framework, often with insufficient detail on uncertainty drivers specific to the infrastructure domain [9, 10]. Conversely, studies that do delve into these drivers do not explicitly frame them according to more standardized uncertainty classifications, particularly concerning their analytical level and position within the study [11].

All relevant sources of uncertainty must be considered for a thorough uncertainty analysis. This calls for a rigorous mapping of these sources, including knowing where and at which analytical level they first appear, and what triggers them. Understanding each uncertainty source is fundamental for properly managing and analyzing their effects on the assessment [7, 9]. Consequently, this study seeks to foster the development and uptake of uncertainty analysis in LCT applications in IAM by identifying and categorizing the primary types and sources of uncertainty encountered in infrastructure LCT studies, as well what triggers them.

2 Unpacking Uncertainties in Transport Infrastructure LCT Studies

2.1 Uncertainty Categorization

In LCT methodologies, uncertainties can typically be classified by either the analytical level at which they occur or the specific stage of the assessment in which they manifest [7, 10]. At the analytical level, we distinguish between parameter uncertainty, which concerns the quality and variability of the input data and scenario uncertainty, which is related to the methodological choices undertaken during the study [7, 10].

During the initial ‘goal and scope definition’ stage of an LCT study, the fundamental elements that shape the study are established. The goal and scope is underlined by precise

goals and questions, steering it towards a targeted examination of impact categories and indicators that span economic, environmental, and social realms. It is at this juncture that scenario uncertainties often arise due to the pivotal methodological decisions that will influence the direction of the entire study [7, 12].

In the life cycle inventory (LCI) stage, which takes place after the goal and scope definition, executioners gather input data on economic, environmental, and social processes and flows occurring throughout the entire lifespan of the system under examination. This include indirect upstream processes in the background, as well as the direct activities under assessment in the foreground. In the ensuing life cycle impact assessment (LCIA) phase, the LCI inputs are translated into economic, environmental, and social impacts. Parameter uncertainty is usually encountered in both phases. In LCI, it stems from issues with data quality and variability of the quantities and scores characterizing the inputs [7, 10, 13]. In LCIA, it is present in the characterization factors used to compute impacts. Table 1 compiles different uncertainty sources found in literature based on the categorizations presented above.

Table 1. Categorization of uncertainty sources found in LCT methodologies.

Analytical level	Stage	Method	Uncertainties	Sources
Scenarios	Goal and scope definition	All	System definition	[11]
			Functional unit	[9, 11, 14]
			Analysis period	[9, 11, 15]
			Allocation	[16, 17]
			System boundaries	[7, 9, 11]
			Future scenarios	[14, 18]
			Goal and questions to be answered	[14]
			Impact categories and indicator selection	[5, 13, 14]
			Statistical significance of the results	[14]
Parameter	LCI	LCC	Direct and indirect costs unit costs	[12]
		LCA	Input data to describe foreground and background processes and to quantify flows	[7, 9–11, 15]

(*continued*)

Table 1. (*continued*)

Analytical level	Stage	Method	Uncertainties	Sources
	LCIA	S-LCA	Input data to describe processes and to quantify flows	[13]
		LCC	Discount rate values	[10, 19]
		LCA	Characterization, normalization, and weighting factors	[7, 9, 20]
		S-LCA	Elicitation of weight values	[13]

2.2 Uncertainty Triggers in Infrastructure LCT Studies

There are several uncertainty triggers specific to infrastructure influencing uncertainty mapping in LCT studies. Based on the literature, seven key triggers are identified: socio-demographic characteristics, analysis scale, temporal boundaries, future scenarios, the construction industry's nature, and the nature of infrastructure interventions.

In social assessments, where impacts can have different meanings in function of context, socio-demographic factors take on added importance [21, 22]. The assessment scale, whether applied at the network level—examining interventions on a group of assets simultaneously—or at the asset/project level—analysing assets in isolation—affects the system definition and data requirements of the assessment [23]. Temporal boundaries define the period over which infrastructure is assessed. They can cover single cycles—the time elapsed between one intervention to next one—multiple cycles, or all cycles until decommission in EOL. The choice of temporal boundaries thus directly influences the definition of the functional unit and the system boundaries [6, 10, 11].

Future scenarios reflect uncertainties about evolving conditions. These are mainly present in the inputs characterizing processes that are likely to change over time, such as electricity generation [18]. Future uncertainties have an important impact on the analysis, particularly when looking at life cycle phases that take place over the distant future, namely use and EOL. As a result, the importance including these uncertainties in the analysis has received increasing attention in the context of infrastructure sustainability assessments.[11, 14, 18, 24].

The construction industry's nature introduces substantial uncertainty into model inputs due to the unique nature of each construction project, affecting the characterization of foreground input quantities and processes in the model [11]. Lastly, the nature of infrastructure interventions includes specific attributes of these activities, such as post-intervention predicted service life and duration of construction time, all influencing the results [11, 18, 25]. Table 2 summarizes these key uncertainty triggers and provides specific examples applicable to transport infrastructure LCT studies.

Table 2. Uncertainty triggers in the application of LCT methodologies to infrastructure sustainability assessments. Based on [11, 18, 26].

Uncertainty triggers	Description	Examples in transport infrastructure
Socio-demographic characteristics	These features impact the assessment of infrastructure interventions by shaping the value and functions that infrastructure fulfils in its context. These factors inherently influence the way in which the social sustainability of infrastructure projects is evaluated	Social impact categories, indicators, and weights assigned to the S-LCA of restoration interventions to ageing inner city bridges in historical city centres. In this case, for example, cultural heritage aspects may heavily influence social perceptions and, in turn, social assessments
Scale	This relates to the system definition, wherein a network encompasses multiple similar infrastructure assets within a specified area, while an asset/project pertains to a specific, individual asset, each fulfilling specific functions	The analysis scale of a pavement LCA study. Is the analysis at the network level where information is limited, and uncertainty is high? Or is the analysis at the project level, where information is detailed, and more design aspects are known?
Temporal boundaries	This pertains to the analysis period over which infrastructure is analysed. In a single-cycle analysis, an asset is evaluated from construction to the next major intervention, or from major intervention to the next major intervention, considering only minor interventions in between. Conversely, a multi-cycle analysis assesses infrastructure over extended periods, incorporating both minor and major interventions, potentially up to the asset's end-of-life (EOL)	The analysis period of a given highway where a decision must be made on whether to assess the environmental impacts from the moment when rehabilitation takes place up to when it is needed again or including more than one rehabilitation cycle at a time, examining environmental impacts at the longer-term

(*continued*)

Table 2. (*continued*)

Uncertainty triggers	Description	Examples in transport infrastructure
Future scenarios	This encompasses the approach to defining future scenarios in the analysis. Infrastructure is analysed over an extended timeframe, during which changes to both the background and foreground systems are likely to occur. These changes influence the analysis and its results. A static future definition assumes continuity of current conditions into the future, while a dynamic definition accommodates expected changes	The considerations of long-term, network-level pavement maintenance and rehabilitation plans. Shifts in background systems, such as changes in electricity grids, energy sources, and waste processing techniques, as well as developments in construction materials, methods, and use (e.g., traffic volume and composition) influence the impact assessment of these assets
Nature of the construction industry	The construction industry is distinguished by the uniqueness of each project. Although construction processes and materials might share similarities across various infrastructure interventions, even of the same type, they are seldom identical due to variations in sites, contractors, and local conditions across different locations and projects	The calculation and designation of budgets for bridge restoration programs based on LCC analyses. There are no bridge projects exactly equal because, even if they share the same typology of bridge with standardized components and dimensions, different contractors might be assigned to different works, and each site has its unique conditions
Nature of infrastructure interventions	Infrastructure interventions aim to prolong the lifespan of assets, though the additional years and the activities to ensure the intended lifespan are subject to varying uncertainties regarding their timing and nature. Likewise, construction time and/or capacity are likely to fluctuate across projects, influence the analysis and its outcomes	The assessment of lifespan extension measures to rehabilitate quay walls lining inner-city canals. The actual life extension that will be granted by applying these measures is uncertain, so is the actual construction time that these works will take when applied at larger scales

3 Discussions and Conclusions

Navigating uncertainty in LCT studies is crucial for enhancing the reliability of sustainability assessments within the transport infrastructure sector. Despite a recognition of the threat of uncertainty to the reliability of LCT studies, there has been a conspicuous lack of dedicated efforts towards the development and integration of uncertainty analysis approaches in these studies [20, 27]. This underscores a pressing need for more coordinated and deliberate research efforts by the infrastructure community to address and account for the effects of uncertainty in LCT assessments. To do this, it is essential to 1) meticulously map and comprehend the sources and triggers of uncertainties that pervade the assessments, 2) establish robust methodologies for characterizing, propagating, and conducting sensitivity analyses to trace the effects of uncertainties in the analysis, and 3) encourage a collaborative research approach that standardizes the use and application of uncertainty analysis in the field.

This study contributes to improving uncertainty mapping in infrastructure LCT studies, seeking to lay the groundwork for further advancements. It focuses on outlining various types and sources of uncertainty, integrating different categorizations from existing literature, and linking them to specific triggers within LCC, LCA, and S-LCA studies in the context of transport infrastructure sustainability assessments Furthermore, it provides insightful examples illustrating how these uncertainties unfold in practice. Our work seeks to pave the way for further progress, aiming to improve the quality and reliability of sustainability assessments in IAM, facilitating more informed and sustainable decision-making and strategic planning.

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Environmental Assessment of Components for Trains Based on the Use of Fiber Reinforced Plastic

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Abstract. Sustainable development is considered one of the most important global challenges facing the world today and is an important aspect of transport development. Rail has a central role to play in decarbonising transport as the backbone of the future sustainable transport system.

Various developments have been undertaken by railway stakeholders: decarbonisation of diesel trains, noise and vibration reduction, circular economy initiatives, improving the attractiveness of passenger trains, transferring goods to freight trains, etc., i.e. different methods to further improve the energy intensity consumption (kJ/km) of rail transport. One way of reducing energy consumption is to reduce the weight of the train, and Talgo has been working intensively in this area since the beginning, pioneering the use of aluminium structures in the early 1950s and, in recent years, the use of composite materials in primary structures.

There is a lack of clear guidelines on recycling and the circular economy, or official information is outdated. This lack of clarity is an obstacle to the design of robust policies for recycling and circular economy in composites and could be an obstacle to the wider uptake of these types of materials.

In this article, we will shed light on the uptake of composites from a Life Cycle Assessment (LCA) perspective, discussing recyclability, circular economy opportunities and whole-life impacts from a cradle-to-cradle perspective.

The study is divided into two phases, starting with an LCA of the new prototypes, including the production, assembly, transport and use phases. This is followed by an LCA of conventional structures and a comparison between them. The second phase concludes with a comparison of the environmental impact of replacing conventional structures with these innovative composite structures at the end of their useful life (EoL).

The figures obtained suggest that at EoL, composites will be more economically and environmentally attractive than current materials. In addition, new developments in composite materials and recycling processes will lead to significant improvements in the circularity of these components, increasing the recyclability rate.

Keywords: composites · LCA · circular economy · recyclability · structure · lightweighting

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1 Introduction

The rail sector is working together to remain competitive and to meet the challenge of making the sector more sustainable, by decarbonising diesel trains, reducing noise and vibration, implementing circular economy initiatives, making passenger trains more attractive or putting goods on board freight trains.

Since the 50s, Talgo has been convinced that weight reduction must be one of the main lines of action to meet the challenges mentioned above. In line with this approach, the new concept of lightweight construction involves replacing conventional materials with new, high-performance materials. An example of this is the frame of the new bogie (Rodal), which is mainly made of composite material (carbon fibre reinforced plastic (CFRP)), with a significant reduction in weight (~50%), resulting in greater energy efficiency and a reduced impact on railway infrastructure, among other benefits.

Today, however, it is unthinkable to manufacture without taking eco-design into account, as circular development models focus on sustainability. These new materials must have recyclability or reusability solutions at the end of their life, avoiding as far as possible energy recovery and end-of-life disposal of materials.

2 Case Study Definition

Firstly, this study is focused on the estimation of the Life Cycle Assessment (LCA) profile of the Rodal by evaluating a set of environmental indicators. Furthermore, an additional objective of, it is a preliminary comparison with the manufacture and use of a conventional Rodal (made in steel) (Fig. 1).

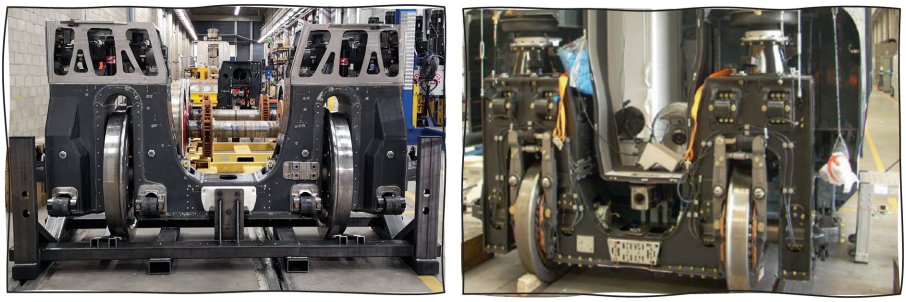


Fig. 1. A running gear: left) frame made of composite; right) frame made of steel.

3 Recycling Process

Potential benefits of the use of lightweight composites in trains could be further enhanced by using recycled materials, such as recycled carbon fibre (rCF) for CFRP.

The thickness and the complexity of the studied piece require the development of a specific process to ensure the final quality of the rCF product. It combines different recycling techniques, obtaining clean recycled fibre, with minimal loss of properties and material, reaching ca. 90% of material recoverability factor. The procedure is as follow:

i. Low **pyrolysis** temperature: gas and liquid fractions generated are internally used as an energy source.
ii. The solid residue is **shredding and sizing** to an optimum size.
iii. Continue with a **solvolysis** to complete removal of the polymer matrix: oxidizing environment and reagents are recovered by distillation.
iv. Fibre is **cleaned** with water (Fig. 2).

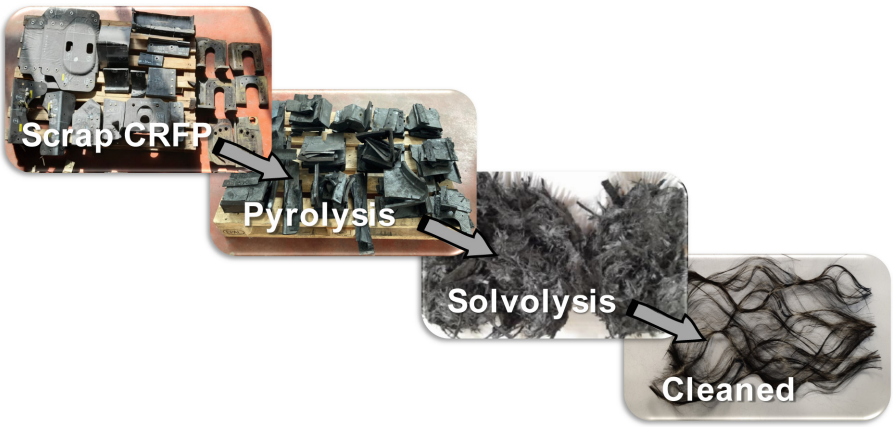


Fig. 2. Process diagram of the carbon fibre recycling process.

4 LCA Study

The increased awareness of the importance of environmental protections, and the possible impacts associated with products, has increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is life cycle assessment (LCA) [1]. For a correct implementation, it is necessary to consider the following stages, according to reference [1]:

- Goal and scope definition.
- Life Cycle Inventory analysis (LCI).
- Impact assessment.
- Interpretation.

The following environmental indicators were selected to characterize the potential life-cycle impacts: global warming, acidification, use of mineral and metal and freshwater and marine eutrophication.

4.1 Goal and Scope Definition

The first goal of this LCA study was defined the environmental life-cycle profile to produce a kilogram of recycled carbon fibre and compare it with virgin carbon fibre. A

characterization of the LCA of the lightweight running gear was then analyzed. First, a cradle-to-gate was presented (including production - raw materials extraction and transport to manufacturing sites, manufacturing, and transport stages); secondly the use phase (electricity consumption) is contemplated.

An additional objective was defined to explore the environmental suitability of the lightweight running gear against the conventional one. The comparison is made in two level, including or not the use phase.

LCA – A Kilogram of rCF and vCF

The inventory data for rCF are collected in the following table. The ones necessary for virgin carbon fibre is obtained from the Ecoinvent v3.8 database (Table 1).

Table 1. Main inventory data: inputs and outputs for rCF.

Inputs	rCF		Outputs	rCF	
CFRP waste	1,43	kg	rCF	1,00	kg
Acetic acid	2,46	kg	Aqueous phase	0,0369	kg
Hydrogen peroxide	4,57	kg			
Water	1,07	kg			
Electricity	10,29	kWh			

The advantages of use rCF instead of virgin ones are shown in the following table in terms of the five environmental indicators. The recycling process described above commitments with the circular economy as it allows to increase the recyclability and recoverability of CFRP material, i.e., near 100% on MRF (material recycling factor) which is an improvement from the current state of the art [2] on thermoset material (Table 2).

Table 2. Environmental life-cycle profile: rCF and vCF (virgin carbon fibre).

Impact	vCF	rCF	Units
Global warming	35	12	kg CO_2 eq
Acidification	0,26	0,06	mol H^+ eq
Freshwater eutrophication	0,0068	0,0045	kg P eq
Marine eutrophication	0,032	0,011	kg N eq
Use of minerals and metals	$2{,}8{\cdot}10^{-5}$	1,22·10–4	kg Sb eq

LCA – Cradle to Gate: One Running Gear

The inventory for a piece system was built using data for manufacturing and carbon

fibre recycling process. Some data were complemented with the literature data for CFRP production as well as with data from Ecoinvent database for secondary low-alloyed steel, secondary aluminum, and titanium (Table 3).

Table 3. Main inventory data for manufacturing of one Rodal (values per functional unit).

Inputs	Lightweight Running Gear	Conventional Running Gear		Outputs	Running Gear	
Secondary low-alloyed steel	256	743	kg	A piece	1	unit
Secondary aluminium	-	7	kg			
Titanium	26	-	kg			
CFRP	155	-	kg			
Water	731	2122	kg			
Heat	3237	9395	MJ			
Electricity	3181	2625	kWh			

The next table presents the environmental LCA results for one unit of each alternative piece. SimaPro 9.5 software has been used.

Table 4. Environmental life-cycle profile: **cradle-to-gate**.

Impact	Lightweight Running Gear	Conventional Running Gear	Units
Global warming	4,39·103	1,96·103	kg CO_2 eq
Acidification	$2{,}64 \cdot 10^{1}$	$1{,}02 \cdot 10^{1}$	mol H^+ eq
Freshwater eutrophication	1,58	$6{,}00 \cdot 10^{-1}$	kg P eq
Marine eutrophication	4,47	1,76	kg N eq
Use of minerals and metals	2,93·10–2	1,36·10–2	kg Sb eq

With respect to the results, the use of CFRP instead of metal in the lightweight running gear is not justified because the environmental impacts of the conventional running gear are all minor. However, it must be noted that these results do not yet contemplate the use phase.

LCA – Use Phase: One Running Gear

The environmental impacts in terms of the use of a standard train have been obtained from EcoInvent database [3] (Table 5).

It is estimated that a train runs over 500.000 km per year and knowing that its end-of-life (EoL) is about thirty years and a total of 15.000.000 km (Table 6).

Table 5. Environmental impact per kilometer and ton of train.

Impact	Diesel Engine	Electric Engine	Units
Global warming	5,68·10–2	3,87·10–2	kg CO_2 eq
Acidification	6,03·10–4	2,28·10–4	mol H^+ eq
Freshwater eutrophication	6,98·10–6	2,52·10–5	kg P eq
Marine eutrophication	$2{,}58{\cdot}10^{-4}$	$5{,}38{\cdot}10^{-5}$	kg N eq
Use of minerals and metals	2,19·10–7	2,30·10–7	kg Sb eq

Table 6. Environmental life-cycle profile: **use phase**.

	Diesel Engine		Electric Engine		
Impact	Lightweight Running Gear	Conventional Running Gear	Lightweight Running Gear	Conventional Running Gear	
Global warming	3,72·105	6,39·105	2,53·105	4,35·105	kg CO_2 eq
Acidification	3,95·103	6,78·103	1,49·103	2,56·103	mol H^+ eq
Freshwater eutrophication	4,57·101	7,85·101	1,65·102	2,84·102	kg P eq
Marine eutrophication	$1{,}69{\cdot}10^{3}$	$2{,}90{\cdot}10^{3}$	$3{,}52{\cdot}10^{2}$	$6{,}05{\cdot}10^{2}$	kg N eq
Use of minerals and metals	1,43	2,46	1,51	2,59	kg Sb eq

As makes sense, the greatest environmental impacts come from the use phase.

LCA – Cradle to Cradle

In this analysis is shown the combinate impact of production, manufacturing, transport, and use phase. Thus, the values obtained in Table 4 (cradle-to-gate results) and Table 6 (phase use results) are seen in a full LCA.

The emissions credit represents the effect of the differences in environmental impacts between conventional and lightweight pieces. It is calculated as follows and shown in Table 7:

$$Emissioncredit = Emission_{conventional} - Emission_{lightweight}$$

A positive value would suggest a favorable performance of the piece for the environmental indicator. The environmental benefits associated with the full-life operation of the train with the lightweight piece were found to be much higher than the aforementioned manufacturing penalties.

Table 7. Environmental life-cycle profile: **cradle-to-cradle - CREDITS**

	Diesel Engine	Electric Engine	
Impact	Emission Credit	Emission Credit	Units
Global warming	2,65·105	1,79·105	kg CO_2 eq
Acidification	2,82·103	1,05·103	mol H^+ eq
Freshwater eutrophication	3,18·101	1,18·102	kg P eq
Marine eutrophication	$1{,}21 \cdot 10^3$	$2{,}50 \cdot 10^2$	kg N eq
Use of minerals and metals	1,01	1,07	kg Sb eq

5 Conclusion

With the work performed, lightweight structures show benefits from an environmental point to view mainly on CO2 equivalent emission due to use phases.

This work fills the gap in LCA studies on lightweight, waste-based train components by exploring the environmental suitability of alternative pieces for trains based on the use of rCF including a proposal for a new recycling process reaching ca. 90% of material recoverability factor.

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Refining Design Approaches and Implementing the Material Matrix Assessment to Foster Structural Components Circularity

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Abstract. Integrating eco-design strategies is crucial when developing sustainable structural components. In the automotive industry, eco-design strategies are becoming essential as the industry faces pressure to reduce its carbon footprint and comply with regulations to reduce greenhouse gas emissions. Integrating these strategies into vehicles' design and manufacturing processes can significantly improve resource efficiency and reduce emissions, e.g. using lightweight and recyclable materials, such as aluminium, carbon fibre composites, and bio-based plastics, can enhance fuel efficiency and minimise energy consumption. Consequently, refining the eco-design strategies can participate in shifting from traditional linear production into circular design, i.e., using design for repair, reuse, refurbishment, and recycling approaches can limit the generation of waste products and reduce the pressure on the environment by reducing the need to extract raw materials. Several studies explained the best approach to selecting the proper design strategies, and more needs to be done on how the design strategies can be applied to support product circularity. It is crucial to understand that implementing eco-design strategies is challenging, and the main challenge is that product designers and manufacturers need knowledge and awareness. Consequently, incentives to implement eco-design strategies are still immature, and many companies focus on short-term profits rather than long-term sustainability. The archival value of this report is to:

- Define tactics and general circular design approaches (DFX) to preserve structural components and materials integrity.
- Guide designers while considering the product circularity and end of life (EOL).
- Provide an illustrative way to select the best material for the component based on a decision from the material matrix assessment.

Keywords: Design Approaches · Structural component circularity · Material Matrix Assessment · Automotive Industry · Carbon footprint

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1 Introduction

Eco-design involves integrating environmental considerations into product design to minimize the environmental impact throughout the product's lifecycle [1]. This includes extracting raw materials, manufacturing, distributing, using, and end-of-life disposal. Designers must consider the product's impact on the environment, such as greenhouse gas emissions, energy consumption, and waste generation, and identify areas where improvements can be made [2, 3]. Many authors have classified and identified strategies, methods, and tools that support product design for facilitating the transition to eco-design. These studies have emphasised the vast and diverse range of supporting approaches and the criteria for selecting the most appropriate eco-design approach [4–6]. Additionally, implementing eco-design strategies can directly improve crashworthiness and vibration performance through proper structure design optimisation. This involves optimising the size, shape, and topology of developed components to reduce material use and enhance structural performance [7].

The automotive sector is under pressure to diminish its carbon footprint to keep up with the EU Fit for 55 and zero carbon by 2050 goals. It has been estimated that up to 80% of all environmental impacts are determined during the design phase of products. That is why the refinement and development of Eco-design strategies and assessments are vital to the industry. Some popular strategies vehicle manufacturers usually rely on are using lighter materials [8], design of assembly/disassembly [3], and designing for remanufacturability [9].

The main challenge in eco-design is the need for product designers and manufacturers to have the right knowledge and awareness. This article aims to help end-users and designers tailor and streamline their approaches by providing guidelines and support in choosing the best circular design for their application.

2 Eco-Design Approaches

The typology of eco-design approaches encompasses diverse strategies and principles aimed at reducing the environmental impact of products and systems. Figure 1 represents the most straightforward framework. These approaches can be broadly categorised into several key themes. One prevalent approach is related to preserving the product's integrity, and the other is keeping the material's integrity.

2.1 Design for Preserving Product Integrity

Product integrity was defined for the first time as the extent to which a product remains identical under the loads encountered during its life cycle [10]. A design approach for longevity, life span extension, and recovery should be applied to maintain product integrity.

The design approach for longevity involves evaluating a product's life cycle to ensure a long lifespan, considering user needs, business objectives, and resource efficiency [10]. Physical durability is crucial, influenced by factors like wear, fatigue, and corrosion, all addressed through strategies such as design for reliability and durability [5, 11,

12]. Designing for life extension in the automotive industry includes choosing robust materials, optimizing maintenance, and adhering to standards like EN 13306:2018 for maintenance types [13]. Maintenance relies on strategies like design for Assembly and Disassembly to facilitate accessibility and reduce costs [3]. Design for recovery aims to salvage economic and ecological value, with options like repair, refurbishing, and recycling considered to maintain product and material integrity [14].

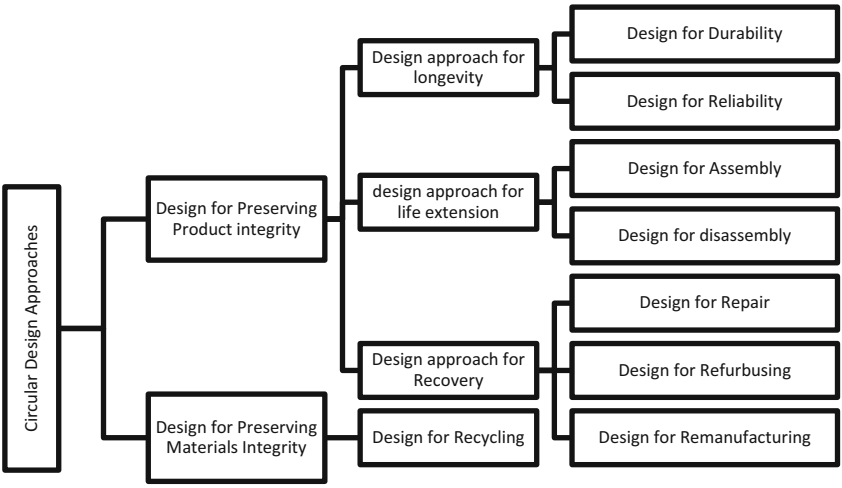


Fig. 1. Typology for design approaches. The chart also shows an example of related DFX strategies that should be implemented.

2.2 Design for Preserving Materials Integrity

Materials integrity significantly contributes to the safety and environmental success of any product/vehicle circularity. Design for recyclability is the leading player in preserving product material integrity and is a crucial eco-design strategy that aims to reduce product environmental impact throughout the product life cycle.

3 Considered Aspects of Eco-Design

Incorporating environmental considerations into product development and redesign is a practice known as eco-design. Eco-design aims to balance ecological and economic requirements by systematically addressing environmental aspects at every stage of the product development process. Its overarching goal is to create products that minimise their environmental impact across the entire product life cycle. Within the framework of eco-design, various design alternatives that align with specific targets and constraints can be evaluated. This evaluation process aligns with eco-design principles emphasising sustainable practices and environmental responsibility. As indicated in Fig. 2, the environmental footprint assessment encompasses various stages of a product's life

cycle, including the production phase, use phase, and end-of-life options such as recycling or landfilling. These aspects are integral to the holistic assessment of a product's environmental impact.

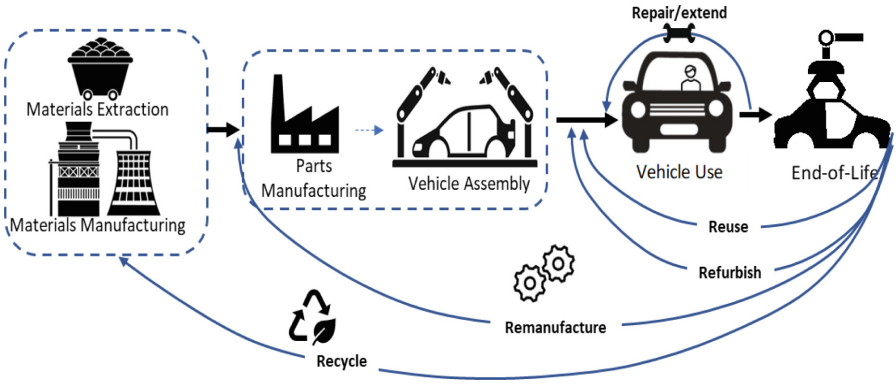


Fig. 2. Product System, showing different vehicle production phases and Eco-design strategies that can be implanted to shift from linear to circular production.

The Production Phase includes critical elements such as raw material extraction, manufacturing of the structural part, and associated logistical activities. The weight of the part plays a pivotal role in raw material extraction and logistics. The efficiency of the manufacturing process, including scrap generation, ratio of faulty parts, and energy and water consumption, is a key focus. Strategies to increase process efficiency include energy-conscious manufacturing, streamlining references, and compatibility with current assembly lines at OEM facilities.

The environmental impact of automotive components is intrinsically linked to their weight due to their direct correlation with the vehicle's energy consumption during its operational phase. While mass-induced fuel consumption (MIF) is comparatively lower in Battery Electric Vehicles (BEVs) than in Internal Combustion Engine (ICE) vehicles, it remains a significant factor [15]. Consequently, weight reduction is the principal approach to diminishing the environmental footprint of a vehicle component throughout its usage period.

The structural constituents of an automobile possess the potential for reuse, refurbishment, recycling, or deposition in a landfill upon reaching the end of its life cycle. Each of these end-of-life routes has its own environmental impact, ranging from minimal to significant. However, except for landfill disposal, the least favourable option, the initial step in the process is dismantling. Designing for disassembly is especially important in cases where a vehicle's components consist of multiple materials, as specific joining methods can complicate the sorting process and may even hinder recycling efforts [3].

4 Implementing Material Matrix Metrics

When considering eco-design, designers can make informed choices based on carefully curated parameters that balance ease of assessment with environmental impact relevance. These parameters can be defined based on the project's target. Table 1 depicts examples of the metrics parameter and the weighting factor.

Table 1. An example of the Material Matrix Metrics parameters and the weighting factor.

Metrics parameter	Meaning and method of evaluation
Potential for Weight Reduction	Achieving weight savings is critical for reducing environmental impacts and costs. It is directly linked to energy consumption during production and usage. A simplified assessment using alternative material density is needed, followed by a more precise evaluation tailored to the chosen material and manufacturing
Process Recyclability	This factor considers the recyclability of the material. It is evaluated on a scale of 1 to 3: 1.“ Not recyclable with conventional techniques” 2.“ Difficult to recycle with conventional technics.” 3. “Easily recyclable”
Assembly/disassembly	the complexity of the assembly/disassembly is related to the lifecycle: production (simple assembly methods increase the manufacturing efficiency), use (to allow maintenance) and end-of-life (to allow easy sorting for reuse, refurbishment, and recycling) 1. “Currently not disassembled, medium complexity for assembly (welding)”, 2. “Difficult to assemble/disassemble” (adhesives) 3. “Easily as assemble/disassemble” (bolts)
Reduction of references	integrating different functions in fewer parts contributes to cost-effectiveness and environmental footprint reduction. This metric is measured in terms of the total number of parts saved. The decrease in references can be implanted only by understanding the part's complexity and the manufacturability
Compatibility with the current assembly line	This metric is evaluated on a scale of 1 to 3: 1. “Significant changes on the assembly line are required” 2.“ Minor changes on the assembly line are required.” 3. “No changes required”

Let's consider a hypothetical scenario to understand the material matrix's importance in achieving product circularity. Designers need to establish specific criteria for any redesign, such as weight reduction, use of available materials, manufacturability, performance standards, and maintenance facilitation. By following the following steps, a decision can be made efficiently regarding the suitability of different materials for specific subcomponents:

- **Comprehensive Evaluation:** Each design will undergo a thorough assessment based on the established criteria. For example, manufacturability will be assessed in collaboration with part manufacturers and process experts, and crash performance will be simulated to ensure compliance with safety standards.
- **Environmental Assessment:** Designs that successfully meet the predefined criteria will then be subject to an environmental evaluation using specified metrics.

- **Scoring and Weighting:** Ultimately, a score will be assigned to each design in accordance with each category, and these scores will be weighted accordingly.

Then, to calculate the global score of each alternative design, different scores of each parameter will be weighted as per project or condition.

5 Conclusions

In conclusion, this paper investigated the possibilities of redesigning products to align with eco-environmental goals. While the eco-design approaches explored in this study share many commonalities with existing strategies concerning product and material integrity, we introduced a novel and practical tool, the Material Matrix Assessment. The Material Matrix can be used to enhance decision-making when selecting the optimal material for structural components. Our paper not only outlined the concept but also provided a step-by-step procedure for implementing the Material Matrix Metrics, accompanied by an example. By doing so, we aimed to contribute to the growing body of knowledge in eco-design and empower designers and engineers to make more informed choices that can positively impact both the environment and product sustainability.

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Feasibility of Concrete Paving Blocks Produced with By-Products from Construction and Coconut Industries

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Abstract. This paper aims to analyze concrete paving blocks (CPB) with construction and demolition waste (CDW) and coconut fibers (CF) for light traffic road pavements, applying physical and mechanical characterization. Therefore, nine mixtures, three without by-products, three with CDW recycled materials, and three with CF, were used to produce rectangular CPB 20 cm × 10 cm × 8 cm (length × width × thickness). Tests, such as water absorption, air void, and compressive strength at 7 and 28 days, were done on CPB. The results showed that the mix with CDW materials, 75CDW-0.73, presented CPB at 28 days with the lowest average air void of 11.88%, demonstrating the significant compactness by the jackhammer in mixing recycled aggregates with the water/cement ratio of 0.73. Furthermore, the mixtures REF-0.63F and REF-0.73 presented CPB at 28 days with a characteristic compressive strength 139.33% and 148.42% higher than the mix REF-0.63, being a positive effect of CF and water for the mixtures' workability. Also, the mixtures REF-0.73 and 75CDW-0.73 showed average water absorption below the Brazilian and European specifications of 6%. Finally, the CPB application with by-products is possible for light traffic according to the Australian specification for bike paths or parking areas.

Keywords: Concrete Paving Blocks · Construction and Demolition Waste · Coconut Fibers · Physical and Mechanical Characterization

1 Introduction

The interlocking pavement (IP) consists of a flexible, rigid, or semi-rigid structure, depending on the composition of the base and sub-base layers. These two layers can be roller-compacted concrete for rigid pavement, graded crushed stone treated with cement

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or soil-cement for semi-rigid pavement, and simple crushed stone for flexible pavement. Furthermore, the IP layers above the foundation are the sub-base, the base, and the surface (concrete paving blocks, bedding sand, and joint material).

The IP adaptable structure assessments must be made during the planning of this structure. For a more effective construction, the concrete paving blocks (CPB) must show mainly mechanical and physical properties, such as compressive strength and water absorption, according to standards: Brazilian ABNT NBR 9781 [1], European CEN EN 1338 [2], and Australian SA AS/NZS 4456.4 [3].

By-product reuse is an alternative strategy to manufacture CPB. Due to civil construction activities, construction and demolition waste (CDW) is widely generated in urban centers. In Fortaleza, Brazil, the amount of CDW destined for the 61 eco-points is 276,000 tonnes per year [4]. Also, CDW activities generated over 850 million tonnes of by-products in the EU [5]. Another by-product is coconut fiber (CF) from the coir's waste. During their decomposition, 80% to 85% of the coconut weight becomes waste, and their disposal causes a decrease in the lifetime use of landfills [6]. Then, in Brazil and Portugal, Francisco et al. [7] and Cravidão [8] evaluated the application of CDW recycled aggregate and fiber, respectively, for concrete.

Finally, this paper aims to analyze the feasibility of CPB with recycled aggregates from mixed CDW and CF for light traffic road pavements, applying physical and mechanical characterization.

2 Experimental Program

2.1 Materials

Natural materials were gabbro-diorite, 12/20 mm and 6/12 mm gravels (coarse aggregates), and crushed sand 0/4 mm (fine aggregate). Two mixed CDW's recycled coarse aggregates (12/20 mm and 6/12 mm gravels) and a recycled fine aggregate (sand 0/4 mm) were used. CF had an average length of 130 mm. High-early-strength Portland Cement, CEM I 42,5 R, and water were also used. Figure 1 and Table 1 show the aggregates' granulometric composition and materials' physical characteristics.

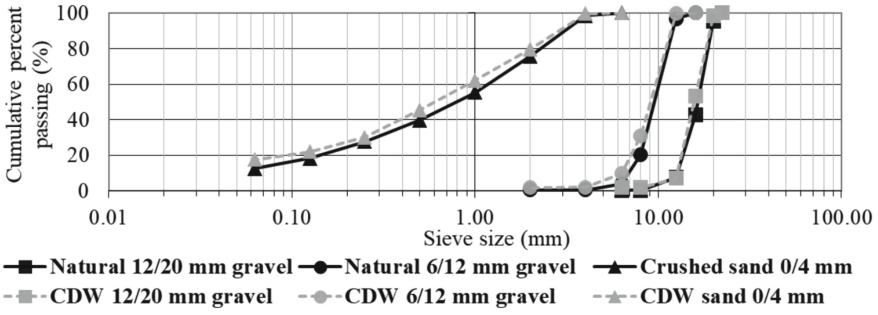


Fig. 1. Aggregates' granulometric composition.

Table 1. Materials' physical characteristics.

Materials	Dry density [9] Mg/m^3	Bulk density [10] Mg/m^3	Water absorption [9] (%)	Fines under 0.063 mm [11] (%)
Natural 12/20 mm gravel	2.85	1.45	0.42	0.20
Natural 6/12 mm gravel	2.84	1.44	0.51	0.24
Crushed sand 0/4 mm	2.72	1.67	0.93	11.98
CDW 12/20 mm gravel	2.22	1.13	5.78	0.76
CDW 6/12 mm gravel	2.26	1.14	6.01	0.99
CDW sand 0/4 mm	2.16	1.42	5.81	17.20
Cement	2.97	–	–	–
CF	–	1.42	140.0	–

Note: the mixed CDW's composition by mass is 42.5% concrete particles, 32.1% rock fragments, 22.8% red bricks, and 2.6% wood, plastic, and bitumen

2.2 Concrete Mixes and Tests on Concrete Paving Blocks

Nine mixtures for dry concrete were used with three water/cement ratios of 0.63, 0.73, and 0.83, a CDW replacement level of 75% by aggregate weight, and a CF addition of 0.1% by mix weight. Therefore, there are three mixes without by-products (REF-0.63, REF-0.73, and REF-0.83), three with CDW recycled materials (75CDW-0.63, 75CDW-0.73, and 75-CDW-0.83), and three with CF (REF-0.63F, REF-0.73F, and REF-0.83F). It is essential to highlight that, to keep the materials' proportions in the reference mixes, the mortar (70.05%) and moisture (7.80%) contents of the concrete were kept constant. The nine mixtures tested are shown in Table 2.

Rectangular CPB 20 cm × 10 cm × 8 cm (length × width × thickness) were manufactured in wooden molds using a jackhammer (model 638 from Kango brand), with a 750 W engine responsible for vibration. The following tests were made on the hardened CPB at 7 and 28 days: air void (three blocks) [12], water absorption (three blocks), and compressive strength (six blocks) [1].

3 Results and Discussion

The average air void, water absorption, and characteristic compressive strength for CPB are shown in Figs. 2, 3, and 4, respectively, with standard deviation bars.

In Figs. 2 and 3, the alternative mix 75CDW-0.73 presented the lowest average air void of 11.88%, related to the second-lowest average water absorption of 5.58%. The compactness of the jackhammer may explain this finding because, according to Chu et al. [13], with an appropriate packing density optimization, CPB with only recycled aggregate showed a 156% compressive strength increase from 30.9 MPa to 79.2 MPa. Then, the material packing by the jackhammer in mixing recycled aggregates with the water/cement ratio of 0.73 provided a significant compactness of the concrete.

Table 2. Concrete components' consumption.

Mixtures	Consumption (kg/m^3)							
	Cement	Natural aggregates			CDW recycled aggregates			Water
		Crushed sand 0/4 mm	6/12 mm gravel	12/20 mm gravel	Sand 0/4 mm	6/12 mm gravel	12/20 mm gravel	
REF-0.63	269.7	1257.0	531.4	121.4	–	–	–	169.9
REF-0.73	228.3	1269.3	520.5	118.7	–	–	–	166.7
REF-0.83	202.7	1307.7	527.1	119.6	–	–	–	168.3
75CDW-0.63	244.8	285.2	120.6	27.5	855.7	361.7	82.6	154.2
75CDW-0.73	212.0	294.7	120.8	27.6	884.0	362.5	82.7	154.8
75CDW-0.83	182.3	293.9	118.5	26.9	881.7	355.4	80.7	151.3
REF-0.63F	261.9	1220.4	515.9	117.8	–	–	–	165.0
REF-0.73F	230.1	1279.2	524.5	119.6	–	–	–	167.9
REF-0.83F	195.8	1262.7	509.0	115.5	–	–	–	162.5

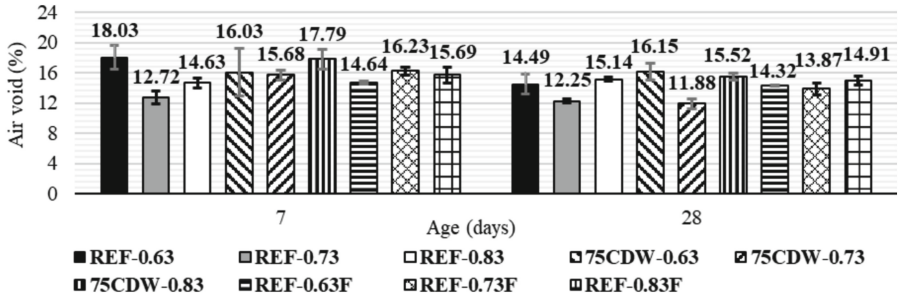


Fig. 2. Concrete mixtures' average air void.

