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Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates

COLOMBO: Deliverable 4.3

Pollutant Emission Models and Optimisation

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Authors	Martin Rexeis (TUG), Martin Dippold (TUG), Raphael Luz (TUG), Stefan Hausberger (TUG) Michael Haberl (TUG) , Daniel Krajzewicz (DLR), Peter Wagner (DLR), Marko Wölki (DLR), Robbin Blokpoel (IMTECH), Thomas Stützle (ULB), Jérémie Dubois-Lacoste (ULB)

Table of contents

Abbreviations

Name	Unit	Description
AD	-	Index for case vehicles entering road from stand still
CD	-	Index for case vehicles entering road with constant speed
CO	g	Carbon monoxide
CO_2	g	Carbon dioxide
FC	g	Fuel consumption
FR	-	Ratio of vehicles entering from a side road to the maximal possible number of vehicles which could pass the green light on the side road
GD	s	Green duration time (main road)
GDT	s	Green duration time (side road)
HC	g	Carbon hydride
I2V	-	Infrastructure to vehicle communication
ISV	-	Institute for Highway Engineering and Transport Planning
IVT	-	Institute for Internal Combustion Engines and Thermodynamics
LDV	-	Light duty vehicles
l_{vt}	m	Covered distance to accelerate to target velocity
$l_{Intersection}$	m	Length between the intersections
l_{veh}	m	Length of a standard vehicle (4.5m)
l_{side}	m	accumulated length of vehicle queue from side traffic
m_{veh}	kg	Mass of the empty vehicle
m_{rot}	kg	Equivalent rotational mass of the wheels
m_{load}	kg	Mass of the vehicle loading
NEDC		New European Driving Cycle (EU type approval test cycle)
NOx	g	Nitrogen oxide
$n_{lanes,SR}$	#	Number of lanes before the traffic light (Side Road)
$n_{lanes,MR}$	#	Number of lanes before the traffic light (Main Road)
PM	g	Particle mass
RPA	m/s^2	Relative positive acceleration
$t_{green,prolong}$	s	Green duration prolongation because of side traffic
$t_{offset,const}$	s	Offset between the intersections (vehicles arriving at constant driving)
$t_{offset,acc}$	s	Offset between the intersections (vehicles accelerate from standstill)
t_{safety}	s	Safety time
t_{side}	s	Influence of side traffic on offset time
$t_{sideTraff}$	s	Duration of the green time of the side traffic light
$t_{vehPass}$	s	Gap between two vehicles passing the traffic light
t_{vp}	s	Time to accelerate to target velocity
v_t	m/s	Target velocity
V2X		Vehicle to vehicle and vehicle to infrastructure communication
Λ	-	Rotating mass factor: ratio of acceleration work necessary with versus without rotational accelerated components (representing therefore the rotational inertia of the powertrain converted to translational inertia)

1 Introduction

The COLOMBO project develops a set of modern cooperative traffic surveillance and traffic control applications that target at different transport related objectives, such as increasing mobility, resource efficiency, and environmental friendliness. The COLOMBO project relies on simulation models that allow benchmarking the applications' performance in-vitro. The work presented herein was done within the project's Work Package (WP) 4, which is dedicated to the extension, development, and usage of models for vehicular emissions.

The coupling of the microscopic traffic model SUMO with the microscopic vehicle emission model PHEM was already described in [COLOMBO D4.2, 2014] (D4.2). The model PHEMlight, which was developed for integration into the SUMO software, is also described in D4.2. Since PHEMlight was still under development when D4.2 was produced, the progress made in the meantime is reported here (chapter 2). Chapter 2 also shows the model validation results and gives an overview on functions relevant for the development of emission optimal solutions.

For the simulation of the effects different traffic light control strategies have on emissions and on traffic indicators, the SUMO software including PHEMlight was applied. The software proved to be a very useful solution. With this tool, correlations between traffic indicators and emissions have been measured (chapter 2).

Since also the driver behavior has high influence on energy consumption and emissions, the driving style to minimize emissions was derived based on physical relations using the model PHEM. Suggestions for acceleration and deceleration levels at junctions and for best cruising speeds are made in chapter 3. This data set is also implemented in SUMO and is used to evaluate an "Eco-driver" behavior. Different approaches from the literature as well as approaches developed in COLOMBO are presented and evaluated regarding their emission behavior (chapter 3).

Setting up microscopic traffic models to design traffic control systems is, however, often seen as too time consuming and expensive. To provide tools for optimizations towards low emissions also for low budget applications, in COLOMBO the following work was performed and is described in chapter 4:

- A simple microscopic traffic model was programmed (NITRA) which simulates only the actual speed of vehicles on a route using routines for vehicles approaching target speeds, decelerating towards junctions and following other cars. NITRA includes also PHEMlight for emission simulation.
- A road section with several traffic lights has been implemented in NITRA with different distances between the junctions. Also traffic volumes and numbers of vehicles entering from side roads have been varied. For each setting the optimum green light duration and the best offset time between the junctions was tested using NITRA.
- A guideline was developed which gives instructions on how to calculate optimal values for the offset time between the junctions and for the green light duration with a few simple equations based on the NITRA results.
- The emission optimum considers CO_2, NO_x, NO_2, CO, HC, CH_4, particle mass and particle number emissions. For optimization a weighted total emission index is used, which may vary according to local air quality issues. For the computations here CO_2 for climate effects and representing also the fuel consumption, NO_x relevant for NO_2 air quality targets and particles relevant for PM_{10} air quality targets have been combined for the index.

Traffic engineers thus may use this guideline to find basic settings in traffic light coordination, which shall lead to low emissions and minimum fuel consumption. Since local boundary conditions influence the vehicle speed levels, adaptations to local situations usually will give better results than the simple generic equations. These adaptations may be done using the NITRA model directly and calibrating target speeds and acceleration functions. Also different local targets for exhaust emission reductions could be considered in NITRA applications. It has to be noted, that NITRA and the guideline should not replace more sophisticated tools but should improve the situation in applications where so far no sufficient methods have been used.

These findings shall be used also to elaborate which information an I2V communication system shall provide the driver to reduce energy consumption and emissions adapted to traffic control algorithms. The combined optimisation of driver behaviour and traffic control functions should lead to overall minimum emissions. A common understanding of the best interaction between infrastructure control systems and drivers could be used then also to optimise vehicle technologies for such traffic control systems to finally include vehicles, infrastructure and users in the optimisation process. Mainly for energy consumption and CO_2 emissions such an approach could bring an important contribution to the ambitious targets for 2030 and 2050 in the European Union.

1.1 Document Objectives

The main targets of COLOMBO described in deliverable 4.3 are:

(1) Development of a robust and validated set of simulation tools to provide the instruments necessary to assess effects of optimizing traffic control systems
(2) Validation of the emission simulation tools to ensure reliable results
(3) Analysis of the driver influences on emissions in urban areas with traffic lights and elaboration of an “optimum driver behavior” for low emissions.
(4) Application of the simulation tools to produce guidelines how to optimize traffic light coordination towards low emissions.

1.2 Document Structure

The document is structured as follows: Chapter 2 presents the recent steps in modelling pollutant emissions performed in COLOMBO as well as basic approaches to determine the correlation between different performance indicators obtained using the new model versions. Chapter 3 discusses how a single driver’s speed choice influences the emission of pollutants, including a report on methods to obtain an emission-optimal driver behaviour, including methods from literature as well as one developed in COLOMBO. Chapter 4 presents the work on designing environmentally friendly traffic light systems. The document ends with a summary given in Chapter 5.

2 Emission Behaviour Modelling

2.1 Overview

Models applied for assessing emission effects resulting from changes in the traffic flow have to distinguish at least between acceleration, cruising, deceleration, and stop time. Each deceleration using mechanical brakes annihilates energy which afterwards has to be delivered by the engine to accelerate again. Stop times add emissions without covering a distance and different speed levels result in different driving resistance losses. Also the acceleration levels are relevant for the actual engine power demand and thus for the engine efficiency and for the emission levels. Such effects cannot be simulated correctly by simple models, such as average speed models. A suitable model has to be based on physical relations to calculate the actual power needed to drive a vehicle and on characteristic curves or maps to define representative emissions as function of the engine power demand. This was found already end of the 1990ties and lead to the development of the vehicle model PHEM [Hausberger, 2003].

Today PHEM is used to simulate the basic emission factors for the Handbook Emission Factors (HBEFA), for the average speed model COPERT, for NEMO and for several national emission models. Unique characteristics of PHEM is the huge data base of emission measurements used for the parameterisation which leads to representative emission values for the vehicle fleet under real world driving conditions. Many other features useful for simulating vehicle fleet emissions on a very detailed level are implemented in PHEM. Within COLOMBO alternative propulsion systems have been implemented in PHEM (CNG, Hybrids) to provide a suitable vehicle fleet for simulation of future traffic control systems. A description of PHEM and of these new functions is already given in D4.2. The manifold functionalities however made PHEM quite complex and it requires the knowledge of the speed and acceleration history of a vehicle over several seconds to compute temperature levels of exhaust gas aftertreatment systems and to correct for transient effects on engine out emissions. For these reasons, PHEM is only suitable for microscopic traffic models as post processing tool.

Since especially for optimisation loops a cascade of simulation tools is inefficient, PHEMlight was developed within COLOMBO to be integrated in the SUMO software. PHEMlight is also described in D4.2. Since PHEMlight was not finally developed when D4.2 was produced, new features and results are described in this chapter.

2.2 Emission Models used in COLOMBO

In COLOMBO two emission models developed by TUG are applied: PHEM and PHEMlight. As described before, PHEM can be used “only” for post processing the vehicle speed trajectories computed by SUMO, since PHEM needs information on several time steps before and after the actual computed time. PHEM needs this information to calculate the thermal status of aftertreatment systems, to consider effects of transient engine loads on the engine out emissions and to feed the driver model which selects the gears in the virtual vehicles. Since keeping long time series for each vehicle in the simulator leads to high storage demand and long computation time, PHEM cannot be integrated into a micro-scale traffic model. This certainly is a handicap when optimization loops have to be run and is in general a reduction of the user friendliness.

Thus PHEMlight was developed in the COLOMBO project and was designed to be integrated into SUMO by replacing the detailed simulations from PHEM needing the time steps before and after the actual computed time by generic functions using only information available in SUMO for the actual second.

A detailed description of PHEM and PHEMlight is already given in [COLOMBO D4.2, 2014]. The development of PHEM relevant for the COLOMBO project was already finalised at this stage. This paper gives a description of the additional model elements added to PHEMlight after D4.2 and shows also the actual validation results, which have been massively improved against the last PHEMlight version. The validation of the new – and "final" - PHEMlight version is shown by a comparison with results of the more detailed "parent model" PHEM.

Since the model PHEM and its database for typical "average vehicles" - which also represents the baseline data for the HBEFA emission factors - were already verified in several publications (e.g. [Rexeis et al., 2013], [Zallinger 2010], [Rexeis, 2009]), a validation of PHEM by comparison with measurement data is not performed at this point. A validation of PHEM for new propulsion concepts (e.g. hybrid powertrains) is given in [COLOMBO D4.2, 2014].

2.2.1 Limitations in Applications for PHEMlight

PHEMlight includes several simplifications compared to PHEM. Consequently, also some of the PHEM functionalities are reduced or not existing in PHEMlight compared to PHEM. In Table 2.1 the main differences between the models are explained. For the application in microscale traffic models yet no other relevant consequences of the simplifications on the calculated emission levels made in PHEMlight are known.

Table 2.1: Main user relevant differences between PHEM and PHEMlight.

PHEM	PHEMlight	Effects
Gear choice and corresponding engine speed is calculated from transmission ratios and gear shift model.	Engine speed implicitly approximated as function of engine power.[1]	Influence of different driving styles in terms of gear shift behaviour cannot be computed with PHEMlight. High road gradients – which lead to selection of lower gears in PHEM – are computed with engine speeds for normal road gradients in PHEMlight. For simulation of fleet averages in traffic models the elimination of gear shift manoeuvres is seen as advantage, since in reality drivers shift very differently and no "sharp" gear shift effects on emissions exists for the driver+vehicle fleet mix. In PHEM small speed differences can cause higher emission differences if a different gear is selected (e.g. Figure 3.1).
Exhaust gas after treatment temperatures are simulated using heat transfer and energy balance functions. Efficiencies of catalysts are	Exhaust gas temperatures are not simulated. Results from PHEM for representative cycles are used to produce characteristic curves for the tailpipe emissions as a	The influence of the duration of low and high load driving on emissions cannot be calculated with PHEMlight (e.g. catalyst cool down at long stop&go cycles). PHEMlight uses always normal temperature levels. Also cold start cannot be simulated with PHEMlight. Usually the history of single vehicles is not accurately known from traffic models for

[1] Engine speed is not explicitly modelled in PHEMlight. In the calculation of fuel consumption and emissions the influence of engine speed is implicitly covered as function of engine power. For the „fuel cut-off" driving mode engine speed is approximated as function of vehicle speed.

PHEM	PHEMlight	Effects
simulated as function of the temperature and exhaust gas mass flow	function of engine power only.	sufficiently long time spans to calculate thermal effects on emissions on a vehicle to vehicle basis. Thus average temperature levels are for most applications sufficient. However, especially for long stop&go or long stop phases PHEMlight will underestimate pollutant exhaust gas emissions.
Power calculated based on more detailed longitudinal dynamics.	Power calculated based on simplified longitudinal dynamics	Small deviations can occur for calculated engine power demand between PHEM and PHEM light which seem not to be relevant when fleet average emissions are calculated since also vehicle masses, loading, rotational inertias and driving resistances for the fleet average are not known exactly.
Simulates vehicle fleet by randomly mixing gasoline, diesel etc. with different EURO classes to meet total fleet distribution	Can use a weighted average vehicle (different for cars, LCV, trucks, buses). Mixing different vehicles as in PHEM is also possible.	Influence of random generator is eliminated in PHEMlight when the weighted average vehicles are used. Thus reproducible results are produced already from one single simulation run (see chapter 2.2.4).

2.2.2 PHEMlight: "Fuel cut-off" Driving Mode with Zero Emissions

If a vehicle decelerates in a way that all losses in the powertrain system including the internal combustion engine can be "covered" by the kinetic energy of the decelerating vehicle, the engines fuel injection system goes into the so called "fuel cut-off" mode. In this operation state – due to zero fuel injection - the emission output for all exhaust gas pollutants is zero[2]. The correct simulation of this effect is important in the evaluation of the effects of driving behaviour on the emission output (see also section 3.1.3). Which deceleration level (value in m/s^2, program internal parameter "`decel_coast`") is required to reach the fuel cut-off mode depends on the vehicle mass, the driving resistances and the losses in the engine and the drivetrain system. The latter is also significantly influenced by the selected gear.

