HOW SYSTEM CONFIGURATION SHAPES DEMAND

Agent Based Simulation of Mobility-on-Demand systems & policy insights

Tilmann Schlenther, DLR-VF-MSE, 28 November 2025

Agenda

1. Context and research objectives
2. Using agent-based transport simulation as a decision support tool
3. The relationship between MoD system configuration and ridership
4. Rebalancing as a tool to decrease heterogeneity of wait times
5. Summary and Conclusion

HOW SYSTEM CONFIGURATION SHAPES DEMAND

Context and research objectives

Project Context
KelRide: Weather-Proof Smart Shuttle

Source:[1]

- Funding ~11 mill. €
- Total budget ~15.6 mill. €
- Project duration: 2021 - 2023
- The aim of the project was to **integrate an autonomous on-demand ridepooling (MoD) service** which can be operated in all weather conditions **into an already existing human-driven MoD service**
- www.kelride.com

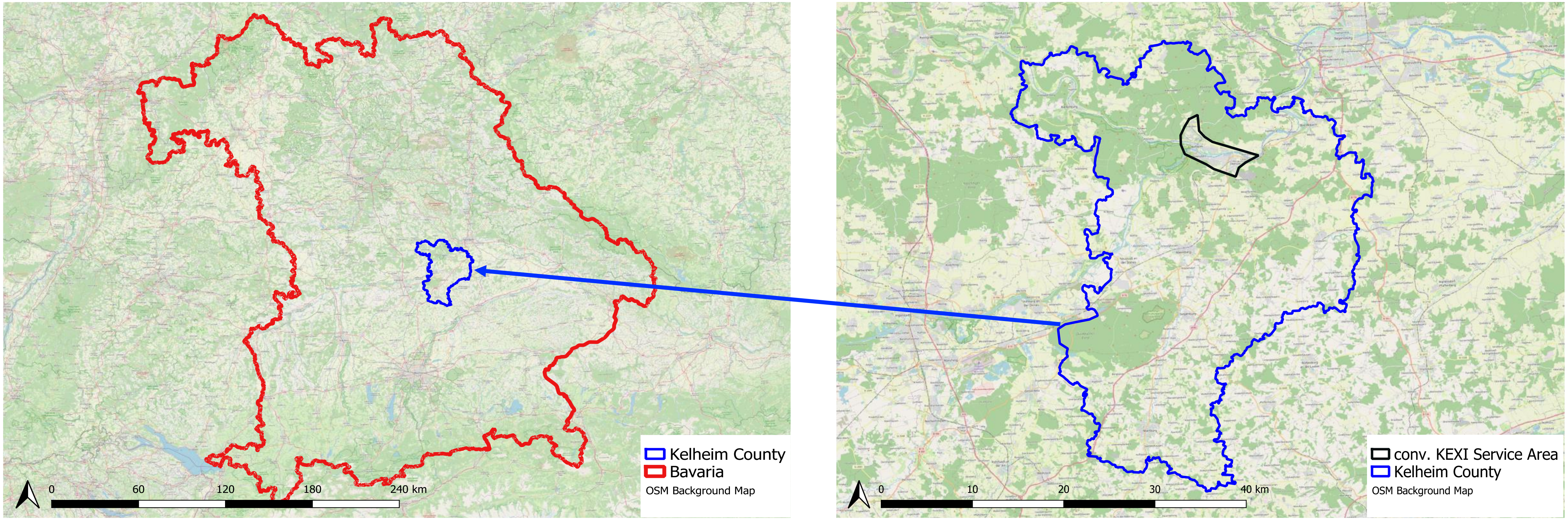
Funded by:

Federal Ministry for Digital and Transport

Landkreis Kelheim
easy MILE
Technische Universität Berlin
via
P3
TÜVRheinland® Precisely Right.

Source:[1]

Spatial Context
Kelheim County and Kelheim Town (Municipality)



Based on sources:[2], www.openstreetmap.org

Planned Project Timeline: 2 Phases = 2 Fleet Sizes

DLR

03/21
- Project start

06/21
- Definition of Phase 1 AV area

09/22
- **Phase 1** Launch
- 2 vehicles

07/23
- *Planned* **Phase 2** Launch
- 5 vehicles

12/23
- Project end

Vehicle / Service approval needed a period of time (pilot project)

Which areas of Kelheim should the AV KEXI service cover in Phase 2?

Research Objectives and Questions

Objective 1:

Using agent-based transport **simulation as decision support tool** for the configuration of AV KEXI.

Objective 2:

Investigate how MoD services can be integrated into existing transport systems, with a particular focus on the **relationship between MoD configuration and user demand.**

Research question (RQ) 1:

Which areas of Kelheim should the AV KEXI service cover in Phase 2 to ensure efficient operation and meaningful integration into the existing transport system?

Research question 2:

What is the **quantitative relationship between key MoD configuration parameters and the average number of MoD passengers per day**, and through which mechanisms do these effects occur?

Research question 3:

To what extent **can strategic positioning of idle MoD vehicles improve spatial service provision equity?**

USING AGENT-BASED TRANSPORT SIMULATION AS A DECISION SUPPORT TOOL

Which areas of Kelheim should the AV KEXI service cover in Phase 2?

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Simulation Framework
MATSim – Multi-Agent Transport Simulation

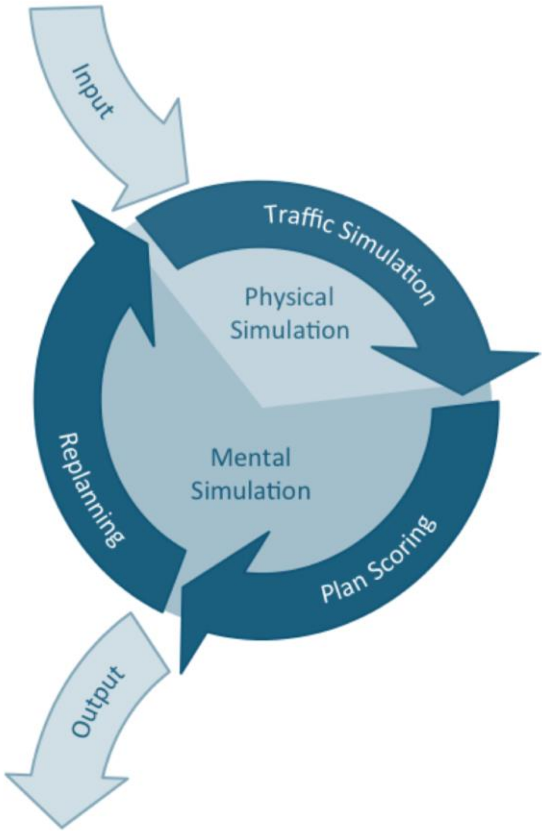


Image based on sources: [3,9]

- Agent-, activity- and event-based, dynamic transport simulation framework [4]
- Modular, various extensions, widely used and adopted
- **Physical simulation**
  - Queue model
- **Mental simulation**
  - Behavioral adoption through **co-evolutionary learning algorithm**
    - Mode choice, Route choice, Departure time choice, …
- Approximates stochastic user equilibrium
- **Allows to investigate interaction of transport demand and supply**

Project and Study Timeline

03/21	06/21	Spring 2022	09/22	07/23	31/23
• **Project start**	• Definition of Phase 1 AV area	• **Investigation of Phase 2 AV area**	• **Phase 1** Launch • 2 vehicles	• *Planned* **Phase 2** Launch • 5 vehicles	• *Planned project end*

Study 1 = Projection of
- Phase 1 (already configured)
- Phase 2 -> decision support