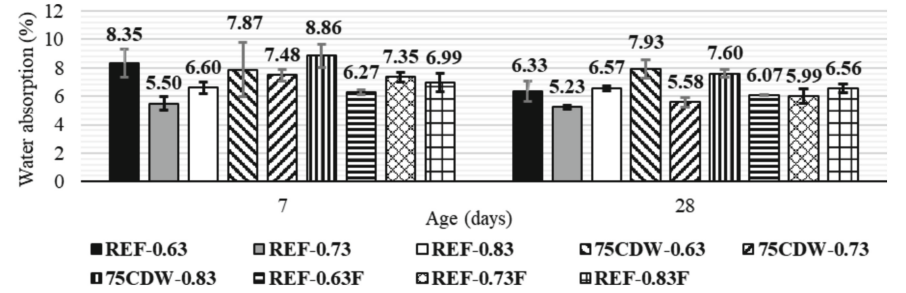


Fig. 3. Concrete mixtures' average water absorption.

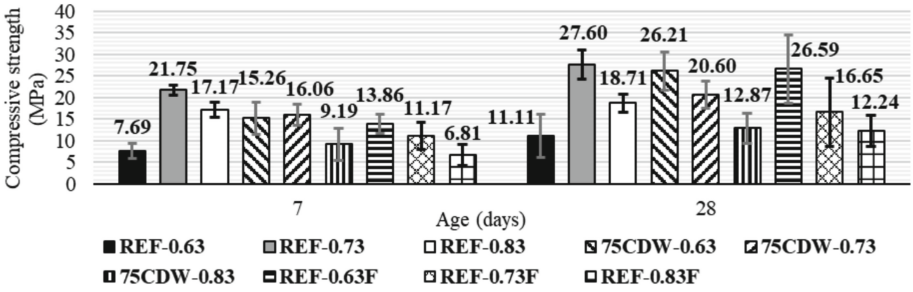


Fig. 4. Concrete mixtures' characteristic compressive strength.

In Fig. 4, the mix with CF, REF-0.63F, presented CPB at 28 days with a characteristic compressive strength 139.33% higher than the reference mixture with the same water/cement ratio, REF-0.63 (26.59 MPa > 11.11 MPa). This positive effect of adding CF may be due to the fiber's potential to minimize concrete cracking when applying vertical loads [14]. Furthermore, the reference mixture with more water, REF-0.73, showed a characteristic compressive strength 148.42% higher than the reference mix with less water, REF-0.63, at 28 days (27.60 MPa > 11.11 MPa). As dry concrete has reduced water content, the laws that explain the mechanical properties of dry concrete are not always similar to mixes of consistency plastic [15]. Then, adding more water can improve the mixtures' workability, favoring the compressive strength increase.

Positively, in Fig. 3, the mixes REF-0.73 and 75CDW-0.73 showed average water absorption at 28 days (5.23% and 5.58%) below 6.0%, a specification of the standards ABNT NBR 9781 [1] and CEN EN 1338 [2]. Negatively, in Fig. 4, all the mixtures presented compressive strength results below 35 MPa, a Brazilian specification for special and commercial vehicles at 28 days [1]. However, the Australian standard SA AS/NZS 4456.4 [3] states a minimum compressive strength of 15 MPa for CPB in cycle paths and parking areas. Finally, new criteria for bike paths with a lower specification can be created for the Brazilian standard ABNT NBR 9781 [1].

4 Conclusions

This paper presented research with the primary objective of analyzing the feasibility of CPB with recycled aggregates from mixed CDW and CF for light traffic road pavements. With the main results, the leading direct inferences can be as follows:

- The material packing by the jackhammer in the alternative mixture, 75CDW-0.73, with a water/cement ratio of 0.73, was a key factor for the greater compactness of this mix, showing the lowest average air void of 11.88%.
- The mixes REF-0.63F and REF-0.73 presented a characteristic compressive strength 139.33% and 148.42% higher than the reference mixture REF-0.63 at 28 days. Then, adding CF and water with compacted energy can significantly improve the workability and mechanical behavior of the concrete.
- All the mixes showed characteristic compressive strength results below 35 MPa, a Brazilian specification. However, according to an Australian specification of 15 MPa for CPB, a new category for bike paths or parking lots can be made.

Finally, this study recommends using CPB in areas with little to no motorized traffic. It also supports CPB on low to intermediate-trafficked roads but notes the need for adaptation.

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How Does Circular Economy Disrupt Business Models: The Case of Ballast Reuse in Railway Projects

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Abstract. The European rail infrastructure industries are incited to rethink their supply chain to achieve carbon neutrality by 2050 (European Green Deal). This leads them to undertake a paradigm shift from a linear to a circular economy based on reusing and recycling materials.

However, industries may be reluctant to invest in new circular models when they lack in estimating the potential benefits and costs of the new circular businesses. Nevertheless, the Ellen MacArthur Foundation argues that a circular economy develops new and strategic opportunities and generates benefits if well thought out.

This paper analyses the economic impact of moving from a linear to a circular economy, focusing on the ballast reuse for rail regeneration projects for the case of SNCF Réseau. We propose a multistakeholder activity-based costing approach and apply it to three ballast supply scenarios.

The results show that reusing ballast generates winners and losers. While it can be economically attractive for a project to reuse its ballast, it becomes more complex to determine the profitability of reusing ballast for sharing between different project sites; additional parameters should be considered, such as the distance between sites or to ballast pits as well as other environmental costs. The paper thus argues that circularity does not always equate to sustainability. The deployment of a circular economy should require a systemic vision that not only allows one to pilot a project but also to map and interact with its industrial environment.

Keywords: Circular economy · Railways · Ballast reuse · Activity-based costing · circular supply chain

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1 Introduction

The ecological transition is prompting rail infrastructure managers to rethink and innovate their supply markets. For example, the French railway infrastructure manager, SNCF Réseau, has targeted collecting 100% of the structural materials used in railroad construction (rails, sleepers, ballast, and copper) for recycling. The company thus undertakes a shift from a linear economy based on the end-of-life concept to a circular model based on reusing and recycling materials.

Despite SNCF Réseau's stated ambitions, the literature tells us that such a transformation can be challenging due to barriers, such as the need for more communication between stakeholders [1], or the capacity to invest in new circular models [2]. However, the main obstacle concerns the lack of estimation of economic benefits [3].

Economic benefits are either the main driver or the primary barrier to adopting circular models [4]. Companies are reluctant to invest in new circular models that may be costly in the short term or economically unprofitable in the long term. However, if well designed, a circular economy may develop strategic opportunities while generating benefits.

Several tools and methods exist for estimating and subsequently improving the economic (and extra-financial) impact of integrating circular activities into companies. These methods are based on weak sustainability, where sustainable development capitals are substitutable [5]. These methods can make more explicit the trade-offs involved in achieving the best overall corporate performance, i.e., the best strategy and organization of resources. However, this point of view is not always shared in the literature, as it can be considered anthropocentric when the interest driving the company's change is economic rather than environmental [6]. In this article, we hypothesize that linking circularity to economics can facilitate corporate decision-making and change management. The monetarization methods provide an evaluation criterion for product and project design, allowing industrials to compare their different strategies regarding a standard reference and guiding their choices toward the optimal solution from an economic, social, and environmental point of view. However, we do not mean economic profitability should be the only motivator for moving to circular businesses.

Traditional economic evaluation methods include cost-benefit analysis [7], generally used on projects to measure the socio-environmental impact of a project; the activity-based costing approach [8], used to estimate the cost of a product through the activities carried out to design it; or lifecycle costing [9], revealing the cost of a product throughout its lifetime.

This paper adds to the literature an example of the impact of adopting circular business models in companies. Our research is based on the action research paradigm [10] used in the literature to solve a problem of real situations with continuous transformation thinking. More specifically, we focus on the monetary impact of ballast reuse in railway projects. To this end, in Sect. 2, we adapt the activity-based costing approach to multiple stakeholders. The results of this approach's application are presented in Sect. 3 and discussed in Sect. 4.

2 Methodology

The research was conducted during two months at the end of 2022 in SNCF Réseau under the lead of two in-house experts in charge of deploying ballast reuse in railway projects and with the help of other experts and based on the internal investigation and document analysis. The work aimed to study the direct costs and profitability of reusing railway components, in this case the ballast, and how the reuse process can lead to the introduction of new ways of proceeding within the company.

That is why, this paper compare the profitability of three ballast supply models that can be used in a railway regeneration project: (1) the conventional linear model where old ballast is removed and replaced by a new ballast from external quarries; (2) a circular model where the ballast of a project site is reused onsite; (3) a second circular model where a project site transfers its old ballast to another project site to be reused. We focus in our analysis on the economic impact on the internal stakeholders in the company regarding these three models.

Since the purpose of our work is to understand the potential improvements enhancing ballast reuse at a significant level in the company, we decided to use a multistakeholder activity-based costing (we will call MS-ABC) adapted for industrial projects.

The traditional activity-based costing (ABC) approach is used in the literature for assigning direct and indirect costs to an industrial product, considering the activities carried out to manufacture this product [11]. ABC contrasts with conventional costing systems as it considers that a product consumes activities that consume resources. Over the years, it has acquired the ability to drive change in product design and manufacturing processes as it can be used as a decision-support information system [12], identifying potential cost drivers. ABC is composed of two stages. The first one consists of identifying the main activities and assigning their costs. The second stage allocates each activity's cost to the product.

ABC has inspired other methodologies such as Feature costing [13] based on the variation of costs according to the different possible features of products. More recently, [12] have proposed an ABC based on matrix multiplication that transforms the two ABC steps into two matrices, which combination represents a product-resources matrix. Finally, time-driven ABC has also been used, arguing that costs and revenues depend on resources and time [14].

In this research, we choose to use ABC since it considers that a product is a succession of activities, which also defines a project. However, as rail projects may involve several internal stakeholders, we needed to adapt ABC to attribute each activity's cost and benefit in a ballast reuse project to the stakeholder concerned.

Figure 1 presents the four steps of our MS-ABC. For each ballast model, the methodology consists of (a) mapping the potential internal stakeholders; (b) unfolding the activities executed in the model; (c) assigning activities to the stakeholders; and (d) attributing the cost or benefit of each activity according to each actor, knowing that the cost of an activity may depend on many variables. For example, the cost of transporting ballast to project site depends on the transportation mode. In this paper, we only focus on direct costs, i.e., we do not consider monetary values such as the cost of carbon emissions. In the end, a comparison of the three ballast supply models allows us to assess the profitability of each of the model regarding a particular stakeholder.

Our methodology differs from cost-benefit analysis in that it calculates profitability per activity to a given stakeholder. It also differs from lifecycle costing in considering an activity as a transaction between stakeholders.

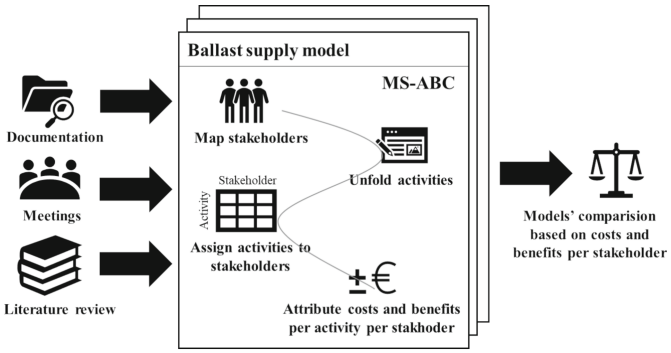


Fig. 1. Overall methodology

3 Results

The methodology is applied to the three ballast models described in the previous section. The final results are shown in Fig. 2. Only standardized costs have been displayed for confidentiality reasons, while the ratio between them remains valid. We mainly observe that:

- For the standard ballast supply model (BM1), two main entities within the company are involved: an internal supplier responsible for purchasing and trans-shipping ballast, and the project to which the ballast is finally invoiced. While the supplier's profit depends on the transported ballast, the project costs mainly depend on the ballast acquisition and the landfilling (stock and watering). The project can, however, generate a benefit if it can sell its old ballast.
- We found no internal supplier for the second model (BM2), which consists of reusing ballast onsite (assuming 100% of the ballast is reused). The project considerably reduces its expenditure, which now depends on ballast screening and washing. Finally, there is no cost of landfilling (stock and watering) since the project no more needs to stock new ballast.
- In the third model (BM3), a supplier project (or ceding project) transfers its ballast to a buyer project for free; the supplier project gains nothing (voluntary model). The buyer project costs depend on transport, screening and washing, and landfilling (stock and watering); the ballast acquisition costs are thus saved. In general, the distance between the two project sites is short in order to reduce ballast transport costs. In addition, in this model, the two projects must Note that, in this model, the internal supplier plays no role, which represents a loss for him and a potential impact on other projects using the standard model.

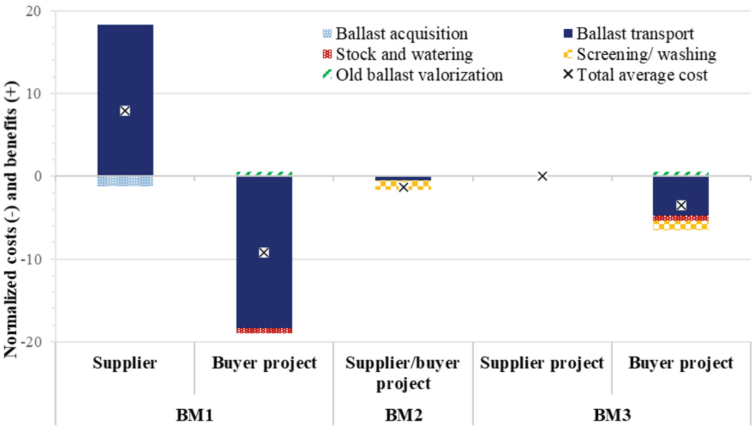


Fig. 2. Costs per ballast model, activity, and stakeholder

4 Discussion and Conclusion

The results show that adopting circular models upsets current balances as it can generate a win-lose situation. For example, in our case, the internal supplier is affected when two projects collaborate (BM3); this can potentially negatively impact projects using BM1. Innovating in the processes and rethinking roles is thus essential.

We also find that on-site ballast reuse (BM2), if the ballast quality permits, is the most economically profitable model for a project. Therefore, when a project manager is well-informed and accompanied by environmental experts, he will have no reason not to reuse the project's ballast. This solution could easily be deployed on a large scale in the industry.

BM3 shows that voluntariness is the main factor for exchanging ballast between projects since there are no economic transactions between the two projects. Here, we argue that the industrialization of circular models can be hindered since that the supplier project has no economic incitation for transferring its ballast. We can thus imagine creating a marketplace for buying and selling ballast. This needs to fix a new way of calculating the ballast economic value as well as to promote new processes in the company. Indeed, we note that ballast transport is highlighted as the most impactful activity in all models. It represents the most expensive activity. It depends on many features, such as the transport mode or the distance between quarries or project sites. During our data collection, we analysed the ballast transport scenarios. We noticed that the standard model BM1 may be more profitable for a project than the circular BM3 if the project is near a quarry. In addition, when calculating the carbon emissions of ballast supply, we find that transport is the leading emitter activity. In other terms, depending on the features, circularity does not always imply sustainability since BM1 may sometimes be less polluter than BM3. This leads to performing our actual methodology exclusively based on direct costs. To assess the overall profitability of circular models, we need to integrate other indirect costs linked to carbon emissions or ballast scarcity. Although the literature on environmental monetarization is rich, we noticed that project managers

only sometimes understand the proposed economic values. That is why we restricted this study to direct costs in a project budget. We emphasize the need for more disclosure on these issues. Nevertheless, our methodology is interesting in allowing us to represent the gains and losses per stakeholder. It allows managers and experts to understand the possible conflicts that could emerge when designing business models.

To conclude, deploying circular models must be economically profitable, but the economic criterion needs to be revised. As we have shown, circularity is not synonymous with sustainability. Companies, therefore, need to innovate and train project managers to enable them to deal with a new, shifting, and complex project environment.

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Life Cycle Analysis of Low Carbon Roller Compacted Concrete Pavements

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Abstract. Roller compacted concrete (RCC) is a zero-slump concrete with lower ordinary Portland cement (OPC) content and water/cement, and a higher proportion of aggregates than conventional concrete. Life cycle analysis (LCA) was performed with a cradle-to-gate system boundary to compare the impacts of continuously reinforced concrete pavements (CRCP) and RCC pavements per mile of dual carriageway. RCC pavements have less than half of the environmental impact of CRCP due to lower thickness of RCC pavement lifts and lower quantity of OPC. Construction processes contributed to only a very small proportion of the total environmental load for both pavement types. In RCC pavements, notable reductions in the GWP were observed with partial replacement of cement. Compared to fly ash and ground granulated blast furnace slag, limestone calcined clay cement has the lowest CO_2e emissions for concretes with similar compressive strength, due to its shorter transport distances. The benefits of using recycled concrete aggregates and reclaimed asphalt pavement aggregates in RCC pavements were outweighed by their long transport distances. The geographic availability of materials is critical to consider when replacing OPC and natural aggregates to reduce RCC pavement environmental impacts.

Keywords: Roller compacted concrete · life cycle analysis · cement replacement · non-virgin aggregates · global warming potential · abiotic depletion

1 Introduction

The global popularity of concrete pavements for use in high-speed applications is growing because of their longer design life over asphalt pavements due to their higher durability, stiffness, and improved performance in a range of temperatures [1–3]. Furthermore, it's important to note that concrete pavements offer a significant advantage in terms of routine maintenance costs. They have been consistently proven to be the least costly option over the long term, requiring fewer repairs and resurfacing compared to asphalt alternatives. This cost-effectiveness makes concrete pavements a highly attractive choice

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for sustainable and economically viable infrastructure projects worldwide [4]. However, cement contributes up to 90% of greenhouse gas emissions associated with concrete production, with clinker attributable to 60% of UK CO_2 emissions from concrete and cement production [5]. Roller compacted concrete (RCC) pavements provide opportunities for reducing these environmental impacts due to their lower cement content. They combine the durability of conventional concrete pavements with the ease of construction of asphalt pavements using high-compaction pavers and vibratory rollers [1]. The environmental benefits could be further exploited through partial substitution of OPC with fly ash, ground granulated blast furnace slag (GGBS), and limestone calcined clay cement (LC3) and of natural aggregates with recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) aggregates.

Life cycle assessment (LCA) quantitatively evaluates the sustainability of producing RCC pavement over its entire life. Both one cubic metre (m^3) and one kilometre (km) of RCC pavement have been used as functional units for existing LCAs, with system boundaries ranging from cradle-to-gate to cradle-to-grave [6–9]. Studies by Hashemi et al. (2020) and Anastasiou et al. (2015) found that partially replacing OPC with fly ash (45% and 50% respectively) reduced global warming potential per m3 by 40% and per km by 60% [7, 8]. Adamu et al. (2018) and Hashemi et al. (2020) also showed OPC replacement rates of 38–45% using fly ash or GGBS decreased CO_2 emissions by 39–40% [7, 9]. However, long transport distances for fly ash and GGBS, discussed by Kurda et al. (2018) and Adamu et al. (2018), should not be overlooked [9, 10].

LCA of RCC with the replacement of natural aggregates with RAP aggregates has been investigated by Debbarma et al. (2021) and Shi et al. (2018) with contrasting findings [11, 12]. A 50% replacement rate was shown to reduce the CO_2e emissions by 1.5% for the former and a 40% replacement rate was shown to increase the GHG by 3% for the latter. Other non-virgin aggregate replacements have been investigated by Aghayan et al. (2020), Anastasiou et al. (2015), and Adamu et al. (2018), with similar patterns of small increases or decreases in the GWP [8, 9, 13]. The impacts of mixes with non-virgin aggregates are more greatly influenced by their longer transport distances and are sensitive to differences in the assumed distances across the LCA.

This paper aims to quantify the environmental impacts of RCC pavements and the effect of low carbon substitutions on GWP and abiotic depletion (ADP) of fossil fuels.

2 Experimental Program

OpenLCA, an open access, robust tool for conducting LCA was used to determine the environmental impacts of RCC pavements. CML 2001 1A Baseline mid-point impact assessment method was used for impact assessment. The main environmental impacts were the GWP over 100 years and the abiotic depletion (ADP) of fossil fuels.

2.1 Life Cycle Analysis ISO 14040

The functional unit considered was one mile of dual carriageway with a minimum target compressive strength of 40 MPa at 28 days for the concrete mixes analysed [14, 15]. The system boundaries were cradle-to-gate with a construction phase accounting for the

fuel, energy, and water inputs of the processes. The inventory consisted of supply-chain data from the Ecoinvent 3.7 Database and information obtained from the literature and Environmental Product Declarations (EPDs). The provider regions were chosen to be the UK, then Europe or a European country, with the Rest of the World average as a last resort. Table 1 shows the mix pairs of similar strength obtained from the literature, allowing for more valid comparisons of percentage change of impacts. The pavement width of 21.1 m was designed per DMRB CD 127 guidelines [16]. Following DMRB CD 226 and 224, the lift thicknesses were designed to be 270 mm and 200 mm for CRCP and RCC pavements respectively [14, 17]. For transport, single trip distances were obtained from various literature and are detailed in Table 2. Machine specifications were used to obtain the required information about the construction processes to enable the impacts of these processes to be calculated.

Table 1. Concrete design mixes used in LCA analysis.

Substitution	Literature	Mix
Reference RCC	Mohammed (2018) [18]	Granite mix
Reference OPC	Zimmerman & Lehký (2014) [19]	C40/50
RCC with fly ash	Tangtermsirikul et al. (2004) [20]	RCCP:31 & RCCP: 17
RCC with GGBS	Afroughsabet (2021) [21]	RCC REF & LCC RCC
RCC with LC^3	Dhandapani et al. (2018) [22]	Mohammed (2018) in proportions [17]
RCC with RAP aggregate	Mahdavi et al. (2021) [23]	R0 & R25
RCC with RCA	Nehar et al. (2022) [24]	100% NA & 25% RA

Table 2. Transport distances of materials.

Material	Distance (km)
Portland cement	105
Fly ash	155
GGBS	220
LC^3	110
Natural aggregates	55
Non-virgin aggregates	140
Reinforcing steel	250
Concrete	12

3 Results and Discussion

3.1 RCC Pavements vs CRCP

Figure 1(a) and (b) show that RCC pavements have a lower environmental impact per mile across all processes within the system boundaries. The concrete mix accounts for 85% of the GWP for RCC pavements and 93% of CRCP. The difference is attributable to the smaller required thickness and lower cement content of RCC pavement lifts for the same design parameters as CRCP. The impacts of construction account for 0.05% and 0.1% of the GWP and ADP respectively for RCC pavements. Transport of constituents accounts for a higher percentage of the overall environmental impacts for the ADP than for the GWP, of which 85% of the constituent transport impacts are due to aggregate. The findings align with Hashemi et al. (2020) and Adamu et al. (2018) when considering the same boundaries and functional units [7, 9].

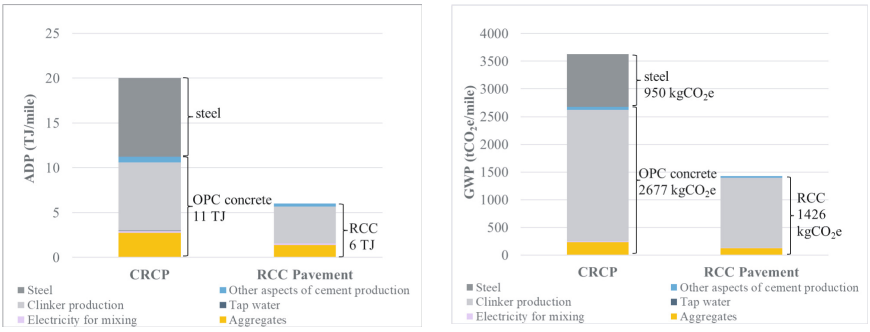


Fig. 1. Comparison of ADP and GWP of CRCP and RCC pavements

3.2 Ordinary Portland Cement Replacement

Substitution of OPC saw a 30–40% reduction in the GWP and a 6–24% reduction in the ADP depending on the material. LC3 with 50% replacement of OPC saw the greatest savings in the GWP per kilogram of OPC substituted when compared to the fly ash and GGBS mixes. However, as this mix was only hypothetical, it requires testing before it can be proposed for high-speed pavement applications. For the ADP, 50% fly ash substitution of OPC saw the overall greatest reductions per kilogram of OPC replaced, compared to GGBS and LC3. For both GWP and ADP, the mixes using fly ash and GGBS resulted in an increase in the environmental impacts due to constituent transport distance being 1.5 and 2 times longer than that of OPC respectively, which is in alignment with literature [7, 8].

3.3 Natural Aggregate Replacement

Natural aggregate replacement with RAP/RCA aggregates saw a small increase in the GWP (0.1%) and ADP (1%). Whilst there is a reduction in the environmental impacts

associated with the concrete mixes in both substitutions, these are outweighed by the increase in the impacts associated with constituent transport for the system boundaries and assumptions made in this analysis. The longer transport distances of these non-virgin aggregates assumed 2.5 times that of virgin aggregates, cause this overall marginal increase in the impacts due to RCC pavements.

3.4 Sensitivity Analysis

The LCA showed that the environmental impacts of RCC pavements are most sensitive to the pavement lift thickness as they are directly proportional (See Fig. 2(a)). RCC pavements are also greatly influenced by the percentage of OPC replacement, with an overall decrease in the GWP of 12.7 tCO_2e/mile per percentage replacement of OPC (See Fig. 2(b)). This is compared to natural aggregate replacement where there is an overall increase in the GWP of 0.78 tCO_2e/mile per percentage substitution. Hence, it can be concluded that impacts are insensitive to changes in natural aggregate replacement rate for RCC pavements.

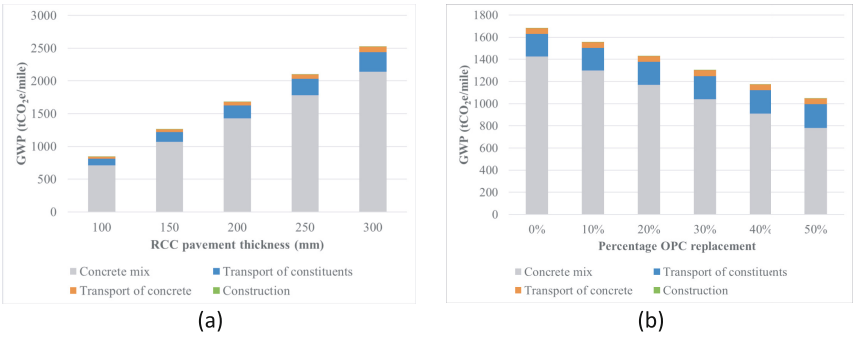


Fig. 2. Effect of pavement thickness and OPC replacement on GWP

Finally, the sensitivity to transport distances was analysed. Overall, there was very little change in the total environmental impacts when the assumed transport distances for OPC, aggregates, and concrete were separately adjusted. The GWP and ADP were affected most by changes in the aggregate transport distance, however, this was still relatively insignificant compared to the variations in the total environmental load due to changes in the lift thickness and OPC replacement rate.

4 Conclusions

Based on the LCA the following conclusions about RCC pavements are made:

(1) RCC has a GWP and ADP less than half that of conventional concrete pavements, providing a viable solution to reduce the environmental impacts.
(2) Replacement of OPC with SCMs can reduce the GWP of RCC pavements by 30–40% per mile of dual carriageway, with LC3 providing the greatest savings.

(3) Natural aggregate replacement with RCA and RAP aggregates increases the environmental load of RCC pavements by 0.1–2.5% per mile of dual carriageway demonstrating the impact of long transport distances of nonvirgin constituent.
(4) RCC pavement impacts are directly proportional to the pavement lift thickness and are also heavily impacted by changes in the OPC replacement rate.

In general, the geographic availability of materials is an important consideration to reduce the environmental impacts of RCC pavements in addition to low clinker content.

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The Norwegian Approach to Future Design, Construction, Maintenance, and Rehabilitation of Asphalt Pavements

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Abstract. Many actions are being undertaken by Norwegian road owners to reduce the environmental impact of construction and maintenance of pavements. Thanks to the collaboration with the local contractors association, a new procurement system, based not only on the financial cost of maintenance operations but also on CO_{2eq} emission, has been introduced. In three years, it has already led to a 30% reduction of CO_{2eq} emissions in maintenance projects. In addition, an analytical pavement design and analysis system, built to consider the local conditions (available materials, traffic loads, climate), will soon juxtaposed to today's guidelines based on empirical methods. It will facilitate not only the use of customized solutions but also the prediction of the pavement service life.

Through the introduction of more flexible and performance-oriented procurement and design systems, the aim is to increase the consultants and contractors' freedom in choosing the right solution, as far as the environmental and economic impact are balanced with the expected service life; the final purpose being encouraging the technological advancement needed to achieve the common climatic goals. This paper intents therefore to evaluate the progress and consequences of the Norwegian pavement sector's strategy for a more sustainable infrastructure.

Keyword: Pavement design · Procurement · Service life · CO_{2eq}

1 Introduction

"*We must take care of what we have, improve where we can, and build new where we have to*" expresses the vision of the Norwegian Public Road Administration (NPRA) of contributing to the transition into a low-emission society [1]. It intuitively summarizes the progressive societal shift in the western countries from a consumerist prospective of resources abundance and constant growth, to a future premised on sufficiency and resiliency [2]. Encouraged by the international acknowledgment of the ongoing climatic change and the ambitious greenhouse gas emissions goals, it extends to any aspect of the country's society and economy, including the asphalt pavement sector.

After years of relatively limited and slowly implemented advancements, the emphasis on the reduction of greenhouse gas emissions has been the kickstart the pavement

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industry needed to begin a small revolution leading to the flourishing of new technologies, materials and routines.

In Norway, the introduction of new technologies and materials was initially led by the larger asphalt companies and industry's associations, thanks to the possibility to focus on R&D and the availability of resources to implement internal changes. While their motivation might swing between improving EHS (environment, health and safety) and the strictly financial gains, the repercussions spread to the whole asphalt industry and led to a National Transport Plan encouraging technological advances and daring to think differently [3].

On the road owner side, the need to keep abreast with the industry and to contribute to the national emission target for 2030 triggered drastic changes in how pavements are designed, built, maintained, and rehabilitated. New tendering processes have been introduced both at national, county and municipality level, and a new design method is being developed to increase the contractors' and consultants' freedom in the choice of materials; to stimulate the use of low emission technologies and to overall increase the service life of pavements.

This paper will give an overview of how the Norwegian road owners (NPRA, counties and municipalities) are striving to reduce the environmental footprint of their infrastructure and develop a future-oriented pavement sector.

2 Procurement Process

Starting from 2018, the NPRA, together with other road owners and the Norwegian Contractors Association (Entreprenørforeningen - Bygg og Anlegg), has gradually introduced the use of Environmental Product Declarations (EPD) in pavement maintenance contracts. In just four years, the NPRA went from requiring delivering any available EPD to use CO_{2eq} weighting in almost 90% (24 of 27) of its contracts. Four of these using a combination of CO_{2eq} weighting and life-cycle costs. The implementation process, a detailed description of the framework for EPDs and how an EPD-calculator has been developed specifically for the paving industry can be found in [4].

The scope behind the introduction of the new tendering process, is to both reduce the emissions linked to pavement maintenance contracts and, at the same time, encourage the development and purchase of low emission technologies, materials and giving more freedom to the industry. The aim is to reduce the amount of emission linked to maintenance contracts by 65% compared to 2020 within 2030.

2.1 CO2eq Weighting and Life Cycle Costs

When presenting a bid for a paving contract, each bidder is required to attach an EPD, describing the product's environmental performance, to the monetary price. The values corresponding to the stages A1 to A5 (product and construction stages) are then used to determine the environmental cost of the product in terms of CO_{2eq}.

In tendering process, the bidder with the lowest CO2eq cost establishes a baseline. All other bidders, with higher emissions, will have a certain among NOK/kgCO_{2eq} added to the monetary price. Depending on the road owner, this amount varies between 5 and

20 NOK (≈ 0,5 to 2 €/kgCO_{2eq}). The adjusted bidding sum (original price plus price based on the emissions) will determine the winning contractor. At the end of the contract, the actual CO_{2eq} cost will be documented by the winning bidder.

In the following Table 1 are shown the results collected between 2020 and 2023 by three road owners: the NPRA that manages the national roads and two counties, Troendelag and Viken, that manage the county roads in the proximity of Trondheim and Oslo. The 2020 values correspond to a traditional tendering process based on the lowest price, while the following years saw the introduction of CO_{2eq} weighing in more and more processes. The results are therefore to be considered as an average value from both types of contracts for the years 2021 to 2023. The introduction of CO_{2eq} weighing in 2021 has led to a clear impact for the NPRA contracts with a consistent decrease of emission, 30% in three years, in accordance with increasing amounts of tendering processes based on the new criteria. The same conclusion cannot yet be drawn for the county roads. However, it is clear from the EPDs that the contractors are taking several initiatives to reduce their footprint. So far, particular focus has been put into the use of bio additives and recycled asphalt (to reduce the emission quota of the bituminous products), low temperature mixes, and in the use of more environmentally friendly energy sources such as wood chips.

Table 1. Amount of kgCO_{2eq}/tonn asphalt between 2020 and 2023 as provided by the contractors in the EPDs (A1 to A5); the measured values (a) and including the end-of-life stages, C1 to C4 (b). The data are provided by the NPRA and counties of Troendelag and Viken.

	2020	2021	2022	2023
NPRA	62	54	48	41 (49)b
Troendelag County	69	75	53	-
Viken County	-	32 (31)a	27 (31)a	-

2.2 Challenges and Future Plans

One of the main difficulties to evaluate the effect on the new tendering processes is in the data collection. This is due to the large amount of road owners in the country and municipal level and the internal communication challenges. The lack of data makes it difficult to evaluate the effect of the new tendering process in the asphalt sector on a national level. The introduction of routines and increasingly familiarity with the terminology will hopefully improve the data quality and quantity.

As visible in Table 1 there are discrepancies between the declared and measured emissions. This is being partially solved by introducing a bonus/penalty system where, when the effective CO_{2eq} differs by more than 5% from the declared one a bonus (5 NOK/kgCO_{2eq} for lower total emissions) or a penalty (10 NOK/kg CO_{2eq} for higher total emissions) is triggered [4]. Nevertheless, there is still a possibility for a contractor to exploit the system, giving a lower bid if they determine the profit from the project

can outweigh the penalty, especially in areas where the market does not allow for strong competition. In these cases, the road owners are considering the possibility of introducing a maximum amount of acceptable $kgCO_{2eq}$/tonn asphalt, over which the contract will not be assigned.

The next steps, already initiated by the NPRA, are the extension of the CO2eq evaluation to the C1-C4 end of life stages and the introduction of the pavement service life in the tendering process to incentive the production of better mixes. In this case the adjusted bidding sum is divided by the expected service life and the final price per year determines the winner.

3 Analytical Pavement Design and Analysis System

In Norway, pavement design is currently based on the N200 design guidelines [5]. An empirical design system developed by the NPRA in the 60ies. The system, based on material requirements and design tables/graphs, considers boundary conditions such as type of underground and traffic volume and partially taking into account local climate, traffic projections and material availability.

The current system is somehow straightforward but offers limited freedom for pavement design and does not take advantage of the local conditions and material to optimize the road structure. The advent of among others new non-regulated materials and technologies, emission requirements and leaner budgets have exposed the need for a better design tool able to customize and optimize a pavement structure based on the local conditions.

3.1 The VegDim Project

In 2018 the NPRA started an ambitious R&D project, VegDim, with the goal of developing and implementing an analytical pavement design and analysis system. The result is the ERAPave PP program (Elastic Response Analysis of Pavements – Performance Predictions) in collaboration with the Swedish Transport Administration. The program is based on a response and a performance component that calculates the stresses and strains induced in the pavement structures due to traffic loading under the local climate conditions and predicts the pavement degradation as a function of time [6].

A large amount of construction and underground materials commonly used in Norway, have been tested to determine their response to induced stress and strains due to traffic and climatic loading. This information has been used to compile a material database available to all users. During the design process, this information will be combined will the available boundary conditions to determine the pavement service life according to the current regulations. A detailed description of the project can be found in [7, 8].

Although the program is being developed by the NPRA, it can, as the N200 design guidelines, be used by any road owner in Norway.

3.2 Challenges and Future Impact

While a working version is already available [6], the NPRA is expected to officially launch the Norwegian adaptation of ERAPave PP, as a part of its design methodology, at the end 2024. The tool will then be available for all road owners, consultants and industry, and will allow a better customization of the road structure based on the local conditions and available materials. It will help optimize the pavement structure, increase quality, accuracy and reliability, and provide long term reduction of financial and environmental costs [9].

On the road owner side, the system will allow for better maintenance and rehabilitation planning. ERAPave PP will be able to: generate degradation models for both new and existing pavements with known construction allowing for a long-term maintenance planning and resources optimization; create documentation of the user's choices and resulting consequences for future use and contribute to a conscious use of the resources. The users will be able to quickly create several design options for each section to analyze in terms of cost, resource use, service life and so on, and in the future, to create a proprietary material library.

However, given the complexity of the system, the introduction of ERAPave PP will generate several challenges for the NPRA, starting from establishing how and who will have the authority to submit and to approve the designs.

The introduction of a new system, based on models cryptic for many, could trigger insecurity in the end-user due to lack of trust in the quality and reliability of the results. During the last sixty years the industry has followed the N200 guidelines, browsing from table to graph to design an approved pavement structure based on empirical and cemented knowledge. The trustworthiness of ERAPave PP will be a critical factor for determining its success. To smoothen its implementation, the project group has already investigated the challenges encountered in USA and Sweden by MEPDG and PMS Objekt respectively. Validation of the results, guidelines updated according to the new design methodology and knowledge have been identified as important elements to look after [10]. The NPRA has started a series of seminars to gradually introduce the new design method to the larger audience, focusing on the background, data validation and implementation plan. In addition, an IT team has taken the task of rendering the tool user friendly to help ensure increased buy-in and adoption.

A deep knowledge about mechanistic-empirical design and understanding of ERAPave PP's approach will be necessary to verify the quality of the input data, understand the results and introduce proprietary materials. The NPRA will have to, in collaboration with education institutes, organize courses in advanced pavement design for professionals in both road owners, consulting and construction companies for a general knowledge update.

Potential new materials will require extended testing with equipment generally not available outside research institutes. How larger and smaller asphalt producers will have access to it is still not clear.

It is difficult to determine how long it will take for a shift towards the new tool to take place and how it will be received. Large funds and resources have been invested in this project and the hope is that it will encourage better customized solutions to extend the pavement service life while still looking at the economy and the environment.

4 Conclusions

The Norwegian pavement sector is working hard to contribute to the 2030 climatic goals. While there are many obstacles between today and its success, it has so far been clear that both road owners, consulting and construction companies are willing to collaborate and are daring to make big changes in an industry that has been so far advancing at a slow pace.

During the last three years, road owners and contractors have collaborated to reduce the CO_{2eq} emissions in the product and transport stage of paving already up to 30% compared to 2020. The expectation is to reach a CO_{2eq} value of about 20 kg/tonn asphalt. The introduction of the pavement service life among the awarding criteria will be crucial to achieve this goal and to stimulate the consultants and contractors to plan and design for longer lifetime. Central in its evaluation will be the soon to be launched analytic design and analysis system.

Introducing these new tools will help professionals in all positions make conscious choices where both the now and the future are taken into account.

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Non-Contact Measurements of Wind Turbine Blades Repurposed as Pedestrian Bridges

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Abstract. Decommissioned wind turbine blades can get a second structural life through implementation in other sectors, contributing to the circular economy. This avoids an increase in landfill and ensures sustainable construction. The use of wind turbine blades at the end of their lifetime as a pedestrian bridge is one such example. However, assessment of such structures is complex due to the age, repurposing and the new requirements of performance from these structures. In this paper, we demonstrate how Short-Wave Infra-Red scanning Laser Doppler Vibrometry (SWIR-LDV) can rapidly assess these repurposed blades in terms of their responses, by carrying out modal analyses. To demonstrate this, a repurposed wind turbine blade currently being used as a pedestrian bridge in Cork is monitored. The results indicate that it is possible to rapidly assess modal estimates, and consequently the condition of the blade via non-contact measurements. This testing method can be particularly important in terms of new and rapid assessment methods of such structures with a complex lifetime history and evolutions of stress, fatigue and material characteristics, leading to safe design and assessment of their re-use.

Keywords: Bridge · Non-Contact · pedestrian · structural health monitoring · Laser Doppler Vibrometry · Wind Turbine Blades · repurposing · sustainability

1 Introduction

The use of repurposed structures is an important aspect of sustainable construction. While the importance of such usage is convincing, the safety and serviceability criteria and condition of such structures are less investigated. Benchmarks and demonstrative evidence can bridge this gap and establish best practice guidelines and recommendations, which can eventually create a pathway towards standardization. One such important area of application is the repurposing of end of life wind turbine blades [1]. With the rise of renewable energy demand and interest around the world, the manufacturing of

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wind turbine blades has increased exponentially. This essentially also means that the possibility of such blades at the end of their lifetime becoming landfill is a major issue to tackle. Several first generation wind farms are now coming to the end of their lifetime and consequently, this is a problem that requires attention. An interesting proposition around re-use of such blades [2] has been in the form of using them as general furniture or architecture and also in a more structural sense in the form of pedestrian and cyclist bridges [3]. While the spans are shorter for such bridges and residual fatigue effects can be neglected based on the levels of stresses over the lifetime, there is inadequate understanding and information about residual capacity, degradation and the rates of the same [4]. Such uncertainty directly impact the lifetime performance criteria from serviceability and even from the point of view of safety. Under such circumstances, for a re-use sector of wind turbine blades to be popular at the end of their lifetime, techniques of assessing them around their structural reuse must be validated.