In order to determine `decel_coast` for a given vehicle and a given vehicle operation state[3] PHEMlight performs the following calculations:

- Determination of the selected gear from a vehicle specific characteristic line as a function of vehicle speed. This characteristic line is parameterised by the gear shift provisions for the ERMES cycle for passenger cars and light commercial vehicles and for HDV by PHEM calculations for HDV specific cycles considering typical "average" gear shift behaviour.
- Determination of the engine speed considering the vehicle speed, the total transmission ratio in the drive train and the wheel diameter
- Determination of the engine drag from a characteristic line as a function of engine speed

[2] Only a very small amount of hydrocarbons and particle emissions originating from lube oil can be found in the exhaust gas.
[3] In PHEMlight the vehicle operation state is defined by the actual values for vehicle speed, acceleration and road gradient

- Converting the losses in the powertrain (consisting of the engine drag and additional losses in the transmissions assuming 90% efficiency) to a force “F_loss” at the driven wheels
- Calculation of the forces at the driven wheels originating from the driving resistance (F_roll rolling resistance, F_air air resistance, F_grd gradient resistance)
- The deceleration where the vehicle then would be exactly operated in “Fuel cut-off” driving mode can then be calculated by:

$$\mathrm{decel}_{\mathrm{coast}} = -\frac{F_{loss} + F_{roll} + F_{air} + F_{grd}}{(m_{veh} \cdot \Lambda + m_{rot} + m_{load})}$$

where:

m_{veh}…………mass of the empty vehicle

Λ……………..rotating mass factor (depicting the rotational inertia of the powertrain)

m_{rot}…………..equivalent rotational mass of the wheels

m_{load}…………mass of the vehicle loading

If the actual acceleration of the vehicle operation state is lower than decel_coast the result of PHEMlight for fuel consumption and emissions are set to zero. Typical values for decel_coast for different vehicle categories are shown in section 3.1.3.

2.2.3 Validation of PHEMlight by Comparison with PHEM Model Results

All characteristic emission curves and vehicle data necessary as input for PHEMlight have been calculated with the model PHEM using representative driving cycles. The methods to produce input data from PHEMlight has been improved since the first version of PHEMlight and some software bugs were eliminated. Thus the validation of PHEMlight was done once again with the final version of the software and the input data.[4]

In order to validate the simulation results of PHEMlight, comparisons have been performed with the results of the more detailed “parent model” PHEM for all vehicle segments and several real world cycles. Exemplarily in Figure 2.1 to Figure 2.3 a comparison of results is shown for the average EURO 4 Diesel passenger car driven in the ERMES real world driving cycle.

[4] Emission models need to be updated regularly based on the latest available set of in-use emission tests, data on vehicle and emission technologies as well as fleet data. For updates of PHEMlight an automatic export routine was implemented into PHEM. So the parameterisation of PHEMlight can be updated with low efforts each time the parent model PHEM is fed with new input data.

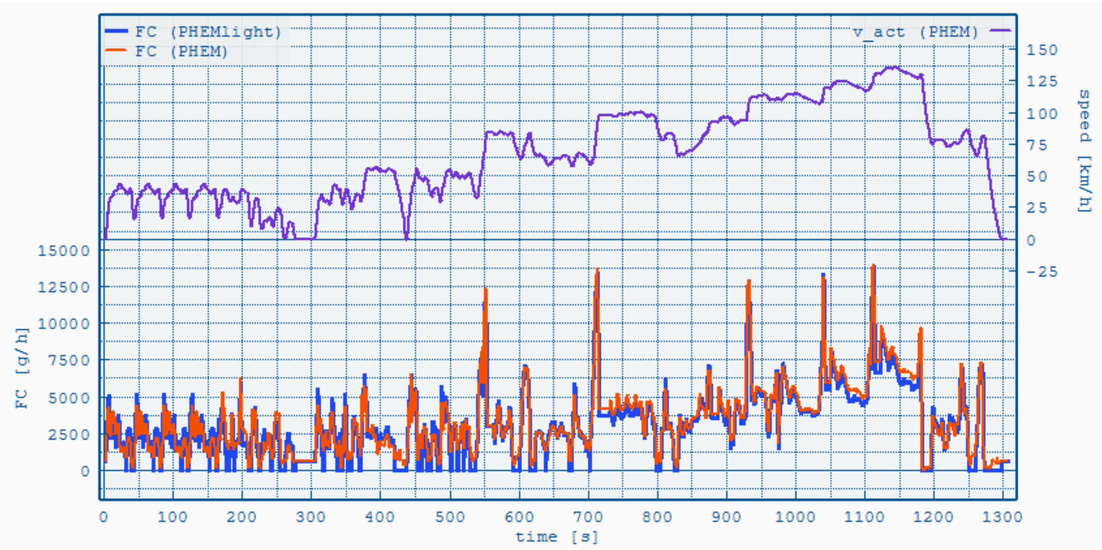

Figure 2.1: Fuel consumption comparison between PHEM and PHEMlight.

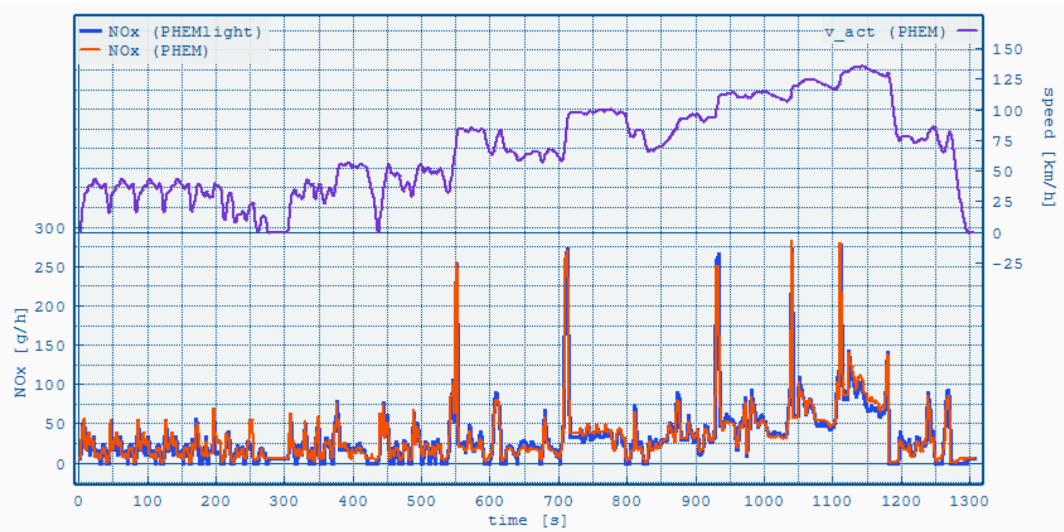

Figure 2.2: NOx comparison between PHEM and PHEMlight.

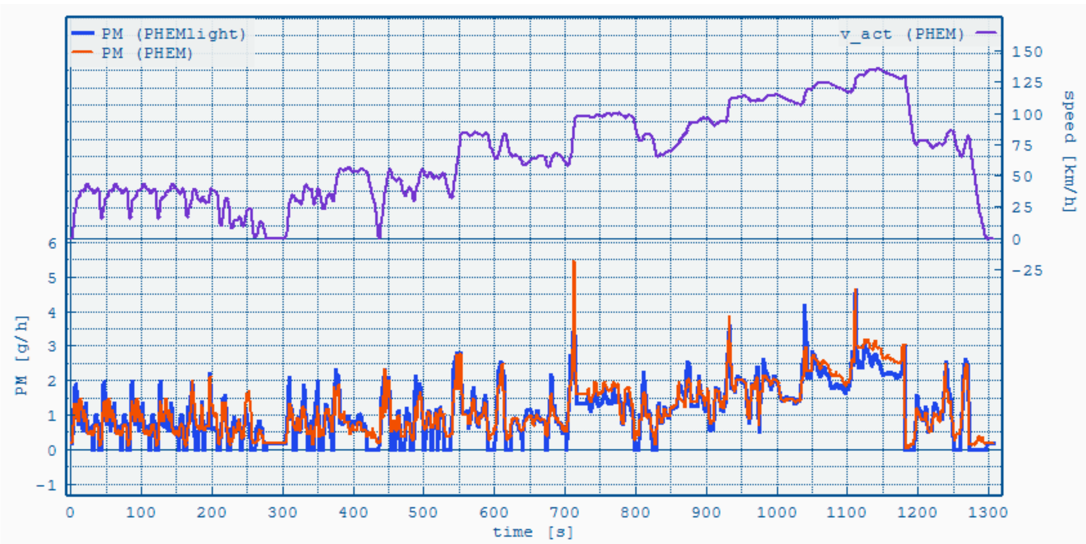

Figure 2.3: PM comparison between PHEM and PHEMlight.

The results present very good correlation between the two models over the whole cycle despite the fact the PHEMlight uses a significantly simpler approach with no explicit consideration of gear shifting and engine speeds.

Table 2.2 shows the cycle average emission results for fuel consumption and emissions. PHEMlight slightly underestimates the cycle average PHEM result. This underestimation is to a high extend caused by the PHEMlight "fuel cut-off" model element, which has been implemented in order to better depict relative influences of changes in driving style on the emission output. In the parent model PHEM the motoring emissions are based on measurements on the chassis dynamometer where, due to technical limitations of the emission measurement systems, the measured emission level is not entirely cut off at the same moment as the engine stops injecting fuel. This effect causes that the emissions calculated with PHEM are generally closer to the raw measurement data. It is planned to update PHEM in this regard for more realistic behaviour by developing sophisticated correction methods for input data from the chassis dynamometer.

Table 2.2: Average emissions in ERMES cycle for PHEM and PHEMlight (EURO 4 Diesel Car).

	FC	NOx	PM	CO	HC
PHEM	3352.8	33.83	1.18	1.76	0.59
PHEMlight	3183.6	33.13	1.12	1.62	0.54
Deviation	-5.0%	-2.1%	-4.9%	-7.6%	-8.1%

2.2.4 PHEMlight: Generation of "average" Vehicles

The vehicle fleet consists of various vehicle types and propulsion concepts which can differ significantly in terms of emission behavior. As a consequence in emission modelling the vehicle fleet is subdivided into vehicle groups with characteristic emission behavior, the so called "fleet segments". A common method of fleet segmentation is to differentiate by the following criteria:

- vehicle category (e.g.: passenger cars, light duty vehicles, rigid trucks, …)
- engine concept (e.g. gasoline, diesel)
- size class (differentiating factor: capacity or maximum allowed gross weight) and
- emission standard (legislation which was applicable at the vehicles type approval, e.g. "EURO 5")

A vehicle segment is for example a "rigid truck with diesel engine, gross vehicle weight with more than 18 tons, emission standard EURO 5").

When the emissions of a typical fleet mix e.g. on a particular road network shall be calculated, the shares of the different vehicle segments on the overall mileage have to be known. This information can be calculated by fleet models (see Appendix B for more information). In the link of micro-scale traffic models (like SUMO) with micro-scale emission models (like PHEM or PHEMlight) the common approach is to allocate a certain "vehicle segment" to a particular vehicle driving on the virtual road network by a random generator based on the probabilities defined by the mileage shares. This approach has the disadvantage that – unless a very high number of vehicles is simulated on the road network – the emission result contains an influence of the output of the random generator. Additionally micro-scale traffic models themselves use a random algorithm e.g. to generate the vehicles entering the model area. These random elements add a certain margin in the emission results for the coupled simulation run. A common way to handle this problem is to perform simulations several times - with several start values ("seeds") for the random generator - and to analyse the overall outcome in terms of average result and scattering of single simulation runs. This approach requires much computational time and additional efforts in the data analysis.

In PHEMlight, for the modelling of the fleet mix an alternative approach was developed, which allows to consider the fleet mix without the use of a random generator. Instead of attributing a particular vehicle segment to a particular vehicle on the road network a “weighted average” vehicle is allocated. This is done in PHEMlight by weighing of all input data (e.g. vehicle mass, driving resistance parameters, characteristic emissions curves) according to the fleet mix data. In this way it is possible to generate an average “light duty vehicle” (covering passenger cars and light commercial vehicles), an average “truck” (comprising rigid trucks as well as articulated trucks and truck- and trailer combinations) and an average “bus”.[5]

For a validation of this method the ERMES test cycle was calculated with a passenger car fleet mix configured for Austria in the year 2020 and compared with the weighted result of each single vehicle of the fleet. Figure 2.4 shows the results for NO_x. Nearly similar emissions are obtained by the “average vehicle” when compared to the weighted average of the single simulations. The deviations are in the range of the overall model accuracy and result from averaging effects of nonlinear dependencies.

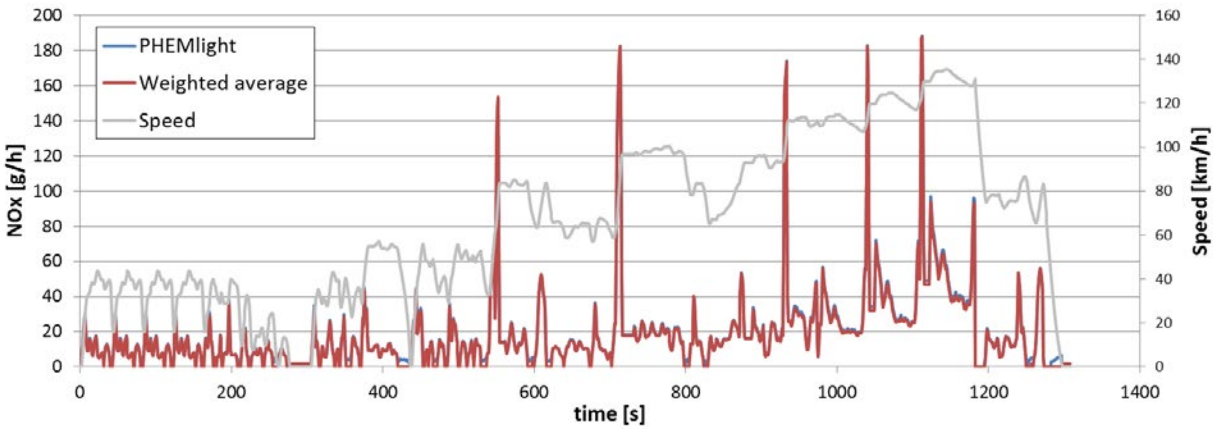

Figure 2.4: Comparison of NOx emissions for the PHEMlight average passenger car with the weighted result for the single associated vehicle segments.

However, this method of generation of a fleet average vehicle by weighting averaging of the model input data is limited to the less complex model structure of PHEMlight. For PHEM such an approach would not result in meaningful model behavior, as e.g. the modelling of engine speeds needs a harmonized set of vehicle data (integer number of gears, gear ratios, engine full-load characteristics etc.) which cannot be expected to be the case for weighted vehicle datasets.

2.3 Correlations between Performance Indicators

One of the major applications of the emission model in COLOMBO is to evaluate the performance of a traffic light in means of reducing pollutant emission. Usually, traffic lights are evaluated based on traffic efficiency measures, incorporating the effects of constraining the flow on emissions are relatively new.

Incorporating new measures – or performance indicators – increases the amount of values that can be shown after an evaluation, but may reduce the expressiveness of the results as a reader may need to choose the measure she/he is interested in. The need to deal with a growing number of available performance indicators of different kind counts even more when going from a plain

[5] A further combination of these three vehicle types into a “total fleet average” vehicle would not be meaningful due to differences in the emission modelling depending on the vehicle category (e.g. different normalisation methods of characteristic emission curves).

presentation of the numbers towards using them to optimise a system (e.g. a traffic light). The development of a single performance metric for unambiguous determination of a traffic light performance was attempted in COLOMBO within the Work Package 5 and is reported in [COLOMBO D5.3, 2014]. Still, for optimising traffic regarding emissions, it is good to know how these correlate and whether correlations with conventional metrics exist.