→ no real AV booking data available

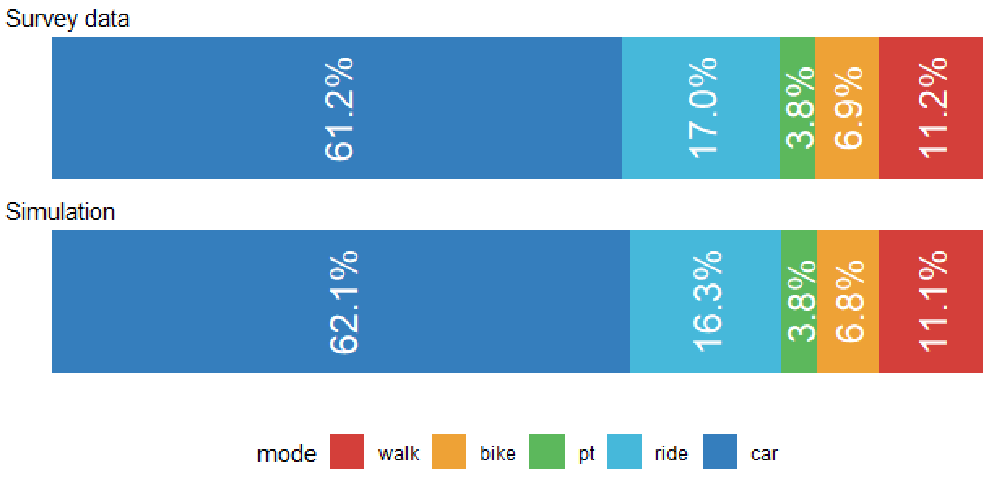
Base Model Calibration + Validation

Synthetic transport demand

- Trajectories derived from mobile phone data
- Regional statistics
- Travel surveys
- …

Calibration & Validation

- Modal split
- Modal distance distribution
- Travel times
- Traffic counts



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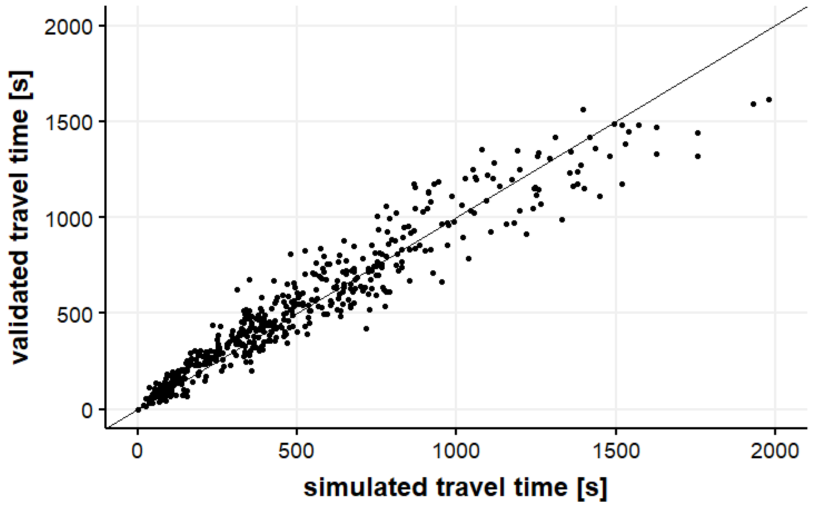
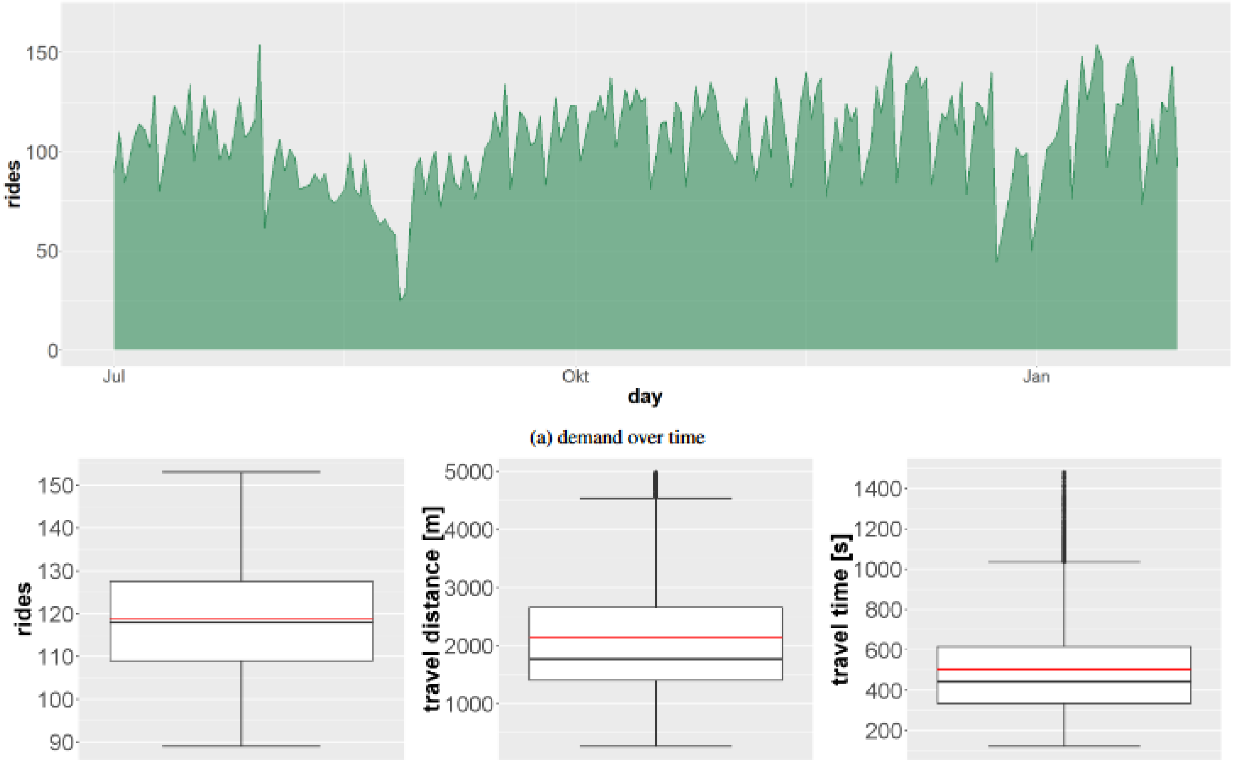


Source:[2]

Mobility-on-Demand (MoD) Real-Data-Driven Calibration



(a) demand over time

(b) rides per day

(c) travel distances (stop to stop)

(d) travel times

Source:[2]

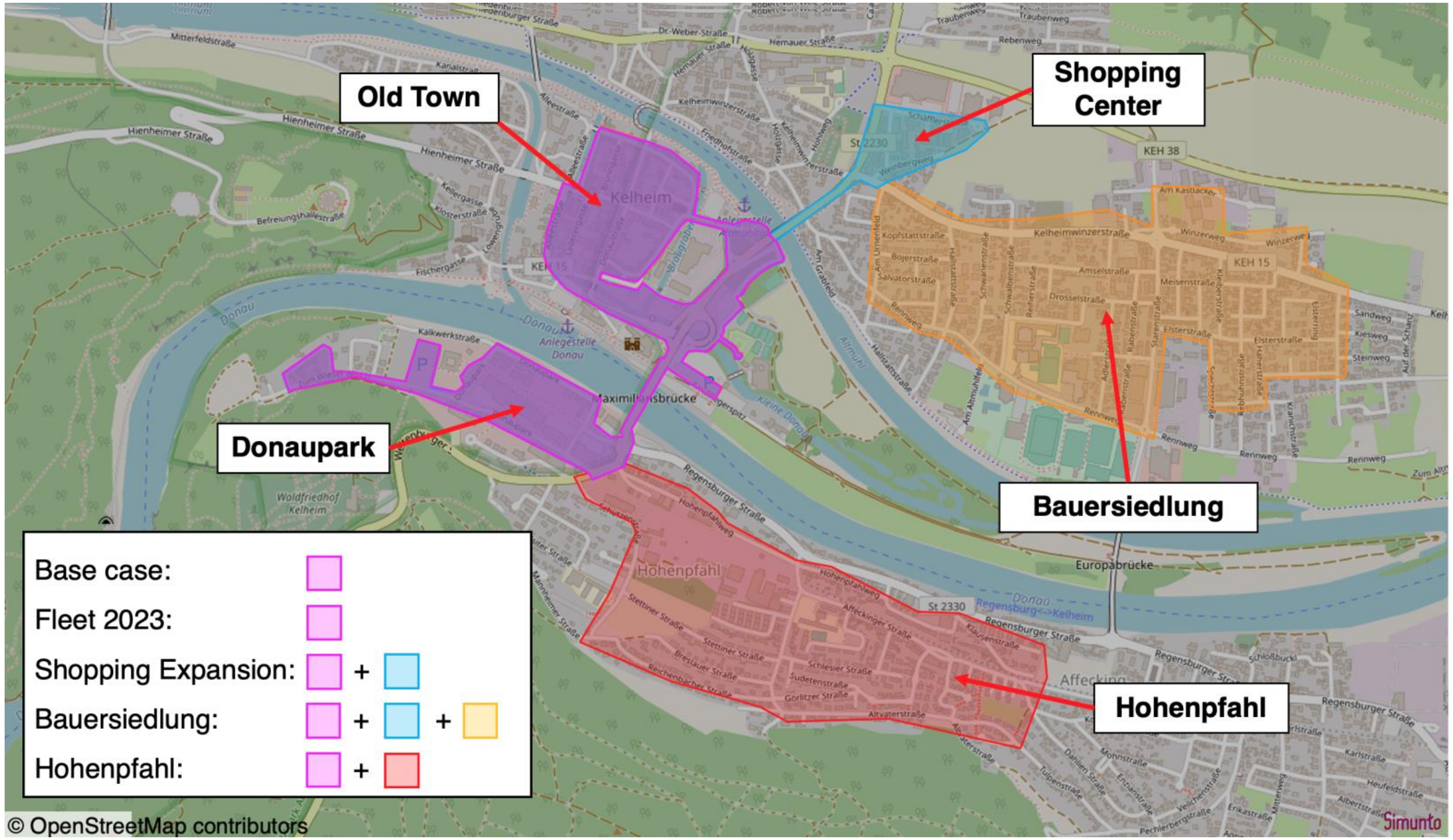
The red lines in the box plots display the mean value, while black lines inside the boxes display the median.