This paper directly addresses this issue and carries out non-contact rapid measurements with Laser Doppler Vibrometry [5, 6] and connects it with wireless accelerometer results. The work instruments and measures an actual pedestrian bridge in Ireland made out of end of life wind turbine blade and investigates its vibration responses and some of the modal parameters. The comparison provides an idea of the consistency, repeatability, opportunities and challenges for such a structure. It can lead to guidance of sensor placement, measurement strategies, rapid detection and model updating procedures, including investigation of novel artificial intelligence applications and digital twinning [7, 8].

2 Experimental Details

2.1 Blade Bridge

The Blade Bridge, a first in Ireland and one of the few globally, is a pedestrian footbridge traversing a small river on the Midleton-Youghal Greenway Co. Cork, Ireland and is constructed using two recycled wind turbine blades (Nordex N29 turbine, 13.4 m original length), acting as bridge girders on either side of the bridge (Fig. 1).



Fig. 1. Blade Bridge, Co.Cork, Ireland used for rapid assessment with Laser Doppler Vibrometry. The blade length is 11 m, the bridge span is 5 m and the maximum chord is ~1 m.

2.2 Instrumentation and Measurement

One of the turbine-blade girders of this symmetric bridge is measured (Fig. 2). Accelerometers were securely placed at 1/4, 1/2 and 3/4 span, sampling at 512 Hz for 1 h. The accelerometers used in this thesis are LORD G-Link3D piezoelectric wireless ones with rugged removable plastic covering and a base allowing for easy fixture to magnetic surfaces. The accelerometers were connected to a laptop via a Wi-Fi USB base station and corrected for drift. A multi-point infra-red scanning OptoMet Laser Doppler Vibrometer (LDV) was set up 9.7 m from the blade, on a bank near the bridge with a dense mesh of 27 scanning points were considered on the surface of the turbine blade sampling (Fig. 3) at 1024 Hz with a spectral resolution of 0.5 Hz. Speckle noise was present for some of the points of the mesh. Excitation of the bridge was from ambient wind.

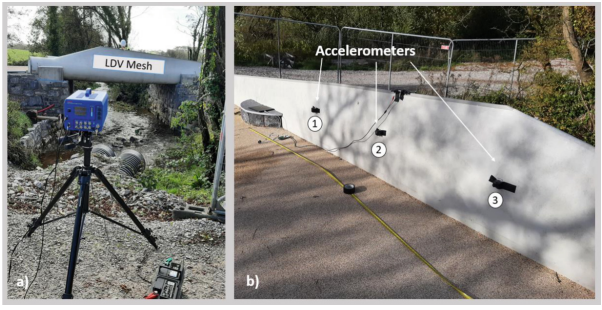


Fig. 2. Instrumentation and Measurement of Blade Bridge with (a) Multi-Point Short-Wave Infra-Red Laser Doppler Vibrometer and (b) Wireless 3D Accelerometers.

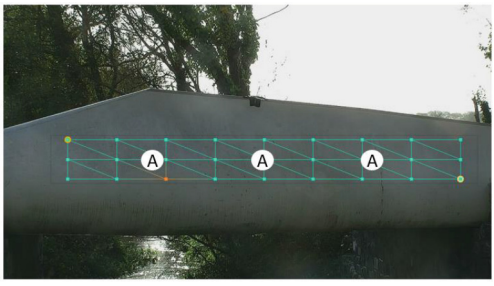


Fig. 3. Measurement mesh of Laser Doppler Vibrometer on one of the Blade Bridge girders repurposed from an end of life wind turbine blade.

The effects of speckle noise in terms of magnitude is summarized in Table 1. Derived values of acceleration from LDV measurements are compared with direct acceleration measurements in terms of Root mean square magnitudes. The LDV points in Table 1 should be compared based on whether there are speckle effects (marked by an asterisk) or not. The small variances are not just due to variability in the devices but rather from the

fact that wind conditions were variable during the time. The overall orders of magnitudes match well but the errors are higher for lower acceleration magnitudes.

Table 1. Speckle noise (asterisk) effect of LDV for accelerometer locations (AL), g = 9.91 m/s^2

AL1 (average RMS = 0.0018g)	**RMS acceleration m/s^2 x g**
LDV Point 1*	0.0203
LDV Point 2*	0.0196
LDV Point 3	0.0022
AL2 (average RMS = 0.0035g)	**RMS acceleration m/s^2 x g**
LDV Point 4	0.0042
LDV Point 5	0.0017
LDV Point 6	0.0013
Mean of all LDV Points	**0.0024**
AL3 (average RMS = 0.0006g)	**RMS acceleration m/s2 x g**
LDV Point 7	0.0012
LDV Point 8*	0.0093
LDV Point 9*	0.1206

3 Results

3.1 Modal Estimates with LDV

Natural frequencies were determined simple by peak picking from the first singular values of the power spectral density matrix. Figure 4 compares this using a PSD matrix with all 27 points, as well as using one which includes only the 17 points deemed to be unaffected by speckle noise.

The effects of speckle noise is evident, introducing artificial frequency peaks unrelated to structural dynamics and also masking natural frequencies. The first natural frequency is likely near 10.5 Hz. However, the spectral resolution was 0.5 Hz and the real value is somewhere between 10 Hz and 11 Hz. There is also a significant peak at 105.0 Hz, as well close peaks at 61.5 Hz and 73.0 Hz. It is therefore likely that there is another natural frequency around 105 Hz, and possibly the two around 61.5 Hz and 73.0 Hz link to off the plane modes. Long term measurements can validate these further. A consistent mode shape in real-time was difficult to achieve due to lack of synchronization of the points.

3.2 Modal Estimates with Accelerometers

The accelerometers pose some challenge in terms of mounting and subsequent trend over time which has to be corrected for. This problem around instrumentation and measurement makes the non-contact LDV measurement more attractive and rapid. Figure 5

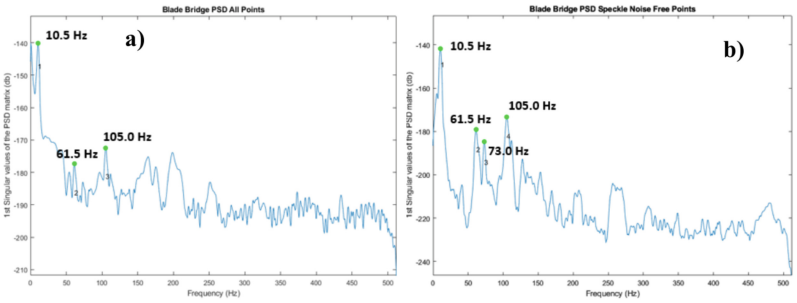


Fig. 4. Power Spectral Density estimate of blade bridge for points (a) affected by speckle noise and (b) unaffected by speckle noise for non-contact measurements.

shows that the in the singular value decomposition plot is significantly more noisy than that obtained from LDV measurements. The small frequency peaks at approximately 65 Hz, 73 Hz and 107 Hz may correspond natural frequencies of the turbine blade girder and they overall align with those obtained from LDV. The accelerometers were unable to measure what it likely the first natural frequency close to 10.5 Hz.

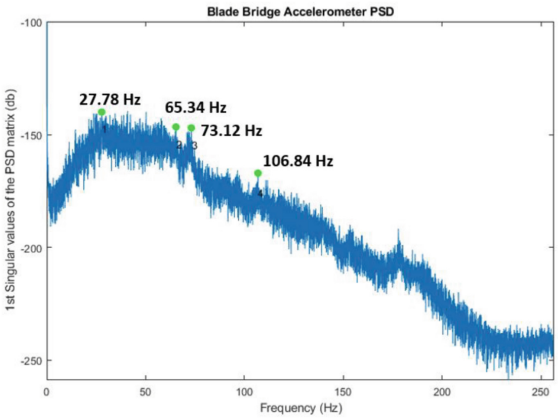


Fig. 5. Power Spectral Density estimate of blade bridge for accelerometer measurements.

4 Conclusions

This paper provided a rapid assessment of a full scale bridge of an end of life wind turbine blade repurposed as a pedestrian bridge. A comparison of non-contact measurement between multi-point short-wave infra-red Laser Doppler Vibrometry and wireless 3D accelerometers indicate that there such rapid assessments can be particularly important in terms of obtaining modal parameters and kinematic responses, which in turn are linked to the current state of the structure and its lifetime performance metrics. While

non-contact LDV measurement was observed to be easier and more competitive, the challenges of handling speckle noise and uncertainties in excitation forces were observed, as well as the challenge obtaining live modeshapes in a reasonable manner. Accelerometer measurements were observed to be more noisy and with the challenge of mounting. With reasonable models and updating possibilities, such rapid non-contact techniques of measurement can not only be important in assessing lifetime performance of wind turbine blades repurposed as structural elements after their useful life on a turbine, but they can also be critical in establishing a pathway towards guidelines, recommendations and standardization of such structural repurposing.

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A Contribution for a Sustainable, Resilient Road Infrastructure Management from Brisa, a Portuguese Road Concessionaire

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Abstract. Nowadays, there are increasingly efforts to introduce an economy based on circularity principles, but there is still a gap between the intentions and the actual measures to achieve it. In Portugal, reclaimed asphalt is generally used as granular material for unbound road layers or reused mainly as asphalt mix in the municipal road network, instead of reusing this premium material in new asphalt mixes for medium/heavy traffic, mainly due to the lack of knowledge on how to use these materials without compromising the performance or durability of the pavement.

The purpose of this study is therefore to evaluate the technological suitability of using two different rejuvenator additives (rejuvenator solid additive and terminal blend bitumen with rejuvenating additive) for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures for motorway surface courses. To achieve this objective, three gap graded asphalt mixtures (one of reference) for surface course were produced with 20% highly aged reclaimed asphalt milled from Brisa's motorway network. The results show that asphalt mixtures with reclaimed asphalt had better performance (water sensitivity, resistance to permanent deformation) and similar surface properties compared to reference asphalt mixture (without RA), regardless of the rejuvenator additive used.

Further studies will consider pavement monitoring the asphalt mixtures studied as well as mixtures with other rejuvenator additives in order to expand the possibilities of using reclaimed asphalt in Portugal.

Keywords: Road pavements · Circular economy · Resilient infrastructure

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1 Introduction

Nowadays, there are increasingly efforts to introduce an economy based on circularity principles, but in some countries there is still a gap between the intentions and the actual measures to make it happen. Reclaimed asphalt (RA) generated by road maintenance is equivalent to about 850 million tonnes per year in Europe, the United States and China combined [1, 2].

According to the European Asphalt Pavement Association (Europe) [3] and the National Asphalt Pavement Association (United States) [4], almost all reclaimed asphalt is reused\recycled for the construction and maintenance of new roads (96% and 99% respectively). Looking at these figures in detail, we see that in the United States, of the 99%, only about 4% of the reclaimed asphalt is recycled for such as granular material for unbound road layers and only 0.1% ends up in a landfill. In Europe, the approach is slightly different, with the use of asphalt recycled as granular material for unbound road layers increasing to an average of 20% (from 0% in Croatia to an overwhelming 99% in Turkey) and 4% still ending up in landfill (from 0% in countries such as Austria, France, Germany, Hungary, Norway, Slovakia, Spain and Turkey to a remarkable 53% in Croatia).

As Europe has a consolidated road network, most of the reclaimed asphalt comes from maintenance/milling of surface courses, which have the scarcest aggregates, highest quality and therefore most expensive material for a road pavement. Landfilling these premium materials or using them as unbound materials whose properties are not so strict and not taking advantage of aged bitumen surrounding the aggregates is a luxurious prospect and shows the enormous effort needed to put us on the path of responsible valorisation of these materials, which means reusing them in surface course where they belong.

According to [3], no figures are given for Portugal, and the reality is perhaps not so different from Turkey or Croatia. In general, the reclaimed asphalt is used as granular material for unbound road layers or reused mainly as asphalt mix in the municipal road network, where the properties are not as important as in the national or motorway network, so the waste of a first-class material remains. Several factors lead to this reality, but the most important is probably the lack of openness of road concessionaires, as there are no specifications that allow the reuse of this type of material in new asphalt mixes for medium/heavy traffic due to the lack of knowledge on the use of these materials without compromising the performance or durability of the pavement.

Brisa has committed to the goal of achieving carbon neutrality by 2040 and to the promotion of circularity on the assets under its management (responsible consumption and production), and one of the steps towards that goal is maximizing the reuse of RA in surface courses, tackling issues as production and construction.

To achieve this goal, the ongoing study on new materials [5, 6] in this manuscript evaluates the technological suitability of two rejuvenator additives (rejuvenator additive and terminal blend bitumen with rejuvenating additive) for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures (gap graded asphalt mixes with 20% reclaimed asphalt (according to current limitations in Portuguese asphalt plant

production) from an existing surface course in Brisa's motorway network) for motorway surface courses. The asphalt mixtures performance evaluation considered water sensitivity, resistance to permanent deformation and surface properties.

2 Experimental Programme

An experimental programme was carried out to evaluate the technological suitability of two rejuvenator additives for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures for motorway surface courses. The additives used were:

- Pelletized blend of 50% cellulose fibres (type Arbocel ZZ 8-1) and 50% of rejuvenator (cylindrical pellets of type Viatop plus RC, supplied by JRS).
- Terminal blend bitumen with rejuvenating additive (Elaster BM3-C Re-gener, supplied by CEPSA).

The RA (see Table 1 for properties) was obtained from porous asphalt mixtures milled from 17-year-old surface courses of the A3 motorway in northern Portugal (Brisa's motorway network). The reclaimed asphalt used corresponds to the coarser-grained fraction (RA 8/16 mm) obtained after grinding the milled aged asphalt mixtures. In addition Table 1 also shows the characterization of the base bitumen (PMB 45/80-65) without/with rejuvenator additives plus RA after recovery of the bitumen in the asphalt mixtures (centrifugation, EN 12697-1).

Table 1. Base bitumen and reclaimed asphalt characterization.

RA visual aspect	Properties	Base bitumen	Bitumen in RA without/with rejuvenator additives		
		PMB 45/80-65	No additive	Viatop RC	Regener
	Bitumen content (%)	-	3.3	-	-
	Penetration (0.1 mm)	49	6	36	36
	Softening temperature (°C)	68.0	93.0	69.6	69.0
	Elastic recovery (%)	87.3	-	-	82.8

Table 1 shows that the existing bitumen in the reclaimed asphalt has very low penetration values, requiring the use of rejuvenator additives or soft polymer modified bitumen in the production of the new asphalt mixtures. As expected, the addition of Viatop RC or Regener increased the penetration and softening temperature of the recovered bitumen (centrifugation, EN 12697-1), reducing the brittleness of the bitumen in the asphalt mixture with RA. With both additives, the softening temperature could be brought to a similar value as for the base bitumen (PMB 45/80-65).

The asphalt mixtures used in the study are listed in Table 2. They consist of virgin aggregates (granite 10/16, 4/12, 0/6 mm and limestone, filler) and reclaimed asphalt

(granite, 8/16 mm). The base bitumen is a polymer modified bitumen classified as PMB 45/80-65 (commonly used in Brisa's motorway network) without/with rejuvenator additives.

Table 2. Asphalt mixtures studied.

AC 14 surf ID	Aggregate nature	RAP		Binder type	Binder content (%)		Rejuvenator	
		Fraction	Content (%)		Virgin	RAP	Type	Content (%)
M1-REF	Granite	-	-	PMB 45/80–65	5.0[1)]	-	-	-
M1.1		8/16 mm	20		4.7	0.3[1)]	Viatop RC	1.5
M1.2							Regener	-[2)]

(1) optimum bitumen content; (2) confidential information.

The performance evaluation of the asphalt mixtures considers the assessment of: Marshall properties according to EN 12697-34 at 60 °C after conditioning the specimens at 60 °C for 40 min; water sensitivity according to EN 12697-12 (method A) at a test temperature of 15 °C after conditioning in air at 20 °C and vacuum in water at 40 °C for 72 h (dry and wet specimens respectively). For Marshall and water sensitivity, the cylindrical specimens were compacted with a Marshall compactor with 50 strokes on each side. Resistance to permanent deformation was evaluated according to EN 12697-24 (air method, 60 °C with 10000 cycles). In addition, the macrotexture depth of the asphalt mix surface was evaluated using the volumetric patch method on test specimens to assess resistance to permanent deformation in accordance with EN 13036-1.

3 Results and Discussion

Figures 1, 2, 3 and 4 show the Marshall properties, water sensitivity, resistance to permanent deformation and macrotexture depth of the asphalt mixtures studied (AC14 surf) without/with reclaimed asphalt plus rejuvenator additive for the optimum bitumen content.

As expected, the results in Fig. 1 show a reduction in the Marshall stability (S) of asphalt mixtures with rejuvenator additives. The Marshall flow behavior (F) also shows a reduction compared to the reference asphalt mixture and a slight increase in the Marshall quotient (Q), indicating that asphalt mixtures with rejuvenators tend to be more flexible than the reference mixture (without RA), despite the highly aged reclaimed asphalt used, without compromising resistance to permanent deformation. These results are confirmed in Fig. 3 by the slight reduction in permanent deformation (rut depth and wheel tracking slope) for asphalt mixtures with reclaimed asphalt and rejuvenators (M1.1, Viatop RC and M1.2, Regener) compared to the reference asphalt mixture (M1-REF). Asphalt mixtures water sensitivity is sensitive to the use of reclaimed asphalt

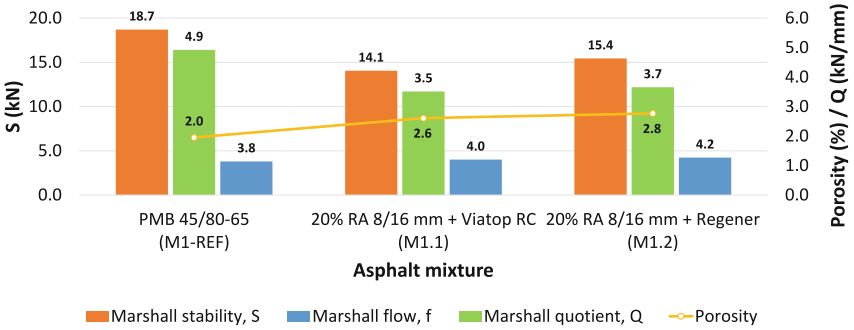


Fig. 1. Marshall results.

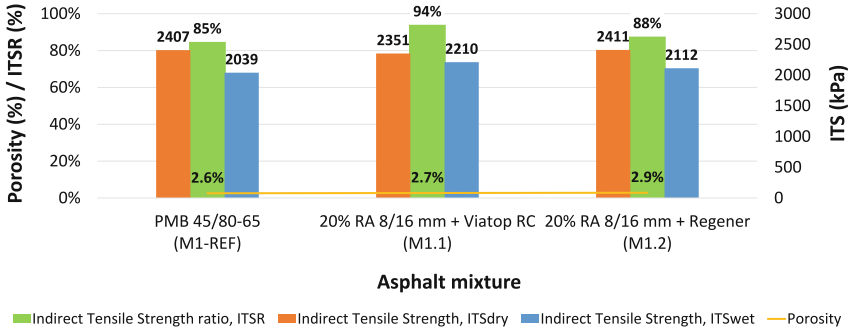


Fig. 2. Water sensitivity results.

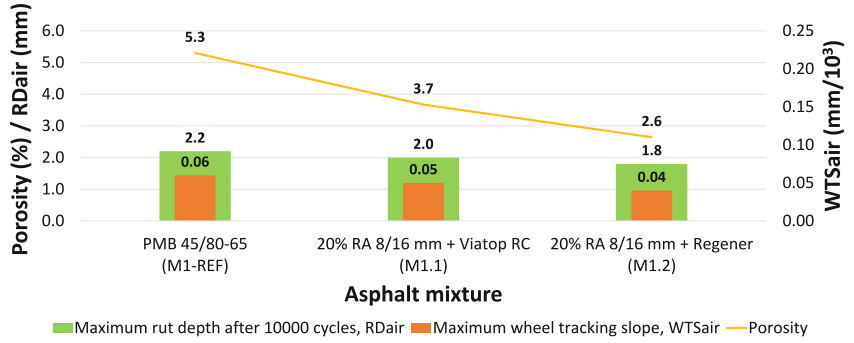


Fig. 3. Permanent deformation results.

(e.g. due to possible insufficient blending between aged and virgin bitumen [7]), but the rejuvenator additives used were able to compensate (M1.2, Regener) and even reduce (M1.1, Viatop RC) the water sensitivity of the asphalt mix, as shown in Fig. 2, without affecting or even slightly increasing the indirect tensile strength (ITS) of the wet and dry test specimens compared to the reference asphalt mixture. As far as the surface

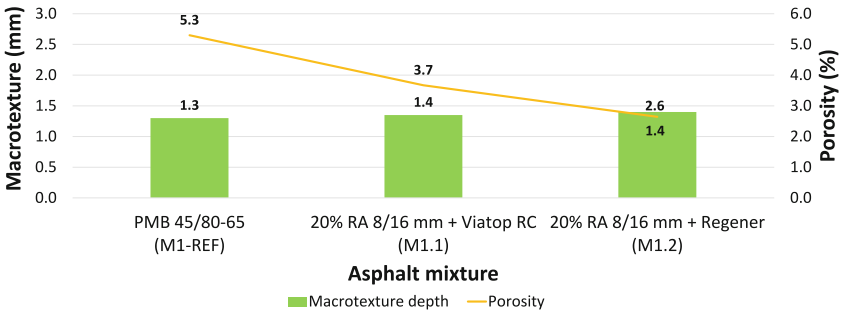


Fig. 4. Surface properties results.

properties are concerned, Fig. 4 shows that the use of reclaimed asphalt or rejuvenator additives has no influence on the surface properties compared to the reference asphalt mixture.

4 Conclusions

Overall, the use of reclaimed asphalt leads to a reduction in the consumption of virgin aggregates and virgin bitumen: promoting a circular economy with environmental benefits and potential economic advantages. It has been shown that the additives used can improve the behaviour of the studied asphalt mixtures with reclaimed asphalt, raising the bar for further studies on higher contents of reclaimed asphalt. However, proper laboratory characterisation is required to correctly determine the type and content of rejuvenator additives. Further steps need to be taken to increase knowledge in Portugal, while in parallel further specifications and proper management of reclaimed asphalt need to be developed.

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Methodologies for Economic Assessment of Rail Technical Innovations: Challenges and New Perspectives

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Abstract. The objectives of the Shift2Rail / Europe's Rail research programme include the doubling of capacity and halving of life-cycle costs. If these could be achieved it would make a substantial contribution to the competitiveness of rail transport. A key challenge in rail technical research lies in the selection of innovations that are likely to achieve a positive business case, as well as a positive financial case for individual actors in the system. However, there are number of significant challenges in operationalising methods to assess schemes such as Cost Benefit Analysis (CBA) in order to deliver useful information to guide rail technology selection. These include obtaining data on key aspects of costs to populate the base case scenario and translating results from engineering testing into cost impacts in the CBA. This paper uses examples from projects undertaken under the Shift2Rail / Europe's Rail research programme to highlight areas of best / novel practice and sets out ideas for future development.

Keyword: life cycle costs · statistical cost models · valuation of benefits

1 Introduction

EU transport policy as set out in, for example, the 2011 European White Paper, is predicated on rail becoming the main means of medium distance passenger transport and of long distance freight transport. This policy was reiterated as part of the EU Green Deal (2019). A number of policies are in place with the aim of achieving this shift, including innovations in rail transport driven by a major research programme (Shift2Rail and now Europe's Rail). If innovation were able to achieve the objectives of the Shift2Rail programme, including doubling capacity and halving life cycle costs, it would make an enormous contribution to the competitiveness of rail transport.

However, a key challenge in rail technical research lies in the selection of innovations that are likely to achieve a positive business case, as well as a positive financial case for individual actors in the system. Whilst Key Performance Indicators (KPIs) can be set out and techniques such as cost benefit analysis (CBA) are well known in principle, there are a number of significant challenges in operationalising these approaches in order to deliver useful information to guide rail technology selection.

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Obtaining the data on key aspects of costs to populate the base case (or AS IS or Do-MINIMUM) scenario is often problematic. Whilst engineering / simulation models can be used to understand the impact that technologies might have on, for example, maintenance intervals, the understanding / modelling to translate these changes into cost impacts (bearing in mind that the research may focus on a single component of an infrastructure system of vehicle) is much more of a challenge. Where scheduled maintenance covers a range of components, extending the life on one component may have little benefit without progress on the life of the remaining components. Further, whilst wider benefits such as impacts on reliability are expected these are notoriously difficult both to quantify and then value.

This paper uses examples from projects undertaken under the Shift2Rail / Europe's Rail research programme to highlight areas of best / novel practice, particularly focusing on how statistical methods utilising real cost data can be used to understand cost drivers in rail, how CBA techniques can be applied to produce useful insights on the overall business case and the circumstances that drive a positive business case, and on how improvements in quality can be evaluated and more systematically incorporated into business case assessments. Finally, the paper calls for future work to generate cost and demand /quality side parameters and approaches in the form of a Business Case Assessment Handbook that can be used to assist business case evaluation of rail technical innovations in the future.

2 Methodology

One of the common approaches for assessing the economic impact of railway innovations on Shift2Rail projects is Cost Benefit Analysis (CBA). CBA analysis takes the perspective of overall society since it aims at accounting for every possible impact. For this reason, it can be referred to as a Social CBA. At the same time, it is important to identify the recipients of each cost and benefit. Therefore, CBA usually includes a stakeholder assessment, where each impact is associated to a specific agent in the economy. The two elements of the CBA can be summarised as follows: a socio-economic CBA, covering all affected parties (i.e. society); and, a financial CBA, analysing the impacts on each of the relevant stakeholders. Table 1 includes a generic description of impacts and groups that could be considered for railway projects.

Table 1. Social and Stakeholder CBA – Impacts Table by Group

IMs	Train Operators	End users	Third Parties
• Changes in costs and revenues	• Changes in costs and revenues	• Change in costs and benefits for passengers and freight users (e.g. improvements frequency, etc.)	• Environmental externalities • Government: grant / subsidy • Residents • Wider economy

To develop the CBA, the starting point is the definition of the baseline scenario, also called the Do-Minimum scenario. The baseline should represent the most likely situation of the railway line if the innovations are not applied (i.e. current context). Secondly, a Do-Something scenario should be defined precisely, e.g. as the situation of the railway line if one particular innovation is applied; and the impacts might vary substantially for different networks (e.g. high speed versus lightly used rural routes). A CBA recommends the implementation of an innovation or change of practice where its benefits outweigh its costs. The costs and benefits are estimated using standardised parameters set out by public bodies in their appraisal guidelines such as in the UK [1] and EU [2].

In the following section examples from Shift2Rail projects are used to highlight some of the challenges of applying CBA on rail projects and the novel practices which have been developed to negate them. See also [3, 4] for further details.

3 Results

In this section two projects (IN2ZONE and GEARBODIES) in the Shift2Rail programme are used as a locus to illustrate some of the challenges/best practice in undertaking the appraisal of rail projects (Sects. 3.1, 3.2 and 3.3). This is followed by suggestions for future work in this field (Sect. 3.4).

3.1 Scheduled Maintenance of Multiple Components

Part of the GEARBODIES project involved the development of innovations for the journal bearing elements on high-speed trains. The main expected impacts of the innovations were expected to emanate from Life Cycle Cost (LCC) reductions, associated with increased maintenance intervals. These impacts arise from the enhanced durability of the components which would allow them to be replaced less frequently.

To estimate the impact on LCC of the increased durability of a component it is not enough to consider only the maintenance schedule of the component itself. This is because an enhanced lifetime of one component may only provide a benefit if this can generate increased intervals between maintenance/replacement activities, which are often planned with respect to multiple components. To identify the interaction of the maintenance activities of different bogie components vehicle maintenance plans need to be considered. For commercial reasons it is difficult to obtain actual maintenance plans and an alternative approach was, therefore, used which was to develop an indicative maintenance plan. Through this process the components which have the shortest maintenance intervals and are therefore key in determining when bogie overhauls are undertaken were identified.

The indicative maintenance plan was established assuming that the timing of bogie overhauls is determined by the wheels as they are considered the bogie component with the shortest maintenance interval, i.e. not capable of reaching 1.65 Mkm (which is the current interval of the technology of interest, namely the journal bearing). This means that the lifetime of the wheels and, therefore, the timing of bogie overhauls is once every 1.5 Mkm. As it is the wheels that determine the frequency of bogie overhauls any LCC savings from an increase in the durability of journal bearings will be realised for

the bearings only as the maintenance intervals of all other bogie components will not be affected. This also means that for LCC savings from the extension of maintenance intervals for journal bearings to be realised in practice the extension must be great enough to reach the next bogie overhaul.

The theoretical modelling undertaken suggests that a maintenance interval for journal bearings of close to 3 million km (3 Mkm) could be achieved but further testing is required to validate this. The estimated LCC saving over a 30-year appraisal period of extending the maintenance interval of the journal bearings from one bogie overhaul (i.e. 1.5 Mkm) to every other overhaul (i.e. 3.0 Mkm) was 42.9%. It is important to note, however, that if a still substantial increase in the maintenance interval had been realised - but less than that required to reach the next bogie overhaul - then no LCC savings would be realised. This highlights that in future research the targets for the length of maintenance intervals for components need to consider the impacts on other components and not only the component itself. This represents a significant step up in complexity in terms of modelling but is necessary to be able to make more definitive statements about the costs and benefits of enhancing the durability of specific components.

3.2 Translation of Engineering Tests Outputs to CBA Inputs

Another constituent of the GEARBODIES study was the development of new elastomeric materials which are used for the bushes in the swing arm on high-speed bogies. As with the journal bearing innovations discussed in Sect. 3.1 the main expected benefit of the new materials was expected to be LCC savings arising from the extension of maintenance intervals resulting from increased durability.

The results from the mechanical tests on the new polymers developed for the bushes suggested that an increase in durability was achieved. The results showed that the new polymers led to an improvement in tear strength (150%), tensile strength (28%), elongation at break (21%) and hardness (6%). While these engineering tests suggested that durability had increased they could not confirm if it would be sufficient to allow an increase in the maintenance interval (from once every four bogie overhauls currently) and further testing is required to confirm this.

The lack of clear and robust results on the durability of the new polymers meant that the impact assessment could only give an indication of the potential benefits of extending maintenance intervals. The LCC savings over a 30-year appraisal period of extending the maintenance interval from every four bogie overhauls (i.e. 6 million km) to every five (i.e. 7.5 million km) were estimated at 24.3%. If the increase in the maintenance interval was less than required to reach the next bogie overhaul then no LCC savings would be realised in practice as the bushes would continue to be replaced every 6 million km. This undertaking of this analysis highlights that for the purposes of impact assessments in future projects it is important that engineering tests are designed to produce inputs which can be used in a CBA, which emphasizes early interaction between technical and economic research in technical rail research projects.

3.3 Utilisation of Statistical Methods to Understand Cost Drivers

The IN2ZONE study involved the design and development of innovations at transition zones which are the areas on railway lines adjacent to structures such as bridges and tunnels. In such locations greater track support is required to allow a smooth transition between regular track and the stiffer support conditions provided on structures. The sudden change in support conditions leads to increased track degradation which requires more frequency maintenance interventions at greater cost. In IN2ZONE prototype next generation transition zone solutions were developed which provide a step-change in track support conditions, leading to a reduction in maintenance interventions.

The benefit of a transition zone solution relies on its impact on the railway system's life-cycle cost and capability. A key challenge in rail technical analysis is obtaining good cost data at a disaggregate level for different assets and in different locations on the network and in turn how costs vary with different cost drivers. This can make it hard to establish a baseline scenario.

In IN2ZONE a cost model was used to generate information about maintenance which built on the approach utilised in the NeTIRail-INFRA project [5]. Let C represent maintenance cost per track km, Q is traffic per track km and X is a vector of infrastructure characteristics per track km – but importantly for our analysis includes the number of structures (bridges and tunnels) on the section (given that each structure will be associated with two transition zones). The cost model can be written as:

$$C = f(Q, \boldsymbol{X}) \tag{1}$$

The double-log specification was used which is common in the literature addressing rail infrastructure costs. Information about maintenance costs, the infrastructure characteristics, traffic as well as some maintenance activities was collected for an Infrastructure Manager in Europe.

The presence of tunnels and bridges on a rail section provides a first indication of the effect of transition zones on track maintenance costs. The results show a positive and statistically significant (at the 1 per cent level) impact of this variable on costs (parameter estimated of 0.131, which can be interpreted as an elasticity). This result indicates that, for example, increasing the number of structures on an average track section by 100 per cent would be expected to increase the track maintenance costs by up to about 13 percent according to the model. The results from the model were used to estimate that the annual extra cost per transition zone is €2,211.90 (2023 Prices). Since not only the transition zone, but also other parts of the structures may require maintenance, this number provides an upper limit for the impact on costs if the number of transition zones would change or if each zone could be reinforced.

3.4 Recommendations for Future Research

In addition to the examples outlined in the previous sections several other recommendations can be made for enhancing impact assessments based on those the authors have been engaged in the Shift2Rail programme. Firstly, there are a range of wider benefits of innovations for which valuation is challenging. For example, enhanced reliability is a

common expected impact of rail innovations but is notoriously difficult both to quantify and then value (the former part, obtaining data on delays caused by different types of failure on different line types being the biggest challenge as values do exist in the literature for delays [6]). Secondly, although public bodies have standardized parameters to use in CBA such as discount rates, appraisal periods, etc. it would be constructive to establish a consistent set of cost and demand /quality side parameters and approaches. These could be brought together in the form of a Business Case Assessment Handbook that could be used to assist evaluation of rail technical innovations in the future.

4 Conclusion

In most (if not all) industries, technological innovations may improve efficiency and productivity and can make goods and services more accessible to all. However, an economic understanding of the implementation and impacts of technologies is necessary but non-trivial: it involves a series of challenges which have surprisingly received little attention in the literature.

Some of the challenges of business cases in the rail sector and novel approaches for alleviating them were illustrated in this paper using examples from the Shift2Rail programme. Obtaining data on key aspects of costs to populate the base case scenario is often problematic and statistical methods were outlined which can be used for utilising real cost data to understand cost drivers. Research into components often may focus on a single component but where scheduled maintenance covers a range of components, extending the life on one component may have little benefit without progress on the life of the remaining components. In this paper it was shown how the development of an indicative maintenance plan can allow an assessment of how an increase in the durability of a component is affected by the maintenance requirements of other components and, therefore, the extent to which LCC savings can be realized in practice. While the methods outlined in this paper can assist in enhancing impact assessments going forwards further work is needed to develop approaches for evaluating some of the commonly expected benefits of rail innovations such as reliability. In addition, the impact assessments of rail innovations would benefit from the development of a Business Case Handbook which contained a standardized set of parameters and approaches for business case evaluation; as well as improved disaggregate data to support decision making.

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Material Supply of Urban Factories Using Circulation Hubs - An Analytical Comparison of the Logistical Effort

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Abstract. Climate change, the responsible use of natural resources, and continuous urbanization raise the question of how urban factories can be supplied more sustainably. The concept of an Urban Circulation Hub can provide a potential solution. An Urban Circulation Hub can meet the resource needs of urban production systems by specifically collecting suitable waste materials generated in urban areas and making them available as input or secondary raw materials. By establishing such a hub, originally unused waste material flows can be made accessible and usable. This paper focuses on the logistical effort of an Urban Circulation Hub, for which scenarios are compared and evaluated with a simulation in AnyLogic. The simulation is based on a case study of an eyewear factory in Sydney. The result shows that an Urban Circulation Hub can be a sustainable, resilient, and cost-effective alternative for raw material supply. However, this requires sufficiently recycling waste streams generated in the urban area.

Keywords: Urban Circulation Hub · Urban Factories · Simulation · Sustainable Development · Reverse Logistics · Circular Economy · Circulation Factory

1 Introduction

The pressure on natural resources to supply production systems for the manufacturing of products is becoming increasingly important due to their scarcity and connected environmental impacts. This scarcity raises the question of sustainable strategies to supply production sites towards circular or cascading material flows. Today, a high share of consumer goods is produced in globalized mass-production systems. On the one hand, this can allow exploiting effects of economies of scale. On the other hand, the concept of symbiotic material flows for smaller, decentralized manufacturing systems can lower environmental impacts associated with material and energy demand of industrial activities. This would allow the utilization of the output flows of waste, energy or by-products

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from one company or consumers as input flows for another enterprise [1, 2]. However, due to technological and organizational barriers, symbiotic concepts are rarely implemented and can be found mostly in controlled environments such as industrial parks [3]. Urban areas in particular need to be considered as they have a high density of waste generation and product demand [4]. This is where the concept of the Urban Circulation Hub (UCH) needs to be discussed, as an UCH can supply the resource needs of urban production systems by collecting suitable waste materials generated in urban areas and providing these as input or secondary raw materials. The paper aims to compare the logistical effort of innovative UCH concepts based on scenarios.

2 Systematic Literature Review and Case-Study

In order to address the research topic of the material supply of Urban Factories using UCHs, a systematic literature review was conducted, based on the guidelines of Durach *et al.* [5]. The search query is *TITLTE-ABS-KEY (circular AND hub) OR (circular AND economy) OR (circulation AND factory) AND TITLE-ABS-KEY (urban) OR (urban AND production) AND TITLE-ABS-KEY (reverse AND logistics) OR (transport*) OR (logistics*).* After full-text analysis, 12 results emerged.

Most of the analyzed literature is of theoretical focus. Furthermore, it becomes apparent that some have an urban focus related to industrial symbiosis and only few have a logistical focus. The concept of industrial or especially urban symbiosis is defined by the fact that the generated waste, pollution and by-products of one production site are reused in other production sites. [6] Urban symbiosis describes the formation of a network for the physical exchange of waste and by-products within a city [1, 7–9], with or without further treatment or recycling processes [10]. The connection of industrial production sites and other resource sources or utilizations in urban area is called urban-industrial symbiosis and describes the idea of industrial symbiosis transferred to the city-factory-system [8, 9, 11, 12]. Another concept for the utilization of local waste to supply productions is the urban secondary raw material factory [10]. Genc *et al.* [3] presented the Circular Eco-Industrial Park as a place of the utilization of waste, but not in an urban context. Rickert *et al.* [13] describe the concept of the Circulation Factory. An UCH networks with other actors in the city-factory-system and sources material flows directly from other traders, thus saving transportation to landfills. This raises the need of taking a closer look at the material flows and analyzing the logistical effort. It turns out that there are studies on certain logistical aspects related to the circular economy and reverse urban logistics [2, 14], but none that address the logistical impacts based on a case study and using an agent-based simulation (ABS).

Following the outlined necessity of analyzing an UCH, a concept evaluation on different scenarios will be performed by conducting an ABS. In the context of logistics, ABS is an important tool that is widely used for decision support. The simulation methodology can compare an actual state with different scenarios (target states) to draw conclusions that can be transferred to reality [15]. Based on this, ABS is used to evaluate the impact on transport logistics activities due to the implementation of an UCH. For a structured approach, the VDI Guideline 3633 Part 1 is used [16].

The case study under investigation is based on the data of a life cycle assessment of a product from a manufacturer in Sydney, an eyeglass frame to be fitted with lenses. It is based on the scenario II from the study by Juraschek *et al.* [11], as baseline scenario.

To identify possible advantages and challenges of UCHs in terms of logistical efforts, the effects of supplying the production using an UCH are compared with conventional supply strategies. For this purpose, a baseline scenario 1-A of the actual supply to the factory is modeled. The further scenarios (Fig. 2) are then used to model the impact of supplying the factory from one, several, and many UCHs in Sydney.

2.1 Simulation Model

The software AnyLogic 8.8 is used to develop the simulation model. The simulation model uses discrete and agent-based modeling (Fig. 1) to map the process of the supply chain by interaction with each other. A main agent serves as a central instance. It links all agents with each other and contains central control elements and a geographic information system map. The routing for individual transports within and around Sydney is implemented using the interface to an online map service provided by AnyLogic. The connections of the agents are shown in the schematic overview in Fig. 1.

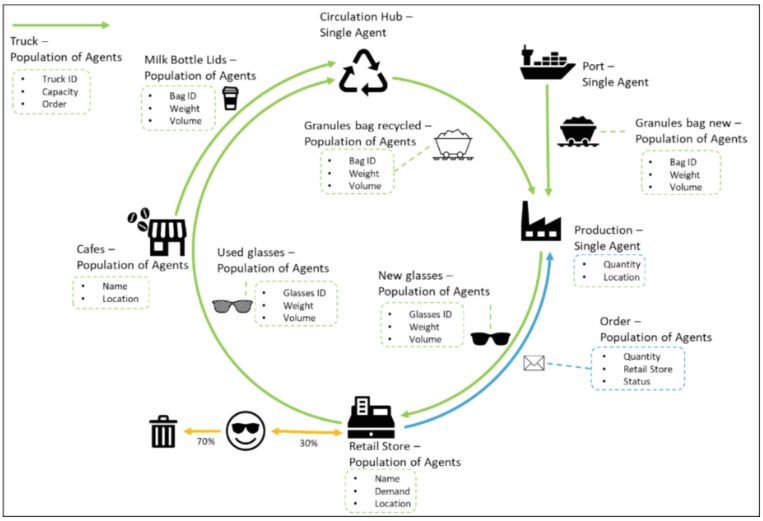


Fig. 1. Schematic representation of the circular process flows

The process begins with the production of the eyewear frames. The materials used are either virgin material (granule) delivered from Asia by ship or recycled materials, for which a share of 25% virgin material with 75% recycled material is set to ensure product quality. The transport of the virgin material is conducted by 40t trucks. Depending on the scenario, a differentiation is made between centralized and decentralized production in the individual retail stores. The frames will be transported by 7.5t trucks to the five retail stores as soon as they are finished. The order frequency depends on the respective stores,

their demand, and the safety stock. When a new pair of glasses is sold, the customer can exchange old glasses for a new pair. The probability of such an event can be set individually in the simulation model. These used glasses are collected in the respective stores and then transported to the UCHs. Depending on the chosen scenario, the mode of this transport varies. In one scenario, the glasses are collected from the UCH by a truck via milk run; in another, they are collected after the delivery of new glasses. At the UCH, the eyeglass frames will be recycled. In addition to the glasses, milk bottle lids are recycled and collected in advance from the respective cafes.