In the following, different attempts to determine the correlation between the emission of different pollutants and between pollutants and conventionally used traffic efficiency measures are presented. They should support the work performed in WP2 and WP3 on designing an environment friendly traffic light. At first, correlations between measures collected in each time step are given. Then, the correlation between aggregated measures is presented and discussed. Finally, a summary is given.

2.3.1 Instantaneous Measures

Usually, microscopic simulations use discrete time steps to update simulated instances, such as traffic lights, vehicles, or pedestrians. After computing their respective behaviour for the current time step, different measures can be obtained. The following evaluation uses such “instantaneous” data to determine correlations.

A subset of the real-world scenarios presented in [COLOMBO D1.1, 2014] was executed. Within these runs, all simulated vehicles had the same emission type “PKW_G_EU4” assigned. From each vehicle, its current speed, acceleration, emission of pollutants CO, CO_2, NO_x, PM_x, HC, as well as the fuel consumption were collected at each time step. Afterwards, the Pearson correlations between these values (the respective measures from a vehicle at a time step) were determined. Figure 2.5 shows the resulting correlation matrices for the “joined” scenario. The results obtained from other scenarios[6] are not given in this document, but are discussed as well. To use a well-balanced[7] scenario, only values between simulated second 1800 and second 2700[8] were used.

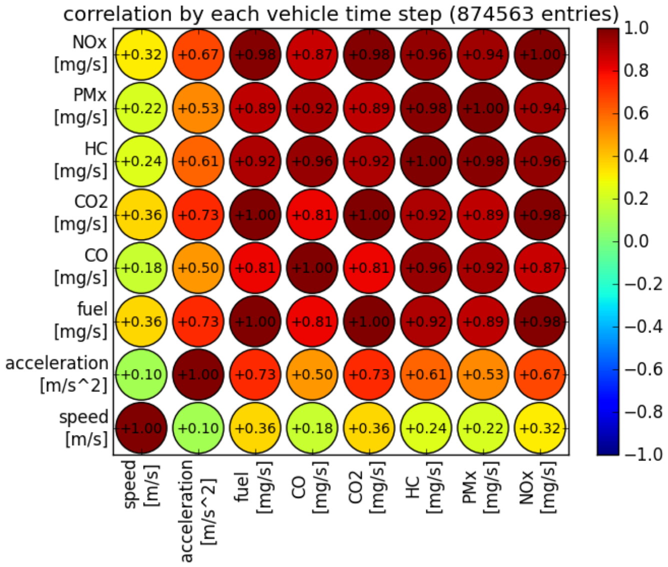

Figure 2.5: Correlations between selected instantaneous measures obtained from the “joined” scenario, all vehicles are assigned to the emission class “PKW_G_EU4”.

[6] RiLSA examples 1-4, “A.Costa”, “Pasubio”, and “Joined”
[7] Neglecting the warm-up phase and the cool-down phase
[8] Initially between 1800 and 3600, but this failed due to memory errors; the in-between obtained correlations for this bigger time range differ only marginally from the ones presented here.

Speed and acceleration do not correlate, which was expected. The fact that emissions rather depend on the acceleration than on the speed is visible as well. The pollutants among each other as well as the fuel consumption show high correlation. The correlation value of 1.0 along all scenarios shows that fuel is almost completely burned to CO_2. For the investigated scenarios, the correlation between the other pollutants spans between 0.68 and 0.98.

Figure 2.6 shows the correlations obtained the same way, but using a vehicle type distribution that resembles the year 2010 emission fleet as described in [COLOMBO D5.3, 2014], section 5.4. One can see that the correlations are generally lower, especially those between different pollutants. The correlation between CO_2 and fuel consumption still remains high since all vehicle concepts convert nearly all fuel into CO_2.

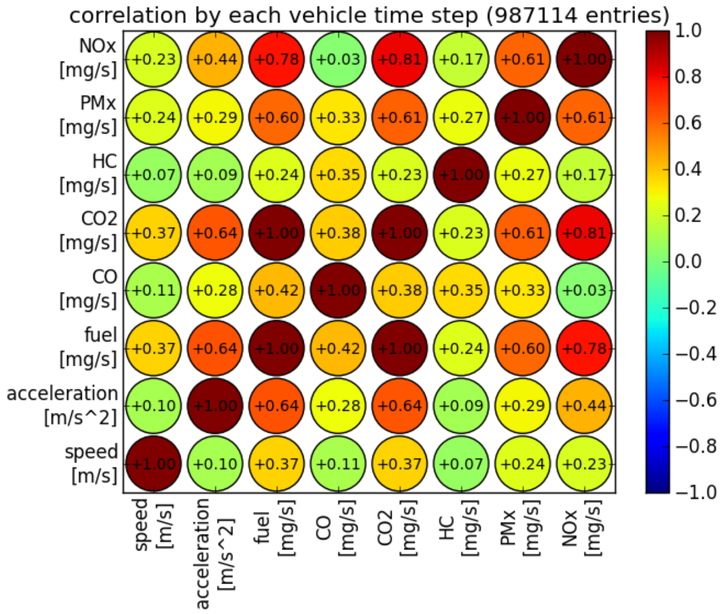

Figure 2.6: Correlations between selected instantaneous measures obtained from the "joined" scenario, The vehicles are assigned by sampling the Austrian vehicle fleet for 2010.

2.3.2 Aggregated Measures

Instead of using instantaneous measures, aggregated information about a vehicle's journey may be a source of information about a developed system's performance. In the following, the correlations between the following aggregates are given: (journey) duration, route length, wait steps, as well as (overall) fuel consumption and emission of CO, CO_2, HC, PM_x, and NO_x. Figure 2.7 shows the covariance matrix for the 2010 fleet, again based on the "joined" scenario.

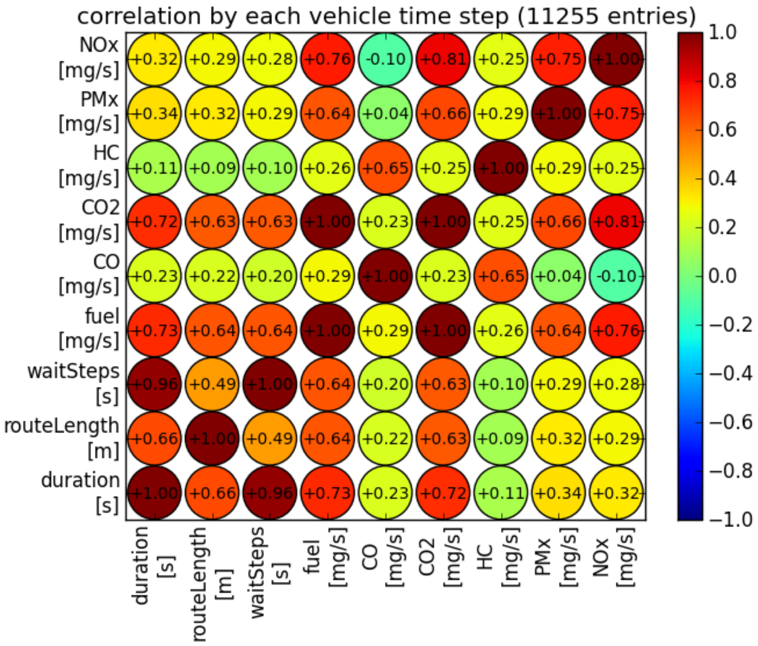

Figure 2.7: Correlations between selected aggregated performance indicators obtained from the “joined” scenario (vehicle fleet 2010).

A large-scale scenario of Brunswick (see [COLOMBO D4.2, 2014]) was used to obtain the same measures, shown in Figure 2.8. In contrary to the scenarios delivered by COLOMBO, the Brunswick scenario spans a bigger area that includes not only urban roads, but as well high- and motorways. In addition, the routes are longer. Again, the correlation between most pollutants is rather low.

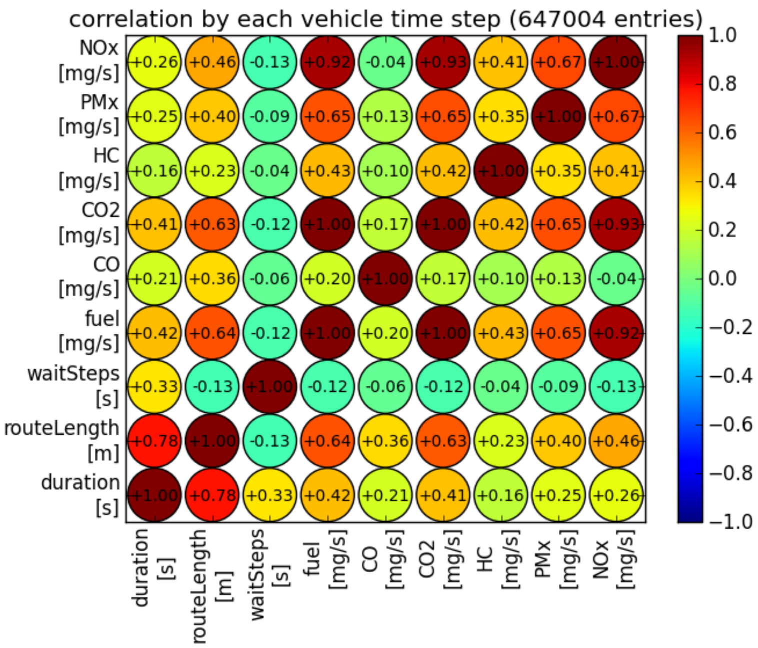

Figure 2.8: Correlations between selected aggregated performance indicators obtained from the “Brunswick” scenario (vehicle fleet 2010).

2.3.3 Summary

Different attempts to determine the correlation between conventionally used measures and performance indicators were presented. Different aspects could be shown having the according conclusions:

- emissions and fuel consumption depends more on the acceleration than on the speed;
- fuel consumption and CO_2 emission have a linear dependency (as the majority of fuel is burned to CO_2);
- the Pearson-correlation of instantaneous measures is usually positive but may get near to zero;
- as soon as bigger aggregation intervals or emission fleets with several emission classes are used, the correlations decrease.

Summarizing, one should state that the presented correlations do not prove the assumption that a single measure could be used as a replacement for a set of other measures. The only exception is the combination CO_2/fuel, as both have a linear dependency. Thereby, a solution that attempts to optimise a certain pollutant should be optimised against it (the only exception is the CO_2/fuel pair as stated above).

3 Optimising Driver Behaviour

Controlling vehicles by a traffic light is usually described on a macroscopic scale, regarding numbers of vehicles that are passed or that have to wait. At this scale, optimisation of traffic lights will be regarded in Chapter 4 and is additionally covered within the COLOMBO project by the development of self-organising traffic lights performed by WP 2. But every vehicle interacts with traffic light individually and – being the generator of emissions – can contribute to reducing them. Given a single vehicle, this is mainly achieved by choosing the proper speed (including the right gear choice) over time.

This chapter presents the findings on driving style which is optimal in terms of pollutant emissions and fuel consumption and describes the physical and technological background. Then, methods to obtain an emission-optimal driver behaviour for crossing a traffic light are presented.

3.1 Physical and Technological Background

Driving style has a significant influence on vehicle emissions and fuel consumption.[9] These environmental impacts of a vehicle propelled by an internal combustion engine are determined by two influence factors:

1. the amount of work the engine has to deliver to run the vehicle and its subsystems over a certain distance (e.g. road section);
2. the operation conditions of the engine, its exhaust aftertreatment and the vehicles drive train, which determine the efficiency of the powertrain and also the emission output of the engine related to a certain amount of delivered work. Main parameters for operation conditions are: engine speed, engine power (or torque) and temperature of the engine and the exhaust aftertreatment systems.

In real world driving both determining factors are strongly interrelated, so any driving strategy has to take care to optimize the combination of the two factors (e.g. theoretically operating the engine in its best efficiency points would for most vehicles result in powerful accelerations and high cruising speed levels where the high engine efficiency would drastically be overcompensated by a high demand of work per driven distance).

A characterization of driving behavior can be made by isolating the factors:

(a) General level of cruising speed
(b) Acceleration behavior
(c) Deceleration behavior
(d) Stop time duration

As a general rule stop times with engine idling should be minimised. This can for example be done by either turning of the engine during stand still (Stop/Start systems of modern engines do this automatically) or by prolonging the deceleration time with engine in “fuel cut-off” mode (see section 3.1.3).

The interaction of characteristics (a) to (c) with the vehicles emission behavior is described in the following sections.

[9] Fuel consumption is nearly 1:1 proportional to CO_2 emissions. Hence all conclusions discussed for emissions of CO_2 are also valid for fuel consumption.

3.1.1 Optimal Cruising Speed

To determine the optimal cruising speed levels constant speeds in the range from 10 km/h to 120 km/h have been simulated with PHEM for several vehicle segments. Figure 3.1 exemplarily shows results for CO_2 emissions of a gasoline and a diesel passenger car emission standard EURO 5.

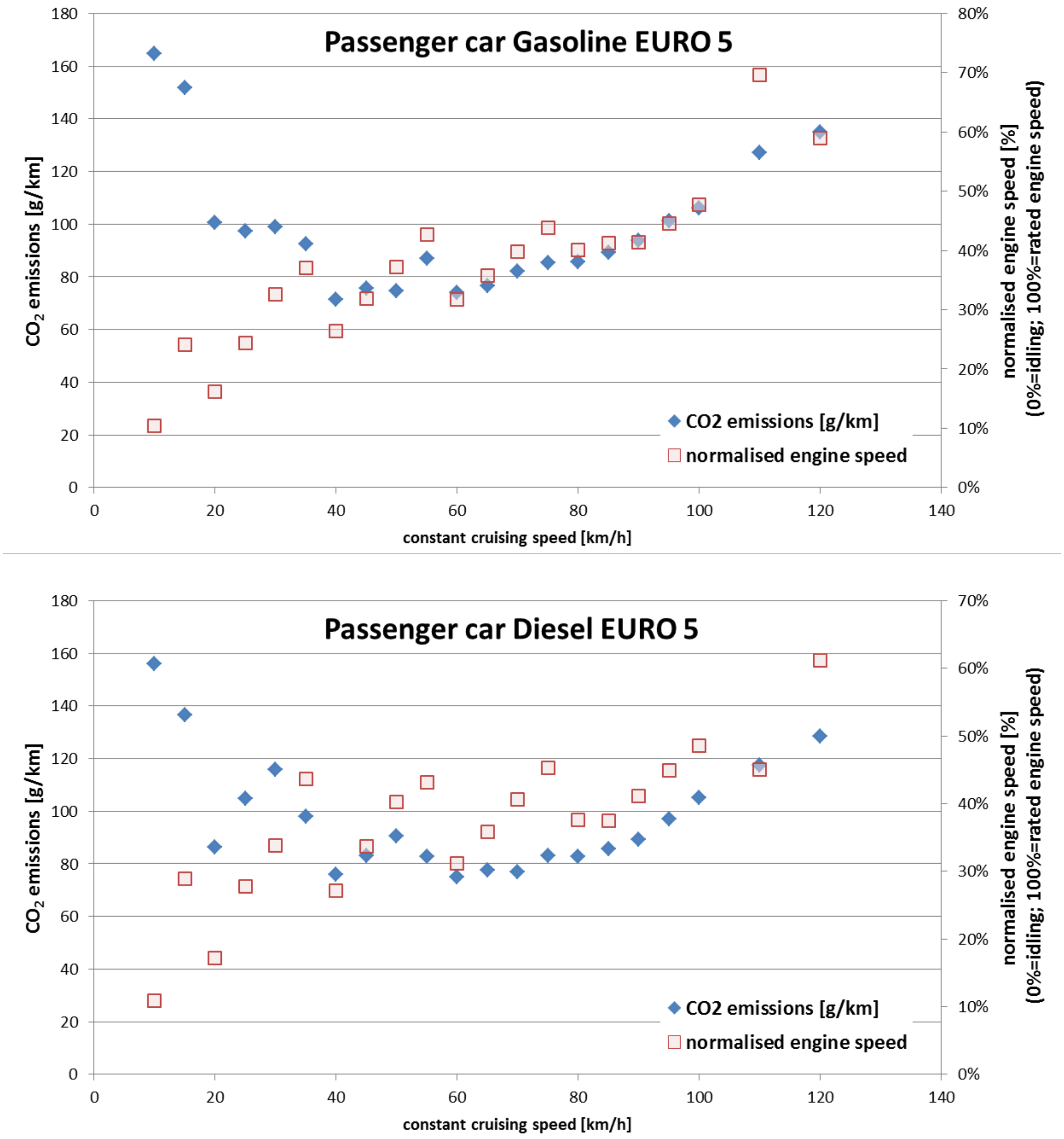

Figure 3.1: CO_2 emissions and engine speeds in constant speed driving (passenger car EURO5 Gasoline and Diesel).