- Statistics of real data on the **conventional KEXI service** for the time span **July 2021 until January 2022**.
- Each simulation case is run with 5 different random seeds (during calibration and for policy cases)

Runs	Nr. of rides	Mean Euclidean trip distance [m]	Mean travel time [s]
Run 1	121	2453	489
Run 2	120	2184	453
Run 3	127	2317	453
Run 4	124	2331	487
Run 5	108	2402	454
Average	120	2338	467
Target	119	2100	503

Source:[2]

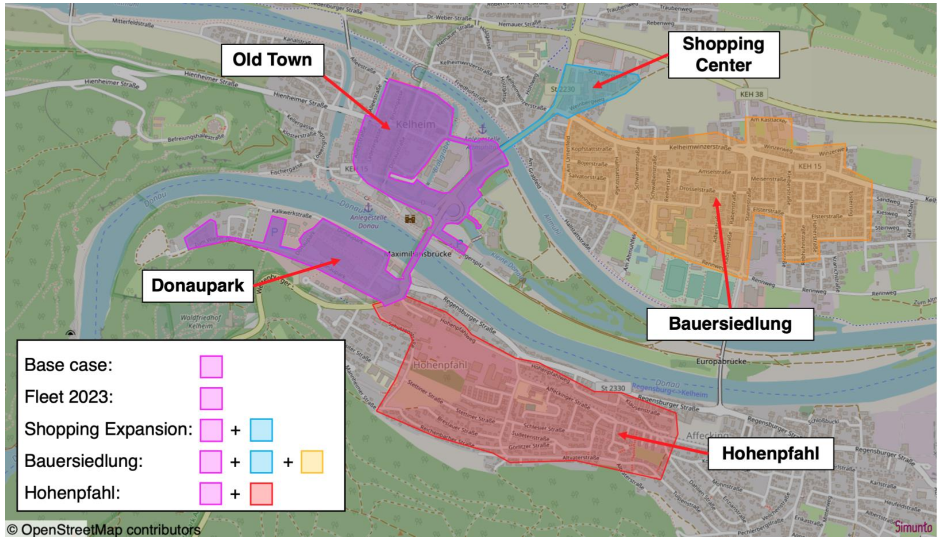
Policy Cases
AV Fleet Expansion + Service Area Expansion



Source:[2]

Case study	Nr. of AV
Base Case	2
Fleet 2023	5
Shopping Expansion	5
Bauersiedlung	5
Hohenpfahl	5

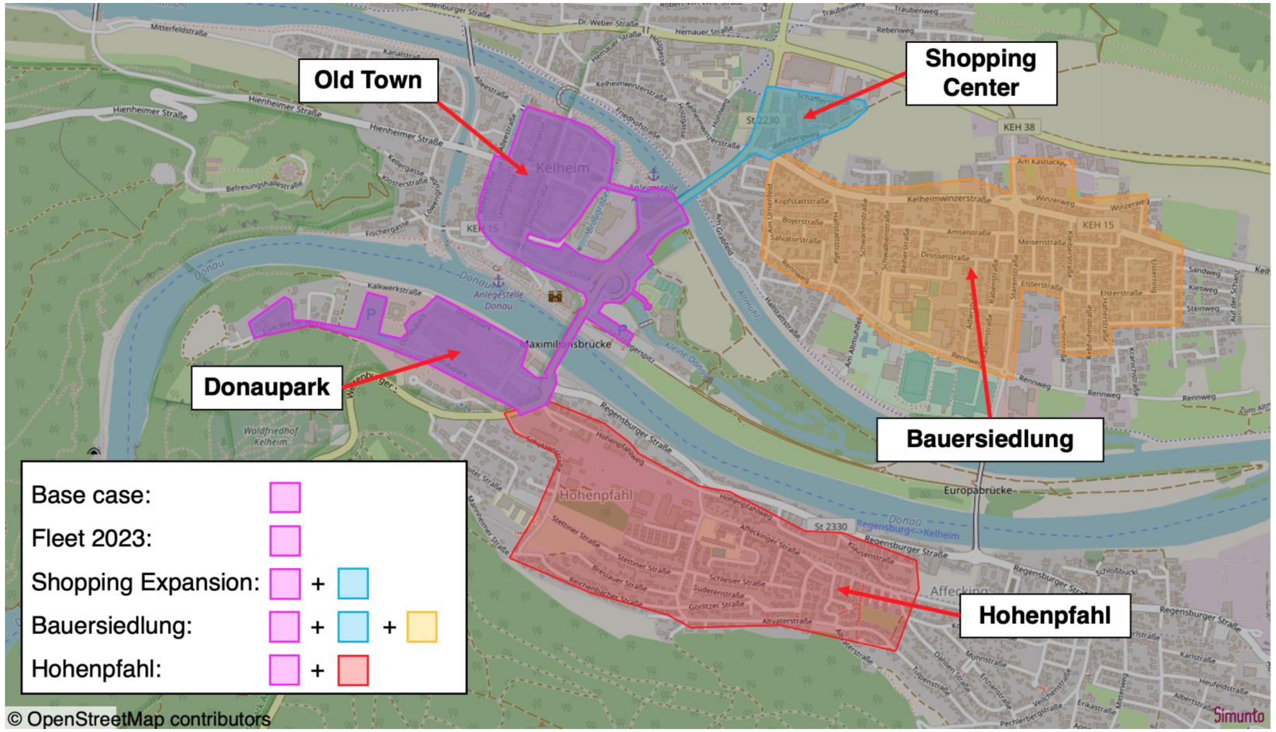
Results
Demand Statistics



Source:[2]

Case	Number of rides per day / per veh-h	Mean waiting time [s]	Mean trip Euclidean distance [m]	Mean travel time [s]	Mean Euclidean speed [m/s]
Autonomous KEXI					
Base	41 / 2.9	199	634	268	2.37
Fleet 2023	51 / 1.5	180	620	272	2.28
Shopping Expansion	65 / 1.8	247	838	395	2.12
Bauersiedlung	103 / 2.9	428	1205	579	2.08
Hohenpfahl	104 / 3.0	397	1154	573	2.01
Conventional KEXI					
Base	120 / 2.5	397	2394	470	5.09
Fleet 2023	119 / 2.5	388	2385	451	5.29
Shopping Expansion	126 / 2.6	398	2355	455	5.18
Bauersiedlung	123 / 2.6	383	2370	452	5.24
Hohenpfahl	125 / 2.6	380	2398	450	5.33