2.2 Scenarios and Results

The simulation observation period was defined as one year. Stochastic effects influence the model due to customer demand shifts, initial inventory and safety stocks. This makes a transient phase necessary, which in this case study is six months and is defined by the Method of Welch [17]. Key performance indicators were defined to compare the logistic effort of the scenarios: tkm, number of transports, and kg CO_2 emissions based on averages per tkm by Mulholland *et al.* [18]. The results are subdivided by the vehicle types 7,5t and 40t. The following Fig. 2 presents the scenarios and results.

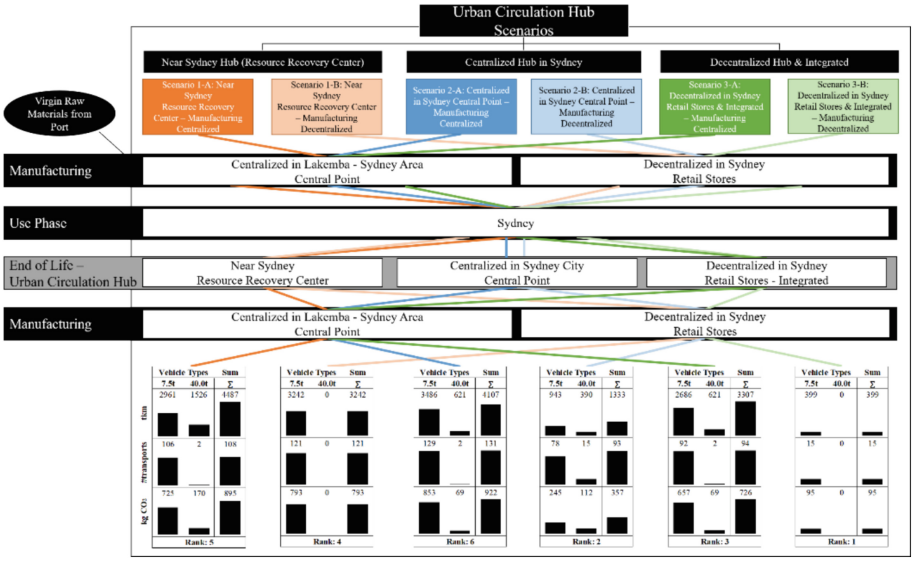


Fig. 2. Scenarios & Logistical Effort

The evaluation of the different scenarios shows that Scenario 3-B, where UCHs and retail stores are organized decentralized and integrated, represents the best results with a total of 95kg CO_2 emissions. This is caused by significantly lower transports. In contrast, in scenario 2-A, including a centralized production and recycling, the average CO_2 emissions determined per replication amount to 922kg CO_2, thus almost 10 times greater than in Scenario 3-B and representing the highest CO_2 emissions of all scenarios.

This is due to the increased transportation processes resulting from waste collection and the distribution of products to the retail stores. It can be seen that production and recycling within the city are preferable in terms of transport emissions. It seems logical, as the integrated UCH scenario or the centralized Circulation Hub scenario eliminate or minimize the corresponding milk runs to supply the retail stores. The main advantage of the UCH is that there is no need for transports, but the main challenge is to find a suitable urban location for the UCH and to cover the operating and construction costs.

3 Conclusion and Further Research

An UCH can meet the resource needs of urban production systems by specifically collecting suitable waste materials generated in urban areas and making them available as input or secondary raw materials. The location of such an UCH is either integrated into the decentralized urban production system or close to the corresponding retail stores. In the best scenario (3-B), the production systems, UCHs and retail stores are organized in a decentralized manner and integrated with each other, which leads to only a few transports. On the other hand, operating and construction costs of the production sites and UCHs can be higher per product output, as the establishment of smaller production units can possess negative economy of scale effects on processing efficiency. These should be compared with transport costs, emissions or the effects of the reduction of overproduction in future studies. Another approach to optimize transport and reduce CO_2 emissions would be to deliver the finished products to the retail stores and collect the secondary raw materials at the same time. Furthermore, in some countries there are legal hurdles to reuse secondary raw materials, which can be overcome by for instance establishing deposit systems. Finally, it should be noted that the operation of the UCHs in our case study is simple, as only a few types of raw materials are needed to produce the eyeglass frames. If many raw materials are used in a product, the processes and structure of the UCHs must also change, for example, the space requirement increases.

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Designing Low Energy Sustainable Asphalt Mixtures Based on Their Mechanical Properties and Performance Characteristics

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Abstract. The term "Sustainability" is a complex word to define. Focusing on the transportation sector as a structural infrastructure, more specifically on pavements, sustainability refers to the impacts on the environment, economy, and society at all stages, including material selection, design, and construction, as well as preservation strategies. The aim of this paper is to evaluate the sustainability of high RAP content asphalt mixes and the testing methodology involved in the determination of the key mechanical properties. Given that pavements are material intensive assets, a large focus in pavement sustainability to date has been on the use of recycled materials in road construction. The present study is part of wider research on the performance and durability of asphalt mixtures incorporating Reclaimed Asphalt Pavement (RAP).

Keyword: Sustainability · Recycling · Sustainable Pavement

1 Introduction

1.1 Sustainability Assessment

Within the past two decades, the asphalt paving industry has responded positively to increasing global concerns over shrinking natural resource reserves and worsening environmental conditions through the development and deployment of RAP and Warm Mix Asphalt (WMA) technologies (Tutu & Tuffour, 2016). In order to promote sustainable practices and to combat price increases, measures with sound sustainability credentials need to be widely implemented. Developing novel materials and technologies to integrate greener material, waste, and recycled materials into the production cycle of asphalt mixtures is a solution that improves both sustainability and cost-efficiency of the asphalt pavement industry. A sustainable pavement has to be economically, socially, and environmentally feasible at an acceptable level of risk over its design life. Practically, a sustainable pavement optimizes a range of performance indicators including cost, functionality, safety, local economic and human development, emissions, climate change and resource use, amongst others, which are measured by using a suite of assessment methodologies (Blaauw, et al., 2022). Pavements are engineered systems present

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in every modern society, and they have significant environmental, economic, and social impacts. In an effort to promote more sustainable decisions regarding pavement design, construction and management, several pavement sustainability assessment tools have been developed (Plati, 2019).

Given that pavements are material intensive assets, a large focus in pavement sustainability has been on the use of recycled materials in road construction (Bryce, et al., 2017). A sustainable pavement can be defined as a pavement that supports long-life engineering reliability, with minimum environmental impact. The need to minimize the use of scarce primary resources is becoming more urgent in the pavement industry (Asres, et al., 2022). Thus, sustainable pavement design is based on some criteria, such as minimizing reliance on natural resources, reducing energy consumption and Greenhouse Gas Emissions (GHG) emissions, limiting air, water, and noise pollution, and improving health, safety, risk prevention, and user comfort (Plati, 2019).

1.2 Performance Based Design

One of the most topical research areas currently concerns the identification and improvement of technologies against climate change, environmental pollution, exploitation of natural resources, and the economic crisis (Daniel & Lachance, 2005). Of course, the field of road pavement engineering has also been involved in this battle. In recent years, themes of sustainability and circular economy have become the main keywords for scientists, administrations, designers, and constructors worldwide (Bochi, 2022). Utilizing recycled asphalt pavements (RAP) in pavement construction is widely accepted as a sustainable approach with significant economic and environmental benefits. RAP has been favoured over virgin materials in recent years for three main reasons: (1) crude oil and consequently asphalt binder cost increases, (2) scarcity of quality aggregates, and (3) increasing necessity for using sustainable materials in road pavements (Daniel & Lachance, 2005).

In the field of pavement engineering, the word "sustainability" can be related to several aspects, including the manufacture of road materials and their performance, the management of temperatures and emissions during road construction and service life, and analyses of the socio-economic and environmental impacts generated by the road infrastructures. This can also be achieved by increasing the performance of the materials against traffic loads and environmental factors, thus extending the durability of the whole pavement system (Bochi, 2022). Performance-based tests can be used to characterize asphalt mixtures regardless of materials and technologies in use, thus allowing the extension of pavement life cycle, cost savings and minimization of their environ-mental footprint (Zaumanis, et al., 2018). For the sustainability of the road pavement, temperature is a key factor not only during the service life of the infrastructure but also when the Hot Mix Asphalt (HMA) is produced. In fact, an incorrect management of the virgin aggregate, RAP, and bitumen temperatures at the mixing plant can give rise to excessive pollutant emissions and substandard performance of the HMA (Bochi, 2022).

In order to guarantee quality construction of asphalt pavements, effective specification is essential. Performance-oriented specifications, which adopt direct performance characteristics of pavements as the quality goals of the construction such as the

performance-related specifications (PRS) and performance-based specifications (PBS), are gaining national popularity to overcome disadvantages of conventional QC/QA specifications (AASHTO, 2003).

2 Materials and Specimen Preparation

2.1 Materials

For this study, two mixtures were selected to be evaluated for their mechanical properties and fatigue performance. These mixtures incorporate two different percentages of RAP: 0% and 40%. A sustainable approach in asphalt pavement engineering should focus on materials, design methods, and technologies that can contribute to minimizing environmental impacts through a reduction in energy consumption and natural resources, while ensuring that all performance standards and requirements are met.

Bitumen is an essential part of the asphalt mix as it allows pavements to take tensile loading. In this study, volumetric and balanced mix designs were conducted to determine the optimum asphalt binder content for three different asphalt mixtures. The type and amount of virgin binder to be used in the RAP mixtures was governed by the RAP binder test results. As the aged RAP binder had lower penetration value than the design virgin binder grade (40/60), a softer 70/100 virgin binder was used to achieve a suitable combined penetration grade of 55 to 60.

The addition of rejuvenators, the method of RAP addition and the temperature and duration of mixing of the recycled asphalt mixture may improve blending between aged and virgin binder (Yin and West 2021). Rejuvenators are added to asphalt mixtures in relatively small quantities to restore the original properties of an aged asphalt binder. The AC20 40% RAP mixture was produced using the additive Iterlow V, and dosage was determined based on the manufacturer's guidelines: 0.13% of the weight of RAP. This dosage was chosen to ensure adequate workability of the high RAP mix.

2.2 Mixture Characterization

To fully characterize the mixtures' performance, both mechanical and functional properties need to be evaluated (Georgiou & Loizos, 2021), this includes stiffness modulus and fatigue resistance, which are two of the key tests undertaken in the current study. Stiffness is a fundamental property of asphalt mixtures obtained by determining the stress–strain response of the material under different loading and environmental conditions. Many studies have been performed to evaluate the impact of RAP on the stiffness of the asphalt mix. A general trend was observed in which the addition of RAP increased the stiffness of asphalt mixtures (Table 1) (Kaseer, et al., 2017). The RAP mixtures will generally have higher stiffnesses than the same mixtures with no RAP. A significant increase in the stiffness of the RAP mixtures could have a detrimental effect on the cracking susceptibility of the mixtures (Mogawer, et al., 2012).

The fatigue resistance of an asphalt mix is its ability to withstand repeated traffic loading without experiencing premature failure. Fatigue cracking as a result of repetitive stress and strain caused by traffic and environmental conditions is considered a primary

Table 1. Stiffness Comparison.

AC 20 - 0% RAP Stiffness @ 20 °C, MPa		AC 20 - 40% RAP Stiffness @ 20 °C, MPa	
Average	7226.8	Average	9393.4
Standard Deviation	411.28	Standard Deviation	943.97
Coefficient of Variation	5.69%	Coefficient of Variation	10.05%

distress mechanism in asphalt pavements (Ghabchi, et al., 2014). Therefore, an effective fatigue performance model is needed that can represent both fatigue damage growth and the fatigue failure criterion in order to define the fatigue life of the pavement (Yin & Pan, 2022). Fatigue cracking starts from the lower layers of the asphalt, where there is higher stress or strain, and moves upward as the frequency of loading increases. Controlling fatigue cracking is one of the most important concerns of experts in this field (Vamegh, et al., 2019). Fatigue cracking is one of the most common distresses in asphalt concrete pavements, it is extremely important to define or predict the fatigue cracking behavior of HMA in flexible pavement design and preservation (Table 2).

Table 2. Fatigue Comparison.

Parameters	Standard	AC 20 - 0% RAP	AC 20 - 40% RAP	Units
Production Temperature	-	160–170		^{o}C
Compaction Temperature	-	150–155		^{o}C
Voids	EN 12697-8	3.5	5.1	%
ε6	EN 12697-24 Appendix E	56	64.0	με

3 Development of a Sustainable Pavement Design

An ideal performance-based mix design would reflect pavement field performance and enable evaluation of mixtures for a specific climate and use application. This would allow for optimization of material selection and proportions, as well as the introduction of unconventional materials and technologies (Zaumanis, et al., 2018). The empirical nature of current mix design procedures and missing protocols for the characterization of RAP components and an approved mix design do not encourage a greater use of this recycled material (Kaseer, et al., 2017). For these reasons performance-based specifications have the potential not only to improve pavement characteristics and extend service life but they can also help improve production technologies, increase cost effectiveness, and minimize the environmental footprint of asphalt production and paving (Zaumanis, et al., 2018).

One of the objectives is to also compare these designs in terms of their carbon outputs. According to the National Asphalt Pavement Association (NAPA) for 1 ton of HMA the total carbon output is 51.5 kg of CO_2/ton. Whereas for 1 ton of HMA with 40% RAP the total carbon output is 39 kg of CO_2/ton (Fig. 1) (Shacat, et al., 2022). Reducing carbon footprint and energy consumption requires materials and technologies aimed at improving the practices for construction and maintenance, and overall minimize the environmental burdens.

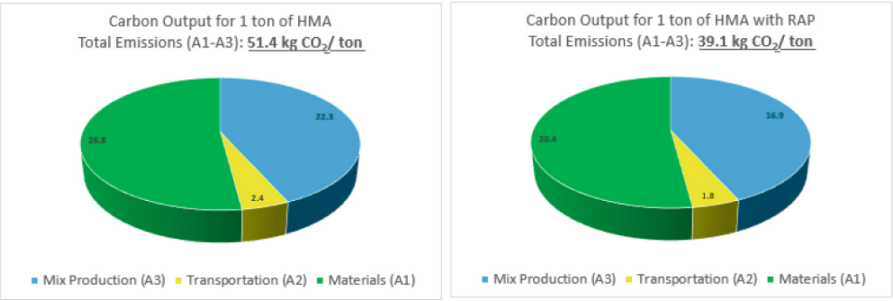


Fig. 1. Potential GHG Emissions reductions.

4 Conclusions

Cost-effectiveness and the environmental impact of asphalt mixtures need to be quantified and compared. Conclusions derived from this study are as follows:

- RAP incorporation increases the stiffness modulus and permanent deformation resistance of asphalt mixtures.
- The RAP mixture performed as well as, or better than, the control HMA mixture with respect to stiffness modulus and fatigue resistance.
- Laboratory fatigue tests aim to evaluate the effect of RAP on durability of asphalt mixes. The RAP mix made with 40% RAP shows the highest number of cycles to failure at each strain level, relative to the control mix. This suggests that the asphalt mix with 40% RAP may have better long-term performance than other mixes made with less or without reclaimed asphalt.
- Both mixtures were designed with similar properties i.e., grading, void, and bitumen content, with RAP content being the most significant variable to affect test results.
- Even though the asphalt mix containing 40% RAP demonstrates a longer fatigue life, possible brittleness issues of the aged binder should be clarified and investigated by testing the rheological behavior of bitumen recovered.
- The use of soft binders and/or rejuvenators can mitigate the stiffening effect of the RAP content, improving the workability of the mix and facilitating the blending between the aged and the virgin binders.

New technologies and practices will need to be developed and implemented to achieve more significant GHG emission reduction goals associated with the cradle-to-gate stages (A1-A3) of asphalt mix production. Several policy changes are needed to accelerate adoption of the technologies and practices needed to achieve these emission reductions. Revision of agency specifications is required to increase the industry's use of RAP and other recycled materials, with balance mix design (BMD) offering a performance-based mix design framework that does not compromise pavement performance (Shacat, et al., 2022).

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Eco-Design of Lightweight Structural Components for Electric Vehicles Made of Advanced Materials

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Abstract. The present paper showcases the results of the ALMA project, whose primary goal is to develop a novel electric vehicle structure for a passenger car, featuring reduced weight and environmental impact. Eco-design principles were incorporated from the early concept stages, integrating approaches like Design for Assembly and Disassembly (DFA/DFD), Design for Recycling (DFR), and functional integration of separate parts into a single structure. A FORD Mondeo with Internal Combustion Engine (ICE) was chosen as a design baseline. Subsequent redesign and material selection iterations led to the development of a novel multi-material Battery Electric Vehicle (BEV) concept, using Advanced High-strength steel (AHSS), low-density grade steel, laminate steel/plastic, and advanced Sheet Moulding Composite (SMC). Crash modeling was performed to virtually validate the design concepts against five different crash scenarios. Ultimately, the ALMA concept car's final design can now boast a mass reduction of 160.5 kg, translating to a 22% weight reduction compared to the baseline BEV.

Keywords: automotive industry · eco-design · electric vehicle · advanced materials · structural components · lightweight · composites · high strength steel · circular economy

1 Introduction

Increasing environmental awareness, as reflected in the recent European Green Deal [1], and concerns related to the growing material demand have motivated the automotive industry to explore new strategies for reducing the environmental impact of both their industrial activities and the entire life cycle of vehicles. In this context, the decisions made in the early stages of design play a crucial role in sustainability. These decisions encompass not only material and manufacturing selections but also extend their effects throughout the entire life cycle of the product, including end-of-life considerations [2].

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ALMA is an EU project initiated in 2021 involving 9 partners from 4 different EU countries. The primary objective of ALMA is the development of a novel electric vehicle structure for a passenger car with reduced weight and environmental impact, achieved through the adoption of an integrated circular approach across the entire life cycle, supported by ecodesign principles, Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) tools.

Advanced lightweight materials with structural performances, such as advanced high-strength steel (AHSS) grades, high-performance composites, and hybrid materials, were developed. Beyond lightweighting, other dimensions of the environmental footprint were considered, including efficiency in energy and material consumption, as well as end-of-life options (sorting, recycling, reusing, etc.).

This paper summarizes the eco-design approach followed during the project to select the "right material in the right place" to minimize the environmental footprint while maintaining cost-effectiveness and manufacturability.

2 Methodology

The project commenced with a detailed assessment of the environmental aspects affecting the product from a circular perspective, incorporating cost considerations as a core action to guide subsequent tasks. A Ford Mondeo with Internal Combustion Engine (ICE) was chosen as the starting point. The initial step involved transforming it into a full Battery Electric Vehicle (BEV) version, serving as the baseline for evaluating the achievement of the goal—specifically, a 20% reduction in weight. The project scope encompassed the body-in-white (BIW), chassis, and closures.

The newly transformed BEV baseline design underwent validation through Crash CAE under 5 critical load cases, ultimately reaching a final weight of 727.47 kg. Therefore, to achieve the 20% weight reduction, the weight target for the ALMA ecodesigned structure was set at 581.92 kg or lower.

The baseline was analyzed to identify parts and subsystems subject to modifications, utilizing the innovative materials proposed in ALMA: advanced High-Strength Steel (HSS), low-density grade steel, laminate steel/plastic, and advanced Sheet Moulding Composites (SMCs).

The first criterion was meeting technical requirements in terms of crash behavior. An initial assessment was conducted to identify parts that should remain unmodified, those that could benefit from advanced steels, and those that could potentially be produced using either SMC or other steel grades.

In cases where different materials were eligible, the decision to use the "right material in the right place" was made considering the following metrics:

- Weight saving, expressed as kg saved compared to the baseline part
- Circularity, where a score was assigned based on recyclability potential, ranging from 1 ("currently not recyclable") to 3 ("easily recyclable")
- Number of references saved
- Assembly line compatibility, assigning a score from 1 ("significant changes are required") to 3 ("no changes required")

BEVSIM allows users to measure and compare impacts resulting from design alternatives, lightweight designs, materials, or subsystem choices, recycling technologies, end-of-life scenarios, and future scenarios resulting from changes in electricity grid mixes. This enables easy comparison of complex trade-offs between materials that may be lighter and more sustainable during use but environmentally more costly during production and end-of-life. BEVSIM can also perform various types of impact assessments, including life cycle hotspot analysis, impact assessment, circularity assessment, and economic impacts analysis.

3 Results

In several systems, particularly in those with high mechanical requirements, steel was the only viable solution in terms of crash behaviour. For such parts, different cases were identified:

- Unchanged steel parts: Some of the parts were not modified when there was no alternative material to propose that could fulfil the technical requirements or the lightweighting potential did not justify the change.
- Steel parts with the same geometry as the baseline but lower thickness: The use of more performant steel grades resulted in a reduction of thickness and associated weight saving. There was no need to change the shape, and no possibility to integrate other functions.
- Steel parts with integration of functions: In this case, the use of a more performant steel grade opened new integration possibilities. Systems composed of several parts in the baseline design could be integrated to reduce the references significantly. The systems chosen for integrated redesign were the door panels and the H-Frame structure.

However, some systems could potentially be produced either with SMC or steel, and the choice required a more detailed analysis. Those systems were the dash panel, the rear floor panel, the rear tray, and the battery lid (Fig. 1).

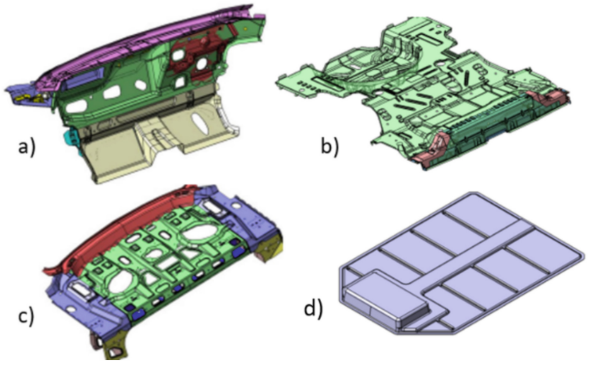


Fig. 1. Images of the considered systems to select SMC vs Steel. a) dash panel b) rear floor panel c) rear tray d) battery lid.. Image produced by the authors using CATIA v4 CAD software.

For these systems, a detailed analysis was made considering the metrics described in Sect. 3. The results are shown in Table 1.

This assessment was complemented by a sustainability analysis using BEVSIM (Fig. 2).

Table 1. Assessment of potential materials for different sub-systems

	Weight saving		Circularity		nº References saved		Assembly line compatibility	
	Kg-saved compared to the baseline		*1 "currently not recyclable" 2 "difficult to recycle/ disassemble" 3 "easily recyclable"*		nº of references saved		1."Significant changes are required" 2."Minor changes are required" 3. "No changes required"	
	Steel	SMC	Steel	SMC	Steel	SMC	Steel	SMC
Dash panel	3,01	5,93	3	1	0	11	3	2
Rear floor panel	17,04	14,09	3	1	0	2	3	2
Rear tray	1,60	3,35	3	1	0	6	3	2
Battery lid	19,84	24,50	3	2	0	0	3	2

The selection of materials for each system was done accordingly:

- The dash panel benefits most from the use of SMC. A drastic reduction in references is possible, with a significant lightweighting potential. The steel option not only maintains the number of references but also has a higher CO2 eq. Intensity, according to BEVSIM analysis. Therefore, this component was selected to be redesigned using SMC materials.
- The rear floor panel in SMC has a lower lightweighting potential than the steel option, which uses a steel laminate. SMC is also more damaging to the environment, according to BEVSIM. It was agreed to select the steel option for this component.
- The rear tray has a lower lightweighting potential for both options. In terms of sustainability, the steel option is less damaging, as shown by the BEVSIM tool. Additionally, no significant changes in the assembly line are needed, while the SMC option would require specific adhesives to withstand an E-coat bath. It was decided to design the component using advanced steel.
- The battery lid has a higher lightweighting potential for both options, and their environmental impact is similar. Since it is assembled after the E-coat process, the SMC allows for the use of debondable adhesives. Therefore, it was agreed to design it using a flame-retardant SMC.

The bill of materials was then completed, and the new total weight of the ALMA structure was reduced to 567 kg. Finally, the new design was validated using CAE

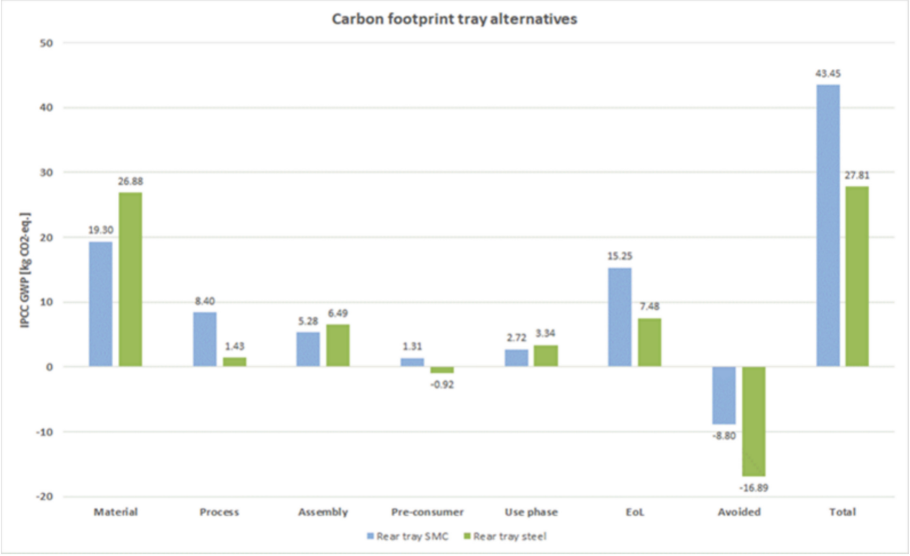


Fig. 2. Example of sustainability analysis comparing SMC vs steel for the rear tray per life cycle stage. "Pre-consumer" considers recycling of pre-consumer production waste.

analysis for 5 crash scenarios and iteratively modified until reaching a validated structure with a 22% reduction in weight (160.5 kg less than the baseline), contributing to a total reduction of 1850 kg CO2-eq.

4 Conclusions and Future Work

The ALMA project adopted an integrated circular approach across the entire life cycle to design a multimaterial BEV structure, optimizing the selection of materials and production processes to achieve a more efficient and environmentally sustainable vehicle structure. This approach produced a new design that resulted in a 22% weight reduction from the baseline while still being able to fulfil the crash requirements, as demonstrated by CAE analysis. The carbon footprint was reduced by 24%, thus fully validating the usefulness of the approach for producing more sustainable vehicle designs.

In the last months of the project, several demonstrators will be prototyped to show the feasibility of such results.

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More information about the project: https://almaproject.eu/

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The PROCEEDR Tool to Assess Environmental Impacts, Circularity and Life Cycle Costs of Roadside Equipment

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Abstract. Road transport was responsible for 24% of all carbon dioxide emissions in the EU in 2020. The majority of the transport sector's carbon emissions is related to the operation of vehicles, followed by infrastructure construction and rehabilitation. Roadside equipment, such as noise and safety barriers make a small contribution. Nevertheless, road infrastructure requires extensive use of natural resources and is a major generator of waste, as well as comprising assets with a lifespan of up to 100 years. The PROCEEDR project, funded by the CEDR Transnational Road Research Programme Call 2020 Resource Efficiency and Circular Economy created a software tool to enable National Road Administrations as well as roadside equipment manufacturers to find innovative and sustainable solutions to ease the transition from linear to circular economy in the field of roadside infrastructure. This paper presents a unique software tool that closes a research and knowledge gap and has been tested and validated in several case studies. The work is also based on a state-of-the-art inventory and analyses performed during the first part of the project. We describe the tool development process, benchmark the tool against other available tools and conclude with a critical discussion on points for improvement.

Keywords: Circular economy · Life Cycle Assessment · environmental impacts · life cycle costs · software tool · sustainable noise and safety barriers

1 Introduction

The roadside infrastructure of today is equipped with various devices that have a direct impact on the total amount of virgin materials used for road construction. The National Road Authorities (NRAs) decided to take the lead and support the design of roadside solutions, requiring fewer virgin materials with lower environmental impacts and costs over their life cycle. NRAs have already developed procedures and tools to assess the environmental or sustainability performance of construction projects (see Sect. 2) but

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there lacks a specific tool that combines environmental life cycle assessment (LCA) with life cycle cost assessment (LCCA) together with a circular economy (CE) perspective. So far, globally no tool exists for assessing noise and safety barriers specifically; such a tool allows NRAs to assess the environmental performance and the circularity potential of different noise and safety barriers and also enables roadside equipment suppliers to optimize the environmental performance of their products.

The research project PROCEEDR – Optimising Resource Use for Roadside Infrastructure [1, 2] closed this research gap by reviewing technical and design aspects of roadside solutions to enable the development of innovative and comprehensive software to assess the environmental performance of noise and safety barriers and their circularity potential. The PROCEEDR software tool contains a unique and comprehensive product and material library of noise and safety barriers applied in the EU.

This paper presents the PROCEEDR software tool in its current form. This paper is divided into five chapters. This introduction is followed by an overview of existing tools for the environmental assessment of road infrastructure is presented. Sections 3 and 4 present the software tool development process and discussion of the tool, while Sect. 5 concludes with possible next steps.

2 State of the Art of Environmental Assessment Tools in Road Infrastructures

The LCA method enables policy planners, NRAs, and road management organizations to evaluate the overall environmental impact of road construction and maintenance. There are various tools available to assess infrastructures' environmental impacts, which have been investigated in the PROCEEDR project. The four most relevant tools are presented below. It should be noted that all the relevant information is based on online references and manuals of the relevant tools.

VegLCA, an Excel-based LCA tool developed by the Norwegian National Public Road Administration (NPRA) to assess environmental impact of road and rail infrastructure based on several environmental indicators, focusses on global warming potential [3, 4]. It has pre-selected processes (mostly based on Ecoinvent) and covers A1-A3, A4-A5, B4 and B5 life cycle stages.

LICCER (Life Cycle Considerations in EIA of Road Infrastructure) is an Excel-based decision-supporting tool to compare road corridor options in Sweden, Denmark, Norway, and the Netherlands [5]. It focuses on GHG emissions and energy consumption relating to the infrastructure components of roads, bridges, and tunnels covering all life cycle stages (from cradle to grave).

DuboCalc, launched by Rijkswaterstaat, part of the Dutch water and infrastructure ministry, calculates eleven environmental impacts of civil engineering works for the whole life cycle including after the end of life (module D) [6]. Its database consists of nationally developed Environmental Product Declarations (EPDs) and users can compare different material and design alternatives of all construction and civil engineering works (not just road or infrastructure projects).

Klimatkalkyl is an online web-based tool, developed by Trafikverket, the Swedish transport administration, enabling energy and emission calculations to be undertaken

for infrastructure projects during their construction, operation, and maintenance [7]. The tool database consists of historic Swedish construction calculations, EPDs, and designers' experience-based data.

3 The PROCEEDR Tool Development Process

The tool development process started with a comprehensive overview of roadside infrastructure solutions currently in use in Europe (see Fig. 1). This informed the definition of the functional requirements for roadside solutions. The functional requirements together with the benchmarking of LCA and LCCA tools (see Sect. 2) provided the basis for prototyping the first version of the PROCEEDR tool. This first version of the tool has been validated through the application of test cases that allowed for refining the tool.

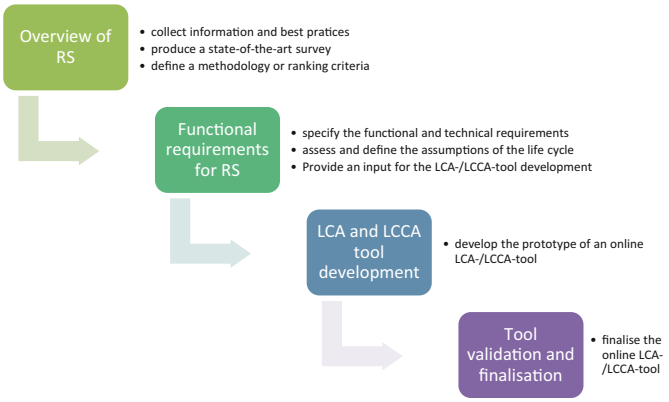


Fig. 1. Work process (RS = Roadside solutions).

The online tool development process to achieve a Minimum Viable Product (MVP) was iterative and followed a combination of software development methodologies including Prototype Methodology and Rapid Application Development (RAD).

After the assessment of existing LCA-/LCCA-software applied by NRA's today (see Sect. 2), a Miro board was created to facilitate the online workshops with the NRA's and manufacturers of roadside equipment to evaluate the flow and functionality of the interface and usability and learnability using the cognitive walkthrough method. The Miro board was used to quickly design and rapidly prototype the frontend with minimal database to support frontend selection list functionality. Initially, wireframe more complex parts of the application with no working functionality. The functionalities have been gradually introduced through subsequent iterations as requirements become more concrete. In parallel, the programming of the software tool began. It was developed using an open-source web application framework supported by a database in the backend. Both Django and Laravel have been chosen for reasons including but not limited to: built-in user authentication system, built-in automated testing environment and writing in Python enables easier integration with backend algorithms.

4 The PROCEEDR Tool

The PROCEEDR tool complies with the relevant international LCA-standards (ISO14040, 14044 and EN 15804.) The main target audience is European NRA's as well as noise and safety barrier manufacturers. Open access LCA software OpenLCA version 2,0 and Ecoinvent version 3.9.1 have been used and the environmental impact assessment method is OpenLCA - EN 15804+A2 Method. The database provides average data for energy, transport distances and material properties for Europe. All default values can be modified by the users to tailor the assessment to their geographical, climatic and economic circumstances for example.

The tool covers the life cycle stages: A1-A3 Production stage, A4-A5 Construction stage, B2 Maintenance, B4 Replacement, C1-C2 Deconstruction and transportation, C3-C4 Waste processing and disposal, and D Benefits and loads beyond the product system boundary. In addition, a CE Indicator has been developed and implemented in the tool.

The following environmental impact indicators are provided by the tool and the users can choose which to include: Fossil Global warming Potential, Biogenic global warming potential, Land use and land use change global warming potential, Total global warming potential, Depletion potential of the stratospheric ozone layer), Acidification potential, Accumulated Exceedance, Eutrophication potential, fraction of nutrients reaching freshwater end compartment, Eutrophication potential, fraction of nutrients reaching marine end compartment, Eutrophication potential, Accumulated Exceedance, Formation potential of tropospheric ozone, Abiotic depletion potential for non-fossil resources, Abiotic depletion for fossil resources potential, and Water (user) deprivation potential, deprivation-weighted water consumption.

To ensure that the tool assesses the environmental impacts of roadside equipment correctly, several case studies of roadside equipment were used and modelled in OpenLCA and calculated the environmental impacts of a few representative noise barriers for the European market. The same system boundaries, inventory data and impact assessment method were selected to enable comparison with the results from the PROCEEDR tool.

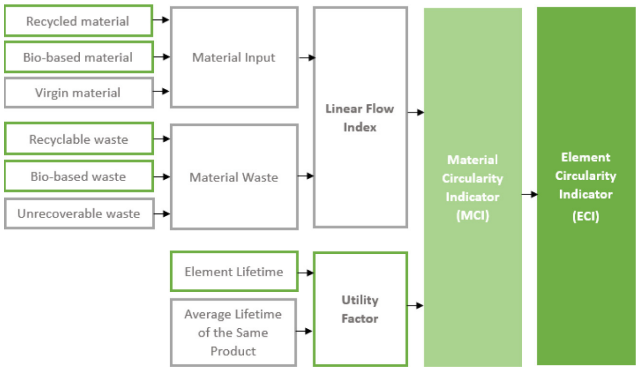


Fig. 2. Tool circularity indicator framework

A comprehensive investigation into the existing circularity methods and tools [8–12] was undertaken as creating an assessment method from scratch would be complex and resource intensive. The concept of a circularity framework (see Fig. 2) is derived from [12] and has been adapted and simplified for the PROCEEDR tool.

Material Circularity Indicators (MCI) are evaluated based on the Linear flow index and the Utility of the product. The linear flow index indicates material that flows linearly and is assessed by the flow of three different categories of materials input and waste. The utility of a product presents how long and intensely a product is used compared to an average product of the same type.

The circularity indicator scores the circularity of each element of barriers on a scale of 0 (fully linear) to 1 (fully circular). Element Circularity Indicator (ECI) is the normalized summation (based on mass) of MCI.

The PROCEEDR tool is composed of six sections:

Log-in: The log-in page allows the user to register or to log in again to continue with an assessment task that has already been entered.

Project Initiation: The project initiation allows the user to select a noise or a safety barrier assessment and the specific type.

Analysis Setting: This step sets the analysis framework. Here the user enters the main information on the roadside equipment to be assessed including the country where construction will take place and dimensions of the roadside equipment study object. The user can also select the environmental impact categories and life cycle stages to be included in the assessment. Finally, the assessment of the circularity potential of the roadside equipment can be enabled.

Input: As a last step before the calculations can be run, the user enters the relevant information for the roadside equipment. To make the solutions more comparable, this step is divided into different parts. This also enables calculations to be performed for existing infrastructure already in situ, for example if only the acoustic panel of a noise barrier needs to be replaced, this can be assessed by the tool. For a noise barrier, these parts are: the foundation, the supporting structure and the acoustic element.

Overview: As you can see in the earlier figures, the user always has an overview of information that has been entered into the software. Before the calculation is initiated, the user has an overview of the chosen parameters so far, enabling them to go back and edit parameters if a mistake is detected at this stage.

Results: After the calculations have been run, the user is provided with a result sheet in the form of a bar chart with the different life cycle stages, the circularity economy potential assessment and costs/ life cycle stage illustrated. Finally, the user can choose to export the data as a csv-file for Excel or as a pdf report.

5 Conclusions

The PROCEEDR project successfully developed a software tool that allows European NRAs to specifically assess the environmental and economic performance of roadside equipment. The development of an indicator of the circularity potential of a noise or

safety barrier will highlight synergies and trade-offs between a circular economy and associated environmental impacts, e.g. in some cases, a circular treatment might result in higher environmental impacts than the use of primary materials. NRAs might use the PROCEEDR tool for other reasons, perhaps to assess/compare the offered solutions in a tendering process. Hence, the tool could support roadside equipment manufacturers in reducing the environmental impacts of their products through a more beneficial ecological product design. The PROCEEDR tool offers many benefits to NRAs and manufacturers, but would benefit from further development work. Its modular software architecture allows the addition of other typical roadside equipment solutions, which would require a larger engagement of manufacturers to enter additional product solutions. Different functions in the result analysis and result interpretation including sensitivity analysis would be advantageous but due to time and resource restrictions, this was not possible. A finer granularity of national and local environmental and cost data would make the results more representative. Finally, additional features such as the resulting output in the form of an EPD would likely result in increased interest from manufacturers to provide more input data.

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The Transition to Circular Economy in Transport Infrastructure - CERCOM and LIAISON Progression

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Abstract. To achieve climate neutrality, synergies between circular economy (CE) and carbon reduction need to be established in the context of transport infrastructure. Implementation of the circular economy and resource efficiency (RE) policies have the potential to facilitate decarbonization targets, while using fewer natural resources, maintaining or enhancing biodiversity and providing regenerative design for generations to come. This paper presents the interpretation of RE and CE within transport infrastructure in the context of the CERCOM and LIAISON projects. As part of CERCOM, a strategic review of current practice was carried out to develop a definition of CE within transport infrastructure, and provide the successes and barriers for further transition from a linear to a circular economy. A Risk Based Assessment Framework (RBAF) and associated software tool were developed to provide a means to evaluate the impacts of certain measures and prioritize areas that require further research or investigation. LIAISON will provide further progression in this regard, and develop a methodology, support tools and close to market technological solutions to transform EU Transport Infrastructure into a more sustainable and low carbon economic activity.

Keywords: Circular Economy · Resource Efficiency · Transport Infrastructure · Risk Assessment · Carbon Neutrality

1 Introduction

Urgent action is required by governments and organizations around the world to mitigate the effects of climate change and all sectors have a responsibility to reduce their climate impact. The transportation sector alone is responsible for approximately one fifth of global CO_2 emissions [1]. Whilst most of these emissions derive from the operation

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of Transport Infrastructure (TI), construction and maintenance also have high environmental impacts and are responsible for significant material consumption and associated CO_2 emissions. To speed up the process for circular TI we need European cooperation to ensure alignment and coordination of policies, strategies, standards and procurement, while also encouraging data collection and knowledge sharing of innovations at EU scale.

Circular economy (CE) has the potential to further the process of decarbonization by transforming the way in which products are manufactured and used. The move away from a linear economy towards the adoption of resource efficiency (RE) and CE principles has the potential to reduce harmful emissions as well as preserve natural resources.

2 Circularity in Transport Infrastructure

To achieve a circular economy, change is required across Europe and beyond, since the supply of raw materials and waste flows are global. It is essential that the entire workforce embrace the change and knowledge, skills and mindset required to make a significant change in achieving decarbonization. Infrastructure management, policy makers, supply chain and delivery teams all need to take responsibility in evaluating options, developing solutions, generating procurement opportunities and delivering available solutions. Procurement policies by national TI administrations have a great influence on the supply chain. A review of circularity within national road authorities (NRAs) in Europe found that many NRAs were including CE principles without formally implementing CE policies or strategies [2]. For progress towards achieving emission reduction and circularity in TI, it is essential that road and rail administrations support evidence gathering, data collection, identification and sharing of successful implementation and lessons learned.

Research Driven Solutions (RDS) were coordinators of CERCOM, which developed tools and frameworks to facilitate the adoption of CE and RE principles in procurement by NRAs across Europe [3]. The project was commissioned as part of Conference of European Directors of Roads (CEDR) Transnational Research Call of 2020 [4]. During the two-year project, various technical, operational, procurement opportunities and barriers were examined in the move towards more circular practices. One of the outcomes was the delivery of an innovative risk-based framework and management tool to facilitate a step change in the adoption of resource efficiency and circular economy principles in procurement and multi-lifecycle management by NRAs. The use of the tool was demonstrated through the analysis of various case studies related to construction and maintenance activities within the road sector.