For modern passenger cars the emission levels in terms of g/km for the main relevant exhaust gas components CO_2 and NO_x are not sensitive to the cruising speed level in the velocity range of about 40 km/h to 80 km/h. Driving at higher constant speeds than about 80 km/h increases the distance specific emissions mainly to the growing influence of the aerodynamic drag, which is a function of quadratic speed. Driving at constant speeds lower than about 40 km/h also increases compared to the 40 km/h to 80 km/h range caused by low efficiencies of the engine and the powertrain system.[10]

The gear selection influences CO_2 emissions (as well as other emission components) to a large extend. Gear shift behavior is highly variable between different combinations of cars and drivers. PHEM uses a model for a generic average driver which causes “steps” in the trends of emissions over cruising speed as shown in Figure 3.1 when the gear shift model selects a different gear than for the previous speed step. In real world conditions - due to real distributions of driver gear shift behavior and vehicle specifications - a much more steady dependency of fleet emissions over cruising speed can be expected.

Independently from the gear shift model of PHEM as a general advice valid for all constant speed levels it can be stated that driving in a rather high gear (resulting in low engine speeds but above a minimum of approximately 1.5 times the engine idling speed) optimizes emission output and fuel consumption.

3.1.2 Optimal Acceleration

Several acceleration behaviors were analyzed with PHEM to find optimal acceleration values. The simulations were performed with average EURO 4 Gasoline and Diesel passenger cars. The test cycle consisted of an acceleration phase from stand still to 50 km/h and a cruising phase. The engine load was varied for the acceleration phases while the cruising time was adjusted towards a constant total driving distance of 500 m to ensure comparability. Figure 3.2 exemplarily shows four speed profiles for four different scenarios calculated with the Gasoline car. The percentage label refers to the engine load used for acceleration as fraction of the car's full load, e.g. "50 %" means half of the vehicle's full load was applied.

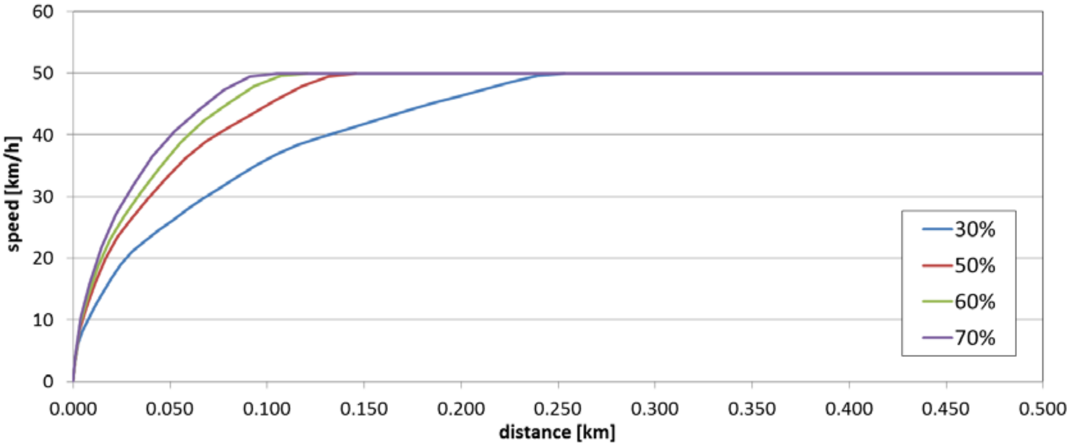

Figure 3.2: Speed profiles for four acceleration scenarios as function of the percent engine load during acceleration for the average Gasoline passenger car.

Table 3.1 shows the results for both average Diesel and Gasoline passenger cars. Regarding the deviation it is important to note that the chosen overall distance for comparison influences the magnitude of the effect. Longer cruising distance shares will certainly lower the relative effect but not the ranking of the different acceleration levels.

[10] In several studies the impact of speed limits in the range of 30 km/h and 50km/h for urban roads was investigated. Extensive measurements and simulations have been performed in Baden-Württemberg, [Toenges-Schuller, 2012] and [Kleinebrahm, 2011]. Main conclusion was that the speeds limits lower than 50 km/h do not necessarily lower emissions levels. Of course other arguments e.g. safety are also relevant for the selection of the appropriate speed limit for a certain area.

Table 3.1: PHEM results for four acceleration variations.

	Gasoline		Diesel	
Engine load level [% of max]	FC [g/km]	Deviation to '30%'	FC [g/km]	Deviation to '30%'
30%	43.11	-	47.34	-
50%	43.62	1.2%	48.95	3.4%
60%	44.12	2.3%	50.07	5.8%
70%	44.47	3.2%	51.15	8.0%

The comparison shows that higher loads and therefore faster accelerations yield higher fuel consumption. While the engine efficiency is generally higher at higher loads this effect is overcompensated by the higher energy demand due to the increased average speed.

The main conclusion is that rather slow or moderate acceleration behavior is favorable in terms of emission optimization. Early gear shifts are advised also during the acceleration phase. Beside the effects considered in the calculations here a rather defensive acceleration behavior in real world conditions should give additional benefits in occasions when - due to events not foreseeable at time of the acceleration phase - the intended cruising speed cannot be reached or held only for a short time. In these cases a slower acceleration helps also minimizing the losses due to mechanical braking and hence further reducing fuel consumption and emissions.

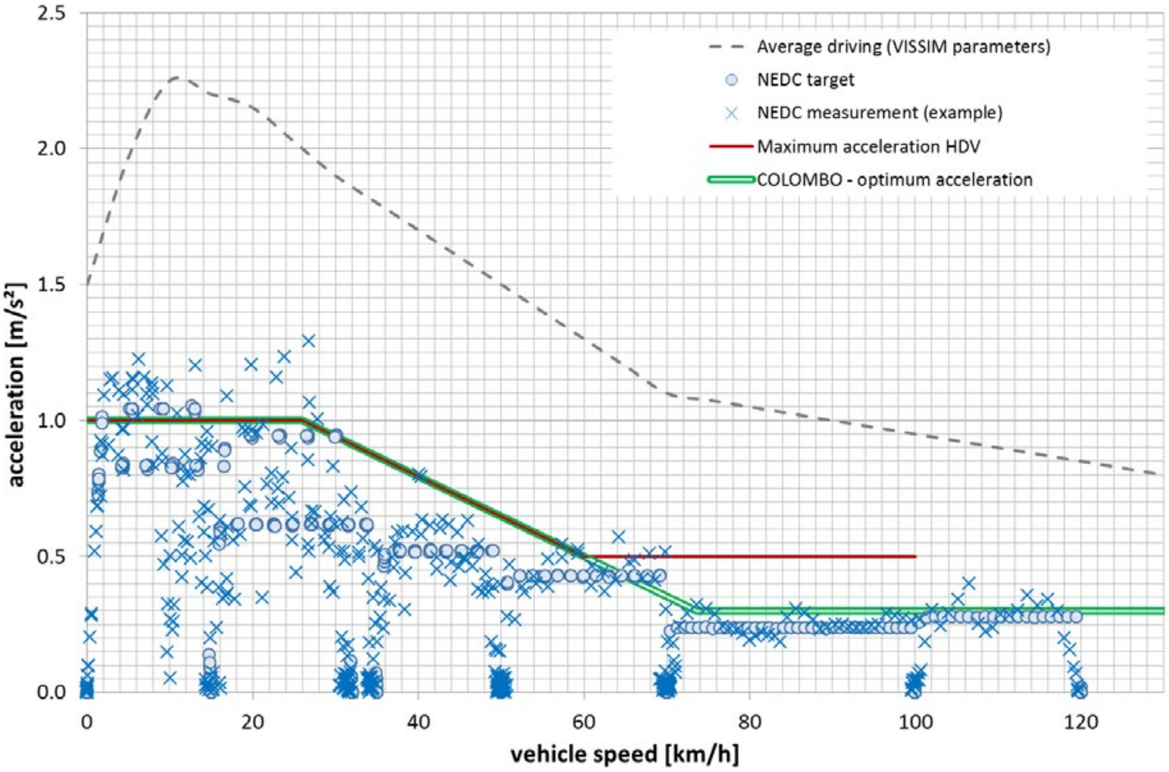

Figure 3.3: Acceleration behaviour as a function of vehicle speed.

For the model calculations in COLOMBO characteristics for optimal acceleration behavior had to be generated. This optimal acceleration behavior has been defined by a function for target acceleration over vehicle speed (Figure 3.3, green line). At low vehicle speeds an acceleration of 1 m/s² is advised. At high vehicle speeds, for minimizing emissions accelerations should not exceed 0.3 m/s².[11] This acceleration behavior is significantly less pronounced (of about a factor of two) than of common "normal" driving behavior (see Figure 3.3, dashed grey line).

This target acceleration behavior for optimizing emission output is advised for all vehicle categories. The function was deviated from the accelerations in the type approval cycle NEDC. It is known that OEMs especially optimize the vehicles emission for these moderate acceleration conditions. This driving behavior also fits to the acceleration capabilities of heavy duty vehicles.

3.1.3 Optimal Deceleration

Mechanical braking converts useful kinetic energy into useless heat. So – from an energetic perspective - any mechanical braking should be avoided. An optimal deceleration phase just uses the kinetic energy of the vehicle to overcome the drag losses of the engine and of the drivetrain system. This is done just by removing the foot from the gas pedal without any further pressing the brake pedal bringing the engine into a "motoring" state. In this operation condition modern engines stop fuel injection resulting in zero emissions output for all emission components.[12] A high gear should be engaged during motoring in order to minimize the drag losses in the powertrain. When the engine speed comes close to the idling speed, the next lower gear should be selected (otherwise the engine would start to inject fuel not to fall below idling speed).

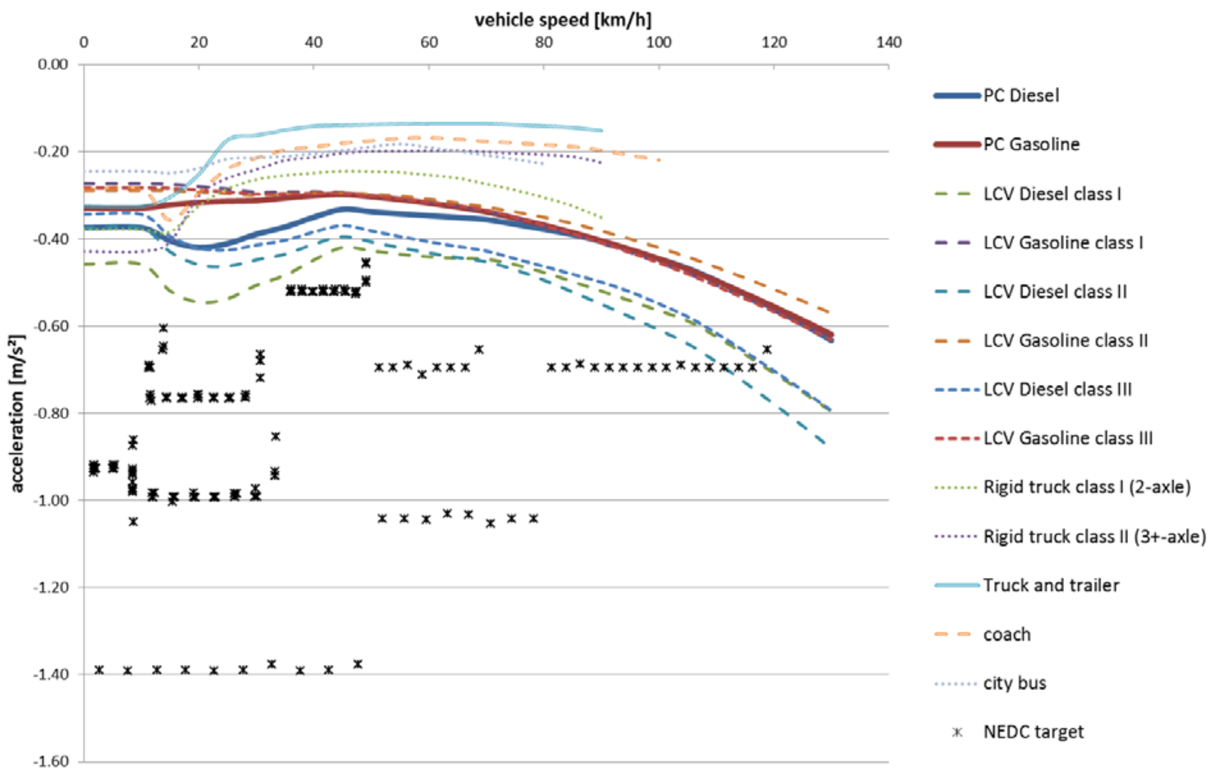

Figure 3.4: Deceleration rates for emission optimal driving.

The resulting deceleration behavior from this driving strategy depends on the vehicle mass, the driving resistances and the losses in the engine and the drivetrain system (see section 2.2.2). In general the resulting decelerations are small compared to typical real world deceleration patterns.

[11] These recommendations only consider emission related effects. Of course in real world traffic situations demands like safety issues (e.g. during overtaking) will overrule the recommendations.

[12] Only a very small amount of hydrocarbons and particle emissions originating from lube oil is found in the exhaust gas during motoring.

In any case, such motoring phases are part of the "normal" driving behavior as a first part of a typical deceleration process. In real world stronger decelerations than resulting just from "motoring" can hardly be avoided, however an anticipating driving style should aim for minimizing the part including mechanical braking.

In COLOMBO for all vehicles categories such optimal deceleration curves have been calculated (Figure 3.4). For passenger cars deceleration rates at motoring are in the range of 0.3 m/s² to 0.6 m/s² depending on the driving speed. Heavy duty vehicles have the lowest deceleration rates at motoring conditions due to the inertia of the high vehicle mass. For comparison Figure 3.4 also shows the decelerations from the NEDC cycle which are in the range of 0.5 to 1.4 m/s².

3.1.4 Validation of theory on optimal acceleration and deceleration behaviour

For a validation of the theory regarding emission optimal acceleration and deceleration rates real world driving data have been recorded in Austria. A route consisting of approx. 25 % urban 30 % rural and 45 % motorway roads has been driven by several drivers in "normal", pronounced "moderate" and "aggressive" driving style and the speed and gradient patterns have been recorded. These velocity trajectories then have been post processed with the acceleration and deceleration behavior as discussed above. Then PHEM simulations and comparison emissions of original v(t) with optimized v(t) for each driving style for a EURO4 Diesel car.