Key Findings Regarding RQ 1 and Project Decision



Source:[2]

Key Findings:

Simulation results suggest that

- AV fleet expansion should be accompanied by area expansion (RQ1)
- AV fleet and conventional fleet are not competing
- AV ridership is attracted from eco-friendly modes

Project Decision

- expand the service area to Shopping Center + Bauersiedlung

THE RELATIONSHIP BETWEEN MOD SYSTEM CONFIGURATION AND RIDERSHIP

Ex-post evaluation of the simulation projections +

Application of the lessons learned

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Project and Study Timeline

Spring 2022
- **Study 1:**
- Investigation of Phase 2 AV area

09/22
- **Phase 1 Launch**
- **2 vehicles**

07/23
- *Planned* Phase 2 Launch
- 5 vehicles

01/24
- *actual*
- **Phase 2 launch**
- **5 vehicles**

Summer 2024
- **Study 2:**
- Ex-post analysis
- recalibration
- sensitivitiy analysis

06/24
- **Project end**

Future
- Follow-up project
- transferability

Study 2 = Evaluation of Study 1 + Projection of possible future scenarios (sensitivity study)

→ real AV booking data from Phase 1 and Phase 2 available

Evaluation of Study 1 and Recalibration based on Phase 2

- **Instead of ~40 rides per day** projected for Phase 1, **~0 rides per day were observed**

- Field tests and surveys revealed **reasons for discrepancy**:

- Average speed ~9 km/h instead of ~18 km/h
- Limited vehicle availability (mostly 1 instead of 2)
- Difficulties in the booking process
- Negative attitude towards AV

Phase 2 yielded

- Speed / Connectivity improvements
- Larger service area
- Larger fleet / higher vehicle availability
- Improvements in booking process

→ **~ 4.5 passengers per day**

Research Objectives and Questions

Objective 1:

Using agent-based transport **simulation as decision support tool** for the configuration of AV KEXI.

Objective 2:

Investigate how MoD services can be integrated into existing transport systems, with a particular focus on the **relationship between MoD configuration and user demand**.

Research question (RQ) 1:

Which areas of a regional town should an AMoD service cover, given different fleet sizes, to ensure efficient operation and meaningful integration into the existing transport system?

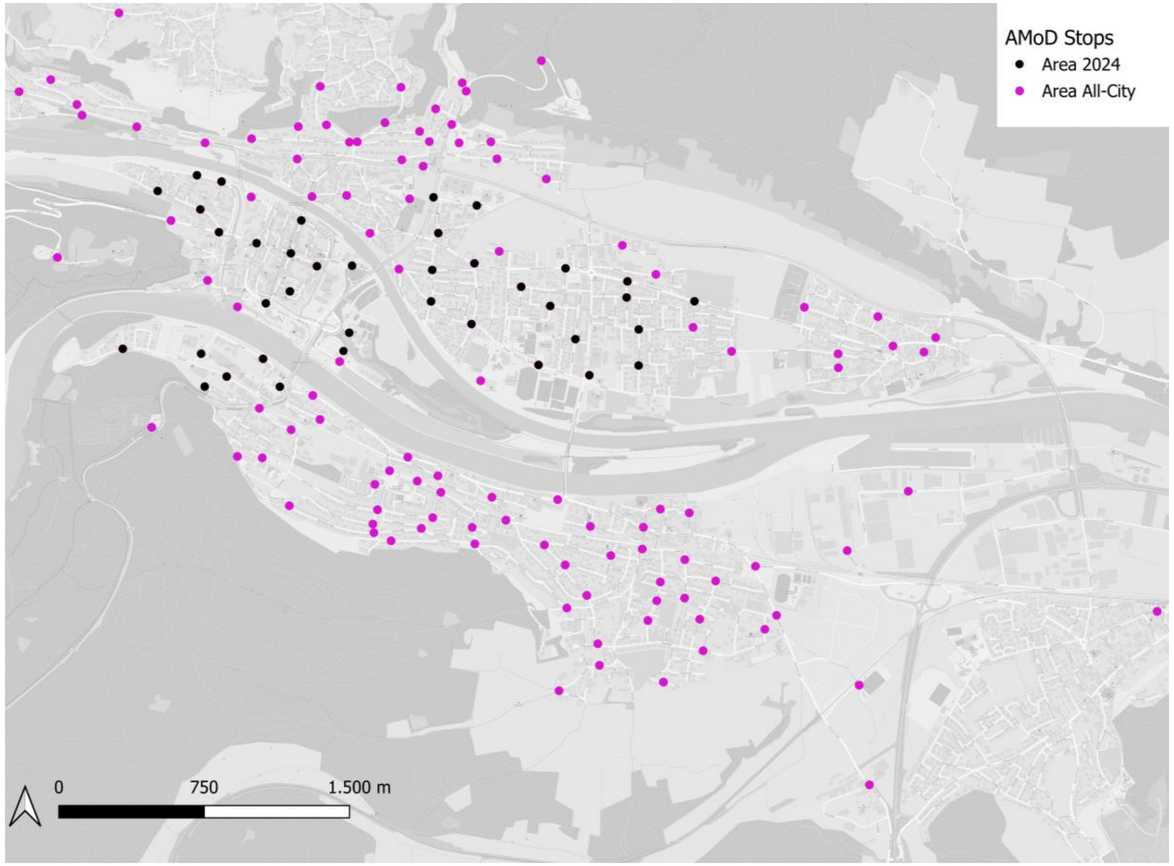
Research question 2:

What is the **quantitative relationship between key MoD configuration parameters and the average number of MoD passengers per day**, and through which mechanisms do these effects occur?

Research question 3:

To what extent **can strategic positioning of idle MoD vehicles improve spatial service provision equity?**