RDS are currently partners on LIAISON, which will further enhance progress made within previous projects and will develop a methodology, support tools and close to market technological solutions to transform EU Transport Infrastructure into a more sustainable and low carbon economic activity [5]. A governance framework will be developed to demonstrate the benefits of these innovations to end-users, which will rank various infrastructure construction and maintenance solutions not only in terms of circularity, but also in terms of essential characteristics of construction works, safety, health, environment, resilience and costs.

3 CERCOM Risk Based Assessment Framework (RBAF)

A key deliverable of the CERCOM project was a risk based framework and software tool to facilitate circular procurement while assessing the technical risk of incorporating novel or innovative solutions into design, maintenance and construction of road infrastructure. The goal was to provide a means to assess current practice and the potential benefits of more circular solutions in increasing resource efficiency, minimizing waste and reducing the use of virgin materials. However, when considering procurement, it is necessary to also consider more traditional criteria such as Performance, Cost, Environmental and Social factors. As such, the Risk Based Assessment Framework (RBAF) was developed to take account of all these factors. There are 5 steps within the risk assessment framework (Fig. 1):

- Establish context - Includes the primary goals of the assessment, the hazards involved, the potential actions to reduce risk, the consequences to be considered and how the hazards and consequences will be calculated, identifying the specific spatial and temporal boundaries of the assessment in question
- Evaluate likelihoods - Includes details on likelihood of a "failure" event (P_f) or the probability of exceedance of a given damage state for given scenarios of hazard and action
- Evaluate consequences – Includes direct and/or indirect consequences/costs associated a with failure event
- Establish additional KPIs – Involves quantification of RE&CE, Cost, Environment and Social Key Performance Indicators (KPIs)
- Optimize – Involves optimization of various assessment criteria and KPIs



Fig. 1. CERCOM Risk-Based Analysis Framework

For each potential construction or maintenance option, the risk associated with this strategy is calculated (Risk = P_f x Consequences of failure event). Within the RBAF, consequences are taken as the costs associated with a failure event (e.g., the direct and/or indirect costs associated with emergency resurfacing due to premature loss of skid resistance).

As part of the tool, single or multiple KPIs can be defined and integrated under the categories Performance, Cost, Circular Economy, Environmental and Social. The

developed KPIs ensure that contractors can be rewarded for producing a scheme that will be long lasting, cost effective to maintain, use limited amounts of raw materials, designed for multiple lifecycles and/or can be readily repaired for (multi) life extension. A system of ranked interpolation is used to quantify KPIs. The first rank for each KPI is assigned a value of 0.0, and the final rank is assigned a value of 1.0. In the simplest case, a linear relationship is assumed between the first and final rank. Where a more complex response is required, a multi-linear or quadratic relationship may be determined between different KPI ranks. Ideally, KPIs should relate to existing targets and practices already defined by the overseeing NRA. For example, an NRA with a target to use more recycled content in maintenance schemes may already define different "levels" or ranks of achievement of this goal. These "levels" can be related to KPI values and ranks for quantifying KPIs for potential schemes, and an example is outlined in Table 1.

Table 1. Example KPI ranks for recycled content.

Rank	KPI Value	Description	Recycled Content Example
1	0	No commitment to KPI ambition	No recycled content
2	0.1	Below minimum industry practice	5% recycled content
3	0.25	Minimum industry practice	10% recycled content
4	0.5	Exceed industry practice	40% recycled content
5	0.75	Far-exceeds industry practice	70% recycled content
6	1	KPI ambition achieved	100% recycled content

Within the developed software tool, these factors are combined into a single metric, a weighted sum giving the user a clear indication of the optimal solution from a range of potential options. As with any tender evaluation, weight factors are used to quantify priorities of each NRA for a specific project/scheme.

The developed tool provides sufficient flexibility to allow NRAs to decide on the level of engagement with the CE process, based on current CE maturity as well as future needs. Within the developed framework and software tool, the functionality and capabilities can be adapted to suit the maturity of NRAs at any given time and can also be tailored to suit the scope and type of scheme under consideration. As such, it will prove to be a valuable tool in the move towards a circular approach in the procurement process of construction and maintenance of road infrastructure.

4 Results and Outcomes

The developed CERCOM Software Tool provides a versatile means for NRAs to assess the risk of using innovative circular construction and maintenance methods and materials along with additional criteria to facilitate optimum selection of scheme options and associated procurement practices.

The framework and software were updated and refined based on the practical experience gained from analyzing various case studies within the final months of the project.

This provided an opportunity to validate and demonstrate the framework within the scope of the CERCOM project. As such, it will prove to be a valuable tool in the move towards a circular approach in the procurement process of construction and maintenance of road infrastructure.

There is flexibility to include output results from independent Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) into the developed software tool to provide additional functionality and complexity. The fundamental limitation associated with the software tool is the availability of reliable data to assign values for criteria associated with alternative maintenance strategies and data to define thresholds for ranked interpolation.

Various training resources developed as part of CERCOM are provided on the project website and can be used to implement the necessary changes towards the adoption of circular economy practices in road construction and maintenance [3]. The resource pack content was tailored to reflect feedback received within various stakeholder workshops. The resources are divided into sections, offering materials with varying complexity, format and length to accommodate NRAs at different stages on the road to circularity.

5 Future Developments

LIAISON will further progress on advances made in previous research projects in the area of circularity and carbon reduction in TI by focusing on the implementation within four main areas:

1. Minimizing the consumption of resources
2. Reusing available resources
3. Evolving towards a prosumer infrastructure
4. Actions to facilitate market uptake by supporting procurement, legislation and standardisation processes

Research has shown that the implementation of innovative circular demonstration pilots has the greatest potential to increase the pace of circularity uptake within public procurement of infrastructure solutions [6]. On this basis, LIAISON will demonstrate a developed methodology using a set of representative and complementary use cases across Europe, comprising of industrialized solutions, circular solutions and smart operation and maintenance solutions.

The methodology will consider a whole life cycle perspective, from conception and design through generative and sustainable performance-based operation and maintenance stages, up to the decommissioning phase. To demonstrate the benefits of these innovations to end-users, a Dynamic Multi-Infrastructure Governance Framework (DMIGF) will be developed to rank various infrastructure construction and maintenance solutions not only in terms of circularity, but also in terms of essential characteristics of construction works, safety, health, environment, resilience and costs. It is essential that decisions are based upon a single framework where each of these indicators can be prioritized together.

This governance framework will act as a system of sustainability principles, procedures, indicators and accountabilities used by TI stakeholders to ensure a transparent measurement of transport infrastructure impacts throughout its full life cycle, and to keep

the safety / performance / cost / zero-emissions targets of the sector optimally balanced. The work will build on the CERCOM RBAF, providing additional progression in the following areas:

- fostering the uptake of the framework across all transport modes
- facilitating significantly more advanced risk-based analysis incorporating structural health monitoring data, uncertainty modelling etc.
- demonstrating and validating the methodology with various new and innovative technologies delivered within LIAISON

It is envisaged that to encourage its adoption, the DMIGF should be prescribed by administrations and TI investors through standards and procurement procedures. This will facilitate the generation of good practices going forward (e.g., setting circularity KPIs targets for TI at network and asset level, for different modes, at different lifecycle stages). Specific actions will be implemented by LIAISON to address these needs, including specific activities towards policy guidelines, standardisation and public procurement guidelines to aid adoption of circularity criteria in TI projects.

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Contribution to Incorporation of Non-recyclable Plastics in Bituminous Mixtures

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Abstract. The incorporation of non-recyclable plastic wastes in bituminous mixtures was investigated. It aims to develop a mixture with greater performance than the reference ones, supporting its incorporation in bituminous mixtures. Ten different samples of plastic waste were selected in a waste treatment centre, with only one having commercial value, while the others were either landfilled or incinerated. Six of the samples presented a heterogeneous composition, while the others were homogeneous. Samples were visually separated by type of residue, colour and using the density test with water, resulting in 75 samples. An initial evaluation of the plastics' melting point was performed to assess their suitability for incorporation using the wet method. Samples that could be incorporated without requiring excessive heating of the bitumen were chosen, particularly sample B, which started melting at 120 ºC. Three other homogeneous samples were selected with thermoset, polyurethane and high-density polyethene. Subsequently, samples were prepared by combining nominal penetration bitumen 50/70 with different percentages of sample B and penetration and softening temperature tests were conducted. The obtained results demonstrated that the wet method did not incorporate effectively the plastics due to their inability to melt into bitumen fully. The study will proceed to incorporate the plastic waste using the dry method.

Keywords: Bituminous mixture · Incorporation of plastic · Recycling · Wet method

1 Plastic - Overview

Plastics are indispensable in the modern world due to their unique properties and cost-effectiveness. They are used for packaging, cosmetics, and clothing, among many other purposes. The plastic industry is massive, estimated as of 2019 to employ more than 1.5 million people in Europe, with these companies generating over 30 billion in European public finances [1]. Every year, the production of plastic continues to increase, particularly in recent decades. Currently, 380 million tonnes of plastic are produced, and half of them are single-use plastics [2].

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As a non-biodegradable material with a recycling rate of 9%, it is found in absurd quantities worldwide, contributing significantly to one of the main environmental crises of the 21st century [2]. Considering this, it is essential to study and propose solutions that allow the valorisation of this waste, turning it into a by-product. Plastics can serve various functions in bituminous mixtures, including modifying and/or partially replacing the bitumen [3]. It is expected that the properties of the plastic will contribute to a bituminous mixture with better characteristics [4]. The innovation pertains to incorporating non-recyclable plastic by analysing the most advantageous manufacturing process. Additionally, it involves formulating a mixture to assess whether it exhibits improved characteristics, aligning with the themes highlighted at the TRA, particularly Efficient & Resilient Systems – Circular Economy& Life Cycle Assessments.

2 Identification and Selection of Samples for Further Tests

The plastic samples were collected in a waste treatment centre considering the selection of non-recyclable plastics. Six samples exhibited a heterogeneous composition, while the remaining samples had a homogeneous composition. The 10 collected samples were the following: Sample A – Plastics and rubbers 10–30; Sample B – Rejected aluminium capsules; Sample C – Washing machines' plastics 10–30, flotation 4; Sample D – PS/ABS refrigerators (PS2); Sample E – Rejected aluminium cans; Sample F – Plastic refrigerators, light flotation 2; Sample G – HDPE Boxes; Sample H – Polyurethane Refrigerators; Sample L – Plastic pallets; Sample J – SDAS, light flotation 2 (Fig. 1).

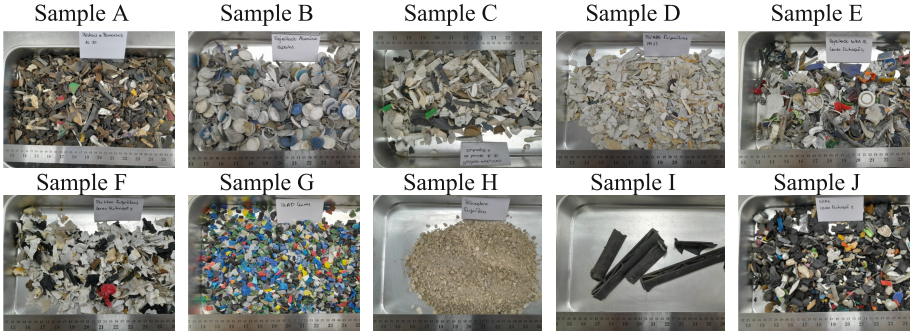


Fig. 1. Tested samples

After Fig. 1 it can be observed that: Sample A is heterogeneous containing 18 different waste types, with prevalent components such as wood, rubber and rigid plastic; Sample B contains 10 different waste types, consisting of mixed paper capsules and white and blue plastic capsules; Samples C and F exhibit 9 and 16 diverse waste types, respectively, with more than half composed of rigid plastic with a melting point around 190 ºC; Sample D is homogeneous and is made up of polystyrene and acrylonitrile-butadiene-styrene plastics commonly found in fridges and washing machines; Sample E is heterogeneous, comprising 20 different waste types like cork, rubber and various

types of rigid plastics with high melting points; Sample G is homogeneous and holds commercial value, consisting of high-density polyethene plastics; Sample H is homogeneous and contains polyurethane used as a sealant in fridges; Sample I is homogeneous consisting of rigid plastic typically used in the form of pallets; Sample J contains 11 different waste types, with over half being rigid plastics with high melting points.

To characterize the plastics, each sample was visually separated based on residue and plastic colour. All sample groups were weighed to evaluate the constituent percentage in each sample (Fig. 2). It was performed the density test in water to separate the floating constituents (<1 g/cm^3) from the non-floating ones (>1 g/cm^3). To determine which samples would have the ability to incorporate in bitumen through the wet method, the melting point of sample constituents was assessed. Therefore, each constituent was placed for 45 min in a ventilated oven at 50 ºC, 75 ºC, and 100 ºC and the temperature was gradually increased with intervals of 10 ºC up to 200 ºC. It was observed that the particles with lower density melted at lower temperatures. Based on constituent melting points, four samples, B, D, G and H were chosen for further testing. Figure 3 shows the melting temperatures of representative constituents from these samples. Sample B, despite being a heterogeneous sample, approximately 77% of started to melt at 120 ºC. Sample D, being homogeneous, did not melt at 200 ºC. Sample G, also homogeneous, began melting at 170 ºC. Finally, sample H did not melt at 200 ºC.

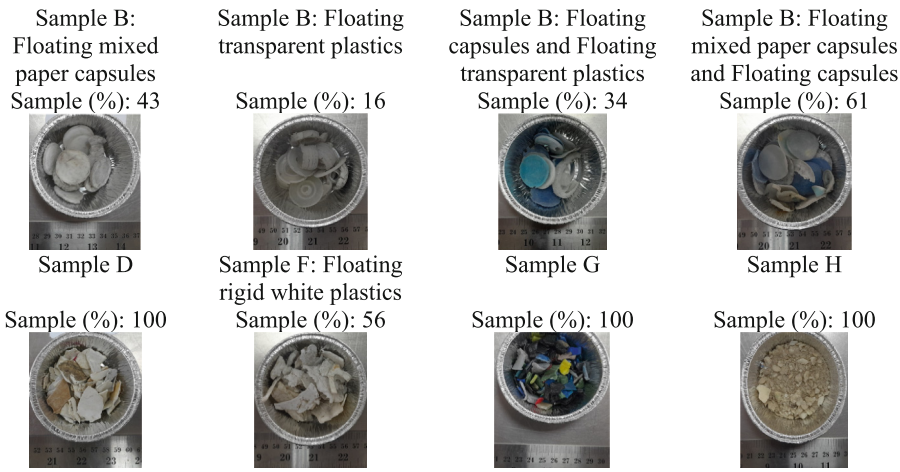


Fig. 2. Samples' representative constituents: presentation and percentages

3 Incorporation of Plastics by Wet Method

To evaluate the ability of plastic to be incorporated by wet method a 35/50 penetration bitumen was used. A portion of bitumen was heated at 150 ºC and up to 20% by mass of plastics were added into the bitumen to try to obtain an extremely saturated bitumen and observed its behaviour when combined with the respective plastics. This allowed

to identified the best percentage of plastic to add for future tests. To reduce the plastics particles' size, they were hand-cut. Sample B proved to be the most suitable for partially mixing with the bitumen resulting in a well-modified, highly viscous bitumen. Despite being in a saturated state, there were no issues with integrating the plastic into bitumen. The result for sample D confirmed the suspicions of it being a thermoset, showing no integration into bitumen. This sample might only have potential if the plastic is incorporated via dry method to partially substitute the fine aggregate fraction. Sample G demonstrated a partial blending with the bitumen, resulting in a modified bitumen with lower viscosity compared to the modified bitumen obtained with sample B. The polyurethane (sample H) when in contact with the bitumen, became extremely saturated, making stirring challenging. The resulting modified bitumen lacked the flexibility and viscosity characteristics observed in samples B and G. Following the test outcomes, the choice for further experimentation was narrowed down to samples B and G. The only advantage of sample G over sample B was its homogeneity. On the other hand, sample B showed much better results in the melting point test and a more flexible and viscous modified bitumen. The environmental aspect should also be taken into account, since sample G is the only one that has commercial value and can be recycled, unlike sample B which is only fit for landfill or incineration. Therefore, considering all presented factors, sample B emerged as the suitable option for further studies.

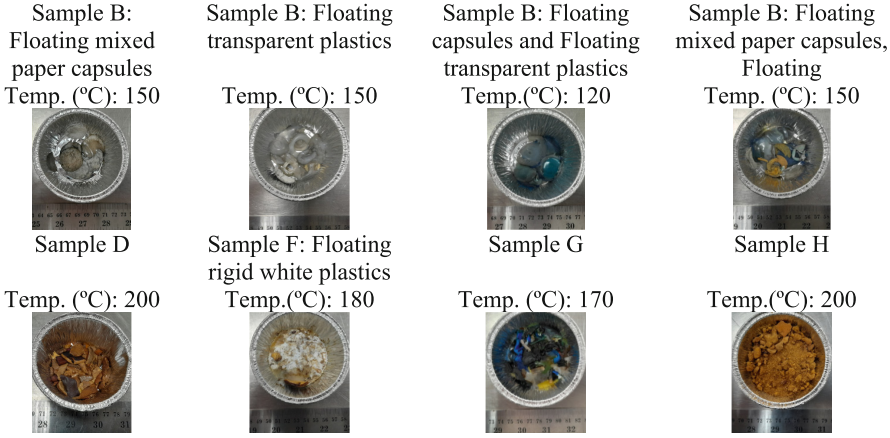


Fig. 3. Melting point of representative constituents of the selected samples

To perform the remaining tests, there was a change in the neat bitumen as sample B had caused hardening upon modifying the bitumen. The penetration test and the determination of softening temperature by ring and ball method were performed using a nominal penetration bitumen 50/70. Aiming to assess differences between the virgin bitumen and the bitumen containing 1%, 2%, 4% and 6% of hand-cut plastic using scissors. Upon mixing at 150 ºC, it was observed that some plastic samples did not properly fuse with the virgin bitumen. Despite increasing the temperature up to 175 ºC, the results remained similar. The tests were performed with the bitumen with incorporated plastic partially fused. Subsequent attempts were made by cutting the plastic into smaller pieces ranging

from 10 mm to 5 mm, yet the issue of partial fusion persisted. Figure 5a) presents a comparison of results between virgin bitumen and bitumen incorporating two different sizes of plastic. Anticipating that an increase in plastic content would modify the bitumen characteristics, rendering it more elastic and subsequently raising the softening temperature, the outcomes did not align with expectations. Although some results display softening temperatures higher than the reference temperature, the observed increase is not as anticipated or consistent. The incorporation of 1% and 2% plastic should theoretically result in a higher softening temperature than virgin bitumen, while the incorporation of 6% plastic should yield the highest temperature. However, the results were opposite to these expectations, nor were they particularly consistent (Fig. 4).

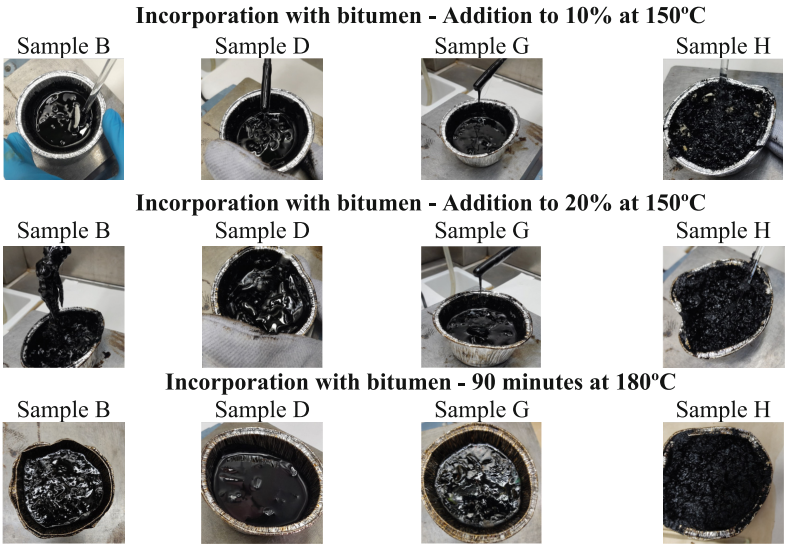


Fig. 4. Incorporation of plastics with bitumen

Regarding the penetration test and the results presented in Fig. 5b), the anticipated expectation was for the penetration to decrease as the percentage of incorporated plastic increased. The graphic does confirm this decrease. However, the lack of a homogeneous mixture led to uneven results within each percentage of plastic, depending on the surface area where the penetration needle was placed.

4 Conclusion

The widespread use of plastic requires applications for managing its waste. In bituminous mixtures, a significant portion of used plastics is processed and converted into pellet form. Aiming to diminish reliance on virgin materials while serving as additives to modify bitumen properties. Such modifications ensure better performance and enhanced mechanical characteristics in bituminous mixtures, notably in terms of Marshall stability [5, 6]. Analysis of the heterogeneous samples reveals that, except for samples B and G, the remaining samples are not recommended for incorporation with bitumen. This is primarily due to considerable variation in waste proportions across different productions and/or elements possessing high melting points requiring higher temperatures than the bitumen specifications proper melting. Incorporation of the sample G does not align with the main objective of addressing the environmental issue related to plastics, as this sample stands as the only one holding recycling potential. In this context, sample B stands out as the most promising option for a high-quality bituminous mixture, as 77% of its constituents have a melting point of 120 ºC. However, during the incorporation of sample B into the bitumen, it was observed that the partial melting of plastic rendered it unsuitable for integration via the wet method. Therefore, future work should focus on incorporating these materials using the dry method in bituminous mixtures. Further tests will also be performed on recovered bitumen from the bituminous mixtures that incorporate plastics.

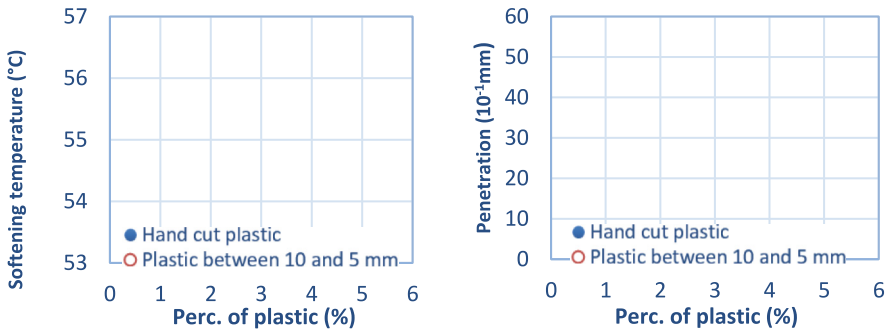


Fig. 5. Comparison between hand-cut plastic and plastic between 10 mm and 5 mm: a) Softening temperature by ring and ball method; b) Penetration test

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Luas Finglas – Delivering a Sustainable Infrastructure – Sustainability, Circular Economy, Active Mobility

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Abstract. The Greater Dublin Area must meet a growing demand for public transport, to cater for an increasing population, while also meeting policy goals for sustainable mobility and climate action. Luas Finglas will be a key component in supporting the planning and development of the Finglas area and provide opportunities to address Dublin's housing challenges by facilitating compact, 'transit-orientated' development. Sustainability is key in the delivery of Luas Finglas. The Project Team, comprising of Transport Infrastructure Ireland (TII) and our Consultant (Barry Transportation - Egis) have taken a highly innovative approach in the project's design, specifically: reducing the environmental impact of the project; use of carbon assessment to inform design solutions; adopting the principles of circular economy; the creation of resilient systems that integrate social needs with nature; and providing integrated transport solutions with better linkages between people, places and resources to drive economic activity. The Project Team worked extensively with all project stakeholders from the outset to: communicate the project objectives, which are linked to strategic policy goals; successfully plan and sustainably co-design the project; and maximise opportunities while considering the future needs of the Finglas area.

Keywords: Sustainability · Circular Economy · Active Mobility · Co-design

1 Introduction and Project Objectives

Luas is Dublin's Light Rail Transit system, which opened to commercial operation in 2004, Since then, there have been several extensions, delivered between 2008 and 2017. There are two main lines: the Luas Red Line (21 km); and the Green Line (22 km). The Luas network has 69 stops and a fleet of 73 trams. Luas customers have completed over 430 million passengers since passenger services started in 2004.

Luas Finglas is a proposed extension of the Luas Green Line from its current terminus in Broombridge to Finglas. The Preferred Route, shown in Fig. 1 below for the proposed extension, is approximately 4 km long, includes four new stops, a cycle and pedestrian path along much of the route, a Park and Ride facility near St Margaret's Road, two

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bridges (Tolka River and Broombridge) and an extension to the tram storage area at the Hamilton Depot at Broombridge.

The alignment is primarily off-road and segregated from traffic providing a high-quality public transport service. In the year of opening, Luas Finglas will provide an additional 1.3 million low carbon public transport trips and remove 440,000 road network vehicle trips, with an approximate journey time of 30 min from Charlestown to Trinity College.

The scheme includes improvements to the walking and cycling network to enable access to Luas and deliver local connectivity benefits, supporting active travel's position at the top of the transport hierarchy.



Fig. 1. Luas Finglas Preferred Route. Image courtesy of TII, reproduced with permission.

The Overarching Objectives for Luas Finglas, informed by policy and the need for the project, comprise:

1. Serve existing and future transport demand;
2. Provide a safe, frequent, reliable, efficient, and sustainable public transport connection from Charlestown and St Margaret's Road (where it also serves a strategic Park & Ride) to the city centre, via Finglas;
3. Reduce public transport journey times be-tween Charlestown, Finglas and the city centre compared to private car trips;
4. Contribute to the Climate Action Plan targets for the decarbonisation of transport;
5. Promote economic growth for the residents and businesses of Charlestown, Finglas and the surrounding areas.

2 Project Approach

The Sustainability Objectives and Strategies for Luas Finglas align with those set out in the National Planning Framework, part of Project Ireland 2040, and the Sustainable Development Goals National Implementation Plan 2018–2020. The sustainability approach to Luas Finglas is also guided by TII's Statement of Strategy 2021 to 2025 and the TII Sustainability Implementation Plan – Our Future (2021).

2.1 Sustainability Plan, Objectives and Vision

At the beginning of the Project, the Luas Finglas Project Team produced a set of realistic and achievable goals with respect to sustainability on Luas Finglas, which are linked to the Overarching Objectives for Luas Finglas. These goals were then incorporated into the Luas Finglas Sustainability Plan, which has been continually updated and tailored for each stage of the project. In addition, each objective within the Sustainability Plan is tracked by the project team across each project phase to ensure full implementation. Key goals include:

- Reduce the environmental impact: Protect, preserve, and improve biodiversity, promote urban ecology, ecosystem services and biodiversity net gain;
- Low carbon transport: Provision of a low-emission light-rail. Carbon assessment and offset of carbon footprint to be fully investigated;
- Circular Economy: Adopt the principles of circular economy to enable sustainable planning and land use management of natural resources and assets;
- Regenerative or restorative design: Creating resilient systems which integrate societal needs with nature;
- Accessibility and sustainable growth: To provide for integrated transport solution with better linkages between people, places, and resources to drive economic activity and enhance regional productivity.

The Environmental Impact Assessment Report (EIAR) for the project, which will be submitted as part of the statutory planning process, documents a thorough industry standard process that assesses the potential environmental effects of the project and establishes appropriate design and mitigation measures to avoid, reduce or offset any predicted environmental impacts.

The Project Team are also using BREEAM Infrastructure, which provides third party verification of the project by an independent assessor from Building Research Establishment (BRE). BREEAM stands for "Building Research Establishment Environmental Assessment Methodology." BREEAM Infrastructure is an evidence-based sustainability assessment scheme for infrastructure, civil engineering, landscaping, and public realm works, which helps to plan, monitor, and later independently verify performance. Luas Finglas is one of the few infrastructure projects in Ireland where BREEAM Infrastructure is currently used, however TII can see the benefits and are also planning to implement BREEAM Infrastructure on upcoming projects.

The following sections set out the innovative approach used on Luas Finglas, whereby emerging sustainable practices are applied to TII's projects, namely: Circular Economy; Regenerative Design; and Accessibility and Sustainable Growth.

2.2 Circular Economy

At the beginning of the project, TII committed to delivering on a Circular Economy (CE) Plan along with a pilot study to apply the principles of CE to Luas Finglas. A series of workshops were undertaken to establish specific CE objectives for the project. Workshop outputs were collated and combined with opportunities developed by Arup into an extensive list of CE opportunities. These long lists of CE opportunities were reviewed by the Luas Finglas Project Team and Arup through two further workshops and refined down to a shortlist of five achievable opportunities. The shortlisted opportunities, which were developed and integrated into the project, include the following:

1. Earthworks Optimisation
2. Design for Disassembly of Track
3. Material Data Integration
4. Material and Asset Sharing
5. Adopting Nature-Based Solutions and Regenerative Design Approach

2.2.1 Earthworks Optimisation

A key opportunity for the project was to identify a way to reduce resource consumption and maximise value of excavated materials by adopting a hierarchy of earthworks materials and an analysis, testing and storage methodology. This methodology was applied as part of a project desk study and later employed within the ground investigations which then developed into a Soil Testing Plan and Strategy for Soil Reuse. Luas Finglas has also utilised the TII Carbon Tool which is specific to light rail and road projects in Ireland. As a result of this tool and its development, TII and the Project team were able to estimate carbon savings on the Project. In terms of cost savings, approximately 20,000 m^3 of material (38–40,000 tonnes) will be made available from proposed cuttings and cut has been minimised overall, both in relation to earthworks balance and to avoid disturbing possible contaminated land on the project.

2.2.2 Design for Disassembly of Track

Existing Luas lines employ both embedded track and grass track. On Luas Finglas it was decided that adopting a design for disassembly approach to the trackform has the potential to increase the maintainability and replaceability of the track and to lower life cycle resource consumption and carbon impacts. A design for disassembly checklist for the track form was prepared by Arup based on ISO 20887:2020 and tested with the project team as part of the design development. The project team also gathered international best practice in track systems for the project track types and developed a reference design that incorporates design for disassembly principles. The key outcome was that carbon savings associated with adopting the grass track design on the project have been estimated by the project team to be a saving of 40% in emissions compared to existing grass track in Dublin. Another benefit is the retention of all components of grass track build up upon rail replacement after 20–30 years, compared to replacement of upper sections of concrete, reinforcement and rails and an improved life duration of rails due to Vignole rail use. The length of embedded track has also been minimised.

2.2.3 Material Data Integration

The Project Team have successfully developed the design using Building Information Model (BIM) for the project, which has been actively used to clearly communicate the design intent with project stakeholders as the design evolved. It will be further developed at later project phases to integrate data collection in the project BIM environment for material data and reuse and recycling information, integrating material and waste register formats prepared for the project enabling re-use of materials.

2.2.4 Material and Asset Sharing

The Luas Finglas Project Team have been actively researching ideas such as sharing of lighting infrastructure (poles and luminaires) with Dublin City Council and Finglas County Council along the Luas Finglas route, which will avoid doubling up of lighting infrastructure. Lighting in public spaces and parks adjacent to stations and crossings is currently designed and maintained separately by TII and local authorities. At stations and crossings, lighting strategies are being coordinated.

2.2.5 Adopting Nature-Based Solutions and Regenerative Design Approach

Biodiversity Net Gain (BNG) is a metric of quantifying biodiversity losses and gains on a project and this idea has also been explored for Luas Finglas. A Pilot Study was commissioned with the Biodiversity and Landscape teams, which resulted in several recommendations including the expansion and enhancement of existing and planned biodiversity wildflower meadows throughout the scheme, which may reduce overall biodiversity loss for the project.

2.3 Regenerative Design

Luas Finglas runs through several parks and local open spaces. It is therefore important that the existing use of these spaces, and opportunities for their enhancement are realised through the design process. Approximately 70% of the line will run on greentrack, which will aid its visual integration in the spaces it passes through. By combining innovative track design and allowing maximum opportunities for successful greening of the track the project will ensure to be sensitive to its landscape setting, be functional in terms of the safe operation of the tram using different vegetation types and be effective for future maintenance. A considered planting palette has been used to create connected green spaces along the route increasing the value of the spaces as ecological corridors for biodiversity. Planting will be multifunctional with all plant types chosen with reference to their adaptability, robustness, and ease of maintenance. Priority will be given to native species and those which provide multiple eco system services and functions. For example, the tree planting palette has been chosen to align form with function. Having a proactive and adaptable tree planting strategy will lead to increased operational efficiency, and therefore reduced risk at all stages of the Trams life. Designers have considered the canopy form of trees near the overhead wires so that they do not become a hazard as trees mature. Trees are a long-term investment in the landscape of Finglas and need to be placed to ensure their long-term viability along the tram corridor. Luas

Finglas stops are located and designed to optimise access, social activity, personal safety, and interchangeability; to make a positive contribution to the built environment by using simple high-quality materials, minimising clutter and respect for the character and context of their surroundings. Universal Design is at the heart of the Finglas extension with consideration given to people with disabilities, people with mobility issues, or women travelling alone. This is manifested in fully accessible and uncluttered layouts, which are safe and easy to navigate and involve prioritisation of walkers, cyclists, and vulnerable users.

2.4 Accessibility and Sustainable Growth

For much of its length, Luas Finglas will form a new transport corridor that will serve an array of local key trip attractors including schools, sporting facilities, parks, and services. The transport corridor will therefore likely generate short distance trips to and from these facilities. The project team leveraged any opportunity to facilitate active travel and improve walking and cycling facilities. As such, an exciting aspect of Luas Finglas is the opportunity to incorporate safe, segregated cycling and pedestrian paths along several sections of the route.

In collaboration with the National Transport Authority, a significant amount of fully segregated-off road active travel corridors are incorporated into the scheme design, consisting of both cycle and pedestrian paths, which run mostly alongside the Luas corridor. Active travel corridors will provide a pleasant environment to walk and cycle, provide access to the Luas stops and raise the attractiveness of the local area. Each Luas stop will include cycle parking facilities, making it even easier to undertake multimodal trips (i.e. Cycle + Ride) and include physical activity as part of daily life.

Luas Finglas will deliver those facilities partly in line with the National Transport Authority Cycle Network Plan for Dublin, and partly in addition to that, as the opportunity became evident. The project provided a unique opportunity to deliver "missing links" in the cycle provision for the area, connecting the future Luas stops with existing and future planned cycle routes.

Measured monetary benefits due to the increase in the levels of physical activity is the key performance indicator that demonstrates the success of the scheme in meeting this criterion. TII's TEAM tool indicates that the scheme will deliver €6.1m of benefits over the 30-year appraisal period due to improvements in modal shift and general health and wellbeing. The proposed off-road walk and cycle infrastructure will link a number of residential areas, local schools, parks, and recreational facilities along the route encouraging sustainable travel, in particular for vulnerable road users and unconfident cyclists. There are 11 primary and 3 secondary schools within approximately 1 km of the Luas Finglas alignment. In total about 3,000 primary school children and 1,500 secondary school pupils attend these schools. The new active travel facilities delivered as part of Luas Finglas will also provide a connection to the Royal Canal Greenway, which offers an off-road link towards Dublin city and is also a great local amenity for recreational trips.

In terms of design of active mode facilities, the layout of cycle tracks within parklands was designed as part of the landscape architect's strategy as such facilities were geared more towards leisure and recreational cycling and had a different "look and feel" to

the more infrastructural role and nature of cycle tracks provided on streetscapes. The principle of designing for all ages and abilities of cyclist has been incorporated. This is reflected in the provision of a high degree of segregation between cyclists and motorists, including the use of protected cycle tracks at signalised junctions. The protected nature of the cycle track will be achieved using a high-kerb to traffic / low-kerb to cycle track separator, which will be landscaped where space allows. There is also an emphasis on segregation between cyclists and pedestrians and avoidance of use of shared surfaces where possible.

The scheme will act as a strong catalyst for social opportunities through improved access to jobs, education, leisure, and social facilities throughout Finglas and Charlestown. Furthermore, areas adjacent to the preferred route will become increasingly attractive for residential, employment and/or mixed-use development, supporting the ambition for compact, 'transit-oriented development' as set out in Project Ireland 2040. The recent rezoning of industrial lands in Jamestown by Dublin City Council is a testament to this process.

The scheme will serve the population of the Finglas study area, which is projected to grow by over 10,500 people to over 56,500 by 2035, a 23% increase on the population in 2016. Through the substantial increase in public transport capacity and improvements to journey times and reliability, Luas Finglas will have a significant economic impact, improving the attractiveness of the area it serves, supporting the delivery of regeneration and development investment, and providing capacity to enable medium and long-term compact and sustainable growth.

The improved connectivity offered by the extension will widen employment opportunities and improve access to education and health facilities, leading to improved economic, health and social outcomes, reducing social exclusion and supporting improvement in the levels of affluence for residents in the area.

3 Conclusions

The Project Team worked extensively with all project stakeholders from the outset to: communicate the project objectives, which are linked to strategic policy goals; successfully plan and sustainably co-design the project; and maximise opportunities while considering the future needs of the Finglas area. Luas Finglas is recognised by key stakeholders, in particular by the local authorities (Dublin City Council and Finglas County Council), in delivering on Environmental, Societal and Economic improvements within the Finglas area. The project will provide a new low carbon public transport corridor, provide an alternative to car ownership, create new opportunities and access to jobs and education, facilitate 'transit-orientated' development along the corridor and integrate with other public transport projects, such as Dart + West and BusConnects. Furthermore, the project will improve areas that Luas passes through and provide new opportunities, such as active travel links, bio-diversity corridors, together with landscaping and urban realm enhancement. The proposals for the project have all been explored, developed, and co-designed in close collaboration with all project stakeholders, resulting in a well-planned, sustainable project that not only meets the needs of stakeholders but also aligns with emerging national policies, particularly those related to climate action and environmental sustainability.

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Sustainability Considerations in the Design of Earthworks for Road Projects

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Abstract. The earthworks associated with the construction of a National Road project can be significant in terms of the sustainability of the scheme. Appropriate consideration of earthworks at the early stage of design and planning, particularly at the option selection, preliminary design, and environmental impact assessment phases of a project, is necessary to achieve objectives such as waste minimisation, optimal material re-use, re-use of materials at their highest value, and minimisation of construction-stage carbon emissions. These early stages present opportunities for designers to optimise the scheme design at the stage at which it is most flexible and sustainability and circular economy objectives can be achieved most easily, rather than requiring reactive, and potentially more costly and less sustainable solutions, at subsequent design phases. However, the early-stage consideration of earthworks needs to be commensurate with the level of detail of the scheme design at this stage, and the geotechnical information available. There is therefore a need for earthworks analysis tools which can be practically applied on projects, with regard to the number of options which may require to be assessed, and the relatively limited site-specific ground information which may be available. This paper outlines the development of spreadsheet-based tools which can be used to undertake material analysis, mass haul assessments, and haulage analysis, while taking consideration of haulage constraints, material sources, and deposition areas. Appropriate application of these tools can make a key contribution to achieving the above sustainability and circular economy objectives. The paper will also describe possible approaches to ground investigations and collation of geotechnical information at the early stages of road projects.

Keyword: Sustainability · Circular Economy · Earthworks · Reusability

1 Introduction

The earthworks associated with the construction of a National Road project can be significant in terms of the environmental impacts, energy usage, and sustainability of a scheme. Globally, the overall construction industry is estimated to account for over 37% of all energy consumption and carbon emissions [1] with earthworks related activities (e.g. excavation, transportation and deposition) typically contributing to the majority of construction related CO_2 emissions on road infrastructure projects [2]. In Ireland,

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between 2017 to 2021, the quantity of waste generated from construction increased from 4.8 million to 9 million tonnes, where 85% of the quantum in 2021 was classified as 'soil and stone' [3].

2 Sustainability Policy

With respect to the National Road Network, TII are committed to lead in the delivery and operation of sustainable transport, and have developed a Sustainability Implementation Plan, outlining key sustainability principles which set-out the aim and ambition of the organization [4]. These sustainability principles include:

- Developing sustainable assets through innovating and improving the planning, design and construction of the network (Principle 3);
- Reduce the carbon impact of construction, operation and use of the transport network through responsible use of resources, reuse and repurposing (Principle 5); and
- Enhance the balanced delivery of economic, environmental and social value through robust planning, rigorous appraisal and decisions that prioritises sustainability (Principle 6).

The Department of Environment, Climate and Communications have also set out various climate actions in the Climate Action Plan 2023 (CAP23) to put climate solutions at the centre of economic development in Ireland [5]. Actions related to earthworks include:

- Transport - Updates to the transport appraisal guidance to provide decision makers with a broader set of information about a scheme's potential climate, social and environmental impacts (TR/23/13).
- Circular Economy - Reduce demand for virgin raw materials and support re-use, by keeping material out of waste streams through streamlined end-of-waste and by-product decision-making processes and national end-of-waste decisions for specific construction and demolition waste streams (CE/23/3).

3 Earthworks Aspects of Sustainability

To achieve the aims and actions above, it is important to consider the following earthworks-related sustainability objectives as part of the scheme design:

- Optimisation of Material Extraction
- Maximisation of Material Re-Use
- Allocation of Material at Highest Value
- Optimisation of Haulage
- Minimisation of Waste
- Minimisation of Reliance of External Natural Resources

Inadequate consideration of earthworks in terms of reusability, allocation and movement/haulage can have a significantly negative contribution to the environmental impacts for a road project. The consideration of measures at planning phases is particularly important because early interventions have the potential to be significantly less costly than

remedial measures implemented during detailed design and construction post-statutory approval [6].

Therefore, to achieve sustainability objectives in the context of road design in Ireland, it is critical that consideration is given to earthworks at the option selection and preliminary design stages prior to statutory approval, at which point further changes to the alignment may be restricted. The scheme design is more flexible at the early phases of a project. Presenting greater opportunities for design to incorporate sustainability objectives. Failure to adequately consider earthworks at these early stages can result in the need to subsequently adopt reactive design solutions or construction requirements after the route alignment is fixed, often leading to higher energy consumption, increased waste, or less sustainable construction practices.

To facilitate consideration of these objectives in a consistent manner, TII commissioned the development of Excel-based tools which provide a structured means to conduct mass haul and earthworks analysis at these early project phases, while using the platform to explore and incorporate earthworks-related sustainability objectives in the scheme design.