Table 3.2 shows results for the three different driving cycles. As expected the highest reduction was calculated for the aggressive driving trajectory (-16% fuel consumption, -21% NOx). Even for the moderate driver a more consequent "compliance" with the strategies as discussed above would result in a further emission reduction (-7% fuel consumption, -3% NO_x). Emissions of CO, HC and PM show other trends but in general are on a very low level for this vehicle technology. Important to note is that it these comparisons only show a theoretical optimum because in real driving the behaviour is influenced and limited by traffic and it would not be possible to follow the optimal acceleration and deceleration behaviour all the time.

Table 3.2: Deviation from original to optimised acceleration and deceleration behaviour.

Driving style	FC [g/km]	NOx [g/km]	CO [g/km]	HC [g/km]	PM [g/km]	PN [#/km]	NO [g/km]
Moderate	-7.0%	-3.0%	-5.6%	+4.3%	+1.9%	+0.9%	-3.1%
Normal	-10.3%	-9.7%	-12.2%	+3.3%	-0.8%	-1.9%	-9.9%
Aggressive	-16.2%	-20.8%	-13.3%	+4.2%	-4.1%	-4.2%	-21.1%

3.1.5 Summary of Strategies for Emission Optimal Driving Behaviour

The guidelines for emission optimal driving can be summarised as follows:

1. Drive as steady as possible ("cruising") in a velocity range of 40 km/h to 80 km/h.
2. Chose the highest possible gear in order to keep the engine speed low (but above about 1.5 times the engine idling speed).
3. Drive as "anticipating" as possible in order to avoid the use of mechanical brakes as much as possible.
4. Perform decelerations in engine motoring mode (i.e. without additional mechanical braking) and using a high gear. Shift back when engine speed comes close to engine idling speed.
5. Accelerate in a moderate way using high gears.
6. Avoid stop times with running engine.

For the hybrid vehicles all above made statements are also found to be correct. Since the hybrids recuperate parts of the brake energy, mechanical braking means lower losses of energy than for conventional vehicles. In addition almost all hybrids shut down the engine during vehicle stand still and thus do not produce emissions there. The main additional driver influence at hybrids is to keep the actuation of the brake pedal to a level that can be covered by the electrical system of the car. Higher brake power demands than available from electric motor and battery properties leads to the activation of the mechanical brakes and thus drastically reduces the recuperated kinetic energy. This limitation seems to be most important for buses with serial hybrid systems since these vehicles have high mass with comparable low electric motor power.

All recommendations for conventional vehicles have been elaborated also quantitatively as input dataset for COLOMBO to allow simulation of “optimal driver behaviour”. For hybrid vehicles yet no data set for PHEMlight was elaborated. This is planned in a next step since priority was given to the actually important technologies.

3.2 Emission-optimal Speed Time-lines

As shown, fuel consumption and therefore as well the emission of pollutants highly depend on the chosen mode of driving and, in conjunction, the chosen speed. Within the context of COLOMBO, the focus is put on optimising emissions while passing an intersection that is controlled by a traffic light, where “passing” may include halting time. Other projects consider other driving situations, such as taking curves, as well.

Besides the goal to design emission-friendly intersections, single-vehicle approaches that optimise a vehicle’s traffic light crossing are as well in focus of the development of V2X solutions. The V2X-based GLOSA (“Green Light Optimized Speed Advisory”) application is one of the “basic set of applications” as defined by ETSI [ETSI, 2009]. GLOSA advices the driver to use a certain speed to pass a traffic light at green. Its major task is thereby similar to the problem discussed here and is targeted in the research as well.

In the following a single intersection with traffic lights is considered. For simplicity, a single vehicle driving towards the intersection and crossing it is regarded, while no other cars are taken into account. Additionally, the vehicle knows the current and the future states of the traffic light. This resembles what is already done in the real world using vehicular communication. As well, the driver is not taken into account; the vehicle’s progress over the traffic light is purely cybernetic. This work targets to help future developments of emission-reducing systems.

The following subsections describe some possibilities how a vehicle may interact with a traffic light in means of choosing a speed to cross it at green. At first, a basic model of real-world behaviour is given. Then, GLOSA approaches are presented. Afterwards, two behaviour models developed within COLOMBO are described. After the presentation of the behaviour models, a comparison that targets on determining their performance at traffic lights is given.

3.2.1 Real-World Behaviour

A very simple approximation of real-world behaviour would be to assume drivers run with a constant speed towards the traffic lights and decelerate only if a) they arrive on red or b) they arrive on yellow and are distant enough from the intersection to halt in front of it.

Figure 3.5 a) shows the trajectories of vehicles that approach a traffic light this way. To achieve this, every vehicle is simulated individually. For every vehicle, the starting position is incremented by $v_{begin}*dt$ to obtain the behaviour for different arrival times at the intersection during the complete cycle time. The individually obtained trajectories are shown in the same Figure. Therefore, they may overlap. Vehicle parameters have been chosen as following:

- *dt* (time step): 1 s

- v_{begin} (initial velocity): 13.89 m/s (~50 km/h)
- v_{max} (maximum velocity): 13.89 m/s (~50 km/h)
- a_{max} (maximum acceleration): 1.0 m/s^2
- d_{max} (maximum deceleration): -4.5 m/s^2

The simulated traffic light has a cycle duration of 60 s, with a green time that starts at second 0 and ends after 25 s. It is followed by a yellow phase of 3 s duration. Thereby, the last phase (red) has a duration of 32 s.

One may note that this model lacks any kind of pre-emption a driver may have regarding the state of the traffic light. It should be assumed that drivers that approach a red light do not drive towards it and brake with -1 m/s^2. Rather, they coast or brake earlier. Figure 3.5 b) shows the occurrences of acceleration/speed combinations for all simulated vehicles. Please note that all occurrences of v=0 and v>13.8 (near v_{max}) with a=0 are not considered; standing in front of the intersection as well as driving with v_{max} are the most common speed/acceleration combinations and the other combinations would not be visible.

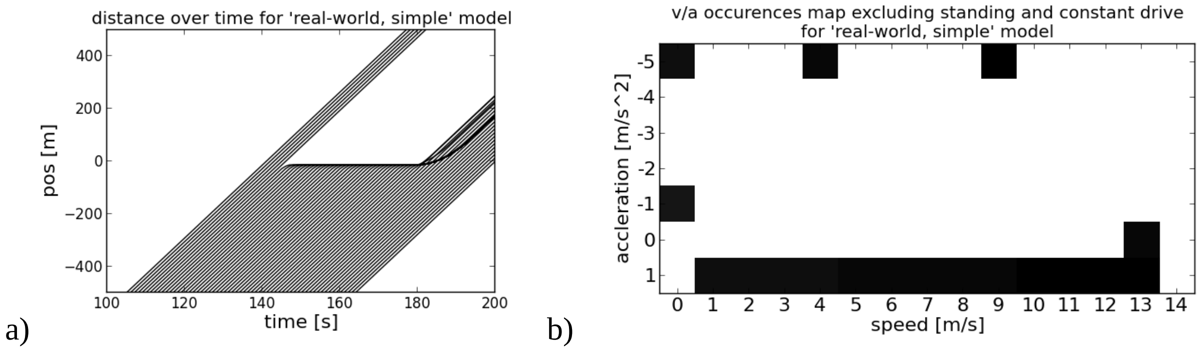

Figure 3.5: Simplified behaviour while approaching a traffic light; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

3.2.2 GLOSA Approaches

The "Green Light Optimal Speed Advisory" (GLOSA) application is an Advanced Driver Assistance System that presents the driver the speed to choose to pass the next traffic light at green. GLOSA belongs to the "basic set of [V2X] applications" that have been standardised by ETSI. GLOSA retrieves I2V[13]-messages from road side units (RSUs) located at traffic light controlled intersections. Two dedicated messages are sent by the traffic light: SPAT ("Signal Phase And Timings") about the current and future states of the traffic signals and TOPO ("Topology") about the controlled roads[14]. Given this information and its GPS-position, the vehicle may compute the distance to the intersection and knows the state of the traffic light. Using this information, the vehicle may compute the speed to choose for arriving at the traffic light when it is green and to advice the driver accordingly.

While GLOSA's main target is to increase traffic efficiency and comfort of driving, it is as well reported to reduce vehicular emissions. In fact, the question whether GLOSA reduces emissions and to what degree is seen controversial. Therefore, respective models for GLOSA have been evaluated and are presented in the following. The representation of the according behaviour is shown as done for real-world behaviour in Figure 3.5. In all cases, the communication range – being same as the range of the system's reaction on the traffic light – was set to 500 m. All presented GLOSA approaches neither model the acceleration after passing the traffic light nor

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[13] Infrastructure-to-vehicle
[14] See also [COLOMBO D1.2, 2014], section 2.2.2, " Investigated Technologies"

braking in front of the red traffic light (what may happen if the communication fails, e.g.). This is solved by additional rules.

Only few of the available reports about GLOSA define the functions used to compute the speed to advice. [Wegener et al., 2008] is one of them and is one of the very first reports concerned with the reduction of consumption and pollutants when using GLOSA. In this paper, two methods are used to reduce the consumption of fuel. The first is realised by a “fuel-cut off” that takes place at a deceleration named $a_{fuelCutOff}$. The second is the use of a start/stop-system that switches the engine off when halting longer than a given time threshold ($t_{minEngineOff}$). The second method is neglected in the following, because as the work presented here concentrates on the speeds to choose while approaching/starting at the intersection. Figure 3.6 shows the behaviour of the system described in [Wegener et al., 2008].

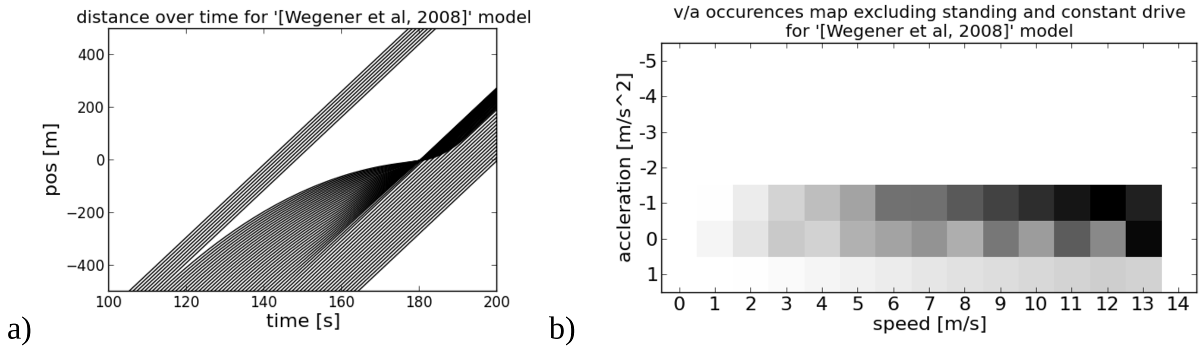

Figure 3.6: Behaviour while approaching a traffic light as described in [Wegener et al, 2008.]; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

[Katsaros et al., 2011] presents a research that focusses not only on reducing the amount of emitted pollutants, but as well on reducing the halting time in front of controlled intersections. The used function to compute the speed to advice differs slightly from [Wegener et al., 2008], but is nonetheless continuously adapting the speed during the approach towards a traffic light, see Figure 3.7. Please note that a further clause exists in [Katsaros et al., 2011] named “check for accelerations”, which is used if the traffic light is yellow. This is not included in the realisation presented here.

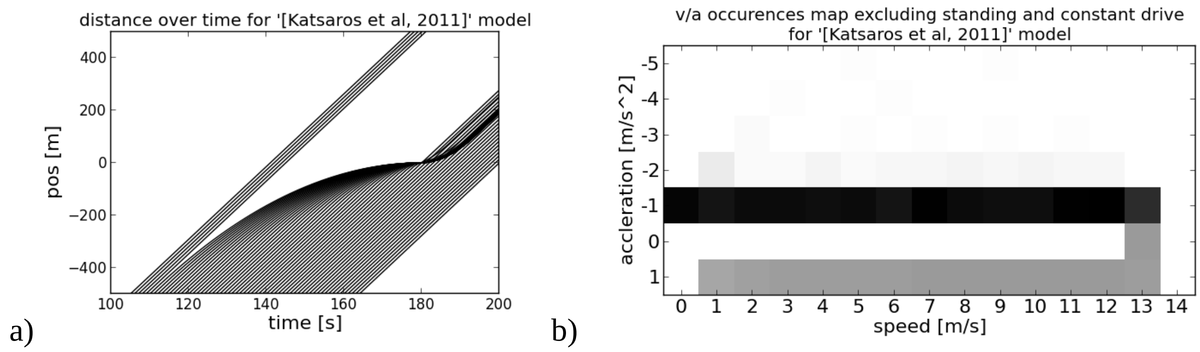

Figure 3.7: Behaviour while approaching a traffic light as described in [Katsaros et al., 2011]; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

A different attempt was used in [Krajzewicz et al., 2012]. Here, a constant speed to pass the next traffic light is computed.

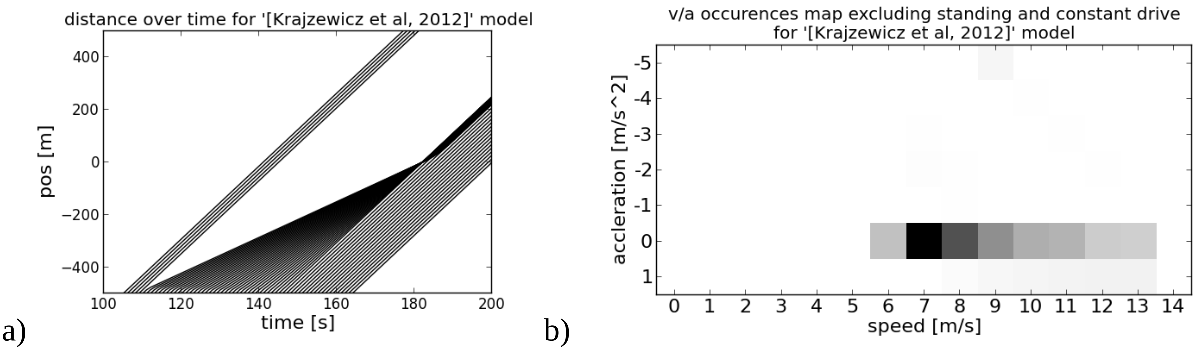

Figure 3.8: Behaviour while approaching a traffic light as described in [Krajzewicz et al., 2012] ; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

It is worth to note that none of the presented approaches for modelling GLOSA takes coasting with cut-off engine explicitly into regard.

3.2.3 Heuristic Optimisation

Some attempts have been performed to optimize the emission behaviour using different kinds of heuristic optimization algorithms and approaches.

An initial try to use genetic algorithms that decide the speed to choose for each simulation step failed as almost expected. The main reason is the randomized sampling performed to obtain new population members and that not enough information on the problem was exploited in the design of the operators. Mainly due to the latter issue, this approach resulted in a large number of time lines to test that are not valid in the sense that, e.g. the vehicle runs over red or exceeds the maximum deceleration/acceleration values.