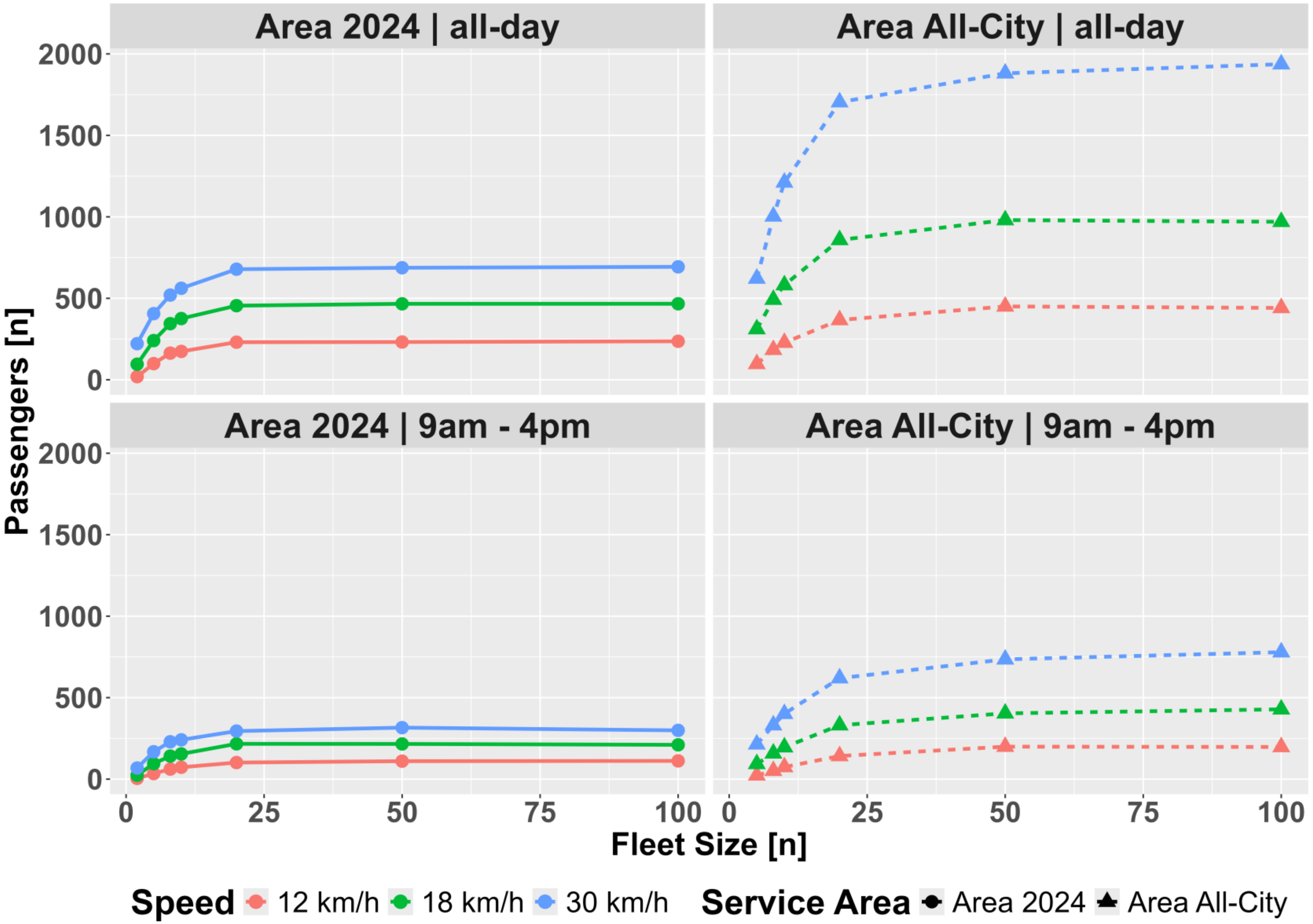
Sensitivity analysis variables



Based on sources:[10], www.openstreetmap.org

Configuration Parameter	Values
Area	Area 2024, All-City
Service times	9am-4pm, all-day
Fleet size	2, 5, 8, 10, 25, 50, 100
AV speed	12km/h, 18km/h, 30km/h

Nr. of AMoD passengers



Source:[10]

Area

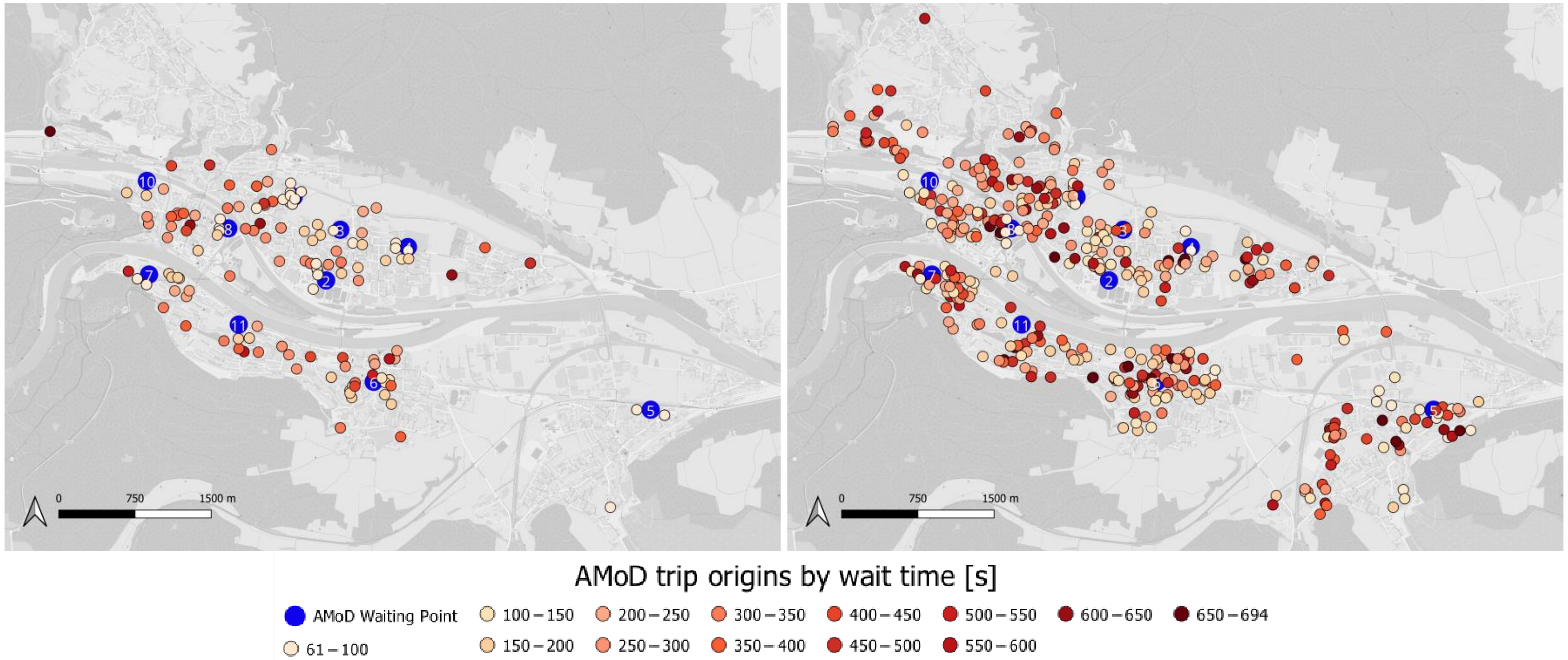
Operating times

Fleet size

Speed

Spatial Distribution of Wait Times

10 AV - 12 km/h | **10 AV - 30 km/h**



Based on sources:[10], www.openstreetmap.org

- The number of idling locations was limited, both in real-world and simulation
  → Implication on the relation of wait time and fleet size
- Results suggest **heterogeneity in wait times**, with higher probability for good service for trips originating near to an idling location (AMoD waiting point)

Results
Log-log Elasticities from Simulation

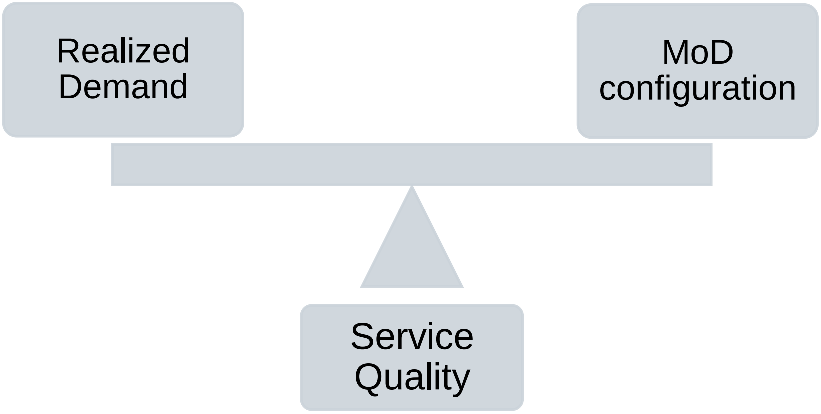
$$pSpeed_{avg} = \frac{totalRideDistance_{avg}}{totalTravelTime_{avg}}\ ;\ \log(passengers) \sim \log\left(pSpeed_{avg}\right) + \log(fleetSize)$$

Area	Service Times	Elasticity w.r.t. Speed β_{pSpeed}	$\beta_{fleetSize}$	Adjusted R^2
Area 2024	All-day	**2.49 *** **	0.27 ***	0.811
	9 am – 4 pm	**2.57 *** **	0.40 ***	0.744
Area All-City	All-day	**2.94 *** **	0.31 ***	0.924
	9 am – 4 pm	**3.03 *** **	0.45 ***	0.892

Stars indicate the significance level: $***p < 0.001$, $**p < 0.01$, $*p < 0.05$

Total travel time elasticities obtained from discrete choice models estimated using stated preference data range between -0.5 and -1.5

Key Findings regarding RQ 2



- Configuration **parameters influencing the demand *potential* of MoD** (service area, operating times) are found to have **linear relations** to the *realized* number of MoD passengers
- Configuration **parameters influencing the MoD service quality** (fleet size, vehicle speed) are found to have **superlinear impacts** on the *realized* number of MoD passengers
- High dependency of the results on the locations where vehicles idle and the distribution logic (rebalancing)

Research Objectives and Questions

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Research question 3:

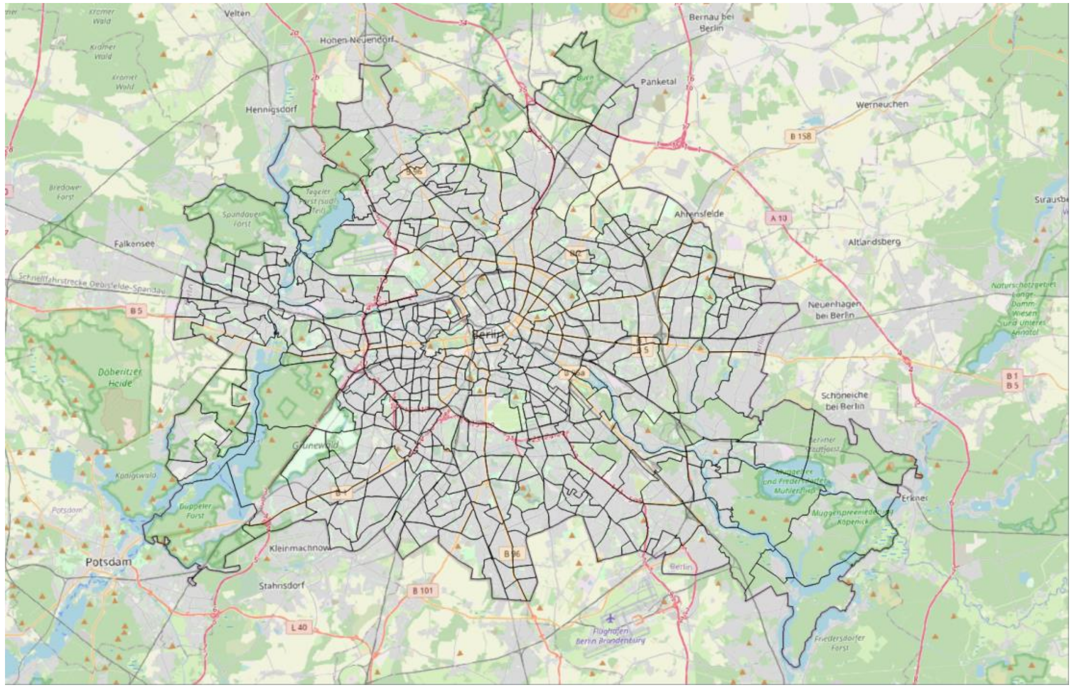
Can strategic positioning of idle MoD vehicles decrease heterogeneity of wait times?

REBALANCING AS A TOOL TO DECREASE HETEROGENEITY OF WAIT TIMES

Application to the use case of Berlin

Motivation and Context

- A profit-oriented operator would concentrate vehicles in the city center [8], leading to unequal access (**heterogeneous wait times**) to the service
- Existing strategies for empty vehicle relocation (rebalancing) focus on demand throughput (ridership) and system efficiency
- Objective: provide equal wait times throughout the service area, while maintaining high ridership and efficiency
- Study area: Berlin



Based on sources:[11], www.openstreetmap.org

Rebalancing as Optimization Problem

- Rebalancing as transportation problem [6]:
  Find the minimum-cost vehicle flows from zones with a vehicle surplus to those with a vehicle deficit.

- Solved at a fixed time interval [5]

- Target function for the desired number of vehicles for zone i at time j: $t_{i,j} = a * e_{i,j} + b$

- Typically, $e_{i,j}$ is associated with the expected demand (ED), leading to inequality of zones

- New target formulations are investigated

Investigated Target Functions

1. No rebalancing (**base**)
2. Estimated demand (**ED-R**) – exactly as in [6]
3. Estimated demand (**ED**) - adjusted parameters
4. Fixed number of vehicles per zone (**FNV**):
5. Equal vehicle density (**EVD**)
6. Equal vehicle-to-population ratio (**EVP**)

- Note that 4. – 6. are not time-dependent

Performance Indicators

1. **(Spatial) Heterogeneity of wait times**:
   Standard deviation and spatial distribution of mean waiting time per zone s_{w}

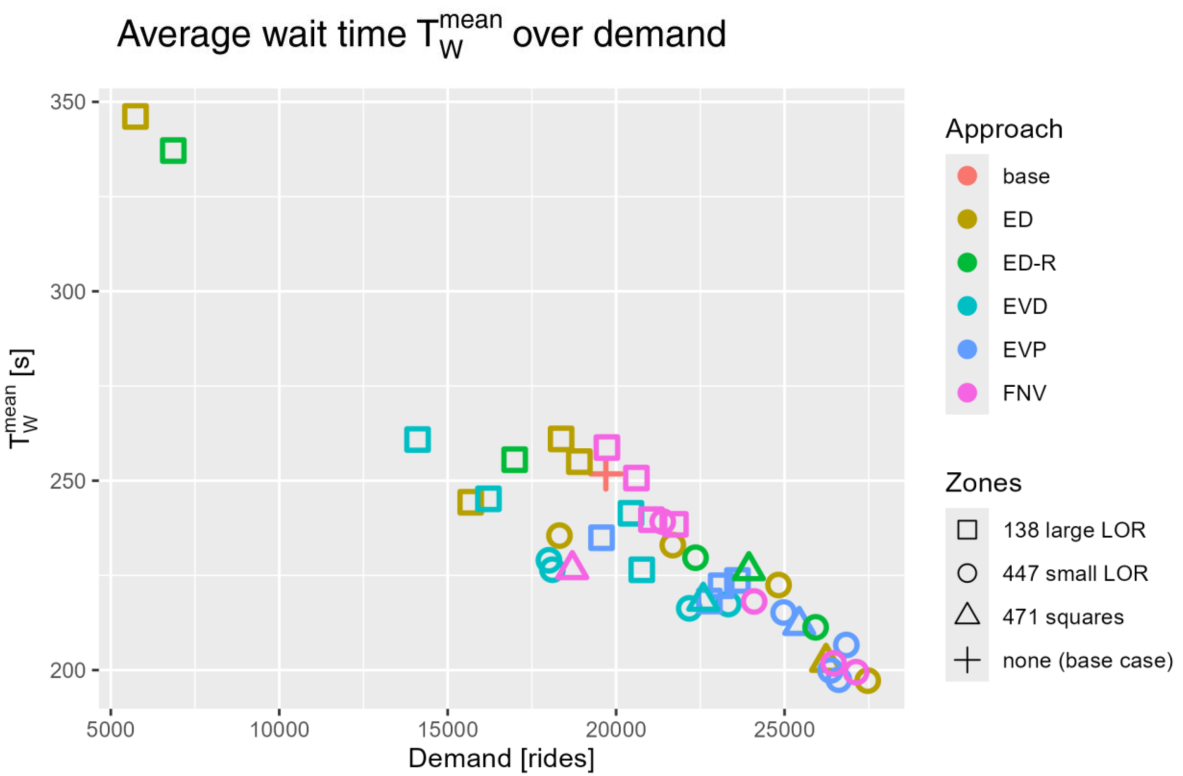
2. **Overall service level**:
   Mean T_W^{mean} and 95th percentile T_W^{p95} of *all* wait times

3. **Ridership** / Realized Demand**:**
   Total number of rides and spatial distribution of trip starts

4. **Operative efficiency**:
   Ratio of empty vehicle kilometres travelled

Wait time and Realized Demand

- Results suggest *linear* correlation between realized demand, mean and 95th percentile of waiting time
- Rebalancing systems with smaller zones lead to ~30% more rides and ~15% lower avg. wait time