4 Mass Haul and Earthworks Analysis

While Mass Haul is often defined as volume of material times distance moved during construction, effective Mass Haul and Earthworks Analysis (MEA) should take account of other important aspects, including,

- Material Acceptability
- Material Bulking and Compaction Factors
- Material Classification and Value
- Source and Destination, including Alternative Sites
- Haulage Distance, Gradient and Constraints
- Haulage Equipment

Excel-based tools have been developed to provide a semi-automated and structured process to undertake MEA at the option selection and preliminary design phases of a National Road Project. Table 1 provides a summary of the functions available within the tool which aid in the consideration of key earthworks-related sustainability objectives. An example of a Mass Haul Diagram is shown in (Fig. 1).

However, the degree of analysis and design varies across these early phases of a project. For example, the engineering and environmental considerations related to option assessment and selection, require an understanding of the geological units within each option. This will typically include the soil and rock strata present, their approximate depths and extents, and identification of significant ground hazards such as peat, soft soils, karst and contaminated ground.

By comparison, during preliminary design, a more refined understanding of the material is typically developed in line with earthworks material classifications, whereby the ground model is further refined and materials are assessed in terms of their suitability and reusability as earthworks materials. This can be informed by reusability and acceptability laboratory testing of samples collected during a ground investigation. To

align with these requirements, two separate tools have been developed for use during Option Selection and Preliminary Design respectively, where the inputs required are aligned with the level of data available typically available or required at the associated phase. The Option Selection MEA Tool relies upon generalised material designations such as topsoil, overburden, and bedrock. The Preliminary Design MEA Tool is aligned with material designations outlined in TII Specification for Road Works Series 600 Earthworks [7].

The effectiveness of the Excel-based MEA Tools is dependent on key ground-related data, where the extent and quality of the ground-related data is intrinsically linked with the quality of the outputs required for the designer to optimise the design and both explore and meet sustainability objectives. Appropriate ground interpretation is also required in order to assess the ground conditions and determine an estimate on the engineering characteristics and critical inputs required such as acceptability and reusability.

Given the complex and variable nature of soil and rock, site-specific ground investigation is required to facilitate appropriate ground interpretation. However, the level of ground information needs to be considered by the designer and should be appropriate for the nature of the project and the phase under consideration.

Table 1. MEA Tool functions for consideration of earthworks-related sustainability objectives

Earthworks-related Sustainability Objectives	Associated Functions within Mass Haul and Earthworks Analysis (MEA) Tools
Optimal Material Extraction	Mass Haul Diagrams are automatically generated to emphasise the cumulative surplus and deficit along the scheme, while also provide tabulated data on the total quantities across the different material classification
Maximisation of Material Re-Use	The tool facilitates the consideration of the reusability of each material designation across all the earthwork areas automatically generated. The reusability process allows the user to distribute the volumes across the categories (from an engineering perspective) of acceptable, marginal, unacceptable, and hazardous. This distribution is to be based on iterative technical reviews, ground investigation information and the professional experience of the Designer

(*continued*)

Table 1. (*continued*)

Earthworks-related Sustainability Objectives	Associated Functions within Mass Haul and Earthworks Analysis (MEA) Tools
Allocation of Material at Highest Value	The user is required to consider and allocate material classifications to the site won material, including high value materials such as Select Fill and Subbase materials. The functionality of the tool allows the user to iteratively review whether the potential value has been optimised (e.g. using the Mass Haul Diagrams and tabulated outputs to investigate distribution and resulting surplus/deficit)
Optimisation of Haulage	Using outputs typically available from Road Geometry Software packages, the tool automatically analyses the movements between earthworks areas and identifies to the user where movements are crossing significant constraints, the concentration of uphill movements and distribution of freehaul (economical) and overhaul (uneconomical) movements
Minimisation of Waste	The tool permits the user to include material deposition areas and borrow areas within the analysis, allowing the user to designate the proposed deposition or extraction potential across different material designations. This function, along with the previous functions mentioned, can allow the user to iteratively review the reusability, classification and allocation of the site won material, and maximise alternative source and destination sites to minimise or avoid waste
Minimisation of Reliance of External Natural Resources	Where no further refinement can be made to the earthworks analysis, the tool outputs can be used to highlight areas of the alignment which could be altered to reduce or remove the need for import or export of material

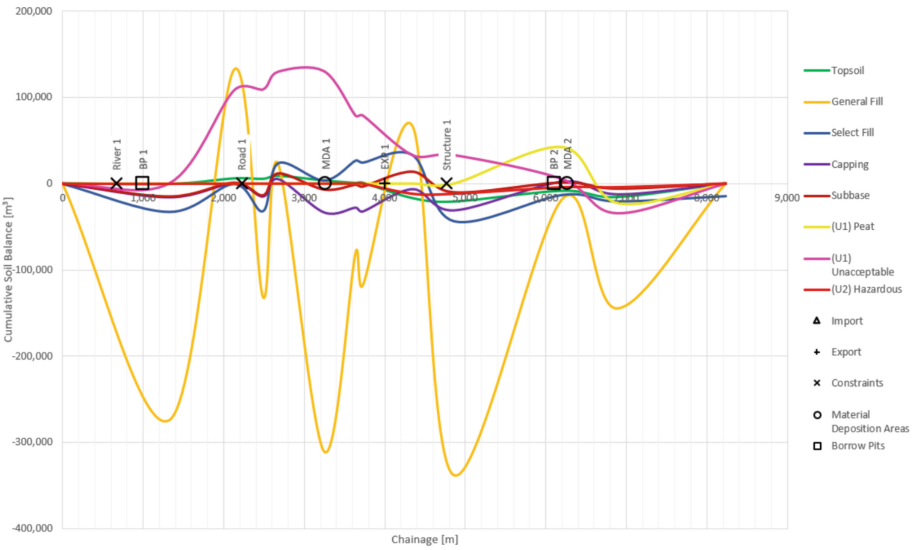


Fig. 1. Example of Mass Haul Diagram output from MEA Tool

5 Implementation and Future Development

Following development of the tools, pilot trials were undertaken on two National Road schemes, the N17 Knock to Collooney Scheme at Option Selection phase, and the N25 Oilgate to Rosslare Scheme at Preliminary Design phase. Both trials demonstrated the effectiveness of the tools as practical aids to design teams at these phases, while assisting in the identification of sustainability opportunities in earthworks design. Feedback from the project teams was used to modify the tools in terms of their operation and outputs.

The tools, along with a User Guide, were subsequently made available to all National Road project teams, by TII. Since that time, feedback from users has been collated, and used to make minor amendments to the tools in order to improve their useability and effectiveness.

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Evaluation of Lignin-Bitumen Blend as a Sustainable Alternative for Asphalt Binder

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Abstract. To address the need to mitigate climate change and reduce carbon emissions, the road industry faces the challenge to reduce its dependence on fossil fuel-derived bitumen in asphalt pavement. This paper presents evaluation of lignin obtained from TNO FABIOLA^{TM} process as a sustainable alternative to traditional bituminous binders. DSC test determined the melting of the lignin, which aided in the selection of the blending temperature. The blending process achieved homogeneous dispersion and dissolution of lignin within bitumen, constituting 25 wt.% in the total binder. Rheological assessments, conducted using DSR revealed that the viscoelastic properties of the lignin-bitumen blend closely resembled those of penetration grade bitumen, suggesting the lignin potential as a viable substitute without compromising rheological performance. Furthermore, MSCR test results showed resistance to permanent deformation in the lignin-bitumen blend comparable to the penetration bitumen. Two asphalt mixtures were prepared, one with the reference PmB and another with the lignin-bitumen blend, as an alternative binder. Water Sensitivity Tests (WST) on both fresh and aged specimens revealed no detrimental effects on Indirect Tensile Strength Ratio (ITSR) values. These findings highlight the potential of lignin as sustainable alternative to bitumen, advancing road materials with reduced environmental impact.

Keywords: Lignin-bitumen blend · rheological properties · sustainable binder · multiple stress creep recovery (MSCR) test · indirect tensile strength ratio (ITSR) · stone mastic asphalt (SMA)

1 Introduction

The urgent need to combat climate change and reduce carbon emissions is driving innovation in the road construction industry. One of the challenges is to reduce the dependence on fossil fuel-derived bitumen. To address this, engineers and scientists are turning to biomass-derived materials, with lignin emerging as a promising alternative binder for asphalt pavement [1].

Recent research extensively explored the potential of lignin as a partial substitute for conventional bitumen in various applications [1–6]. Some studies reported lignin incorporation has shown promise in improving rutting resistance and low-temperature

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cracking, while others highlight the antioxidant properties of lignin and their impact on binder performance [2–4]. In 2015, a patent was filed for blending native and chemically modified lignin with bitumen, revealing the potential to partially replace bitumen to varying extents, with chemically modified lignin exhibiting characteristic rheological properties similar to polymer-modified bitumen [5, 6]. Increasing lignin content increased the viscosity of the blend, where 25 wt.% lignin content showed optimum viscoelastic properties [1].

Current study focused on preparing a lignin-bitumen blend using 'U10' lignin obtained from beech wood, partially substituting (25 wt.%) bitumen. DSC analysis revealed its melting point at 142 °C and the blending process ensured a homogeneous mixture. To assess the potential of the lignin-bitumen blend, a comprehensive rheological evaluations compared the blend to reference PmB and 70/100 penetration bitumen. The results showed that the viscoelastic properties of the lignin-bitumen blend closely resemble those of 70/100 bitumen, suggesting the viability of the lignin as a bitumen substitute without compromising the rheological performance. Furthermore, MSCR parameters predicted resistance to permanent deformation, with the blend showing improved performance compared to neat bitumen. The study extended its assessment to the asphalt level, evaluating Stone Mastic Asphalt (SMA-14) mixes. Water Sensitivity Tests (WST) on both fresh and aged samples revealed positive outcome in ITSR values.

2 Materials and Methods

2.1 Materials

Paving grade bitumen of penetration 70/100 and a polymer modified bitumen (PMB 65/105-60) provided by Breedongroup-Ireland were studied as reference bituminous binders in this study. Lignin-U10, processed from beech wood feedstock by TNO FABIOLA™ process was used for partial substitution (i.e., 25 wt.%) of bitumen. FABIOLA™ is an organosolv process that involves fractionation of biomass using low temperature acetone [7]. 'U10' is the number of the pilot run in which this specific lignin was produced. The lignin was brown fine powder at room temperature as delivered which could be used directly for blending without further drying or milling. The reference penetration 70/100 bitumen was used as a base bitumen to prepare the lignin bitumen blend. The blend is used to prepare Stone Mastic Asphalt (SMA) 14 slab and another reference mixture slab of SMA 14 was prepared using the PmB.

2.2 Methods of Preparation and Characterization

Blend Preparation: Lignin was blended with bitumen using a high shear mixing assembly followed by a low shear mixing according to the procedure described in the patent WO2015/137813. 2015 [5]. 25wt.% (i.e., by mass) lignin was added in penetration grade 70/100 bitumen. The bitumen was pre-heated in the oven for two hours at 140 °C and prior to blending was heated to 170 °C on a temperature-controlled heater plate. Lignin was gradually added using a sieve to control the particle size (<0.5 mm) and to improve the dispersion of the powder lignin during blending. After addition of the lignin, the lignin and bitumen are mixed at high shear for 5 min in 1000–1500 rpm followed by mixing at low shear for 30 min in 200–300 rpm.

Dynamic Shear Rheometer (DSR): The rheology of the original bitumen, a reference polymer modified bitumen and the lignin-bitumen blend were characterized by using DSR - Modular Compact Rheometer MCR 502 from Anton Paar. To obtain the master curves, two parallel plate test configuration was used with 8-mm plates of 2-mm gap for −10 to 30 °C and 25-mm plate of 1-mm gap for the temperatures 30–60 °C at a frequency of 0.1–400 rad/s. The DSR measurements were performed according to EN 14770–2022 where the measurements were carried out first by strain sweeps followed by frequency sweeps at different temperatures [8]. Parallel plate geometry of a diameter of 8 mm was used for the temperatures -10 to 30 °C and a diameter of 25 mm from 30 °C to 60 °C. Using the time-temperature-superposition principle, the frequency sweep data from different temperatures were shifted horizontally at a reference temperature of 20 °C to construct mastercurves of complex shear modulus |G*| and phase angle (δ) as a function of frequency.

MSCR Method: MSCR test was performed at 60 °C using DSR to evaluate the susceptibility of the binders for permanent deformation at high service temperature. The test was carried out according to the standard EN 16659 procedure in a plate-plate geometry of 25 mm diameter with a gap of 1 mm [9]. The binders were tested under shear creep and recovery at two stress levels of 0.100 kPa and 3.2 kPa at 60 °C, where the specimens were loaded at constant stress for 1 s, then the load was removed allowing to recover for 9 s. MSCR was performed first starting at the low stress level of 0.1 kPa for 10 creep-recovery cycles followed by an additional 10 cycles at 3.2 kPa. The MSCR parameters were calculated according to EN 16659 and presented in the result section.

Differential Scanning Calorimetry (DSC): DSC analysis was performed to determine the melting point of the lignin and to scan any additional thermal event. The DSC procedure for lignin was adapted from the ASTM standard -ASTM D4419-90(2021) [10]. To prepare a specimen, lignin sample of 10 ± 1 mg was taken into 50 µL DSC aluminium sample pans as shown in the Fig. 1.

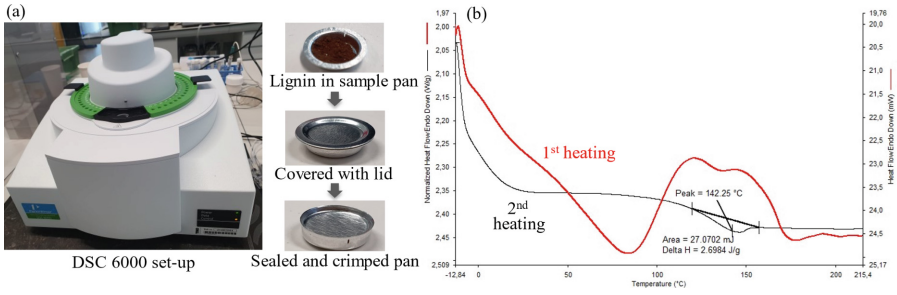


Fig. 1. (a) DSC set-up, sample preparation (left to right) to measure the thermal properties of lignin. (b) Thermal curve showing melting temperature of lignin derived from the heat flow as a function of temperature.

Prior to the DSC run the instrument was calibrated using a reference i.e. Indium sample and its melting temperature T_m (156.6 °C) was used as a calibration reference. The lignin was heated from −10 °C to 220 °C at a heating rate of 10 °C/ min. The heat

flow measured through the sample pan was compared with an empty reference pan and heat flow as a function of temperature was recorded.

Asphalt Preparation: In order to assess asphalt properties, two Stone Mastic Asphalt (SMA-14) slabs were prepared, one with PmB as a control mixture and the other using the lignin-bitumen blend with the same mix-composition. The asphalt mixtures were produced using the standard mix composition. Half of the asphalt specimens were subjected to long-term aging simulation at 85 °C in the oven for three weeks. Subsequently, a Water Sensitivity Test (WST) was conducted according to EN 12697-12:2018 on both fresh and aged specimens to evaluate their resistance to moisture damage.

3 Results

3.1 Binder Evaluation

Thermal Properties of Lignin-U10: Figure 1b showed heat flow curves from DSC temperature scans of U10-lignin. In the first heating, a broad evaporation endotherm indicated residual moisture and the second heating revealed the melting peak at 142 °C in the lignin. Melting point was a useful data to check and verify the mixing temperature for the lignin-bitumen blend preparation. Here the mixing temperature was 170 °C, above the melting point of lignin, ensuring proper dissolution into bitumen.

Mastercurves: The viscoelastic response of a 25wt.% lignin-bitumen blend overlapped with that of the original 70/100 bitumen (see Fig. 2a and b). This study demonstrated that the viscoelastic properties of the lignin blend were similar to those of neat 70/100 bitumen, with overlapping complex shear moduli and phase angles. U10-lignin replaced 25wt.% bitumen without compromising its viscoelastic properties, indicating good lignin and bitumen compatibility. The lignin-bitumen blend did not exhibit the characteristic plateau in the phase angle response at a low frequency or high-temperature region, as seen in the PmB response (Fig. 2b). This plateau is a result of elasticity in PmB, resulting from the polymer network in the bitumen. This suggests that the blend did not have a similar network structure as PmB, and as a result, it exhibited rheological properties similar to 70/100 bitumen.

MSCR: The MSCR test evaluated the high-temperature performance of the lignin-bitumen blend, comparing it to reference PmB and penetration bitumen and the results are summarized in Table 1. The creep compliance parameter "J_{nr}" quantifies a binder's non-recoverable portion due to creep-recovery cycles, indicating its contribution to permanent deformation at the asphalt mixture level. Additionally, the recovery value R reflects the delayed elastic response of the polymer in the binder. The parameters show that 70/100 bitumen exhibited a purely viscous response with no recovery at both stress levels. Whereas, PmB demonstrated a higher potential for recovery compared to 70/100 bitumen, displaying delayed elastic response and substantial recovery. The lignin-bitumen blend exhibited limited recovery at the low stress level (0.1 kPa) but a purely viscous response at 3.2 kPa. The J_{nr} values of PmB were lower than the other binders, indicating better resistance to permanent deformation due to its polymer network. Higher stress levels resulted in higher permanent deformation. The J_{nr} values in lignin-bitumen blend

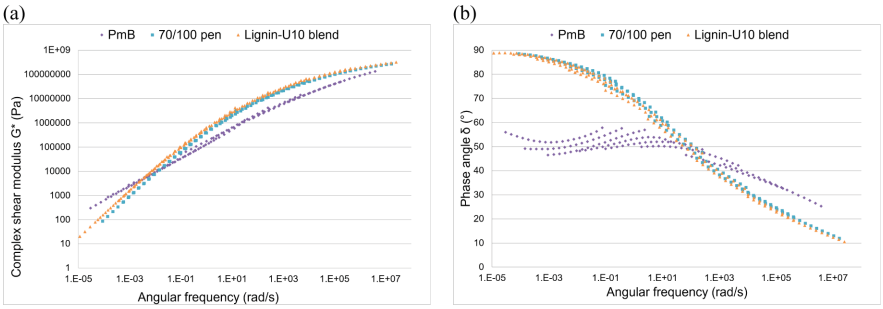


Fig. 2. Mastercurves of original PEN 70/100 bitumen, reference PmB and 25wt.% U10 lignin-bitumen blend as a function of angular frequency. (a) Complex shear modulus and (b) Phase angle.

were lower than those of 70/100 bitumen at both stress levels, demonstrating that the blend improved rutting resistance to some extent.

Table 1. MSCR test results of the binders.

Binder	Average recovery of the 10 cycles R (%)		Difference in recovery R_{diff} (%)	Average non-recoverable part of cycles J_{nr} (1/kPa)		Difference in non-recoverable compliance $J_{nr\text{-}diff}$ (%)
	@0.1 kPa	@3.2 kPa		@0.1kPa	@3.2 kPa	
Pen 70/100	0	0	-	7.0	7.72	10.1
PmB	87.2	86.5	0.73	0.1	0.13	14.2
Lignin-bitumen blend	3.1	0	-	5.3	6.2	16.3

3.2 Asphalt Evaluation

Indirect Tensile Test (ITT) were performed at 15 °C for both fresh and aged specimens of SMA-14 with reference PmB (SMA14-PmB) and lignin-bitumen blend (SMA14-70/100 bio). Indirect tensile strength ITS and ratio ITSR values are measured and the data are presented in Fig. 3.

With ageing, ITS values increases which is due to the hardening of asphalt as a result of the stiffening of bitumen. SMA14-PmB had a comparable wet and dry strength values. Whereas, SMA14-70/100 bio shows higher strength compared to SMA14-PmB and optimum ITSR values.

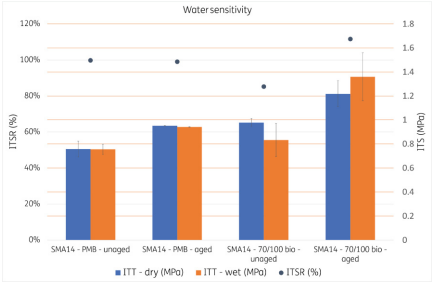


Fig. 3. ITS and ITSR values at dry and wet conditioning.

4 Conclusions

The thermal analysis revealed a melting point of 142 °C for U10 lignin, guiding the blending process to ensure effective lignin dissolution in bitumen. Using both high and low shear mixing processes at 170 °C resulted in a homogeneous blend with minimal lignin sedimentation. The complex shear modulus and phase angle mastercurves indicated that the lignin-bitumen blend possesses viscoelastic properties comparable to penetration 70/100 bitumen showing the potential to replace penetration bitumen without compromising rheological properties. The creep-recovery response aligned with penetration 70/100 bitumen, indicating favorable properties for rutting resistance. It showed some recovery at low stress level, while a fully viscous response at high stress level.

Evaluating the ITS values of SMA-14 mixes, the blend demonstrated optimum ITS and ITSR values, showcasing its potential for optimal asphalt mixture properties. This research showcases lignin as a promising and sustainable alternative to bitumen, with good compatibility, comparable viscoelastic behavior, and enhanced resistance to permanent deformation.

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KPI Framework for Assessing Pavement Sustainability

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Abstract. This paper presents a methodology for assessing the sustainability of pavements through indicators. There are increasingly different procedures, technologies and practices to increase the sustainability of construction works. Especially in the field of roads, research work is being carried out to develop new asphalt mixes with low emissions, as well as to promote the reuse of recycled materials. All of these practices will greatly contribute to sustainability. However, sustainability is a relative parameter that should be used for comparison. There are no sustainable activities in absolute terms, but there are activities that are more or less sustainable compared to others. When the sustainability of two different products or activities is evaluated, the aim is to compare them and, therefore, the evaluation must be carried out following a homogeneous procedure. This paper introduces a methodology based on KPIs that will provide pavement designers with a tool to quantify and compare the sustainability of different pavement structures in order to select the best pavement alternative from a technical, economic and sustainable point of view.

Keywords: Circular economy · sustainable pavements · sustainability assessment · recycled material

1 Introduction

The construction sector, and in particular the road sector, is one of the sectors with greatest potential to contribute to sustainable development. The construction of roads produces significant impacts on the ecosystem, the economy and on social productivity, as it implies a considerable consumption of non-renewable resources and generates greenhouse gas emissions (GHG). Currently, the sector is adopting sustainable practices such as the use of recycled materials and the reduction of the temperature of asphalt mixes.

A sustainable pavement is defined as a pavement that achieves its specific engineering goals, while, on a broader scale, (i) meets basic human needs, (ii) uses resources effectively, and (iii) preserves/restores surrounding ecosystems [1]. Sustainability is a relative parameter that is used for comparison. There are no sustainable activities in absolute terms, but there are activities that are more or less sustainable than others. Therefore, a

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homogeneous and systematic process is needed to quantify and compare sustainability of two different processes or activities. This paper introduces a methodology for assessing the sustainability of pavements through indicators.

The objective of the developed methodology is to create a reference framework that allows engineers to assess and compare the sustainability of different pavement structures in a homogeneous way, in order to choose the most appropriate pavement solution from a technical, economic and sustainable point of view.

2 Sustainability in Road Design

Nowadays, an increasing number of processes, actions, and features are being developed to improve existing pavement construction processes towards greater sustainability [2]. These pavement sustainability best practices aim to achieve the following sustainable development goals:

- To reduce CO_2 emissions and energy consumption, thereby reducing greenhouse gas emissions and improving the energy balance in road construction.
- Apply circular economy principles in pavement design, minimising the consumption of raw materials and encouraging the use of products made from reused or recycled materials (e.g., milling material, recycled aggregates, powdered tyres, plastics, etc.)
- Increase economic sustainability by increasing the durability and life cycle of pavements, thereby reducing material consumption and life cycle costs.

The following chapter presents a methodology based on KPIs that will allow engineers to assess and compare the sustainability of different pavement alternatives, in order to select the optimal solution.

3 KPI Framework for Assessing Pavement Sustainability

The developed framework to assess and compare the sustainability of different pavement alternatives comprises mainly two steps, as show in Fig. 1: (i) an assessment of the sustainability using indicators and (ii) an economic analysis.

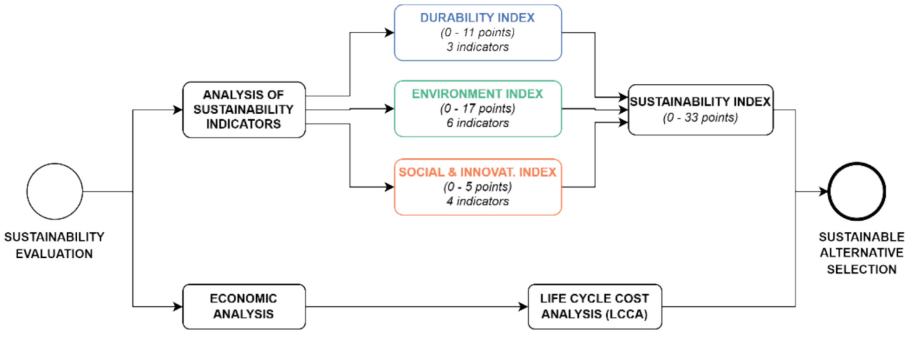


Fig. 1. KPI Framework for assessing pavement sustainability

3.1 Analysis of Sustainability Indicators

Firstly, a set of indicators representative of the different pillars of sustainability are evaluated, grouped into three categories: (a) durability, (b) environmental, and (c) social and innovation. Each indicator is evaluated, and a score is assigned to each indicator depending on the characteristic of the pavement structure. The scores are allocated following a scoring system specifically developed in this methodology. The different indicators considered are briefly described below (Fig. 2).

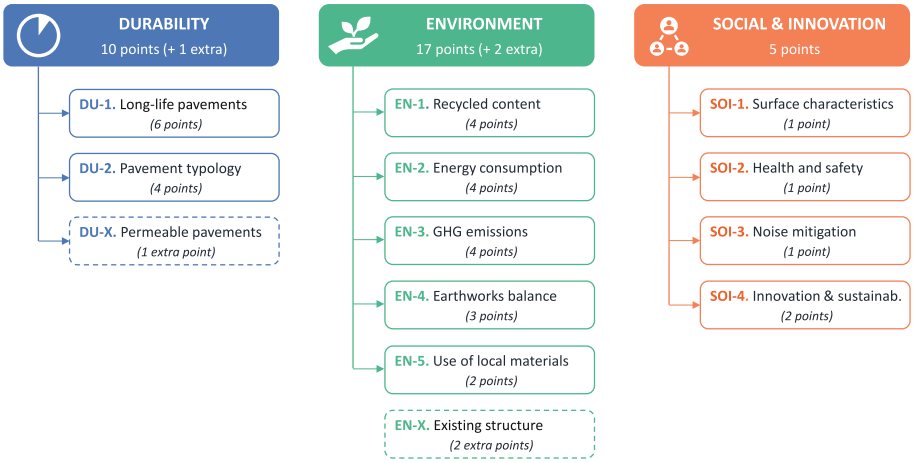


Fig. 2. Indicators and categories for the assessment of pavement sustainability.

Durability Indicators

This category aims to foster the design of pavements that have a long service life and require less maintenance. Road construction, maintenance and rehabilitation activities consume energy and resources, generate GHG emissions and increase traffic congestion. Additionally, traffic congestion increases travel times leading to unnecessary fuel consumption and emissions. Therefore, designing pavement sections that provide a longer useful life and require less maintenance tasks is considered a sustainable practice that will help to mitigate these effects. The following indicators are assessed within this category:

1. **DU-1. Long-life pavements:** this indicator evaluates the theoretical service life of the projected pavement section. Higher scores are awarded to sections projected with a service life greater than the minimum required by regulations. The score of this indicator ranges between 0 and 6 points.
2. **DU-2. Pavement typology:** this indicator evaluates the type of pavement section considered. The score of this indicator ranges between 0 and 4 points. Higher scores are allocated to pavement typologies that provide greater durability and require less maintenance.

3. **DU-X (extra). Permeable pavements:** additionally, this extra indicator is included in order to encourage the design of pavements that provide alternative means of drainage. This indicator gives an extra point to projects that include permeable pavements in areas where they are technically feasible.

Then, once the indicators within this category have been analysed, a Durability Index is obtained as the sum of the scores obtained in each of them.

$$\text{Durability Index} = \text{DU} - 1 + \text{DU} - 2 + \text{DU} - \text{X} \quad (1)$$

Environment Indicators

This category aims to minimize the environmental impact of pavements construction by fostering the use of recycled materials, and minimizing energy consumption and GHG emissions, among other sustainable practices. The following indicators are assessed within this category:

1. **EN-1. Recycled content:** this indicator evaluates the content of recycled materials in the different layers of the projected pavement structure. The score ranges between 0 and 4 points; the higher the recycled content, the higher the score on this indicator.
2. **EN-2. Energy consumption:** this indicator evaluates the energy consumption associated with the materials considered in the pavement design. The lower the energy consumption in material production and/or construction of the pavement the higher the score in this indicator. The score ranges between 0 and 3 points.
3. **EN-3. Greenhouse gas emissions:** similarly, this indicator evaluates the GHG emissions associated with the materials considered in the pavement design. Higher scores will be allocated to the alternatives with lower emissions associated with the production of the material and/or construction of the section. The score of this indicator ranges between 0 and 3 points.
4. **EN-4. Earthworks balance:** this indicator evaluates the balance of excavation and backfill volumes in order to minimize the need for transport of fill materials. The score ranges between 0 and 3 points.
5. **EN-5. Local materials:** this indicator evaluates the transport distance between the sources of materials and the project site. Priority is given to the use of local materials in order to minimize the transport of materials and thus reduce CO_2 emissions and fuel consumption. The score of this indicator ranges between 0 and 2 points.
6. **EN-6 (extra). Existing structure:** in addition, this extra indicator is included to assess the level of impact on the existing road surface. Encouraging the reuse of the existing pavement structure is considered a sustainable practice as it saves resources and reduces emissions. This indicator is optional as it is only applicable to existing pavement rehabilitation projects.

Then, after analyzing the above indicators, an Environmental Index is obtained as the sum of the scores obtained in each one of them.

$$\text{Environment Index} = \text{EN} - 1 + \text{EN.2} + \text{EN.3} + \text{EN.4} + \text{EN.5} + \text{EN.X} \quad (2)$$

Social and Innovation Indicators

This category aims to foster the use of innovative techniques that improve conventional pavement design and construction processes, promoting sustainability, as well as other social and environmental aspects of the road. The following indicators are assessed within this category:

1. **SOI-1. Surface characteristics:** this indicator evaluates the surface characteristics of the pavement, which influence both the comfort and safety of users, as well as the fuel consumption of vehicles on the road. One point is awarded on the basis of parameters such as IRI (International Roughness Index) and SFC (Sideway Force Coefficient).
2. **SOI-2. Health and safety:** this indicator evaluates the use of materials and/or practices that improve the health and safety of site personnel, such as low temperatures asphalt mixes or other practices that improve safety on the construction site. One point is assigned to those projects that include special measures that improve safety on the construction site.
3. **SOI-3. Noise mitigation:** this indicator evaluates the traffic noise mitigation capability of the proposed wearing course. One point is assigned based on the type of wearing course defined.
4. **SOI-4. Innovation and sustainability techniques:** this indicator evaluates any other innovative techniques included in the design and/or construction of the pavement that promote sustainability and that have not been included in the previous indicators.

Then, a Social and Innovation Index is obtained as the sum of the scores obtained in each of the above indicators.

$$\text{Social and Innovation Index} = \text{SOI.1} + \text{SOI.2} + \text{SOI.3} + \text{SOI.4} \quad (3)$$

Sustainability Index

Finally, a Sustainability Index is obtained as a sum of the score obtained for each of the indicators evaluated. This Sustainability Index will allow engineers to compare the sustainability of different pavement alternatives and choose the most sustainable solution.

$$\text{Global Sustainability Index} = (1) + (2) + (3) \quad (4)$$

3.2 Economic Analysis

After analyzing the sustainability indicators, an economic evaluation of the pavement alternatives considered will be carried out.

To this end, it is recommended to carry out a Life-Cycle Cost (LCC) analysis of the different pavement alternatives, covering the following steps (Fig. 3):

Within the developed framework, specific guidelines are provided to perform each of the steps above. Finally, the Life Cycle Cost of each alternative section will be obtained as the sum of the costs:

- Initial costs for the Agency (A).
- User costs (B).
- Future costs for the Agency (C).

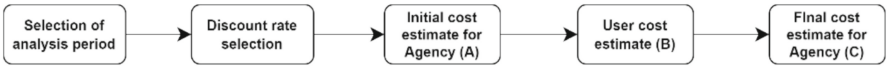


Fig. 3. Indicators and categories for the assessment of pavement sustainability.

4 Application

The developed methodology has been applied to typical pavement sections commonly used in Spain, in particular in Málaga and Asturias. To this end, firstly, a set of new pavement sections were designed using recycled materials and having a bearing capacity and a durability similar to conventional pavements. Then, the methodology was applied to new sections and traditional ones to compare their sustainability through the defined indicators. Finally, a catalogue of pavement sections was created, including conventional pavement sections and new ones (applying sustainable practices), and the associated Sustainability Index of each one. This catalogue constitutes a reference framework for the local authorities of Málaga and Asturias, allowing them to compare the sustainability of pavement sections and to require new designs to reach a minimum threshold in the Sustainability Index.

5 Conclusions

The developed framework will allow engineers to assess and compare the sustainability of different pavement structures in a homogenous way, in order to select the most appropriate pavement solution from a technical, economic and sustainable point of view. On the other hand, the scoring system developed will also allow road administrations to establish a minimum score in order to promote more sustainable designs in procurement processes.

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Facilitating Choice of Long Haul HD Environmental-Friendly Drivetrains: LONGRUN Life Cycle Analysis Tool

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Abstract. The LCA calculation tool is a standalone application developed as part of the EU H2020 LONGRUN project (GA no. 874972) facilitating life cycle analysis of long-distance heavy-duty drivetrains and supporting the choice of the most effective technologies for minimizing overall carbon footprint. Using the substantial amount of life cycle impact data collected during the LONGRUN project, the tool facilitates fast, straightforward and fair LCA impact comparison of heavy-duty battery electric, fuel cell electric, hybrid, plug-in hybrid and ICE powertrains manufactured using different vehicle production methods, running on a range of alternative fuels or plug-in electricity sources, in a standardized and repeatable manner. The current paper details the approach used for calculating heavy-duty vehicle lifetime carbon footprint (gCO_2eq/km) and overall energy consumption (MJ/km) in the proposed tool. It then discusses a generic LCA comparison of fuel cell electric, battery electric, hybrid electric, combustion engine powertrains for a 5-LH category 40T truck running on renewable H_2, HVO, diesel and future grid electricity to demonstrate the effectiveness of this approach in comparing next generation low carbon drivetrain technologies along with their energetic feasibility. Finally, the main outcomes and future improvements are summarized.

Keywords: Life Cycle Analysis Tool · Well-to-Wheel · Vehicle Manufacturing · Standardized LCA · Heavy-Duty Vehicles · LONGRUN H2020

1 Introduction

Long-distance heavy-duty vehicles (HDVs) contribute to about 25% of CO_2 emissions from the European transportation sector and are under major focus for lowering greenhouse gas impact (GHG) to meet the goals of the Paris Agreement [1]. Given the demanding driving missions and diverse commercial applications, a range of drivetrain technologies may be more suitable across different HDV roles to lower the overall carbon footprint of this sector. The life cycle analysis (LCA) comprehensively addresses the tank-to-wheel tailpipe aspect (TtW) from vehicle running fuel/electricity consumption,

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well-to-tank impact (WtT) due to the production of this propulsion energy source and manufacturing-disposal contribution of powertrain, vehicle and trailer production to help understand the complete lifetime GHG impact and corresponding energetic feasibility of a drivetrain solution [2].

The LONGRUN project, funded by the EU Horizon 2020 program (GA no. 874972), aims at lowering fuel consumption and the environmental impact of long-haul HDVs in real driving, including reliance on fossil fuels through the development of new alternative internal combustion engines and hybrid drivelines [3]. By integrating a substantial amount of life cycle impact data collected during the LONGRUN project and automating LCA calculations in a standalone robust application, this tool aims at facilitating a fast, straightforward and fair initial comparison of different drivetrain technologies and propulsion energy sources with the goal of selecting the most environmental-friendly solution for a specific HD application. The LCA results are calculated over standardized HDV lifetime mileages and global warming potentials (GWP 100, 20) providing overall environmental GHG impact (gCO_2eq/km) and energy consumption (MJ/km) along with a detailed distribution of the TtW, WtT and vehicle manufacturing contributions. This will help the stakeholders to analyze appropriate drivetrain technologies, the possibility of their further GHG impact mitigation and the scope of their implementation for a specific HD application. The subsequent sections describe software architecture and calculations integrated in the LONGRUN LCA tool. This is followed by a generic comparison for an HD 5-LH category 40 T truck running on renewable H_2, HVO and diesel B7 fuels powering H_2 fuel cell electric (FCEV), internal combustion engine (ICEV), hybrid electric (HEV) and, 2016 and 2030 EU grid charged battery electric (BEV) technologies. Finally, the main outcomes of this activity and future improvements are summarized.

2 LCA Calculation Tool

Using vehicle test data and collected life cycle impact parameters, the LONGRUN LCA tool integrates tank-to-wheel (TtW), well-to-tank (WtT), and vehicle manufacturing-disposal aspects to compute the complete lifetime environmental impact (gCO_2eq/km) and corresponding energy consumption (MJ/km). The vehicle data, sourced from VECTO tool, LONGRUN simulation platform, or real-world tests, provides fuel/electricity consumption (MJ/km) and tailpipe CO_2 emissions (gCO_2eq/km), along with the main drivetrain specifications and vehicle category which are crucial for selecting standardized LCA criteria and lifespan. TtW calculations also encompass the greenhouse gas (GHG) impact of tailpipe N_2O and CH_4, along with the renewable biogenic share compensation for alternative or blended fuels [4] (Figs. 1 and 2).