More information on the problem was used within the second approach. In particular, it started with initial solutions that have been derived from the knowledge about emission reducing driving such as described previously in this document. It was then tried to modify these semi-optimal solutions by changing single entries in the timeline systematically. However, for the simple example of approaching a single traffic light no improvements over the initial semi-optimal solutions were found and as larger examples with a sequence of traffic lights were deemed not to be practical, the approach was not further followed.

3.2.4 Kinematic COLOMBO Model

In the following a simple kinematic approach to describe the trajectory of the vehicle is presented. Kinematic means that only constant accelerations are considered so that the whole vehicle movement can be decomposed into time intervals that are characterized by certain characteristic accelerations or decelerations, respectively. Vehicles begin by driving at an initial velocity that is typically given by the speed limit. Then, if they are in a certain space range before the traffic light the traffic light communicates the remaining red time to the vehicle. The driver can react by velocity adjustments. This is typically a deceleration to avoid hitting red and an acceleration to the final velocity after having passed the signal.

Notation

Let x_i, v_i be the initial position and speed of the vehicle under consideration at time $t = 0$ and x_f, v_f be the final position and speed. Red starts at time ϕ (offset) and ends at time $t_R = \phi + R$, where R is the red time. The position of the traffic light is at $x = 0$, which makes the initial position negative $x_\mathrm{i} < 0$. As mentioned, one often has $v_\mathrm{i} = v_\mathrm{f} = v_\mathrm{lim}$.

Consider the situation that the vehicle would arrive at a red signal if it would proceed to drive at its initial velocity:

$$t_{arr} = -\frac{x_i}{v_i} \in [n\,\phi,\, n\,t_R],\;\; t_R = \phi + R,\; n \in \mathbb{N}$$

Obviously, no other adjustments are needed at all. If the vehicle is too close to the traffic light so that it must stop, the needed deceleration is $a_{\text{stop}} = -\left|\frac{v_i^2}{2x_i}\right|$. Otherwise, if distance is "right" then it hits t_R exactly at $x = 0$ with a certain velocity $v_R \geq 0$. A third, not very realistic way: stop at $x < 0$ and at some earlier time $t < t_R$.

The COLOMBO#1 model and decision variables a_R, a^*

Two decelerations are needed:

(1) a_R: Using this deceleration the vehicle comes to a halt exactly at the time t_R where the traffic light switches from red to green. Note that the position where it halts is not specified. It needs $a_R = -\frac{v_i}{t_R}$ to make this happen.

(2) a^*: Is the deceleration needed to arrive at $x = 0$ at time t_R. So this (or even stronger) deceleration is necessary in order not to violate the stop line when the traffic light shows red. It has to apply the deceleration

$$a^* = -2\frac{x_i + v_i\,t_R}{t_R^2}.$$

This originates from $x_i + v_i\,t_R + \frac{1}{2}a^*\,t_R^2 = 0$. Contrary to intuition: parabola cannot be bend at will, i.e. there is but a small window of opportunity to reach $t = t_R$, $x = 0$ with any speed $v_R \geq 0$.

- If $a^* < a_R$ (a^* stronger a_R) then by braking at a_R the vehicle would violate the stop line. Thus is it too close and needs deceleration a_{stop}
- If $a^* > a_R$ (a_R stronger a^*) then by braking with a^* the vehicle will reach $x = 0$ exactly at t_R with a remaining speed $v_R = -v_i - 2x_i/t_R$
- If $a^* = a_R$, then the deceleration needed to come to a halt at t_R and the deceleration needed to come to a halt at $x = 0$ are the same and $v_R = 0$

Using those decision variables it is possible to decide on one special deceleration before the traffic light. Behind the stop line all vehicles accelerate at $1\,m/s^2$. This is implemented in the COLOMBO#1 algorithm and the results are exemplified in Figure 3.9 and following figures for six characteristic trajectories. Later on also decelerating at optimal strength (coasting) is considered in the COLOMBO#2 algorithm.

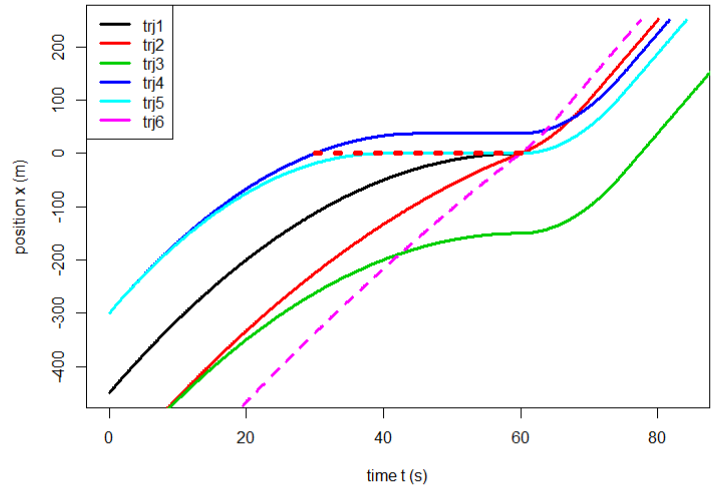

Figure 3.9: Trajectories of cars starting at different initial positions at time t=0. The dashed (red) horizontal line marks the red phase of the traffic signal.

Note that the blue trajectory was intentionally made to violate red. The purple shows very little deceleration at all, since it started at -750 m when there is still a lot of decision space. Figure 3.10 shows the corresponding velocity-versus-time diagram. One clearly sees that all cars start to accelerate at $t=60\ s$ with the same a_2 which is the optimum acceleration for minimum fuel consumption after the position of the traffic light has been passed. The exact value is not available at present but is assumed here as an arbitrary value of $a_2 = 1\, m/s^2$. The value of constant deceleration a_1, however, differs for the various cars.

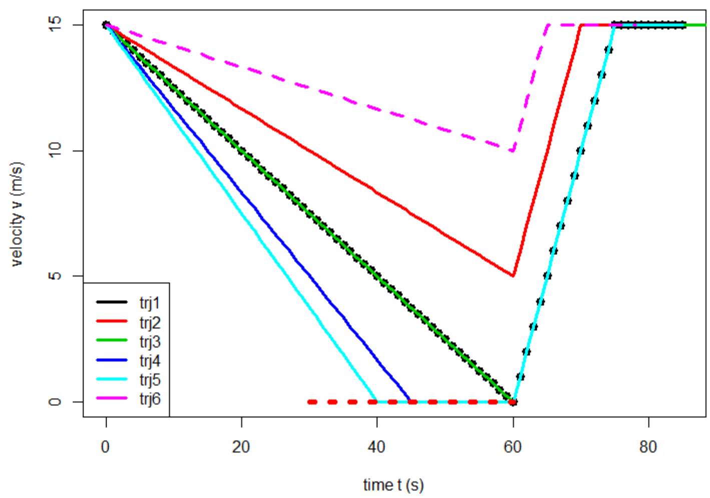

Figure 3.10: Colours correspond to the trajectories in Figure 1. Here, the velocity is plotted versus time.

The corresponding emissions for the six strategies above have been computed with the SUMO tool PHEMlight leading to the following result. As shown in Figure 3.11 (left), the differences in CO_2-emissions that are produced between 0 s and 60 s are marginal. Further, after the acceleration phase when the vehicles have arrived at their maximum speed, the emissions are the same. During the acceleration phase itself one sees a difference in the amount of emissions. The following diagram shows principally the same result for CO emissions (Figure 3.11, right).

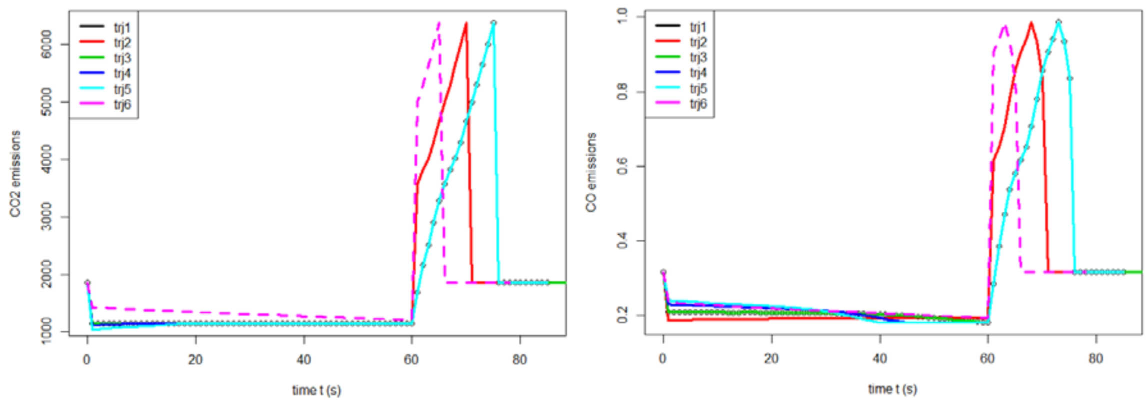

Figure 3.11: CO_2 (left) and CO (right) emissions for the trajectories from Figure 1 and 2 (same colouring, units in [mg/s]).

For all other toxics (HC, PM_x, NO_x) the result is qualitatively the same. In order to compare the total emissions for the different strategies it is therefore sufficient to consider CO_2, as shown in Figure 3.12.

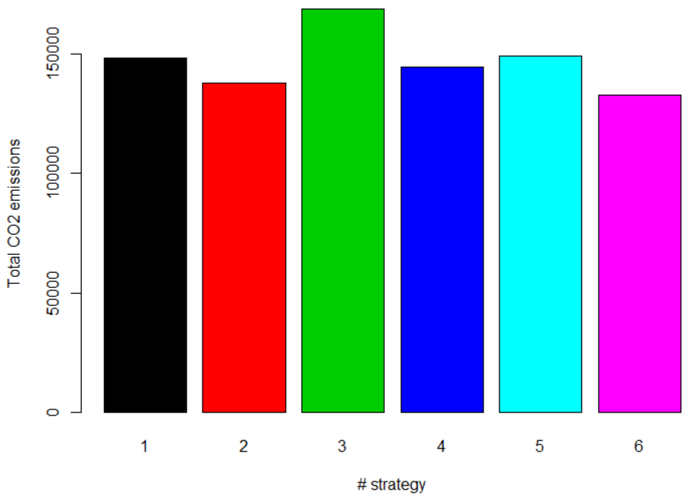

Figure 3.12: Total CO_2 emissions produced for the six driving strategies.

Concluding, one can say that…

- … the slowest deceleration without standing and acceleration is economically **the best strategy** (that produces the least CO_2 emissions) – "pink" strategy.
- …the second best ("red") strategy corresponds to the second slowest deceleration without standing.
- Then something unforeseen happens: Although the "black" and "green" strategies have the third slowest deceleration without standing, the third best strategy is the "blue" one which decelerates stronger and spends a certain time standing. Remember that the blue one violates red but this is not of importance for these considerations.
- Fourth best is the "black" strategy, followed by the "cyan" one which has the strongest deceleration and the longest standing time.
- Finally, the green strategy leads to **most CO_2 emissions**.

So, coming back to the two main differences in accelerations

(1) If $a^* < a_R$ (a^* stronger a_R)

(2) If $a^* > a_R$ (a_R stronger a^*)

One can state that first, it is best to avoid standing (2). Then, by considering strategies with stronger and stronger decelerations, at one point, it is better to decelerate strongly and stand for a certain time (1). Then finally deceleration at intermediate strength without standing (2) is preferable.

Evaluation

The developed model behaves as shown in Figure 3.13. It may be noted that it is similar to the ones described in [Wegener et al., 2008] and [Katsaros et al., 2011].

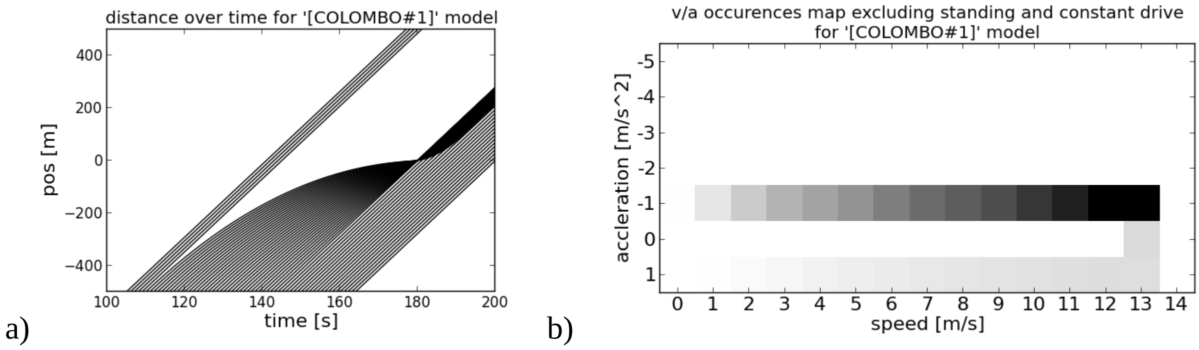

Figure 3.13: Behaviour while approaching a traffic light as described in this section; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

3.2.5 Emission-optimal deceleration – the COLOMBO#2 model

The COLOMBO#2 model builds upon the COLOMBO#1 model in the following way. Consider the case

(2) If $a^* > a_R$ (a_R stronger a^*)

Remember that a^* is the deceleration that is necessary to arrive with the maximum possible velocity v_R at the traffic light exactly when it switches to green at t_R so that $a^* = (v_i - v_R)/t_R$. Consider that there is a certain $a_0(v)$ below which the engine is shut-down (coasting). For the velocities considered here this deceleration is around $a_0 = -0.42\, m/s^2$. Below 10 km/h coasting is disabled.

COLOMBO#2 has the following changes:

- If the deceleration a^* is stronger than a_0 ($a^* < a_0$) then take a^* as before.
- If, however, a^* is weaker than a_0 ($a^* > a_0$) then decelerating at a^* would lead at time t_R to the velocity $v^* = v_i + a^* t_R$. Instead of doing so, it is suggested to coast with a_0 for a certain time until the vehicle obtains the velocity v^*. Then it continues at constant velocity.

The resulting behaviour is shown in Figure 3.14.

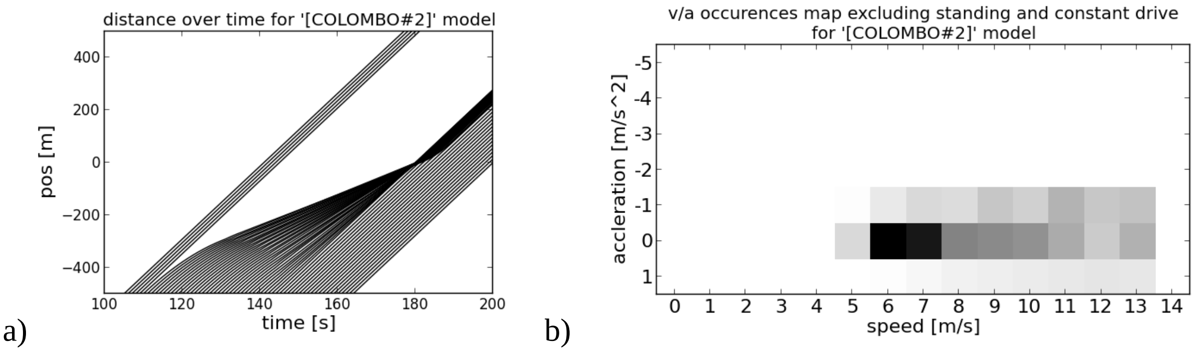

Figure 3.14: Behaviour while approaching a traffic light as described in this section; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs.