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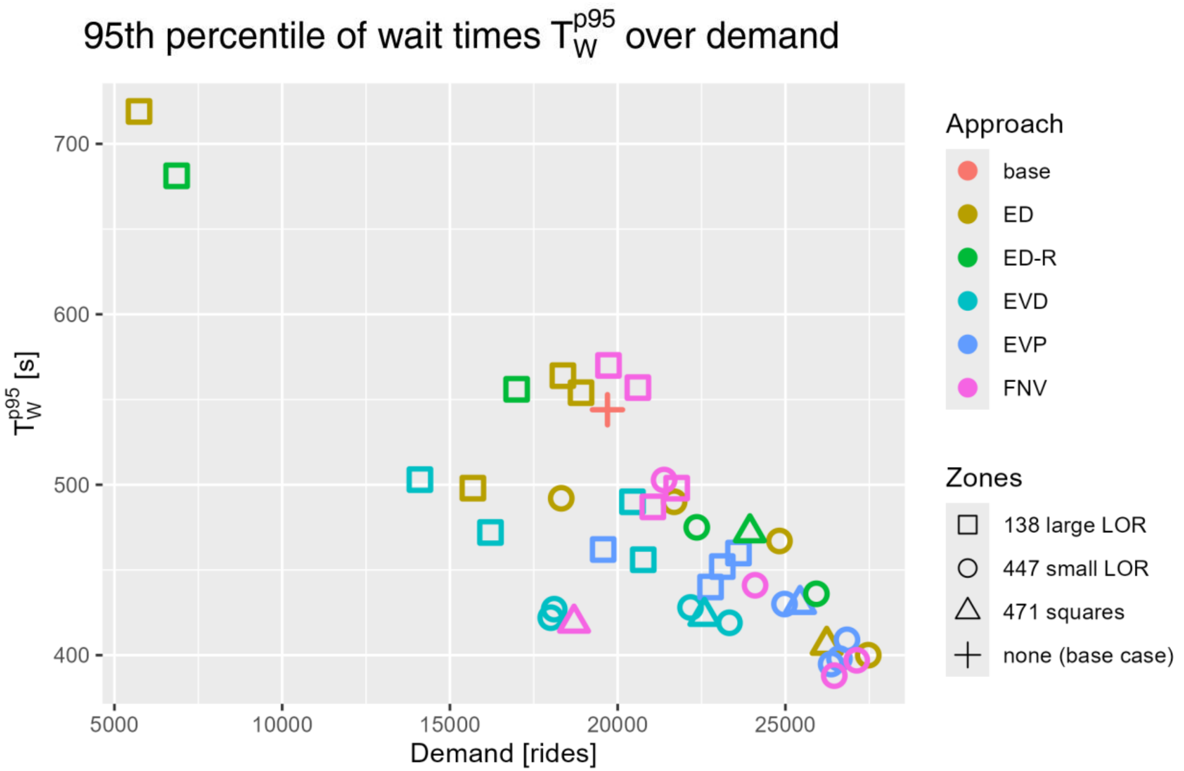
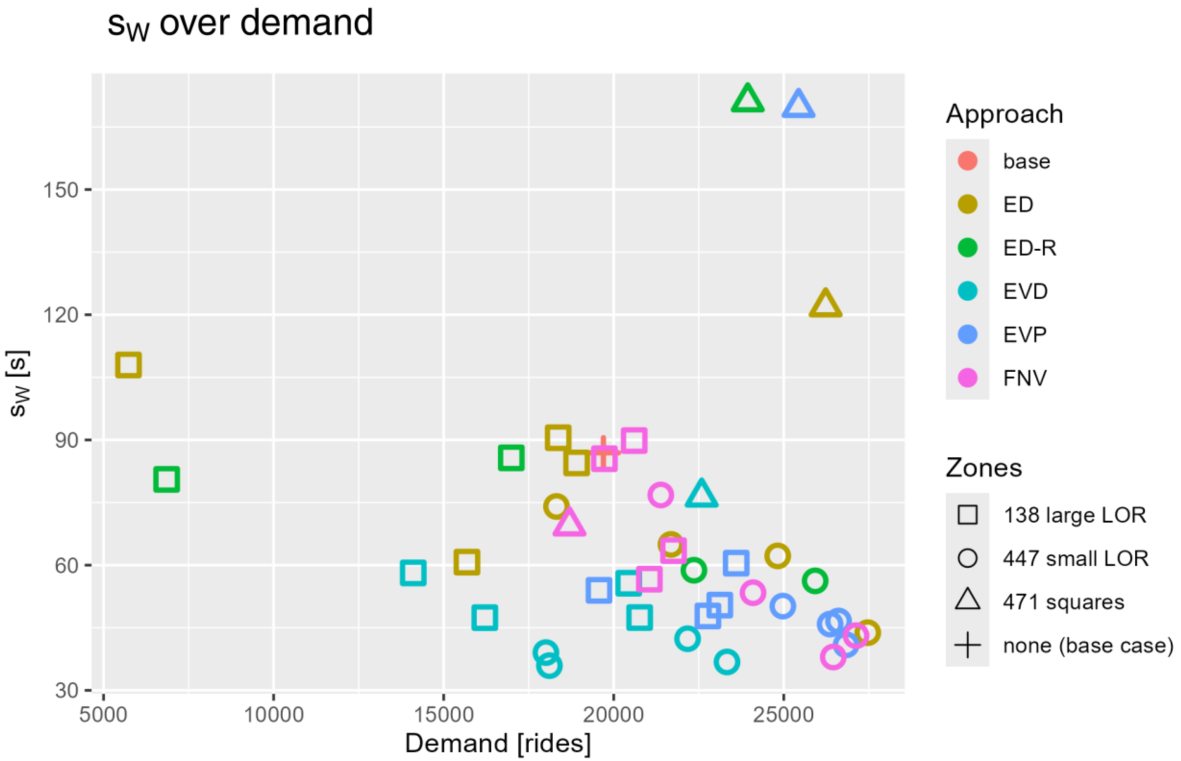


Source:[11]

Standard Deviation of Zonal Mean Wait Time

Approach	$\bar{s}_w$	n
base	86.9	1
ED	79.0	9
ED-R	90.5	5
EVD	48.8	9
EVP	62.9	9
FNV	64.0	9