For the calculation of the WtT aspect, the considered vehicle data is then utilized along with TtW results and a range of electricity/fuel impact parameters. This leads to the lifetime WtT emissions and energy consumption attributed to the consumed propulsion energy source. Finally, taking into account key vehicle components such as the cabin, vehicle, trailer, internal combustion engine (ICE), battery, electric drive, fuel cell system (FCS), and H_2 tank, as well as their respective production methods, the manufacturing

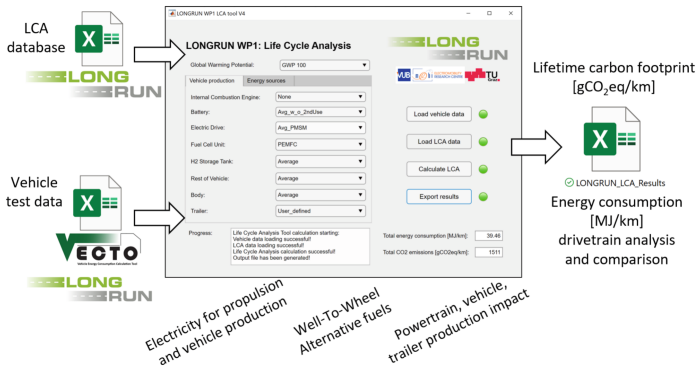
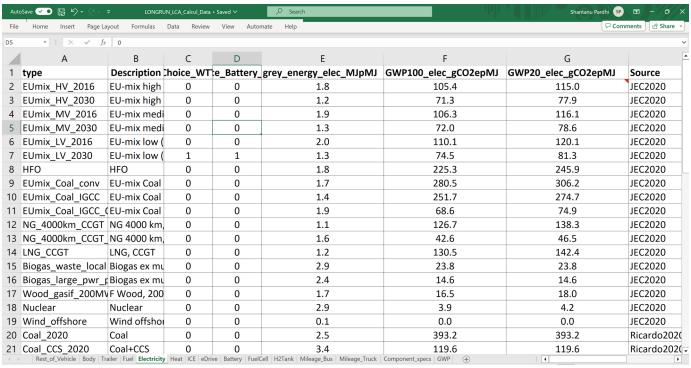


Fig. 1. Schema of LONGRUN LCA tool GUI interface including input vehicle data, LCA parameters data and output LCA results file.



	type	Description	choice_WT	e_Battery	grey_energy_elec_MJpMJ	GWP100_elec_gCO2epMJ	GWP20_elec_gCO2epMJ	Source
2	EUmix_HV_2016	EU-mix high	0	0	1.8	105.4	115.0	JEC2020
3	EUmix_HV_2030	EU-mix high	0	0	1.2	71.3	77.9	JEC2020
4	EUmix_MV_2016	EU-mix medi	0	0	1.9	106.3	116.1	JEC2020
5	EUmix_MV_2030	EU-mix medi	0	0	1.3	72.0	78.6	JEC2020
6	EUmix_LV_2016	EU-mix low (	0	0	2.0	110.1	120.1	JEC2020
7	EUmix_LV_2030	EU-mix low (	1	1	1.3	74.5	81.3	JEC2020
8	HFO	HFO	0	0	1.8	225.3	245.9	JEC2020
9	EUmix_Coal_conv	EU-mix Coal	0	0	1.7	280.5	306.2	JEC2020
10	EUmix_Coal_IGCC	EU-mix Coal	0	0	1.4	251.7	274.7	JEC2020
11	EUmix_Coal_IGCC_(	EU-mix Coal	0	0	1.9	68.6	74.9	JEC2020
12	NG_4000km_CCGT	NG 4000 km,	0	0	1.1	126.7	138.3	JEC2020
13	NG_4000km_CCGT_	NG 4000 km,	0	0	1.6	42.6	46.5	JEC2020
14	LNG_CCGT	LNG, CCGT	0	0	1.2	130.5	142.4	JEC2020
15	Biogas_waste_local	Biogas ex mu	0	0	2.9	23.8	23.8	JEC2020
16	Biogas_large_pwr_(	Biogas ex mu	0	0	2.4	14.6	14.6	JEC2020
17	Wood_gasif_200MW	Wood, 200	0	0	1.7	16.5	18.0	JEC2020
18	Nuclear	Nuclear	0	0	2.9	3.9	4.2	JEC2020
19	Wind_offshore	Wind offshor	0	0	0.1	0.0	0.0	JEC2020
20	Coal_2020	Coal	0	0	2.5	393.2	393.2	Ricardo2020
21	Coal_CCS_2020	Coal+CCS	0	0	3.4	119.6	119.6	Ricardo2020

Fig. 2. Life cycle parameters data base collected by LONGRUN partners including vehicle components manufacturing and range of propulsion fuel and electricity sources.

impact is summated.

$$\textbf{Overall energy consumption (MJ/km)} = TTW_E + WTT_E + Prod_E \quad (1)$$

$$\textbf{Complete carbon footprint(gCO2eq/km)} = TTW_{CO2} + WTT_{CO2} + Prod_{CO2} \quad (2)$$

As stated, TtW CO_2 impact (TTW_{CO2}) is found from the consumed fuel-energy per km (TTW_E), selected fuel carbon mass fraction for tailpipe CO_2 (TP_{CO2}), renewable biogenic GHG share (b), and CH_4, N_2O equivalent GWP (GWP_{CH4}, GWP_{N2O}).

$$TTW_{CO2}\left(\mathrm{gCO_2eq/km}\right) = TP_{CO2}(1-b) + (\mathrm{g}CH_4 GWP_{CH4} + \mathrm{g}N_2O GWP_{N2O}) \quad (3)$$

The WtT aspect (WTT_E, WTT_{CO2}) considers the selected fuel/electricity CO_2 impact factor (IF_{WTT}), required propulsion energy (TTW_E) and production grey energy demand (GED) which is the fraction of consumed energy required to produce it. Vehicle manufacturing impact ($Prod_{CO2}$, $Prod_E$) comprises vehicle, cabin, trailer and above mentioned

powertrain subsystems. Suitable cumulative energy demand (CED_{comp}) and CO_2 impact factors (IF_{comp}) are used to calculate its manufacturing GHG and energetic impact. Powertrain mass is estimated using rated power (P_{comp}) and power density ($\varnothing_{comp}$).

$$WTT_E(\text{MJ/km}) = TTW_E \cdot GED \tag{4}$$

$$WTT_{CO2}\left(\text{gCO}_2\text{eq/km}\right) = TTW_E \cdot IF_{WTT} \tag{5}$$

$$Prod_E(\text{MJ/km}) = \frac{m_{glider} \cdot CED_{RoF} + m_{trail} \cdot CED_{trail} + PWT_E}{D_{life}} \tag{6}$$

$$Prod_{CO2}\left(\text{gCO}_2\text{eq/km}\right) = \frac{m_{glider} \cdot IF_{RoF} + m_{trail} \cdot IF_{trail} + PWT_{CO2}}{D_{life}} \tag{7}$$

$$PWT_E = BAT_E + m_{H2} \cdot \varnothing_{H2tank} \cdot CED_{H2tank} + \sum\nolimits_{ICE,EM,FCS} \cdot P_{comp} \cdot \varnothing_{comp} \cdot CED_{comp} \tag{8}$$

$$PWT_{CO2} = BAT_{CO2} + m_{H2} \cdot \varnothing_{H2tank} \cdot IF_{H2rank} + \sum\nolimits_{ICE,EM,FCS} \cdot P_{comp} \cdot \varnothing_{comp} \cdot IF_{comp} \tag{9}$$

Battery production energy (BAT_E) and CO_2 GHG impact (BAT_{CO2}) are calculated with separate factors for the manufacturing process CED_{BAT}, its electricity and heat requirement ($e_{BAT}.CED_{eBAT}$ and $q_{BAT}.CED_{qBAT}$) per kWh of battery pack (E_{BAT}). With this approach temporal and regional aspects along the specific supply chain can be covered.

$$BAT_E = E_{BAT}(CED_{BAT} + e_{BAT} \cdot CED_{eBAT} + q_{BAT} \cdot CED_{qBAT}) \tag{10}$$

$$BAT_{CO2} = E_{BAT}(IF_{BAT} + e_{BAT} \cdot IF_{eBAT} + q_{BAT} \cdot IF_{qBAT}) \tag{11}$$

3 Heavy-Duty Vehicle LCA Comparison Results

Seven HD 5-LH category truck cases utilizing various drivetrain technologies (Table 1) and propulsion energy sources have been compared including: ICEV running on diesel B7, alternative hydrotreated vegetable oil (HVO) composed of 50% rapeseed and 50% waste oil, and H_2 fuel; HEV using diesel B7; FCEV using H_2 from planned EU renewable H_2 threshold (3000 gCO_2eq/kgH_2) and current nature gas steam methane reforming source (NG SMR); and BEV manufactured and propelled using grid electricity from 2016 EU mix and from 2030 EU mix with 50% battery second life use. The LCA impact data are sourced from several recent publications and internal calculations including Ricardo study performed on behalf of DG CLIMA and JEC WtT report v5 [2, 5, 6]. All cases carry 28-tonne high payload and ICEVs are assumed to emit 0.15 gCH_4/km and 0.05 gN_2O/km contributing to the equivalent TTW GHG impact [7]. Compared to diesel, the H_2 ICEV is assumed to have 10% lower fuel efficiency while the HEV is 7% more efficient. A 90 kg 700-bar H_2 storage is considered. For HEV and FCEV cases, two battery packs are needed over vehicle lifetime due to the high power usage. BEV case considers propulsion and grid charging losses, and its NMC622 battery is sized for 500 km range (780 kWh).

Table 1. Compared drivetrain specifications.

	ICEV	HEV	BEV	FCEV
Propulsion energy [MJ/km]	11.8, 13 (H_2)	11	4.68	11
Gross curb weight [kg]	39700, 41800 (H_2)	40000	44000	42000
ICE rated power [kW]	350	350	-	-
eDrive rated power [kW]	-	200	350	350
Fuel cell system rated power [kW]	-	-	-	225
Battery pack energy capacity [kWh]	-	32.5	780	32.5

Figure 3 summarizes the overall LCA comparison results for lifetime carbon footprint (gCO_2eq/km) and corresponding energy consumption (MJ/km). The diesel B7 fueled ICEV emits about twice the equivalent CO_2 emissions of any other solution. For HEV both CO_2 impact and overall energy consumption are lowered by about 6.1%. If production is streamlined with availability of raw materials, HVO could ideally cut down CO_2 emissions by up to two thirds of the diesel B7 case, requiring 40% higher fuel production energy. FCEV running on NG SMR sourced H_2 pollutes even more GHG than the diesel ICEV. The planned EU renewable H_2 threshold could lower GHG impact drastically at the cost of higher production energy requirement. Even though the H_2 FCEV needs greater manufacturing efforts compared to H_2 ICEV, improved efficiency and lower H_2 consumption over the 1.2 million km lifetime mileage more than compensates for it. When comparing the BEV EU mix 2016 solution, the carbon footprint savings could be highly significant featuring low overall energy consumption affected mostly by the grid electricity and large battery pack manufacturing. Considering a cleaner EU mix 2030 grid and with 50% battery seconding life, up to 32% reduction in lifetime CO_2 emissions could be further obtained with 23% lower energy requirement.

Figure 4 compares GHG contribution of powertrain components towards overall vehicle manufacturing-disposal impact. H_2 tank in case of FCEV was found to be the most significant carbon footprint contributor whereas for BEV technology, the large onboard battery pack led to more than 61% of its GHG impact.

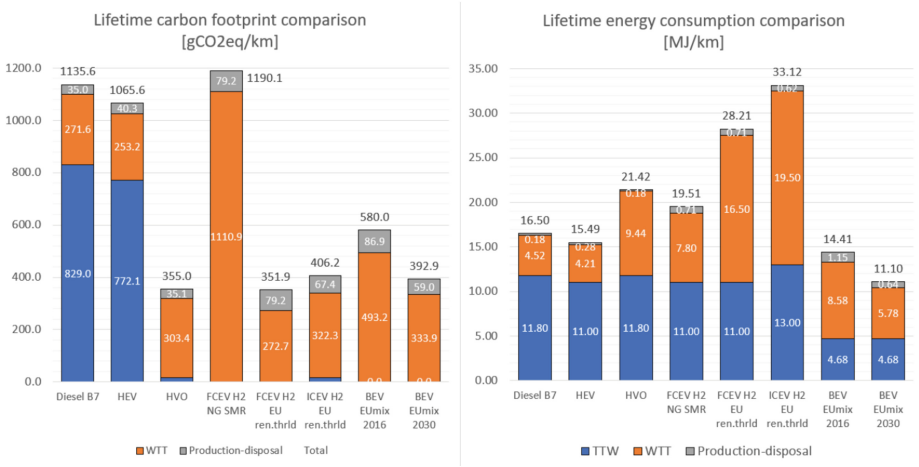


Fig. 3. Comparison of lifetime carbon footprint and overall energy consumption.

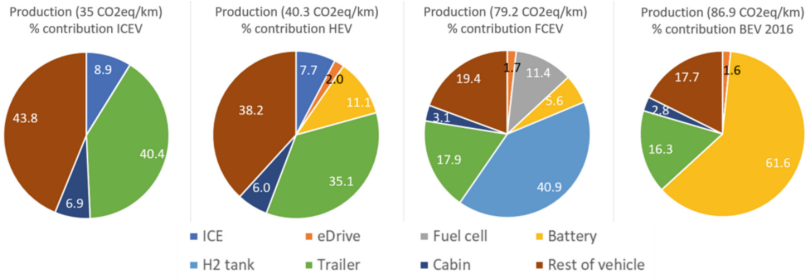


Fig. 4. Percentage components contribution to vehicle production GHG emissions.

4 Conclusion

The LONGRUN LCA calculations tool proposes a robust, holistic and all-round method for GHG impact comparison of different HD drivetrain technologies and propulsion energy sources towards decarbonization of the long haul heavy-duty vehicle sector. The calculation integrates tank-to-wheel CO_2, CH_4 and N_2O emissions including renewable biogenic fuel share; well-to-tank propulsion energy production and vehicle manufacturing aspects in a standardized manner to compare overall GHG emissions for ICE, hybrid electric, battery electric and H_2 fuel cell technologies along with their overall energy requirement feasibilities. The tool is supported by an extensive LCA database covering a range of possible powertrain technologies, grid electricity sources, alternative fuels and component manufacturing approaches. Future steps could include the addition of EU HD vehicle classes, standardization of the LCA calculation and collected database, addition of ICE AdBlue reagent impact and integration of the proposed LCA approach as an extension to the VECTO platform.

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Reducing Carbon Through Transport Investment – Transport Infrastructure Ireland Pavement Renewal Programme

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Abstract. Transport Infrastructure Ireland's (TII) purpose is "*to provide sustainable transport infrastructure and services, delivering a better quality of life, supporting economic growth and respecting the environment*". To this end TII is implementing a Sustainability Implementation Plan across its organisation. Transition to net zero emissions is a key pillar of this plan. As part of this transition, a carbon emissions assessment of the TII Pavement Renewals Programme was undertaken in Q1 2023. This is the first time TII incorporated a carbon emissions assessment in the identification of an optimal investment scenario, allowing them to better manage their long-term environmental impacts in line with European and national decarbonisation targets. Key activities relating to carbon emissions from road network pavement renewal, including the extraction, manufacture, transport, installation of materials and their reuse and recycling were assessed.

The analysis quantified carbon emissions associated with four default treatments applied as part of the TII Pavement Renewals Programme; reconstruct, strengthen, overlay and replace surface. During the life of the pavement asset, users of the national road network generate varying carbon emissions depending on the condition of the road. Carbon emissions associated with a 'Do Minimum' scenario were compared with 7 different economic investment scenarios. Carbon emissions associated with a theoretical 'Backlog' were also calculated. These are the carbon emissions which would result from bringing the network back to "Good/ Very Good" condition at the end of the analysis period.

A key finding is that the TII Pavement Renewals Programme can generate from 19 and up to 26 percent reduction in carbon emissions, a beneficial impact for an infrastructure investment. This paper sets out the findings of the assessment and the reasons why this investment, into a significant national transport asset, results in the identification of an optimum investment, in terms of carbon emissions, into the renewal programme for the Irish National Road network.

Keyword: Pavement renewal · carbon · sustainability · transport investment

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1 Introduction

TII is Ireland's national road authority whose purpose is "*to provide sustainable transport infrastructure and services, delivering a better quality of life, supporting economic growth and respecting the environment*" [1].

TII is responsible for the maintenance and development of a diverse set of road assets that includes the most fundamental element – the road pavement. TII's overall strategic objective of the pavement renewals programme is to maintain the overall pavement asset value at the minimum life cycle costs through optimal management of the National Roads network. In early 2023, TII produced their latest Business Case [2] to set out the basis for its pavement renewals programme.

The scope of the Business Case covers the need for investment in pavement renewals and focuses on the need for implementing a lifecycle planning approach to support decision-making in developing pavement renewals policies [3] and selecting pavement schemes.

In the previous business cases, the pavement renewals programmes were developed by identifying programmes of works over a 20-year period that would maximise the whole network condition over the same period, for a series of fixed investment scenarios. In October 2021, TII published its Sustainability Implementation Plan (SIP) [4] in which transition to zero emissions is a key pillar. For the 2023 iteration of the Business Case, TII decided to give the environmental cost a greater function in the identification of the optimal pavement renewals programme and associated investment scenario.

The present paper is an illustration of how TII is starting the journey of applying the SIP to the optimal management of its pavement assets. It explains how TII's pavement renewals 20-year investment strategy already delivers carbon emission savings and where further reduction opportunities may lie.

2 Method

2.1 Life Cycle Assessment Scope

The key standards relating to lifecycle environmental impacts assessment of civil engineering works EN 15804 [5] and EN 17472 [6] were followed in undertaking this assessment. The Business Case solely focuses on the replacement activities occurring during the "Use Stage" of TII's pavement assets and the effects of such activities on the user. This is depicted in Fig. 1 below with, highlighted in orange, the modules included in the scope.

The effects on the environment of eight investment scenarios ranging from 'Do Minimum' to €140 m per annum have been quantified in terms of greenhouse gas emissions (tCO_2eq) and used to carry out a carbon emissions analysis.

B4 – *Replacement*: for this analysis, this module covers the impact of renewing the pavement asset by removing part of the asset (module C1), transporting what has been removed to a facility where it will be processed for reuse or recycling (modules C2 and C3), and producing new materials from primary constituents (modules A1 to A3) to be transported and installed (A4 and A5) as new parts of the renewed pavement asset.

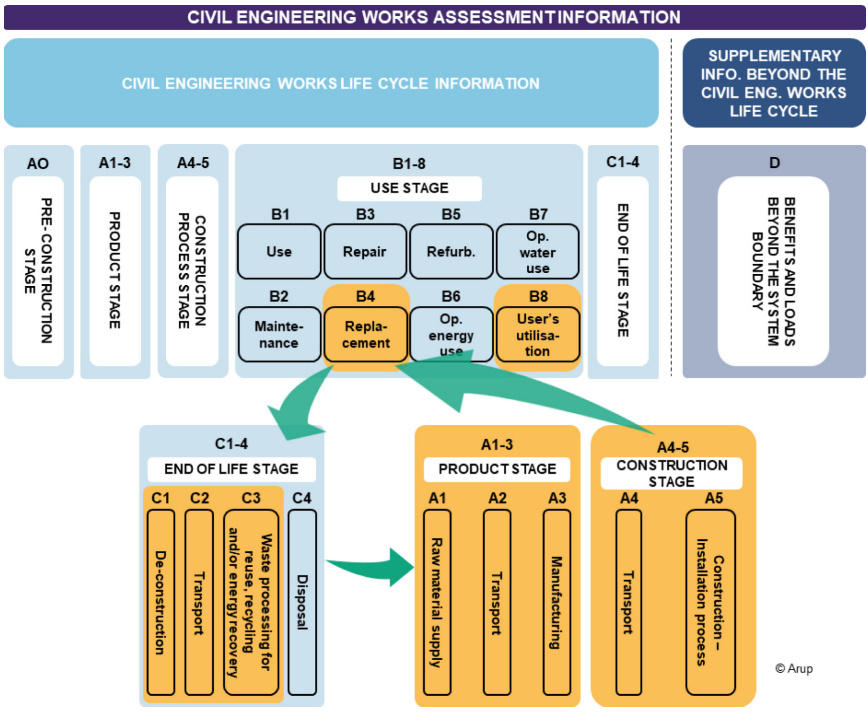


Fig. 1. Lifecyle modules of civil engineering works from EN 17472:2022

For all investment scenarios but the 'Do Minimum' one, a carbon emissions assessment was undertaken for the four default treatments from the PAMS (Pavement Asset Management System) assessment, i.e. 'Replace Surface', 'Overlay', 'Strengthen', and 'Reconstruct'. This was based upon the number of required interventions during the 20-year analysis period within the budgetary constraints of each investment scenario.

For the 'Do Minimum' scenario, a carbon emissions assessment was undertaken for non-structural surface works to provide skid resistance at critically important locations, and activities such as pothole repair and other emergency repair activities. This source of carbon emissions is referred to as 'Safety' in the remainder of this paper.

For all investment scenarios, a carbon emissions assessment was undertaken for the four default treatments from the PAMS assessment. This was based upon the type of interventions required at the end of the 20-year analysis period to bring the whole network back to a "Good/Very Good" condition (this is defined as the 'Backlog').

Figure 2 below is an illustration of how each lifecycle module included in the scope contributes to the overall carbon emissions of each default treatment. The carbon emissions profiles below are specific to TII's Subnet 0 which represents about 44% of TII overall network's area. Although the variability in the carbon emissions profiles between Subnets is limited, they are however specific to each of them [7].

B8 – *User's Utilisation*: for this analysis, this module covers the impact of the road condition on users linked to the renewal programme, including the positive impact of

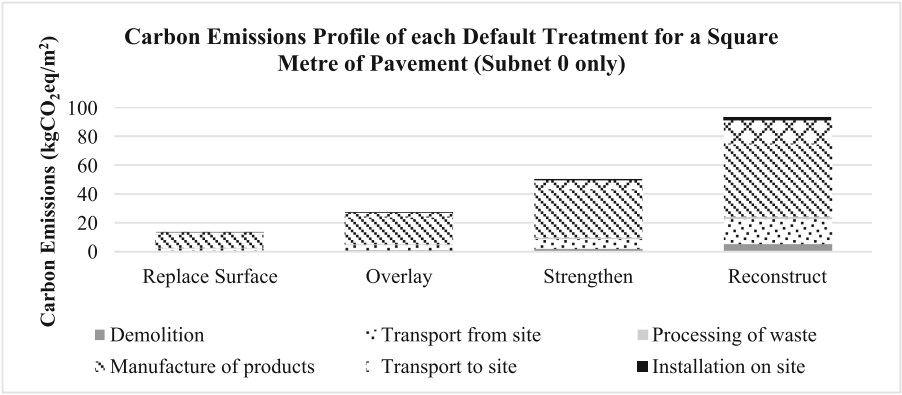


Fig. 2. Carbon emissions profile of each default treatment on TII's Subnet 0

improved road condition on users. The carbon emissions from the road users are mainly the direct consequence of burning fuel for each internal combustion engine vehicle travelling on TII's road network. The methodology used for the economic and financial appraisal to quantify the incremental litres of fuel consumed as a result of the pavement condition is based on NCHRP Report 720 [8]. In this exercise, only the incremental fuel consumption resulting from a pavement in a less than "Very Good" condition was taken into account. The pavement condition indicator referred to here is the International Roughness Index (IRI).

2.2 Modelling Inputs

The primary sources of carbon emission factors for the purposes of the assessment are from the TII Carbon Tool [9], TII's Publication DN-PAV-03077 [10], and the Inventory of Carbon & Energy [11]. Sources of other default inputs for the purposes of the assessment are from EPD Ireland [12], MQP Ltd [13], and TII network information.

The four treatments considered in the assessment are described as follows:

- Surface Replacement: The technical objective of resurfacing is sealing of the pavement surface improving skid resistance, roughness and rutting.
- Overlay: The technical objective of overlay is to increase strength, retard ageing, improve or restore surface characteristics and improve or restore functionality (inlay 50-100mm, overlay up to 100 mm).
- Strengthen: The technical objectives of strengthening are to increase strength, retard ageing, restore surface characteristics, improve or restore functionality (inlay 100–200 mm, overlay up to 200 mm).
- Reconstruct: The technical aims of reconstruction are to increase capacity and pavement strength to provide a long-life pavement.

3 Results

In the 'Do Minimum' scenario, a €15m per annum fund is included to cover what has been defined as being 'Safety' works. The carbon emissions associated to these works account for 11,389 tCO2eq/annum and 227,779 tCO2eq/20-year period.

For each investment scenario under assessment the areas for treatment using 'Replace Surface', 'Overlay', 'Strengthen' and 'Reconstruct' were obtained from the PAMS over the period from 2021 to 2040. From these, material quantities were calculated. Carbon emission factors were applied to these to determine cumulative carbon emissions associated with each scenario. Results are summarised in Fig. 3 below.

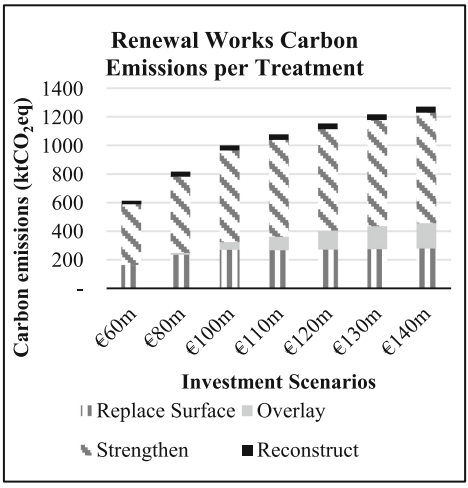


Fig. 3. Pavement Renewal Works Carbon Emissions

Included within the business case is the estimated 'Backlog' cost of restoring the whole network to "Good/Very Good" condition at the end of the analysis period based on the forecasts of road condition produced by the PAMS. Carbon emissions associated with the 'Backlog' are summarised in Fig. 4 below. Increased user carbon emissions associated with deteriorating pavement condition where it falls below "Very Good" condition were assessed for each scenario. This is defined as "Incremental Road Users Carbon". This is included within Fig. 5 below.

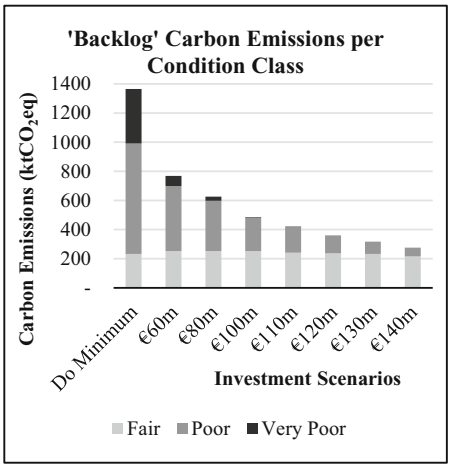


Fig. 4. 'Backlog' Carbon Emissions

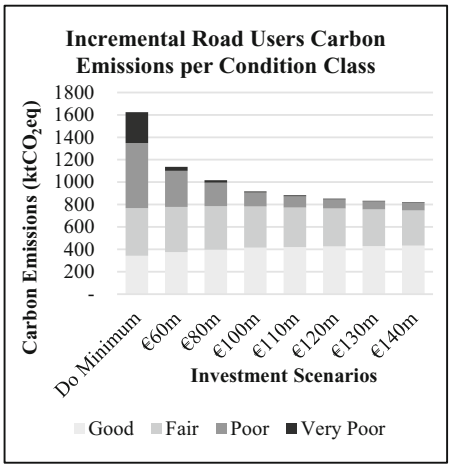


Fig. 5. Inc. Road Users Carbon Emissions

4 Discussion

In TII's 2023 Pavement Renewals Business Case, the 20-year pavement renewals programmes associated to each of the eight investment scenarios were developed on the same principle as before: maximising the network condition for a fixed investment scenario over the 20-year analysis period. The optimal investment scenario was initially identified following an economic and financial appraisal. The carbon emissions assessment of these same programmes was performed afterwards to challenge the outcome of the economic and financial appraisal from an environmental cost aspect.

The introduction of the carbon emissions assessment into the Business Case opened perspectives on the following questions:

- What are the environmental benefits of investing into the renewal of the pavement assets network?
- Is the optimal investment scenario from an economic and financial perspective the same as the one from an environmental perspective?
- Where do opportunities to improve the methodology behind the carbon emissions assessment lie?
- Where do opportunities to reduce carbon emissions from the pavement assets lie?

The discussion below is an attempt to start answering these questions.

When carbon emissions borne from the pavement maintenance strategy and the incremental road users over the 20-year period are combined with those borne from the 'Backlog' at the end of the analysis period, it can be clearly seen that the greater the investment, the lower the overall associated carbon emissions are Fig. 6 below illustrates this benefit.

In fact, compared to the base case of 'Do Minimum', any of the assessed investment scenario delivers carbon emission savings ranging from about 600,000 tCO2eq to almost 850,000 tCO2eq over the 20-year analysis period. This represents a 19% to 26% reduction from the 'Do Minimum' scenario.

The greater the investment in renewing the pavement network over the 20-year period, the greater the quantity of works and associated carbon emissions will be generated (Renewal Works and 'Safety'). But these works lead to an improvement of the pavement condition over the same period compared to the 'Do Minimum' scenario. That improvement in pavement condition generates savings in road users carbon emissions as well as 'Backlog' works at the end of the analysis period, compared to the 'Do Minimum' scenario. Figure 7 below shows how these balance for each investment scenario – Renewal Works and 'Safety' figures being combined under 'Pavement Renewal Works', and 'Backlog' and 'Incremental Road Users' being combined under 'Road Users'. An equilibrium is reached for an investment comprised between €120m and €130m.

An optimal sustainable investment is one that balances economic, financial, social and environmental priorities.

The financial appraisal covered the financial cost of each of the eight programmes, and the financial cost of restoring the whole network to "Good/Very Good" condition at the end of the analysis period (the 'Backlog').

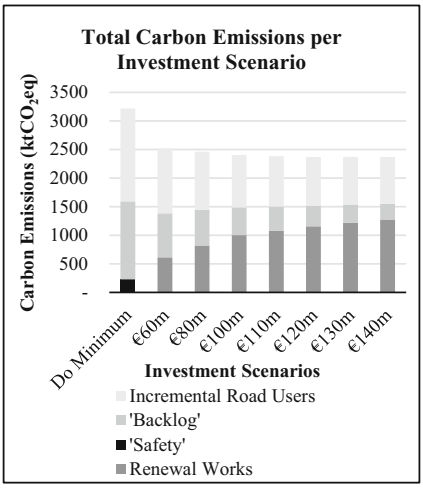


Fig. 6. Combined Renewal Works, 'Backlog', 'Safety' and Incremental Road Users Carbon Emissions

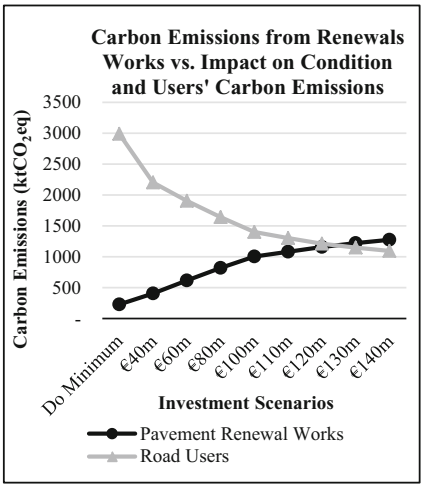


Fig. 7. Carbon Emissions from Renewals Works vs. its Impact on Network Condition and Road Users' Carbon Emissions

The economic appraisal covered the costs imposed on TII to carry out pavement renewals on the national road network under each option, the additional vehicle operating costs imposed on road users when road condition is below "Very Good" and, the additional travel time costs imposed on road users when road condition is below "Very Good".

The environmental assessment covered the carbon emissions impact of each of the eight programmes of works, the carbon emissions impact of restoring the whole network to "Good/Very Good" condition at the end of the analysis period (the 'Backlog') and, the carbon emissions impact of road users.

The financial appraisal found that the investment scenarios with the lowest financial costs were those ranging from €60m per annum to €100m per annum. The economic appraisal identified the €110m per annum scenario as being the optimal one while the environmental assessment of the same scenarios identified the €120m scenario as being the optimal one.

In the present case, we can observe that each appraisal gave a relatively similar answer, the environmental assessment not significantly challenging the conclusions from the economic and financial appraisals.

This initial environmental assessment allowed TII to have an appreciation of the environmental impact of its pavement renewals programme, based on some initial assumptions. Further iterations of this assessment intend to improve on the employed methodology and data inputs where and when practical. This assessment also allowed TII to identify and quantify sources of carbon emissions for which carbon reduction measures could be explored.

5 Conclusions

The key findings and conclusions of the carbon emissions assessment of TII Pavement Renewals Business Case are as follows:

- investing in the long-term renewal of TII's pavement assets is expected to generate estimated carbon emission savings of up to 26% compared to a 'Do Minimum' maintenance scenario,
- The economic and financial appraisal of the eight investment scenarios found the €110m per annum scenario to be optimal while the environmental assessment identified the €120m per annum one. Both exercises broadly align.
- More importantly, this is the first time TII assessed the environmental impact of its pavement renewals programme. This and future iterations of this assessment will allow TII to quantify and monitor the benefits of existing and future decarbonisation measures and strategies. This will also help TII to identify sources of environmental impacts and prioritise their decarbonisation.

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Low Energy Bound Materials: A Sustainable Solution for Regional and Local Road Pavement Renewal?

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Abstract. Ireland's regional and local roads require strengthening and renewal to provide an adequate level of service to road users impacting rideability, comfort and accessibility for tourism, goods, and service delivery to local communities. Over the past two years the Department of Transport and Transport Infrastructure Ireland (TII) have funded the development of a trial section of Low Energy Bound Material (LEBM) on the R180 to the south of Lough Egish, Monaghan, incorporating a cold-mix, high reclaimed asphalt content LEBM as part of the pavement renewal overlay. By using predominantly Reclaimed Asphalt (RA) material and bound with a bitumen emulsion, a highly sustainable pavement material was produced due to reduced virgin material use and reduced energy consumption. This paper summarises the findings from the development of the trial section and the performance of the renewed pavement structure and LEBM layer after one year of opening to traffic.

Keywords: Low Energy Bound Materials (LEBM) · cold-mix asphalt · pavement · sustainability · circular economy

1 Background

There is significant pressure on National and local government to implement sustainable solutions in their everyday operations. Transport Infrastructure Ireland (TII), the Department of Transport (DoT) and local authorities have identified an opportunity to promote sustainability in their operations by using Reclaimed Asphalt (RA) in the renewal and maintenance of their road pavement networks.

The overlay and strengthening of road pavements on the National, regional and local road network to date has predominantly used hot mix asphalt material comprising of

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virgin aggregates and bitumen binder. Monaghan County Council have identified an opportunity to re-use asphalt planings from their road network as an input to a new bituminous mixture to be used as a pavement strengthening or overlay material. Further sustainability benefits are achieved by using bitumen emulsion as the material binder rather than hot bitumen. Currently this bituminous mixture type is referred to as a Low Energy Bound Material (LEBM) as specified in TII Publication CC-SPW-00900 [4].

This paper will present findings to date from one of the pavement trial sections currently being implemented by TII, DoT and Monaghan County Council studying the design, construction, and long-term performance of LEBM materials as specified in CC-SPW-00900 [4].

The trial section where the LEBM layer was constructed is located on the R180 to the south of Lough Egish, Monaghan. The LEBM layer was constructed along a 1.4km length of the R180.

2 LEBM Mixture Design

The development of a suitable LEBM for use as a pavement overlay or strengthening material was carried out by COLAS [1].

2.1 Constituents

Site-won asphalt material, stockpiled at Glenmore Quarry, Monaghan was processed by a 32mm hydraulic screener attached to a 360° excavator to produce a 0/32 graded RA [6]. This RA material was used as feedstock to the LEBM production process. The characteristics of the RA as detailed in Table 1 were determined and used as input to the mix design process.

Table 1. Characteristics of the reclaimed asphalt

Characteristic	Value	Test Method
Binder content (% by mass) (Sample 1 / Sample 2)	3.8 / 4.2	EN 12697-39
Water content (% by mass) (Sample 1 / Sample 2)	3.6 / 4.8	EN 1097-5
Reclaimed binder - Penetration (mm)	20	EN 1426
Reclaimed binder - Softening Point (°C)	64.6	EN 1427

A bitumen emulsion supplied by COLAS was used as the LEBM binder. A summary of the LEBM constituents and their source is provided in Table 2 below.

2.2 Mixture Design

The optimal binder content was assessed by manual coating tests performed in accordance with I.S. EN 12697–55 [2] and determined that 85 to 90% aggregate coating would

Table 2. LEBM constituents

Constituent		Source
Aggregate	RA 0/32mm	Site-won asphalt
Aggregate	0/2 mm virgin aggregate	FP McCann Ltd
Filler	Portland Cement (CEM II)	Quinn Building Products
Binder	C60B4 ValorCol™ (60% residual 70/100 bitumen)	COLAS Bitumen Emulsions

be achieved using 4.5% emulsion (3.0% residual binder content), 1% cement and 6% total water in the mix [1].

Mixture design was carried out according to I.S. EN 13108–31 [3]. The constituent proportions were adjusted to maximise the performance characteristics of the mixture, see Table 3.

Table 3. Optimized LEBM mixture design

Constituent		% by mass in the mix
Aggregate	RA 0/32mm	94.5
Aggregate	0/2 mm virgin aggregate	
Filler	Portland Cement (CEM II)	
Binder	C60B4 ValorCol™ (60% 70/100 bitumen)	4.5
Added water		1%

3 Pavement Overlay Structural Design

The pavement overlay design was carried out according to TII Publication DN-PAV-03021 [5] to achieve a 20-year design life. This design method uses the Irish Analytic Pavement Design Method (IAPDM) software to carry out a Mechanistic-Empirical pavement design.

3.1 Design Traffic

The future traffic loads to be carried on the R180 were estimated based on traffic count survey data. A pavement design traffic loading of 2.3 million standard axles over a 20-year design period was determined for the design lane.

3.2 Existing Pavement Condition

The condition of the existing pavement structure and identification of homogenous sections was assessed through consideration of Road Surface Profilometer (RSP). Falling Weight Deflectometer (FWD), pavement surface video imagery, test pit and Ground Penetrating Radar (GPR) Survey data.

3.3 Overlay Design

The thickness of the LEBM overlay to be applied to the existing pavement, meeting the design traffic loading requirement, was determined by using the IAPDM. The IAPDM analysis used the back-calculated layer stiffnesses and the LEBM laboratory measured stiffness modulus to develop a pavement structural model. The IAPDM analysis determined that a minimum 150mm LEBM overlay thickness was required to meet the design traffic loading.

4 LEBM Overlay Construction

4.1 LEBM Production

A Wirtgen mobile batching plant was imported to Ireland and setup at Glenmore Quarry to produce the LEBM, see Fig. 1.

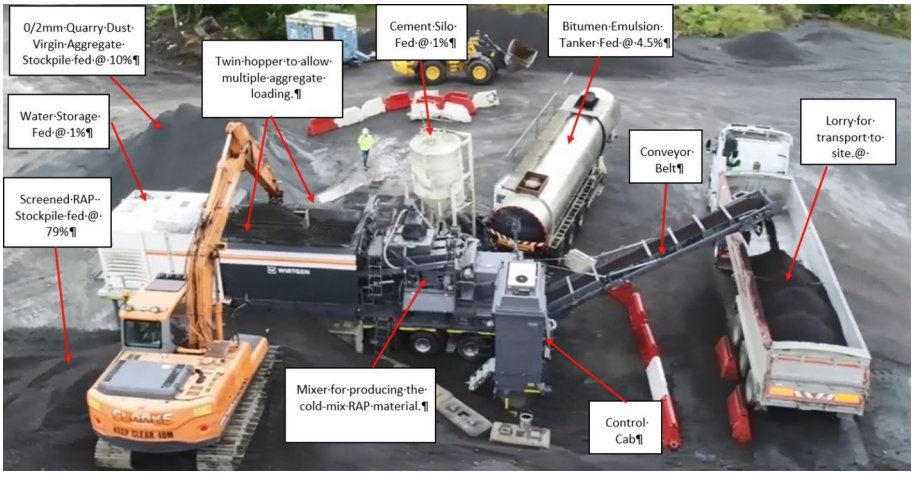


Fig. 1. Wirtgen mobile batching plant arrangement [6]

4.2 Overlay Construction

The LEBM overlay was paved using a Dynapac asphalt paving machine. The LEBM layer was placed in two layers, with bond coats applied on the substrate before each layer was placed. The LEBM layers were typically compacted by two passes of a vibratory steel drum roller followed by 8 to 10 passes of a pneumatic tyred roller. The pavement was surfaced with a double surface dressing [6].

5 Long Term Pavement Performance

5.1 Monitoring Plan

A long-term pavement performance monitoring plan of the trial section was developed to record the condition of the LEBM layer under real-life environmental and traffic loading conditions over a period. An initial one-year monitoring period was planned after which a review of the data collected, and future monitoring of the trial sections will be planned. FWD survey, profilometer and visual condition observations are discussed below.

5.2 FWD Survey

FWD surveys were conducted in both directional lanes of the trial section at 25 m station intervals. FWD surveys were carried using the 150 mm radius load plate with one drop at a target load of 30 kN and two drops at 40 kN target load. The purpose of the FWD survey is to assess the early strength development of the LEBM layer as it cures and the longer term LEBM stiffness development and possible deterioration under traffic loading. All deflection data presented has been normalised to a 40 kN load and temperature corrected to 20 °C.

Deflection Bowl Parameters
Deflection bowl parameters were calculated to evaluate the structural condition of the pavement structure. Figure 2 below depicts the temporal variability of the 15th percentile, average and 85th percentile maximum deflection at the load plate (D1) across the length of the trial section.

Profilometer
The profilometer survey provides for the assessment of the roughness and rutting of the road pavement. Roughness as quantified by the International Roughness Index (IRI) is a pavement condition parameter combining the effects of pavement unevenness and failure into a single index representing the riding quality for a road user travelling on the road pavement.

Rutting measurements provide an insight into the level of deformation of the pavement materials in the wheel paths under traffic loading. Figures 3 and 4 below depict the temporal variability of the average lane width roughness and rutting in the left wheel path for the southbound directional lane.

There is little change in pavement roughness over the one-year observation period as depicted above. The roughness condition observed can be described as very good to

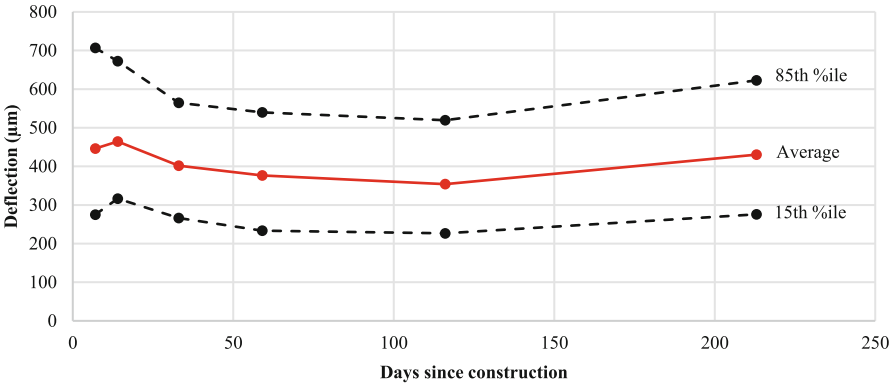


Fig. 2. D1 temporal variability - southbound

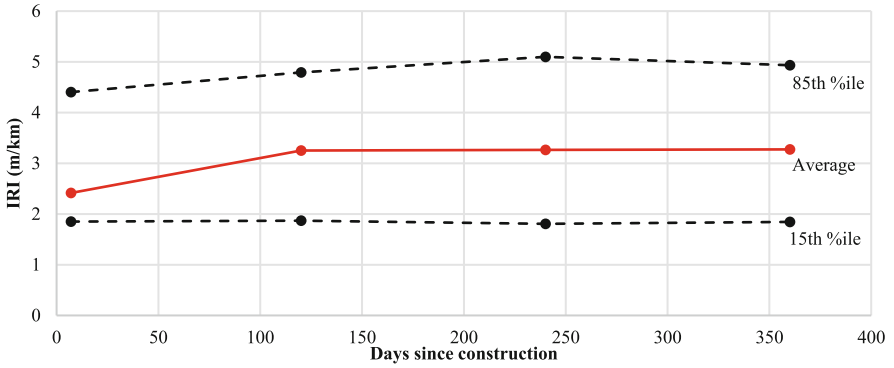


Fig. 3. Roughness temporal variability – southbound

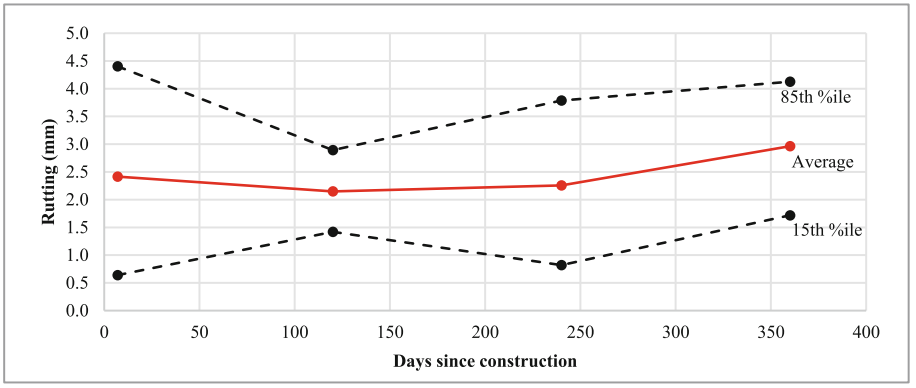


Fig. 4. Left wheel path rutting temporal variability - southbound

good as per the roughness categories used within the TII Pavement Management System for a subnet 4 category road.

Rutting in the left wheel path does not significantly vary over the initial one-year observation period. A slight increase in rutting is noted between eight months and one-year observations. The rutting condition observed can be described as very good as per the roughness categories used within the TII Pavement Management System for a subnet 4 category road.

Visual Condition

The visual condition of the pavement surface is good as observed after one year of being open to traffic. No structural related defects were noted.

6 Conclusions

The LEBM mixture design and pavement design processes applied as part of this trial section development provides a basis for the formalised introduction of this innovative form of LEBM incorporating high quantities of RA material and cold bitumen emulsion binder.