3.2.6 Comparisons

The prior sections describe a simplified "real-world" behaviour model, three models from the literature as well as two models generated in COLOMBO. In the following, the implemented models are compared, focussing on their emission behaviour. For a deeper inspection, a decomposition of the trajectories into modes of driving is performed, first. The driving modes "HALTING", "BREAKING", "COASTING", "CONSTANT", and "ACCELERATING" are distinguished as following:

$$mode = \begin{cases} a < 0: \begin{cases} a < -.2 \text{ and } a > -.43: COASTING \\ otherwise: BRAKING \end{cases} \\ a = 0: \begin{cases} v = 0: HALTING \\ otherwise: CONSTANT \end{cases} \\ a > 0: ACCELERATION \end{cases}$$

The same simulation settings as before are used (see Section 3.2.1). Even though the figures (e.g. Figure 3.5) that show these runs look "dynamic", most of the driving is done with $v = v_{max}$; for avoiding this bias, only data for vehicle positions between -500 m (500 m in front of the traffic light) and 100 m (100 m after the traffic light) are used in the following. For this subset of time lines, Figure 3.15 shows the distributions of driving modes for each of the behaviour models.

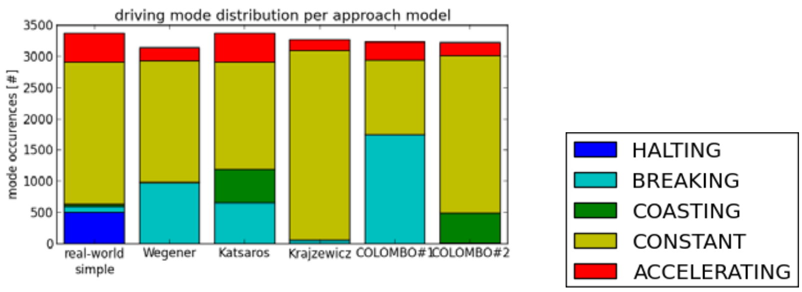

Figure 3.15: Occurrences of driving modes by approach model.

The resulting emissions produced by the simulated vehicles in the boundaries given above are shown in Figure 3.16. Here, the "PKW_D_EU4" emission class was used that resembles a Euro norm 4 Diesel passenger vehicle. The colours have the same meaning as in Figure 3.15. The emissions have been computed by driving the obtained speed time lines virtually within PHEMlight[15]. Please note that the realisation of fuel-cut off at motoring was done by setting respective pollutants to zero when the vehicle was in this driving mode.

[15] Using the "emissionsDrivingCycle.exe" tool described in [COLOMBO D4.2, 2014].

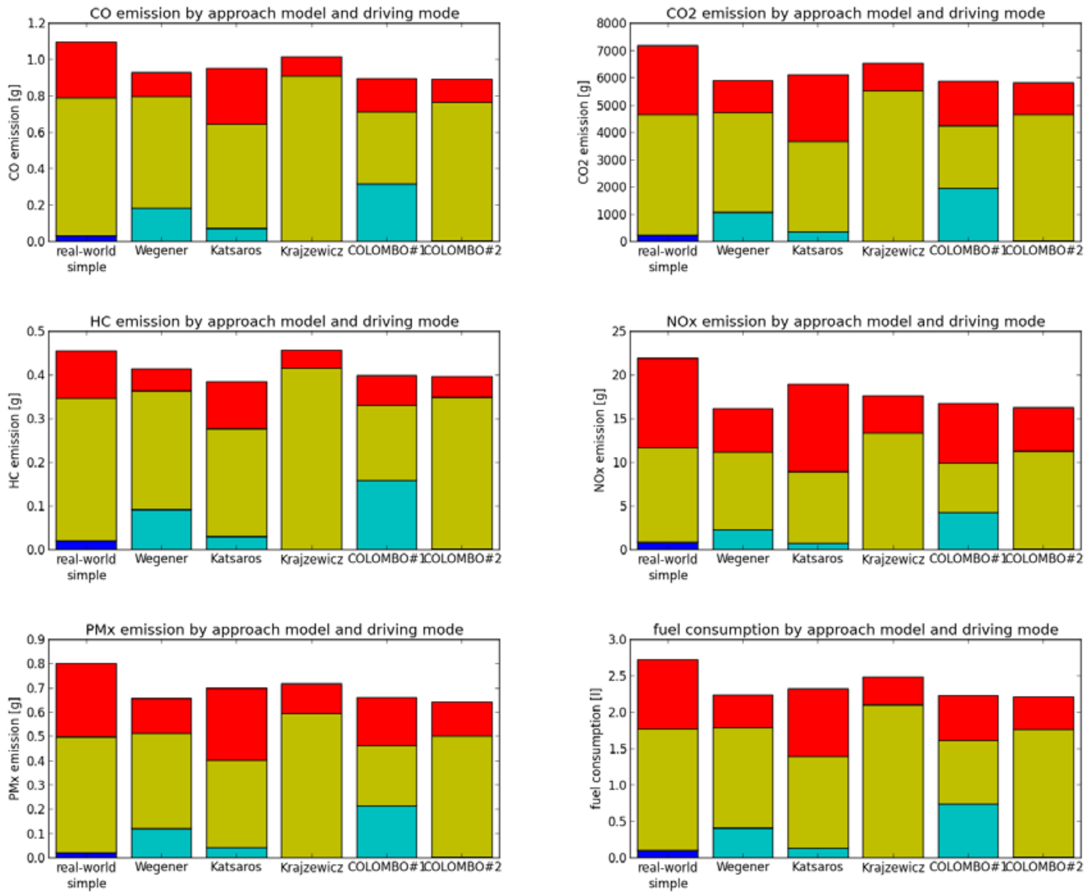

Figure 3.16: Emission and consumption by model (divided by driving mode).

Of course, the resulting emission behaviour differs across different emission classes. Figure 3.17 shows the emissions produced / the consumed fuel for modern passenger vehicles. From left to right, the bars represent the emission types “PKW_G_EU4”, “PKW_G_EU5”, “PKW_G_EU6”, “PKW_D_EU4”, “PKW_D_EU5”, and “PKW_D_EU6” (Gasoline and Diesel passenger cars with Euro norms 4 to 6).

3.2.7 Summary

Different in-vehicle ITS systems aim to reduce emissions by advising the driver the speed to choose. Crossing intersections controlled by a traffic light is one of the most common reasons for changing the speed. The section presented two methods to compute the most emission-friendly speed time line to cross such an intersection.

As vehicles have different emission characteristics, the performance depends of course on the emission class. Therefore, no try to determine a strategy that optimally minimizes the emissions along the completely modelled vehicle fleet was attempted as every vehicle emission class should be optimized for itself, based on its emission characteristics.

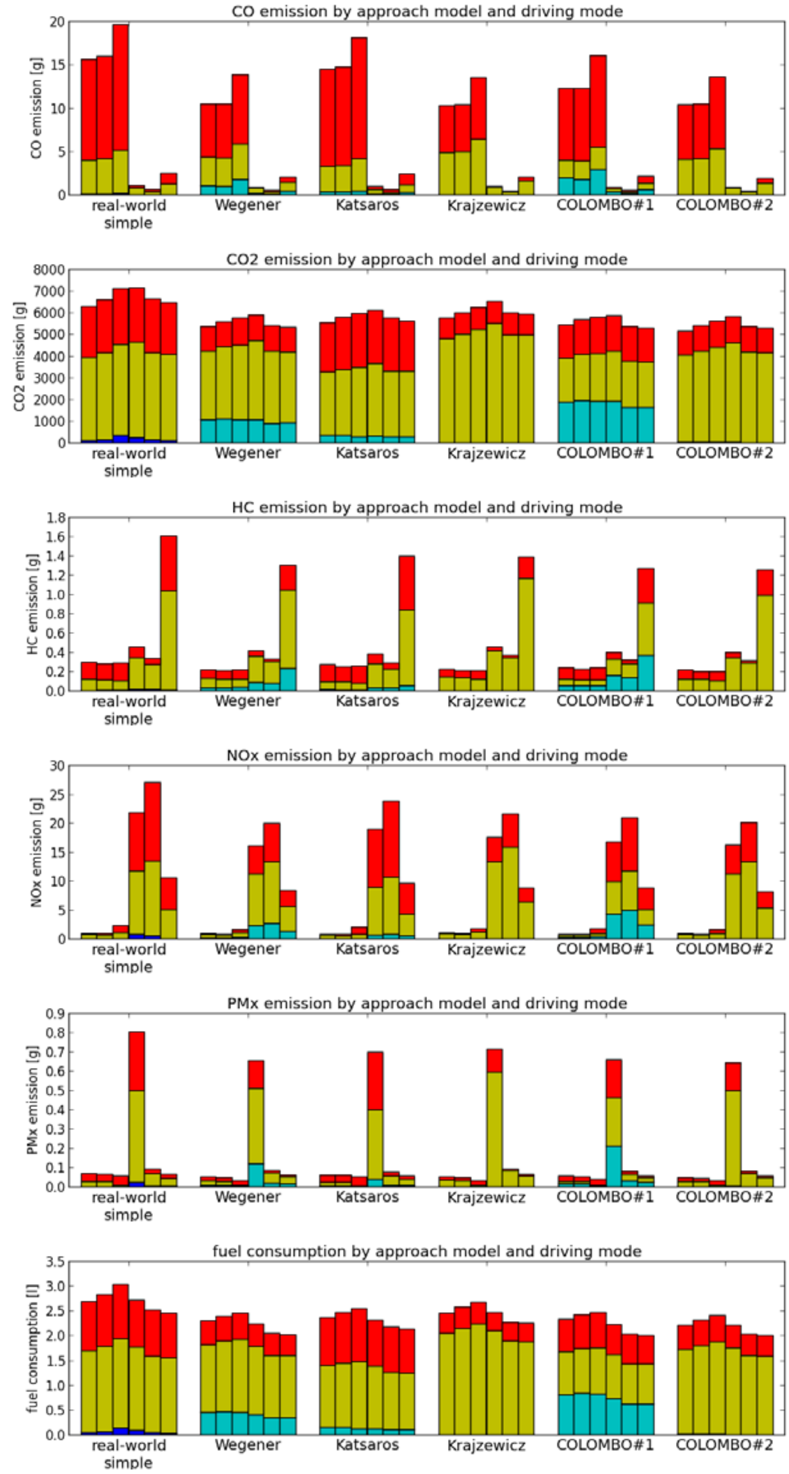

Figure 3.17: Emission and consumption of vehicle classes named in the text by model (divided by driving mode). From left to right, the bars represent the emission types "PKW_G_EU4", "PKW_G_EU5", "PKW_G_EU6", "PKW_D_EU4", "PKW_D_EU5", and "PKW_D_EU6".

4 Optimising Traffic Lights Control

The purpose of this task was to elaborate guidelines that can be used by traffic planners to make an emission optimal traffic light pre-emption control. Main influences to be considered in the method are:

- Distance between the traffic lights
- Number of vehicles on the main road for which the traffic lights shall be coordinated
- Number of vehicles entering from side roads

Control parameters analyzed are

- Offset time between consecutive traffic lights
- Green light duration per traffic light.

Targets are

- Minimum in weighted exhaust gas emission and fuel consumption (expressed by an emission index)
- No deterioration in traffic parameters (travel time, number of stops, etc.)

For a first assessment of the best values for the control parameters a set of equations was established calculating average vehicle fleet velocities. From distances and velocities the relevant time shifts can be computed. For the calculation of time offsets between traffic lights a green wave was the target, i.e. getting as many vehicles as possible without stops through the road sections. Starting from this first setting for the traffic light controller simulations were started varying the control parameters to find the values giving lowest emissions.

For an efficient simulation of the traffic flow and of emissions the model NITRA (Niks Traffic Model) was developed at the Institute for Internal Combustion Engines and Thermodynamics at the University of Technology Graz. NITRA needs only a few data for a simulation. These are a street network with the traffic light pre-emption and the offsets between the intersections. The vehicles move according to a vehicle following model. This driver model can be parameterized by the user. NITRA also includes the model PHEMlight (see chapter 2). The output of the model for each vehicle is the vehicle speed and its emissions in 1Hz. From the instantaneous results the total emissions, the driving time, the average velocity, acceleration, deceleration, the stops and still stand times are calculated.

4.1 Existing Traffic Engineering Planning Software[16]

In order to create signal timing plans of signalized intersections and coordinated arterials, several computer programs have been developed to facilitate the design and analysis of traffic signals. Two of the most commonly used software products in Germany are LISA+ of Schlothauer & Wauer GmbH & Co. KG[17] and Sitraffic Office of Siemens AG[18].

Both products are comprehensive software packages for planning and evaluating intersections, testing traffic-actuated controls and simulating traffic flow. The traffic engineering software allows traffic planners not only to analyze traffic counts and plan and simulate controls, but even to upload data directly to the controller or send it to a central traffic computer.

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[16] An overview on existing traffic engineering software is also given in [COLOMBO D5.3, 2014].
[17] http://www.schlothauer.de/en/softwaresystems/lisa.html
[18] https://www.mobility.siemens.com/mobility/global/SiteCollectionDocuments/en/road-solutions/urban/infrastructure/SITRAFFIC-Office-en.pdf

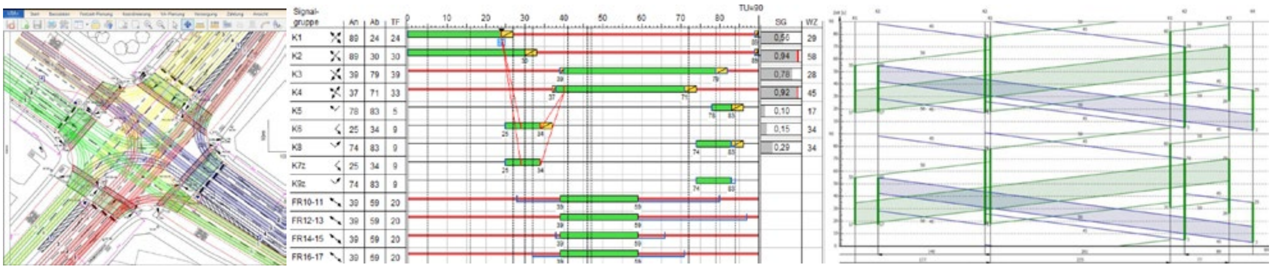

Figure 4.1: Graphic Interface of intersection, signal timing plans and time distance diagrams in LISA+.

The programs create incompatibility matrices and calculate intergreen times by the help of basic data supply and offer extensive features for efficiently creating and editing optimal signal timing plans. Signal timing plans can either be created individually or can be automatically calculated and optimized. Thereafter, detailed simulations and analyses of the proposed signal control allow a comprehensive assessment of traffic flows. The integrated quality analysis features provide information on capacity, queue length or waiting time. Evaluation parameters are calculated in accordance with the [FGSV, 2001] Therefore decisions on the development of road infrastructure can be made reliably. Nevertheless, there is still a lack of environmental assessment of signal timing plans.