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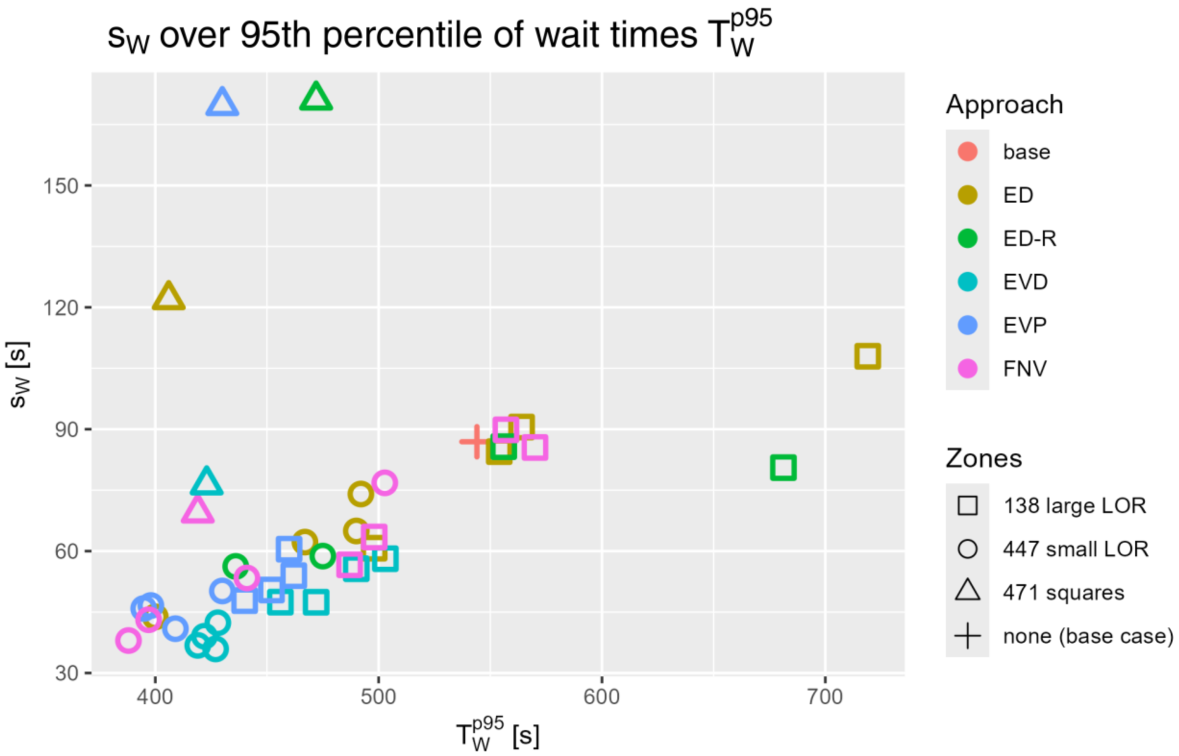
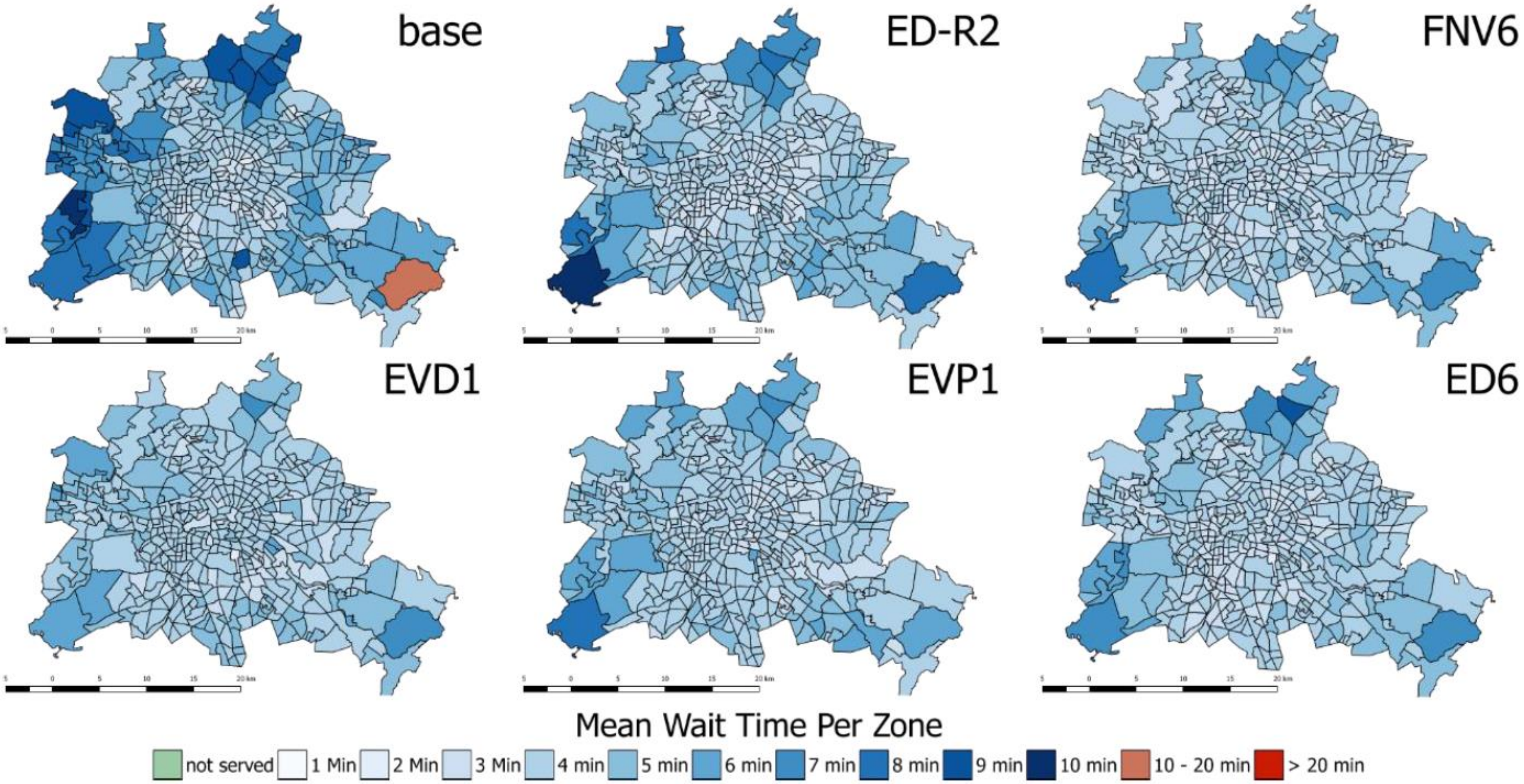


Source:[11]

Spatial Distribution of Wait Times

- **Base =** no rebalancing
- **ED** = estimated demand
- **FNV** = fixed number of vehicles
- **EVD** = equal veh. density
- **EVP** = equal ratio vehicles/population



Source:[11]

Key Findings regarding RQ 3

- Demand-anticipatory rebalancing can lead to unequal wait times for MoD services
- Other rebalancing approaches such as maintaining equal vehicle density can reduce the standard deviation of zonal mean wait times roughly by half
- Total realized demand increases in reaction to rebalancing by 20 - 40 %

Policy implications

- Profit-oriented MoD operators concentrate on city centers

- Demand responds to service quality
  - Poor service quality erodes trust and long term acceptance of new mobility concepts

- Careful planning (regulation) of MoD configuration is essential, if considered as part of public transport
  - A priori definition of service level

- Agent based simulations can inform policy making and system

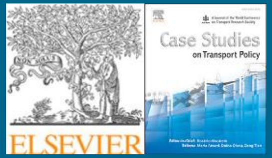
Outlook

Some aspects to improve for simulation:

- Account for taste heterogeneity in mode choice simulation
- Improve simulation procedures for situations with a discrepancy of supply and demand potential (small fleet sizes)

- **Outlook regarding autonomous Mobility-on-Demand:**
  - SAE Level 4 driving (SafeStream, KIRA, …)
  - Transport-as-a-Service (IMoGer, …)

Included publications



Publication 1:

Autonomous mobility-on-demand in a rural area: Calibration, simulation and projection based on real-world data

T. Schlenther, C. Lu, S. Meinhardt, C. Rakow, and K. Nagel
Case Studies on Transport Policy, page 101418, 2025a. ISSN 2213-624X.
doi: https://doi.org/10.1016/j.cstp.2025.101418

MDPI World Electric Vehicle Journal

Publication 2:

The speed of shared autonomous vehicles is critical to their demand potential

T. Schlenther, and K. Nagel
World Electric Vehicle Journal, 16(8), Aug. 2025.
ISSN 2032-6653. doi: 10.3390/wevj16080447.

IET The Institution of Engineering and Technology WILEY

Publication 3:

Addressing spatial service provision equity for pooled ride-hailing services through rebalancing

T. Schlenther, G. Leich, M. Maciejewski, and K. Nagel.
IET Intelligent Transport Systems, 17(3):547–556, Dec. 2023. doi: https://doi.org/10.1049/itr2.12279.

Thank you for your attention ☺

I would like to express my sincere gratitude to my co-authors:

- Chengqi Lu
- Christian Rakow
- Gregor Leich
- Kai Nagel
- Michal Maciejewski
- Simon Meinhardt

References and Image Sources

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- **[2]** Schlenther, T., Lu, C., Meinhardt, S., Rakow, C., & Nagel, K. (2025). Autonomous mobility-on-demand in a rural area: calibration, simulation and projection based on real-world data. *Case Studies on Transport Policy*, 101418.
- **[3]** Ziemke, D. Metzler, S. Nagel, K. (2019). Bicycle traffic and its interaction with motorized traffic in an agent-based transport simulation framework, Future Generation Computer Systems, Volume 97, Pages 30-40, ISSN 0167-739X, https://doi.org/10.1016/j.future.2018.11.005.
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- **[7]** Ziemke, D., Kaddoura, I., Nagel, K., (2019). The MATSim Open Berlin Scenario: A multimodal agent-based transport simulation scenario based on synthetic demand modeling and open data, Procedia Computer Science 151, 870–877. doi:10.1016/j.procs.2019.04.120.
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- **[9]** Ziemke, D. (2022). Person-centric integrated modeling of transport and urban systems. PhD Thesis. Technische Universitaet Berlin (Germany).
- **[10]** Schlenther, T., & Nagel, K. (2025). The Speed of Shared Autonomous Vehicles Is Critical to Their Demand Potential. *World Electric Vehicle Journal*, *16*(8), 447.
- **[11]** Schlenther, T., Leich, G., Maciejewski, M., & Nagel, K. (2023). Addressing spatial service provision equity for pooled ride-hailing services through rebalancing. *IET Intelligent Transport Systems*, *17*(3), 547-556.

Imprint

Topic: **How system configuration shapes demand -** Agent Based Simulation of Mobility-on-Demand systems & policy insights

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