The LEBM layer construction process was satisfactory and no significant issues around the constructability of this type of material were noted.

The performance of the LEBM layer constructed and subjected to traffic loads shows satisfactory performance in terms of layer stiffness, rutting and riding quality for a regional road over the one-year period of observations made. It is however noted that further observation is required to fully understand and gain confidence in the long-term performance of this type of material.

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Circular Economy Transition Actions by a Major Transport Agency–Transport Infrastructure Ireland

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Abstract. The circular economy aims to tackle climate change and other global challenges such as waste, pollution and biodiversity loss, by reducing resource consumption, keeping assets components and materials at their highest value and promoting regenerative and restorative design. This must be achieved while maintaining the safety and technical function of services, assets and components. Transport Infrastructure Ireland (TII) is responsible for delivery and operation of the national road, light rail and Metro networks in Ireland and has set about transformation to a circular economy approach to its assets components and materials.

TII has created an organisation wide policy and strategy informed by an international "state of the art" review of circular economy in transport. Implementation workbooks and guidelines were created to support the transition of projects and programmes to a circular approach for road, light rail and greenway assets. Systems mapping was undertaken along with organisation wide and external collaboration. Applicable TII standards and specifications are being updated with some already complete for pavement and earthworks as priority. Projects undertaken in support of the transition included a performance-based pavement design tool, the Irish Analytical Pavement Design Tool (IAPDM) and a mass haul earthworks optimisation tool. Use of Environmental Product Declarations has been promoted through development of Product Category Rules for key material types. This enables evidence based environmental value driven material selection.

This paper sets out actions taken by a major transportation agency in their transition to applying circular economy approaches to all projects and programmes funded by TII. The paper also outlines learning from the process which might beneficially be implemented by other transport agencies internationally.

Keywords: Circular economy · materials · sustainability

1 Introduction

Transport Infrastructure Ireland (TII) is the Irish government organisation responsible for delivery and operation of the national road, light rail and Metro networks in Ireland. In addition TII publishes design standards which are used along the lifecycle of the TII

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transport network. As a result TII influences the consumption of significant quantities of resources in the Irish economy, in particular asphalt, concrete and steel. In 2020 in light of its role and influence on resource consumption, TII commissioned Arup to undertake a review of international best practice in relation to circular economy. Transition to a circular economy approach by TII will support implementation of the Department of Transport *National Investment Framework for Transport in Ireland (NIFTI)*[1] Intervention Hierarchy which (in order of preference) is: Maintain, Optimise, Improve and New. The European Union Circular Economy Action Plan [3] published by the European Commission in 2020 identifies 7 product value chains requiring urgent, comprehensive and co-ordinated action based on their environmental impact and circularity potential. These include Construction and Buildings. The Irish Department of the Environment, Climate and Communications in its Whole of Government Circular Economy Strategy 2022–2023[3] identifies Transport and Construction as key sectors and also notes as an objective that government will "promote public sector leadership in adopting circular policies and practices".

2 Method

A "state of the art" literature review of selected transport agencies' approaches to circular economy and resource consumption was undertaken in 2020. Through the literature review and TII workshops in 2021 six key focus areas for circular economy in TII were established. These are as follows and were adopted for circular economy transition actions within TII:

- Life cycle assessment;
- Materials and data;
- Asset management;
- Collaboration;
- Transformation to circular systems; and
- Procurement.

Following the workshops a systems map of stakeholder perspectives was created. At this time actions were identified which TII might beneficially take to transition to a circular economy approach in its activities, under the focus area headings, to integrate a circular approach into TII publications and processes. A series of workshops were then taken with TII staff and industry groups to use systems mapping techniques to review and verify the systems map and proposed transition actions. The resulting system diagram is presented in Fig. 1 overleaf.

The Ellen MacArthur Foundation notes that circular economy is based on the principles of "eliminate waste and pollution, circulate products and materials (at their highest value) and regenerate nature"[4]. A tailored version of what circular economy represents for TII was developed between 2021 and September 2023 based on the Ellen MacArthur Foundation definition but also including the need to maintain the safety and technical function of transport services, assets and components. The resulting objectives of circular economy at TII are as follows: "Reduce resource consumption; keep assets, components and materials at their highest value; maintain safety and technical function

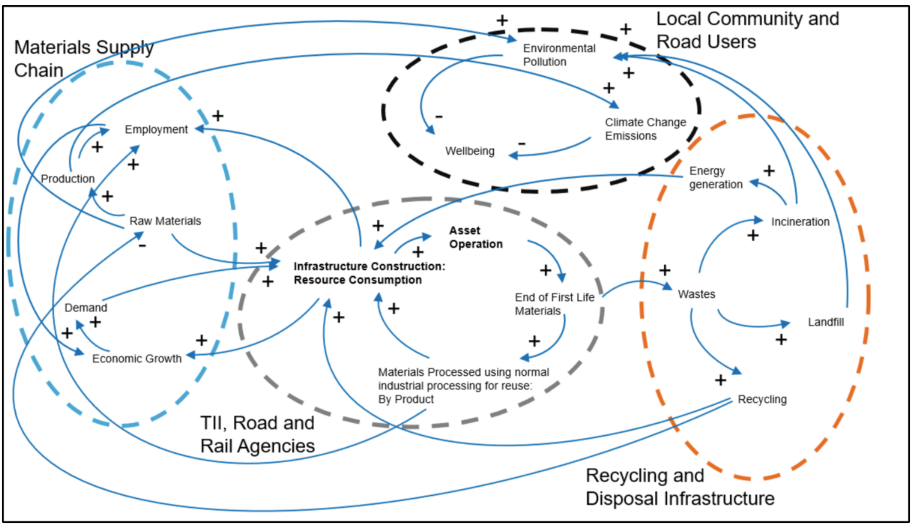


Fig. 1. Transport Infrastructure Circularity and Materials Systems Map

of services, assets and components; promote restorative and regenerative design; and reduce emissions". The 9R approach to circularity has been adopted by the European Commission [5] and the European Investment Bank [6] and this was adapted for use by TII. The resulting framework is shown in Table 1 below.

3 Results

3.1 Introduction

The TII Circular Economy Policy [7] and TII Circular Economy Strategy 2022–2023 [8] were published in September 2023. The policy is TII's statement of intent in relation to circular economy implementation in the activities, programmes and projects it delivers and funds. The policy sets out the purpose of circular economy at TII, the policy and strategy (external and internal to TII) underpinning the TII approach to Circular Economy and TII's circular economy objectives. The TII Circular Economy Strategy sets out how the Circular Economy delivers on TII's Strategic and Sustainability aims, a description of the 6 focus areas is presented and the steps TII will be taking to transition from a linear to a circular approach are summarised under each focus area heading. These include undertaking circular economy pilot projects, creation of new standards and updates to existing standards, publication of design guidelines for projects and programmes, education and training. Table 2 sets out the actions which will be undertaken for implementation of circular economy by TII in the period 2023–2025.

During preparation of the TII Circular Economy Policy and Strategy, pilot projects were undertaken on pavement design and light rail. A number of standards updates also commenced which are of note in the context of TII's transition. They are of particular importance, as they either contribute significantly to TII's transition to a circular economy

Table 1. 9R Categorisation of Circular Economy Strategies adapted for transport infrastructure for TII.

R Category		Description
R1	Refuse	Ensure a clear need is demonstrated for transport assets. Consider alternatives in detail and maximise use of existing infrastructure e.g. reduce the need for construction through reuse of existing roads and local access interventions
R2	Rethink	Intensify asset use e.g. by delivering transport in shared vehicles, and in particular buses, by incorporating a bus lane with priority measures on TII funded schemes
R3	Reduce and Design for Deconstruction	Decrease asset impact in construction or use (throughout the lifecycle) through design for deconstruction and consuming fewer natural resources and materials e.g. integrate modular assets within TII funded schemes
R4	Reuse	Reuse by another asset or organisation of a discarded asset which is still in good condition and fulfils its original function e.g. removing lighting columns no longer required on one scheme for use as lighting columns on another scheme
R5	Repair	Repair and maintain a defective asset which is still in good condition and fulfils its original function e.g. Early surface treatment of pavement to avoid the need for full depth reconstruction
R6	Refurbish	Refurbish an old asset and bring it up to date e.g. upgrading existing signage to align with new symbology, rather than producing new signage
R7	Remanufacture	Use parts of a discarded asset in a new asset with the same function e.g. incorporating reused modular components in new construction
R8	Repurpose	Use discarded asset or its parts in a new asset with a different function e.g. upcycling end-of-life materials for use in pavement design
R9	Recycle	Recover and process materials to obtain the same (high grade) or lower (low grade) quality. eg processing construction materials for reuse in construction, operation and maintenance projects

approach or their implementation is supported by industry via consultation during the development of the standards, awareness raised by workshops and drafting of the TII Circular Economy Policy and Strategy. These are described in the sections below.

4 Discussion

4.1 The Irish Analytical Pavement Design Method (IAPDM) Implementation for TII Pavement Design

In order to allow for the opportunity to reduce, reuse or repurpose materials within pavement construction, adjustments to the current pavement design and specification methods to move to a performance based approach were required. The performance related approach to pavement design is encapsulated within the Irish Analytic Pavement

Table 2. Implementation Actions Categorised by Focus Area

Focus Area	Actions
Life Cycle Assessment	New appropriate models will be used which strike a balance between economic, environmental and social costs. Guidance on LCA and procurement will be published
Materials and Data	TII will commence the process of implementing material passport-type data gathering for assets, components and materials. Pilot projects will be undertaken
Asset Management	Data gathering will commence relating to resource consumption using asset management systems. The pavement asset management system will be first to be updated
Collaboration	The TII Circular Economy External Collaboration Committee will continue to meet to promote implementation of circularity and adoption of TII's Sustainability Implementation Plan
Transformation to Circular Systems	Circular lifecycle implementation workbooks will be published and training provided to embed circular economy in TII funded projects and programmes
Procurement	TII will further embed whole life costing in procurement, this will be achieved through multiple pilot projects The findings of these pilot projects will be incorporated into new guidance on LCA and procurement

Design Method (IAPDM). This method allows for a pavement designer to develop a pavement model based on varying levels of detail of the characteristics of the pavement materials to be constructed and the in-situ condition of the pavement subgrade and foundation. The benefits of application of the IAPDM approach were demonstrated through a circular pilot project as set out in Sect. 4.2 below and as implemented through the updated standard *DN-PAV-03021 Analytic Pavement & Foundation Design* and the accompanying IAPDM web based software.

4.2 IAPDM Circular Economy Pilot Project Application on the N4 Collooney to Castlebaldwin Road Development Project

The N4 Collooney to Castlebaldwin Road Development (N4 CCRD) Project may provide just under 14km of Type 2 Dual Carriageway, and just under 1km of Single Carriageway on the National Road Network. This project was identified as an opportunity to apply the latest version of the IAPDM in 2022, to compare it with the existing nomograph based design method. This information will be used in future development of the IAPDM.

The two aspects of the pavement design process which were considered were pavement subgrade and foundation conditions; and pavement material deterioration modelling. On average, 15mm of asphalt base layer material could be saved by using the IAPDM approach over the pre-2022 DN-PAV-03021 design nomographs for the fully flexible pavement design option. This equates to an 8% material, cost and embodied carbon saving for the bituminous base layer. Table 3 overleaf summarises benefits and savings from taking a performance based approach., Applying the IAPDM demonstrates significant material savings and associated cost and carbon savings in comparison with business-as-usual.

Table 3. Estimated savings due to applying the IAPDM approach to pavement design in comparison with business-as-usual case

Savings	Units	Quantity	Saving	Notes
Bituminous Materials	tonnes	8,715	8% saving in bituminous materials for a typical 150mm layer thickness	Road Type 2 Dual Carriageway (16.5m pavement width), New pavement length 14km
Project Cost	€	647,400	Equivalent 8% saving on a typical 150mm bituminous layer	Dense bitumen macadam with G40/60 penetration binder with 28m aggregate roadbase, TII Schedule of Rates 2019 (CC-GMP-00054 Oct 2019)
Embodied Carbon emissions	kgCO2e	454,923	Equivalent 8% reduction for a typical 150mm bituminous layer	TII Carbon Tool, Asphalt 4% binder content

4.3 Luas Finglas Circular Economy Pilot Project Application

The circular economy pilot project relates to the Preliminary Design Phase (TII Public Transport Project Phase 3) of the Luas Finglas prepared in May 2022. Luas Finglas is the next extension of the Luas Green Line, running from Broombridge to Charlestown through Tolka Valley and Finglas village. The Preferred Route for Luas Finglas is approximately 4km long with four stops. The proposed route, comprises approximately 70% grass track**.** As part of the pilot project a review of the proposed scheme was undertaken and key resource flows identified. Opportunities identified for circularity on the project are as follows:

- **Earthworks optimisation:** As a result of enhanced review of GI data approximately 20,900 m3 of excess material (38–40,000 tonnes) potentially available for reuse on the project were identified.

- **Design for disassembly of track:** The resulting carbon saving is estimated at 1,056 tCO_2eq for embodied and use phase carbon over the length of the scheme.
- **Materials Data Integration:** The project has integrated key material data into the project data environment. This enables identification of reuse or recycling possibilities for assets, components and materials after their first life.
- **Active travel:** In terms of active travel, the pilot project brings additional social value through integration of active travel facilities into the Luas network.
- **Adopting nature-based solutions and a regenerative design approach:**. The Luas Finglas project team is working with Dublin City Council to progress enhancement of biodiversity and design of public space during the construction phase.

4.4 Development of Complementary Product Category Rules (cPcR) for Life Cycle Assessment of Bituminous Mixtures in Road Construction

TII published a draft cPCR consultation document for bituminous mixtures Environmental Product Declarations (EPD) in 2022 [10]. On final publication this will enables evidence based use of EPDs for bituminous mixtures for a range of applications, including procurement.. The greenhouse gas emissions data contained within EPDs is of particular interest in the context of emissions reduction and transition to a circular economy. In the future TII will create and publish cPCRs for further road construction materials which will support circular economy transition.

4.5 Standards Updates for Roads Construction

TII has significant influence on the construction industry in Ireland through publication of standards. A key barrier raised throughout the circular economy workshops described in this paper was navigation of complex regulatory processes. The TII standard *CC-SPW-00600 - Specification for Road Works Series 600 – Earthworks* [11] is currently being updated and this update will ensure alignment with the Irish Environmental Protection Agencies Article 27 regulatory process for reuse of by products and the Article 28 regulatory process to achieve end of waste and use recycled materials and products. This update and alignment will support more circular reuse of by products and recycled materials on transport infrastructure projects in Ireland. The *TII standard CC-SPW-00900 - Specification for Road Works Series 900 – Road Pavements – Bituminous Materials* [12] currently permits 30% recycled materials content in the base and binder layers of road pavements. The standard is currently being updated with one of the proposed updates being an increase in the permissible recycled content to 70% of the lower road pavement layers. This will support reuse of pavement material and reduction of emissions and wastes associated with road pavement at each stage of its life cycle.

5 Conclusion

While the circular economy is a means of achieving TIIs strategic and sustainability aims the circular economy approach required tailoring to transport infrastructure and in particular to safety and delivery of technical functional asset objectives. For this reason

bespoke circular economy objectives and focus areas were created specifically for TII. The tangible benefits of a circular approach were demonstrated by pilot projects and additional projects are proposed in this regard. Standards updates will be delivered in 2023 to support transport infrastructure designers who wish to incorporate circularity, by products and recycled materials in their design. The approach taken was collaborative, including a cross divisional consultation approach and creation of an external industry consultation committee. This collaborative approach will continue during circular economy implementation through the period 2023–2025.

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Towards Harmonised S-LCA: Identification of Relevant Stakeholder and Social Impact Subcategories for Autonomous Electric Car Sharing Fleets

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Abstract. As the automotive industry shifts towards sustainable transportation solutions, autonomous electric car-sharing fleets offer promise in curbing carbon emissions and mitigating traffic congestion. Recognizing the need to account for social impacts, a comprehensive Social Life Cycle Assessment (S-LCA) is essential to assess and manage their social impacts. However, there's a significant challenge due to the lack of standardized methods for S-LCA, particularly for autonomous electric car-sharing fleets (AECSF). To address this challenge, this research article proposes a standardized S-LCA framework, focusing on identifying relevant stakeholder categories and their associated social-impact subcategories for AECSF. The framework incorporates the goal and scope components of S-LCA to define assessment boundaries and objectives. The research method ology adopts a multi-stakeholder approach in three stages. First, a thorough literature review examines stakeholder and social-impact categories for autonomous electric car-sharing. Second, online surveys involve individuals and experts representing stakeholder categories from transportation, automotive, sustainability, and social sciences to gather insights on these aspects. Finally, quantitative analysis validates the findings.

The study identifies five primary stakeholders: users, local communities, value chain actors, society, and workers. Additionally, it pinpoints social-impact categories and sub-categories relevant to AECSF, encompassing accessibility and affordability, safety and cyber-security, and employment and labor conditions. These findings lay a foundation for standardizing S-LCA for autonomous electric car-sharing fleets, supporting future research and development of a comprehensive framework tailored to this field's unique characteristics and challenges. Such a framework can aid decision-making, guide sustainable development, and enhance social well-being in the emerging realm of autonomous electric car-sharing.

Keywords: autonomous electric car-sharing · social life cycle assessment · stake-holder categories · social-impact categories · sustainability

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1 Introduction

The imperative shift towards sustainable transportation solutions in combating climate change and traffic congestion has been underscored by the 2030 climate target plan[1, 2]. Autonomous electric car-sharing fleets, as part of innovative mobility solutions, hold promise in addressing urban mobility challenges [3, 4]. However, understanding their social impacts throughout the lifecycle is critical, aligning with influential policies and initiatives (European Green Deal, Circular Economy Action Plan) [5]. The integration of autonomous vehicles (AVs) into society has far-reaching implications, transforming mobility, safety, and social inclusion [6, 7]. Car-sharing has gained ground, but sustainability assessments must expand beyond environmental factors to include economic and social impacts [8]. Social Life Cycle Assessment (S-LCA) lacks standardization, necessitating research in this emerging field [9].

The emergence of autonomous electric car-sharing services introduces unique challenges like cybersecurity due to their heavy reliance on digital infrastructure [10]. However, a comprehensive list of relevant social impacts specific to this mobility solution is lacking. This research aims to identify these social impact categories and subcategories without classifying them as positive or negative impacts [11]. Existing research on the sustainability aspects of autonomous electric car-sharing fleets is limited, leading to a structured literature review focusing on various aspects, including lithiumion batteries, AVs, electric vehicle components, car-sharing, fleet management, and cybersecurity. Currently, AVs have reached level 2 autonomy, with Waymo's level 4 autonomy serving as a reference case. The research methodology adopts a two-stage approach, starting with the identification of social issues across the autonomous electric car-sharing fleet lifecycle. The second stage involves a participatory multi-actor consultation process through an online survey, prioritizing impact subcategories and aligning them with relevant impact categories for stakeholders. The UNEP Guidelines for Social Life Cycle Assessment (S-LCA) and Methodological sheets are pivotal in guiding the research [15]. Data visualization techniques complement the identification process [12].

2 Literature Review

This study explores the realm of Social Life Cycle Assessment (S-LCA) with a specific focus on autonomous electric car-sharing fleets, addressing a gap in research concerning the comprehensive analysis of the social impacts associated with these innovative mobility services. The research conducts a systematic literature review, emphasizing autonomous vehicles, electric vehicles, and car-sharing, all of which converge to form autonomous electric car-sharing services. The primary objective is to identify and prioritize the social impacts linked to these fleets. S-LCA is an emerging approach originating from Environmental Life Cycle Assessment (E-LCA) and aims to consider social aspects throughout a product or service's life cycle [11]. The European Commission promotes the integration of social and environmental considerations in the entire value chain, promoting sustainability [16]. S-LCA differs from E-LCA by incorporating qualitative information related to cultural norms. Obtaining data on how stakeholders are treated is often done through corporate sustainability reports, surveys, or internal investigations, though full disclosure may be limited due to competitive concerns. Key aspects

of S-LCA include defining the functional unit, system boundaries, social indicators, and impacts, with a focus on iterative goal and scope development. The UNEP/SETAC 2020 guidelines provide 40 social impact subcategories categorized by stakeholders, such as workers, local communities, consumers, society, and children. National laws significantly shape social conditions, with non-compliance resulting in negative consequences. While S-LCA holds potential, it faces challenges related to uncertainties, transparency, and standardization due to diverse approaches [11].

The development of autonomous vehicles (AVs) is traced from its historical roots to the present, with various cities serving as testing grounds for companies like Waymo, Cruise, Aurora, and Uber. AVs rely on sensors, semiconductors, and advanced software for autonomous operation. Non-technical factors such as consumer confidence and governance play a vital role in their widespread adoption, and scientific studies explore their societal impacts. The transition from electric vehicles (EVs) to autonomous electric vehicles (AEVs) is gaining momentum, offering benefits such as improved service, cost reduction, and environmental advantages. However, seamless integration into existing charging infrastructure remains a priority. Environmental life cycle assessments (LCAs) have been conducted for EVs and AEVs, but social life cycle assessments (SLCAs) are relatively unexplored, despite their importance in understanding the social impacts of these technologies [17–20].

Car-sharing, as a practice that reduces reliance on private cars and contributes to environmental and societal benefits, has seen significant growth. The integration of electric vehicles (EVs) into car-sharing fleets is a noteworthy trend. Policy-wise, the European Commission emphasizes shared mobility integration with public transport and considers social dimensions in the transition to sustainable mobility. The study provides a comprehensive overview of these interconnected topics, addressing the need for further research and understanding of the social implications of autonomous electric car-sharing fleets [13, 14, 21, 22].

3 Methodology

The goal of the study is to effectively communicate and raise awareness among various stakeholders about the potential social impacts associated with autonomous electric car-sharing fleets. The scope included policy development, car-sharing operations, and the promotion of sustainable transportation in the context of autonomous electric car-sharing fleets. The relevant functional unit of the study is defined as 150,000 km travelled per vehicle within a fleet consisting of 200 vehicles over a fleet service period of 3 years. Figure 1 depicts the implemented methodological framework.

4 Results and Discussion

In the life cycle of autonomous electric car-sharing fleets, 11 new impact subcategories were identified during the use phase, aligning with recognized social impact topics. References including the European Commission's urban mobility indicators and the Social Value Initiative's reports contributed to these subcategories. Additionally, the impact subcategory "Cyber-security ethical considerations" emerged independently,

focusing on cybersecurity and ethical issues related to autonomous vehicles. These subcategories are integrated into a comprehensive list of 46 impact subcategories, with 35 from UNEP/SETAC Guidelines.

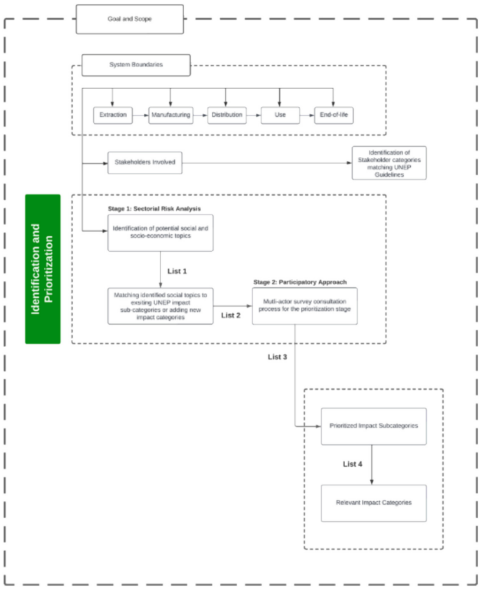


Fig. 1. Methodological Framework Design of the Study

The impact sub-categories are then prioritized based on the prioritization criteria of the study. These were the matched with UNEP's impact categories, including Human Rights, Health and Safety, Working Conditions, Governance, Cultural Heritage, and Socio-economic repercussions. Specific definitions and interrelationships were examined from various sources.

The research aimed to identify key social impact categories related to autonomous electric car-sharing fleets, advancing Social Life Cycle Assessment (S-LCA) standardization. Its core mission was to communicate and raise awareness impartially among diverse stakeholders about potential social consequences tied to innovative shared mobility systems, all in pursuit of mobility sector sustainability. The study carefully connected the research question, initial objectives, and results, yielding insights for various stakeholder categories in advancing sustainability. The examination of five key stake-holder categories - "Local Communities," "Society," "Users," "Value Chain Actors," and "Workers" - unveiled significant social impact subcategories intertwined with sustainability. For local communities, air quality, secure living conditions, public space, and noise pollution emerged as vital for city and community sustainable development, emphasizing collective stakeholder efforts. Society showed diverse perspectives on social impacts, with unanimous acknowledgment of urban development and economic contributions but concern about corruption, highlighting ethical practices' role in equitable development.

Users of autonomous electric car-sharing emphasized accessibility, health, safety, affordability, and infrastructure interoperability. Disparities between user and societal perspectives underlined the need for user-centric policies for sustainable and inclusive mobility. Value chain actors highlighted "Fair Competition" and "Wealth Distribution," emphasizing equitable practices and responsible supply chain conduct. The study focused on workers, identifying concerns like health, safety, child labor, forced labor, and fair wages, crucial for sustainability, particularly in raw materials extraction for lithium-ion batteries. Many prioritized impact subcategories fell under "Human Rights," emphasizing its role in autonomous car-sharing sustainability across stakeholders. Despite challenges, including limited end-of-life phase data and the need for enhanced UNEP guidelines, the study proposed valuable recommendations. These included considering the 11 newly identified impact subcategories for sector-based UNEP Guidelines for Social Life Cycle Assessment within the mobility sector. To enhance future research, increasing survey sample sizes and targeting participant profiles' quality were suggested. Expanding system boundaries for assessments, especially at the end-of-life phase, was recommended for holistic social implications evaluation.

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Author Index

A
Aakko-Saksa, Päivi 153
Acciaro, Michele 127
Acevedo, Andreia Lopes 415
Adams, Peter 859
Adl-Zarrabi, Bijan 802
Ajaykumar, Siddharth 629
Ali, Marwa Ben Taleb 24
Allen, Martin 427
Almeida, Arminda 652
Almeida, Carina 382
Alonso, Gustavo 368
Al-Tabbaa, Abir 747
Álvarez-Lorenzo, Rodrigo 368
Amaral, António 267
Anastasio, Sara 754
Anderluh, Alexandra 361
Anderson, Alan 868
Andreolli, Raphael 375
Andrieu, Vera-Marie 304
Antunes, Vítor 382
Antunes, Vitor 816
Appolloni, Letizia 166
Arandia, Iker 446
Arce, Rosa 160
Arellano, Diana 659
Argerich-Martín, Clara 368
Arregui, Harbil 446
Arrigoni, Vincent 24
Arsenio, Elisabete 93, 609
Astegiano, Paola 569
Aumond, Pierre 58
Ayfantopoulou, Georgia 354, 494, 529, 550, 569

B
Bailey, Helen 809
Baker, Gerry 196
Bañobre, Raquel Ledo 796
Bañuelos-Gimeno, Jorge 160
Barateiro, José 609
Barbu, Corneliu 659
Barfod, Michael Bruhn 304
Barreira, Luis 153
Barroso, Suelly 733
Barry, Stephen 427
Basso, Matteo 726
Batsalia, Nikoletta 65
Becker, Christoph 543
Beil, Denise 246
Below, Michael 107
Benini, Alice 603
Benito, Arturo 368
Berger, Martin 361
Berthet, Kevin 831
Beye, Charly 141
Bielaczyc, Piotr 153
Boos, Adrian 141
Borge, Rafael 45
Boullet, Thomas 10
Bowes, John 427
Brandner, Manuela 395, 636
Brandstätter, Georg 487
Brennan, Alfie 761
Brennan, Dan 38
Brero, Giovanni 802
Brownrigg-Gleeson, Mari Luz 415
Brun, G. 3
Brun, Ghislain 10
Buchegger, Julia 563
Buijs, Paul 623
Bulckaen, Léo 100
Burghardt, Tomasz E. 17
Burguera, Fernando 796

C
Cabral, Antônio Eduardo 733
Caetano, Fernanda 768

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Calado, E. A. 703
Camacho, J. 219
Campbell, Rose 523
Camps, Francisca Rosell 460
Can, Arnaud 58
Capitão, Arminda Almeida 645
Capitão, Luís Picado-Santos 645
Capitão, Silvino 645, 652
Carballal, Miguel Moldes 726
Carrilho, H. 3
Carrilho, Heidi 10
Carriquiry, Juan Pedro 304
Carroll, Paula 388
Cartolano, Fabio 324
Carvalho, Manuela 768
Cejudo, Iñaki 446
Cerdeira, M. 719
Cerqueira, Sofia 609
Cervena, Tereza 153
Chiello, Olivier 58
Ciprés, David 695
Claudio, Ferrari 226
Clausen, Uwe 782
Colpier, UIrika 339
Connolly, Lorcan 809
Conter, Marco 802
Coppinger, John 868
Corazza, Maria Vittoria 31, 166
Cornet, Yannick 172
Correia, Eugénia 768
Cossu, Paola 324, 569
Costa, Francesco Paolo Nanni 603
Crewe, Clive 616
Crowley, Willie 196
Crushell, Patrick 196
Cummins, Stephen 427

D
D'Alessandro, Daniela 166
da Costa, Eduarda Marques 93
da Silva, Manuel Carlos Gameiro 71
Dais, Sofoklis 550
Davies, Ian 38
De Bortoli Vizioli, A. 219
de la Guerra, E. 719
de Macedo, António Lemonde 93
de Melo Akel Thomaz, Diego Bandeira 523
Deakin, David 38
Delater, A. 3
Delhaye, David 153
Dellbrügge, Marius 782
Delmeire, Nik 240
Demetrio, Andrea 543
Derguech, W. 219
Devasia, Dixon 629
Di Mascio, Paola 31
Dittrich, Michael 65
Djordjevic, Boban 460
Domingues, Daniela 768
Dopler, Silvia 246
Dossou, Paul-Eric 253
Drysdale, J. 219
Duarte, Sérgio Pedro 439
Dubey, Mayank 259
Duggan, Alan 196
Duhme, Wiebke 240
Duin, Heiko 285, 474
Duldner-Borca, Bianca 246
Dutta, Nilankur 100

E
Edwin, van Hassel 226
Egger, Martin 298
Einsele, Florian 453
Ekblad, Alf 78
El Baghdadi, Mohamed 852
Elgner, Felix 543
Ellingsen, Linda Ager-Wick 680
Elmarakbi, Ahmed 726
Eschment, Lukas 285, 292, 467, 474
Escuín, David 695
Esneu, X. 219
Evans, Mike 859, 876

F
Fable, S. 3
Falkgrim, Eric 375
Favero, Jérôme 796
Félix, Rosa 85
Fergadiotou, Ioanna 536, 569
Ferreira, Victor 659
Fetka, Jonathan 361
Flynn, Damian 388
Fonseca, João Clérigo 816

Fontes, Tânia 267
Fors, Vaike 515
Fournier, Guy 141
Fox, Eimear 192, 823
Franchina, Federico 212
Franklin, Rod 569
Franzoni, Lorenzo 78, 107
Freire, Ana Cristina 816
Friedman, Miles 831
Funke, Simon 453

G
Gallagher, Ann-Marie 876
Ganeau, Luoise 153
Gao, Bo 616
Garcia-Sanchez, David 809
García Rubio, David 324
Garland, J. 219
Gaspar, Pedro 382
Georgakis, Panos 536
Ghoniem, Engy 726
Ghozzi, Fayes 10
Giannoudis, Vasileios 529
Gibney, Amanda 789
Gournet, Nicolas 10
Graindorge, Tatiana 523
Grau, Josep-Maria Salanova 354
Gulino, Michelangelo Santo 433
Gustafsson, Magnus 480

H
Hall, Gerard 427
Haller, Andreas 453
Halpenny, Alice 876
Hameister, Hannes 543
Harrington, Lauren 38
Hartavi, A. E. 703
Hartmann, Andreas 710
Hasenleithner, Tobias 298
Haubold, Holger 178
Hausberger, Stefan 852
Healy, B. 219
Heaphy, Rachel 196
Hegazy, Omar 852
Hellström, Magnus 480
Helo, Petri 501
Henriques, Rui 609
Herrmann, Christoph 782
Hettich, Greta 311
Hewitt, Alison 802
Himmelbauer, Gabriel Stephan 298
Hinkka, Ville 318
Hoeborn, Gerrit 556
Hogan, D. 219
Hong, Jinhyun 120
Honkisz, Wojciech 153
Hook, Hannah 172
Houssou, U. 219
Hu, Bin 395, 563, 636

I
Ignatavicius, Simonas 868
Illek, Günther 361
Ingratoci, Cinzia 212
Irigoyen, Eider 446
Irudayaraj, Jow 253
Irving, Hugh 761

J
Jäger, Victoria 453
Jakiel, Christoph 292
Jaksic, Vesna 761
Järvinen, Anssi 153
Jenelius, Erik 375
Jezdinsky, Tomas 659
Jiménez-Redondo, Noemi 845
Jose, Davis 885
Josefsson, Andreas 339
Jović, Marija 240
Juraschek, Max 782

K
Kääriäinen, Jukka 318
Kallionpää, Erika 589
Kampa, Maria 536
Kangley, Virginia 427
Känsäkoski, Janne 409
Karakikes, Ioannis 515
Karjalainen, Panu 153
Karlström, Magnus 339
Kavanagh, Alan 868
Kehrt, Carina 311
Kiefer, Maximilian 782
Kiousi, Akrivi 536

Kissane, Paul 196
Klein, Eric 583
Kolarova, Viktoriya 421
Kompp, Ricarda 246
Kontses, D. 703
Kontses, Dimitrios 51
Koukounaris, Athanasios I. 134
Krauss, Konstantin 114
Kublin, Thomasz 474
Kural, Karel 629
Kuusniemi, Heidi 501

L
Lacroix, G. 3
Lamb, Martin 809
Lamme, Sascha 467
Laschi, Maurizio 433
Lawless, Elizabeth 427
Le Bihan, O. 3
Lemaitre, Guillaume 58
Leroy, Yann 740
Leviäkangas, Pekka 409
Levrey, Manon 536
Li, Jinpeng 120
Liberko, N. 219
Ligthart, Tom 796
Liimatainen, Heikki 589
Livingston, Mark 120
Lobo, António 439
Lodder, Taz 802
López, José Luis 695
Louzao, Vanesa Ventosinos 726
Louzao, Vanessa Ventosinos 796
Louzis, Konstantinos 509
Lovelace, Robin 85
Loyo, Estibaliz 446
Lunaas, Thor Asbjoern 754
Lund, Jesper 515
Luppino, Giuseppe 603
Lynch, Alan 838, 859, 868
Lynch, Janet 876

M
Mac an tSearraigh, Cathal 831
MacAuley, Nathan 761
MacCriostail, C. 219
Madden, Esther 876
Magoutas, Babis 536
Mainardis, Olivier 859
Majoral, Genís 596
Maleas, Zisis 354
Malekjafarian, Abdollah 761
Malhene, Nicolas 523
Malichová, Eva 172
Mallidis, Ioannis 494
Mamarikas-Itsios, S. 703
Mansour Salamé, Joseph 740
Maria Rosa Muñoz, B. 304
Marousi, Konstantina P. 134
Martín, Celestino Sánchez 460
Martin, Emilie 304
Martin, Joseph 823
Matyusz, Zsolt 576
McArthur, David Philip 120
McGuinness, Matt 687
Mejia, Alvin 304
Mejía, Hernán 324
Melo, Sandra 439
Michailidis, Dimitris 789
Mikkola, Markku 318
Miranda, Henrique Borges 768
Mobsby, D. 219
Mohammed, Haneen 747
Monzon, Andres 415
Morganti, Eleonora 603
Mørkrid, Odd Erik 509
Moura, Filipe 85
Mujika, Andoni 446
Mulhern, Emma 318
Mulry, Brian 868
Munkácsy, András 576
Muthakana, Nikhil 629

N
Nahar, Sayeda 838
Nair, Sheba 589
Nangah Mankaa, Rose 885
Nassar, Ahmed I. M. 747
Neu, Walter 285, 292, 467, 474
Ngo, S. 3
Ngo, Sylvie 10
Nicolaï, Isabelle 740
Nicolas, Alexandre 100
Nobel, Thomas 285

Nobis, Claudia 421
Nolan, Kevin 761
Nordahl, Håvard 509
Notarangelo, Riccardo L. 501
Ntemou, Amalia 536
Ntziachristos, Leonidas 65
Nybacka, Mikael 375
Nyembwe, Jean-Paul Kapuya Bulaba 71

O
O'Connor, Alan 809
O'Connor, John 831
O'Dea, Gerard 859
O'Malley, Vincent 38, 192
O'Reilly, Ciarán J. 375
O'Shea, Patrick 196
Oertli, Jakob 78
Ogundiran, John Omomoluwa 71
Oliveira Mesquita, Amanda 576
Ornek, Mustafa Arslan 205
Ortega, Ismael 153
Oudin, Anna 153
Ozturk, Cemalettin 205

P
Pagels, Joakim 153
Pakrashi, Vikram 761
Panagakos, George 304
Papageorgiou-Koutoulas, Alexandros 51
Pardhi, Shantanu 852
Pashkevich, Anton 17
Patterson, Fiona 196
Pawlak, Thibault 24
Pekkala, Veikko 409
Pérez, M. 719
Perry, Kimberley 876
Pfoser, Sarah 395, 636
Philipps-Bertin, Chrystèle 58
Picado-Santos, Luís 652, 733
Pierce, David E. 775
Pinto, Tassia Carolina Forasteiro 523
Platzer, Mario 361
Podimatas, Vassilis 509
Polo, Lorena 695
Polydoropoulou, Amalia 515
Ponweiser, Wolfgang 395, 636
Popov, Ilya 796
Portoghese, L. 219
Prandtstetter, Matthias 274, 395, 636
Putz-Egger, Lisa-Maria 246
Pyykkö, Harri 318

Q
Quaassdorff, Christina 45
Queron, J. 3

R
Rabadan, Laura 446
Radziszewski, Paweł 474
Rahim, Ashik 885
Rahnama, Shaghayegh 695
Ramdas, Vijay 809
Rapinc, Philippe 324
Rato, Maria João 768
Realpe, Grace Carolina López 304
Reeh, Lucas 361
Reichmann, Matthias 298
Reimann, Maximilian 361
Reinthaler, Martin 395, 636
Rengaraju, Sripriya 747
Ribeiro, Anabela Salgueiro Narciso 71
Rissanen, Matti 153
Riverso, S. 219
Rizopoulos, Dimitrios 536
Rodrigues, Marta 93
Roldin, Pontus 153
Rönkkö, Topi 153
Rosengren, Lars-Göran 339
Rothbard, Sandra 324
Rounak, Aasifa 761
Roux, Maël 58
Roy, Stabak 402
Ruane, Kieran 761
Rudolf, Sina 782

S
Sahivirta, Hanna 659
Saïdani, Michael 740
Salminen, Simo 318
Samaras, Z. 703

Samaras, Zissis 51
Santos, Joao 710
Saripada, Naressa 304
Saurí, Sergi 596
Schmidt, Franziska 583
Schrevere, Thomas 24
Schroer, Tobias 556
Schuh, Thomas 107
Schüning, Thomas 285, 292, 467, 474
Schwartz, Henry 480
Schwingshackl, Michael 852
Seeßle, Patrick 453
Seidel, Saskia 311
Selz, Emanuel 361
Serna-Guerrero, Rodrigo 659
She, Cliodhna Ni 388
Sheils, Emma 809
Shrestha, Shritu 304
Sieber, Niklas 114
Silva, André Teixeira 439
Silva, Vasco 267
Silva, Webert 733
Simons, Janis 556
Singh, Avishreshth 809
Smith, Andrew S. J. 775
Smyth, Stephen 859
Snilsberg, Brynhild 754
Sobrino, Natalia 160
Sochor, Jana 332
Sofronov, Yavor 659
Solís-Hernández, José 845
Specht, Patrick 240
Sprei, Frances 332
Stadlmann, Burkhard 298
Stamelou, Afroditi 494
Stamm, Marcel 292
Starkl, Fritz 274
Stefanutti, Ronaldo 733
Stein, Sandra 274, 556
Stephanedes, Yorgos J. 134
Stipanovic, Irina 710
Stouraiti, Angeliki 509
Strong, Neil 107, 185
Sund, Even K. 754

T
Tabakovic, Amir 838
Tacoglu, Melis Tan 205
Talreja, Harshit 259
Taurino, D. 219
Tavajoh, Simin 802
Tebby, C. 3
Telford, Alexandra 747
Thierry, Vanelslander 226
Thorne, Rebecca Jayne 680
Timonen, Hilkka 153
Todorov, Georgi 659
Toivanen, Leena 409
Toner, Declan 868
Topinka, Jan 153
Toribio-Díaz, Concepción 845
Traverso, Marzia 885
Triantafyllopoulos, Georgios 65
Tsirimpa, Athena 536
Tsvetkova, Anastasia 480
Turkan, U. U. 703
Tziovas, Athanasios 65

U
Úbeda, Aristarco Tomás 460
Urbano Escobar, Raúl 324
Urquhart, Duncan 38
Uzu, G. 3

V
van den Boom, Nicole 141
van Vliet, Dave 838
Vangi, Dario 433
Vargas-Farias, Andrea 710
Varveri, Aikaterini 809
Ventikos, Nikolaos P. 509
Vieira, Carina 768
Viner, Helen 809
Vojtisek-Lomgand, Michal 153
Vokes, Warren 196
von Stamm, John 556
Voulkopoulos, Vasileios 529

W
Wadhwani, K. 219
Wagner, Adrian 298
Walker, Alan 616
Wallbaum, Holger 802
Wancura, Herbert 298
Warzok, Dominic 543
Weldon, David 823
Wendel, Jochen 543
West, Kevin 868
Widhalm, Peter 274, 563

Wilson, Benjamin P. 659
Winterlich, Edward 868
Wolf, Martijn 78
Wolfram, Daniel 453
Woodburn, Joseph 153
Wouter, Schmidt 226
Wurst, Stephan 285, 474

X
Xenou, Elpida 529

Y
Yatskiv, Irina 474
Yilmazer, Pinar 107
Yılmazer, Pınar 78

Z
Zaiko, Nikita 339
Zajicek, Jürgen 298, 487
Zeybek, Hulya 402
Zlatev, Blagovest 659