4.2 Simulation Tool NITRA

NITRA was developed in the course of the project COLOMBO to allow simple simulation runs of traffic flow and emissions on road sections with traffic light controls. The model was designed to simulate single vehicles as they accelerate, cruise, decelerate and stop to get the data necessary to integrate the PHEMlight model for emission simulation. The traffic model in NITRA is somehow a “light” version of microscopic traffic models, considering the driver behavior but no route selections. Thus the user has to define the number of vehicles entering the simulated road sections and he defines also at each junction the number of vehicles leaving the main road and also the number of vehicles entering the main street from side roads. The driver model follows the IDM model described in [Treiber, Helbing, 2014]. A speed dependent maximum acceleration level was added to provide realistic acceleration levels for the emission simulation. Changes of lanes by vehicles are simplified as “mixers” with user defined probability on which lane the vehicles leave the mixers. Safety margins as time distances to other vehicles are varied as function of the distance to the mixers to get a more realistic picture of lane changes. Traffic lights are simulated via the phase times per signal. To keep the model simple, public transport, pedestrians and bicyclists are not considered in NITRA.

As a consequence of the simplifications the model can be set up very quickly for given road sections and also the calibration proved to be possible with low effort if measured data for the traffic flow on the road are available (chapter 4.3).

The input data for NITRA for each single intersection are listed below and have to be provided in an xml-file:

- coordinates of the in- and outgoing roads with the number of lanes per road
- number of vehicles entering the roads at the system boundaries
- for each lane the probability to be used by the vehicles driving on the road section in the direction of the lane, the speed limit, the probability for vehicles to turn and their traffic light pre-emption (duration of green, orange, red and the offset).

Below an input data set for a junction is shown.

```
<Intersection ID ="0"> //Kalvarienbergstraße (306)(ID 0-6)

  <InRoads>
    <InRoad ID ="0"  X="100" Y="-15" >
      <Lanes>
        <Lane ID="0" Share="0.1883" Speed ="55" />
        <Lane ID="1" Share="0.2921" Speed ="55" />
        <Lane ID="2" Share="0.2921" Speed ="55" />
        <Lane ID="3" Share="0.2275" Speed ="55" />
      </Lanes>
  </InRoads>

  <OutRoads>
    <OutRoad ID ="0"  X="155" Y="-15" >
      <Lanes>
        <Lane ID="17" Speed ="55"/>
        <Lane ID="16" Speed ="55"/>
      </Lanes>
    </OutRoad>
  </OutRoads>

  <Links>
    <Link ID="0" InLaneID="0" OutLaneID="24" Share="0.5" Direction="right" Speed="30"/>
    <Link ID="1" InLaneID="0" OutLaneID="23" Share="0.5" Direction="right" Speed="30"/>
    <Link ID="2" InLaneID="1" OutLaneID="17" Share="1" Direction="straight" Speed="55"/>
    <Link ID="3" InLaneID="2" OutLaneID="16" Share="1" Direction="straight" Speed="55"/>
    <Link ID="4" InLaneID="3" OutLaneID="9" Share="0.5" Direction="left" Speed="30"/>
    <Link ID="5" InLaneID="3" OutLaneID="10" Share="0.5" Direction="left" Speed="30"/>
  </Links>

  <IntersectionTrafficLights GlobalOffset ="36">
    <TrafficLights>
      <Signal ID="5" DurationGreen="9" DurationOrange ="7" DurationRed="64" Offset="0">
        <LinkIDs>
          <Link>0</Link>
          <Link>1</Link>
          <Link>2</Link>
          <Link>3</Link>
        </LinkIDs>
      </Signal>
      <Signal ID="6" DurationGreen="6" DurationOrange ="7" DurationRed="67" Offset="0">
        <LinkIDs>
          <Link>4</Link>
          <Link>5</Link>
        </LinkIDs>
      </Signal>

    </TrafficLights>
  </IntersectionTrafficLights>
```

In- and out-road definition

Turn conditions

Traffic light pre-emption

Figure 4.2: Example for a NITRA xml street network file for one intersection.

4.3 Calibration of the Model NITRA

The calibration of the model was done in cooperation with the Institute for Highway Engineering and Transport Planning (ISV) for the street “Wiener Straße” in the city of Graz. The modelled part of the street consists of six intersections with different offsets (see Figure 4.3 and Figure 4.4).

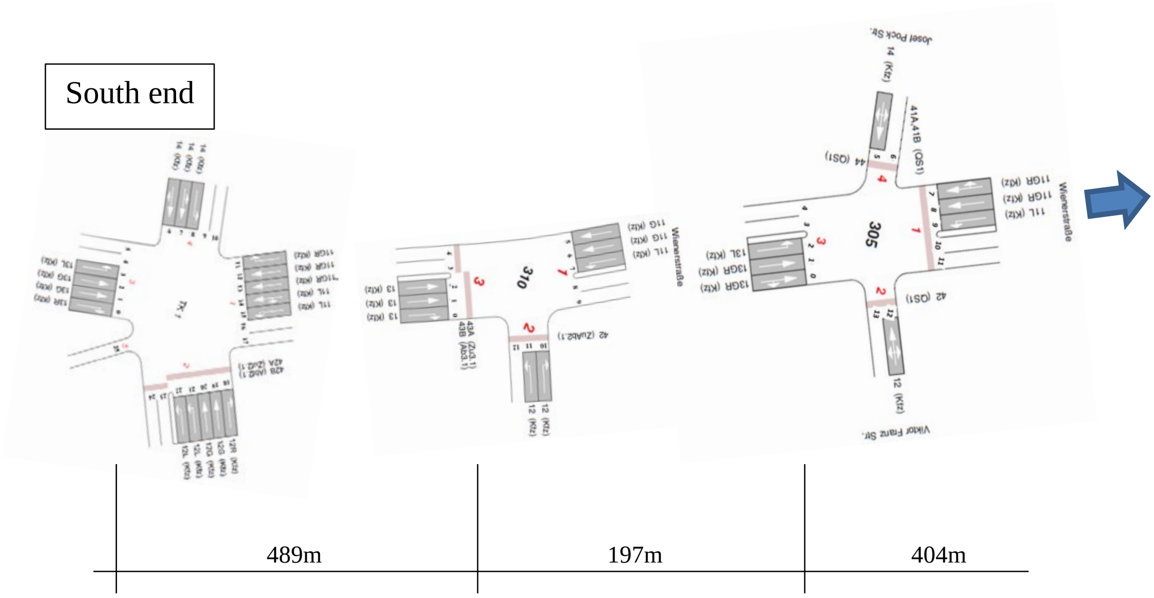

Figure 4.3: NITRA model of the "Wiener Straße" first section.

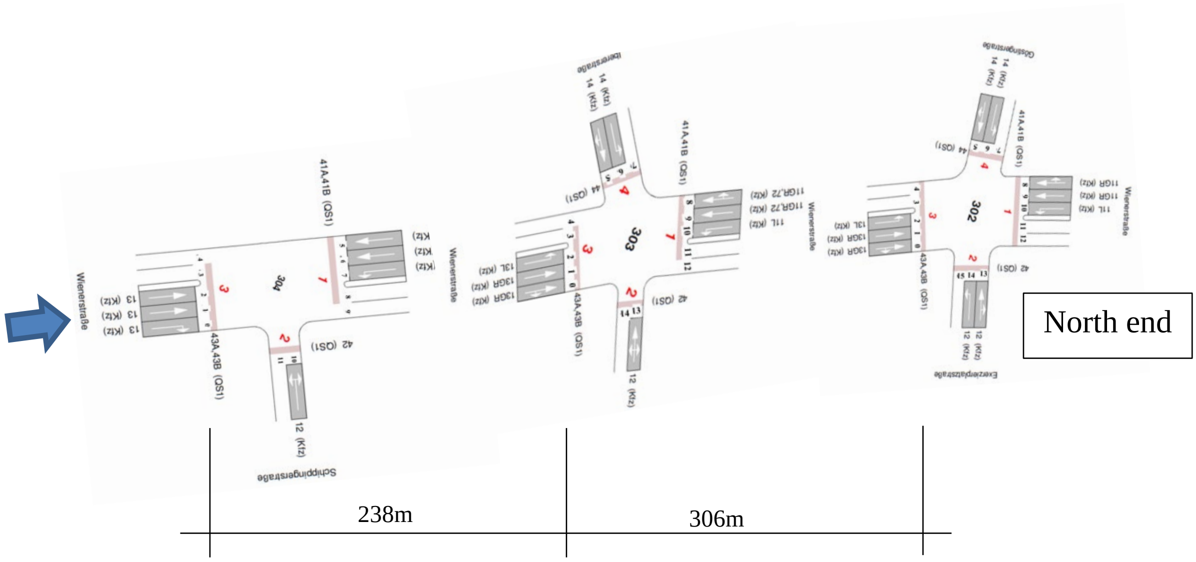

Figure 4.4: NITRA model of the "Wiener Straße" second section.

For the calibration, ten measurements at the morning and evening peak were done using the floating car method[19]. Measured during the tests are the time, the coordinates and the velocity. The emissions were afterwards calculated with the model PHEMlight.

For morning and evening peak the phase durations and the offset times between the traffic lights are known. With this data the street network was compiled for the simulation with NITRA. The results of the simulation are listed in Table 4.3 and Table 4.4.

The model shows a quite good overall accuracy with deviations of 1.8% for average velocity and 2.3% for fuel consumption on the S→N direction and of 7.4% and 1.3% for average velocity and fuel consumption on the N→S direction. Since only the S→N route was used in the further assessments, no extra effort was made for better calibration of the N→S direction.

[19] A vehicle instrumented with highly accurate GPS follows the total traffic flow. The velocity over time is recorded and from the total number of measurements each section average representative traffic data can be evaluated.

Table 4.3: Results morning peak N→S.

Measurement	Driving Time [s]	Still Stand Time [s]	Average Velocity [m/s]	Stops	RPA	FC [g]	CO_2 [g]	NO_x [g]	HC [g]	PM [g]	CO [g]
1	120	5	13.30	1	0.0865	63.8194	201.0310	0.5170	0.0139	0.0221	0.0347
2	128	1	12.34	0	0.1536	76.2333	240.1348	0.6479	0.0157	0.0268	0.0416
3	121	0	12.91	0	0.1972	76.2555	240.2049	0.6917	0.0146	0.0271	0.0409
4	119	0	13.22	0	0.1384	71.5618	225.4196	0.6010	0.0150	0.0252	0.0392
5	133	0	11.58	0	0.2813	88.1043	277.5285	0.8609	0.0158	0.0313	0.0448
6	134	0	11.64	0	0.2321	83.0405	261.5775	0.7750	0.0156	0.0294	0.0420
7	155	0	10.74	0	0.1852	89.6668	282.4504	0.7879	0.0182	0.0315	0.0463
8	141	0	11.64	0	0.2081	90.9313	286.4336	0.7957	0.0182	0.0322	0.0492
9	173	10	9.42	2	0.1950	91.6070	288.5620	0.8030	0.0187	0.0321	0.0481
10	128	0	12.31	0	0.2170	79.5644	250.6280	0.7452	0.0148	0.0282	0.0411
	Driving Time [s]	**Still Stand Time [s]**	**Average Velocity [m/s]**	**stops**	**RPA**	**FC [g]**	**CO_2 [g]**	**NO_x [g]**	**HC [g]**	**PM [g]**	**CO [g]**
Average Meas.	135.20	1.600	11.909	0.300	0.189	81.0784	255.3970	0.7225	0.0160	0.0286	0.0428
NITRA	124.61	1.385	12.788	0.149	0.158	82.1234	258.6888	0.7213	0.0165	0.0287	0.0433
Difference	**-7.8%**	**-13.4%**	**7.4%**	**-50.2%**	**-16.8%**	**1.3%**	**1.3%**	**-0.2%**	**2.6%**	**0.3%**	**1.3%**

Table 4.4: Results morning peak S→N.

Measurement	Driving Time [s]	Still Stand Time [s]	Average Velocity [m/s]	Stops	RPA	FC [g]	CO_2 [g]	NO_x [g]	HC [g]	PM [g]	CO [g]
1	112	0	14.20	0	0.1472	73.2739	230.8128	0.6304	0.0149	0.0257	0.0398
2	109	0	14.75	0	0.1597	73.8935	232.7644	0.6598	0.0147	0.0259	0.0378
3	111	0	14.24	0	0.1545	75.0576	236.4315	0.6401	0.0154	0.0264	0.0405
4	117	0	13.64	0	0.1492	75.6616	238.3339	0.6405	0.0157	0.0265	0.0405
5	113	0	13.99	0	0.1206	72.5536	228.5439	0.6087	0.0153	0.0253	0.0387
6	115	0	13.83	0	0.1444	75.6334	238.2453	0.6520	0.0155	0.0265	0.0402
7	113	0	13.99	0	0.1322	73.5130	231.5659	0.6196	0.0154	0.0257	0.0391
8	117	0	13.41	0	0.0929	70.7134	222.7473	0.5749	0.0155	0.0243	0.0368
9	111	0	14.20	0	0.1278	73.5752	231.7619	0.6325	0.0152	0.0256	0.0382
10	123	0	12.87	0	0.1706	78.0447	245.8408	0.6691	0.0160	0.0277	0.0428
	Driving Time [s]	**Still Stand Time [s]**	**Average Velocity [m/s]**	**Stops**	**RPA**	**FC [g]**	**CO_2 [g]**	**NO_x [g]**	**HC [g]**	**PM [g]**	**CO [g]**
Average Meas.	114.10	0.000	13.91	0.000	0.140	74.1920	233.7048	0.6328	0.0154	0.0259	0.0394
NITRA	111.38	0.368	14.16	0.014	0.123	75.9107	239.1186	0.6436	0.0158	0.0264	0.0406
Difference	**-2.4%**	-	**1.8%**	-	**-12.1%**	**2.3%**	**2.3%**	**1.7%**	**2.6%**	**1.6%**	**2.9%**

4.4 Basic Analysis of Traffic Light Coordination Functions

For the study of the best offset between intersections under consideration of the influence of the side traffic value the given street network “Wiener Straße” was used. The assessment had been done between the last two intersections from S→N while the four intersections in front of this assessment area are used for the traffic flow conditioning.

As described before, basic equations to calculate offset times between consecutive traffic lights and the green light duration have been developed to provide robust start values for later optimization runs.

The calculation of an optimal offset has to distinguish between:

1. The vehicles drive with a constant speed (target speed) over the whole distance from the first to the second intersection
2. All or some vehicles have to accelerate first from zero or low speed to their target velocity and then follow the case 1

The first case is presumed here for the vehicles on the main road, if the intersection lies inside of the network which shall be connected by the green wave algorithms. Vehicles entering from side traffic and vehicles which had to stop before passing a traffic light fall into case 2.

For vehicle groups at target speed equation [1] can be used for the calculation of the offset.

$$t_{offset,const} = \frac{l_{intersection}}{v_t}$$ valid if no vehicles enter from side roads **[1]**

The second case also occurs if the intersection is the start point of the green wave control. For this calculation the acceleration progress from the individual vehicle is needed. The problem in this case is the difficulty to calculate the acceleration process from a fleet, where the acceleration of all accumulated vehicles is limited by the first vehicle in the group. Also each vehicle accelerates in a different way depending amongst others on the driver and the engine power to weight ratio. This is simplified here by using the same acceleration for all vehicles.

For NITRA the acceleration rate dependency on the velocity was elaborated in cooperation with the ISV out of real measured accelerations. With this acceleration curve NITRA produces for an average vehicle the velocity, distance and time plot shown in Figure 4.5. The plot shows the time and the distance necessary to reach a target speed on the x-axis when accelerating from stand still.

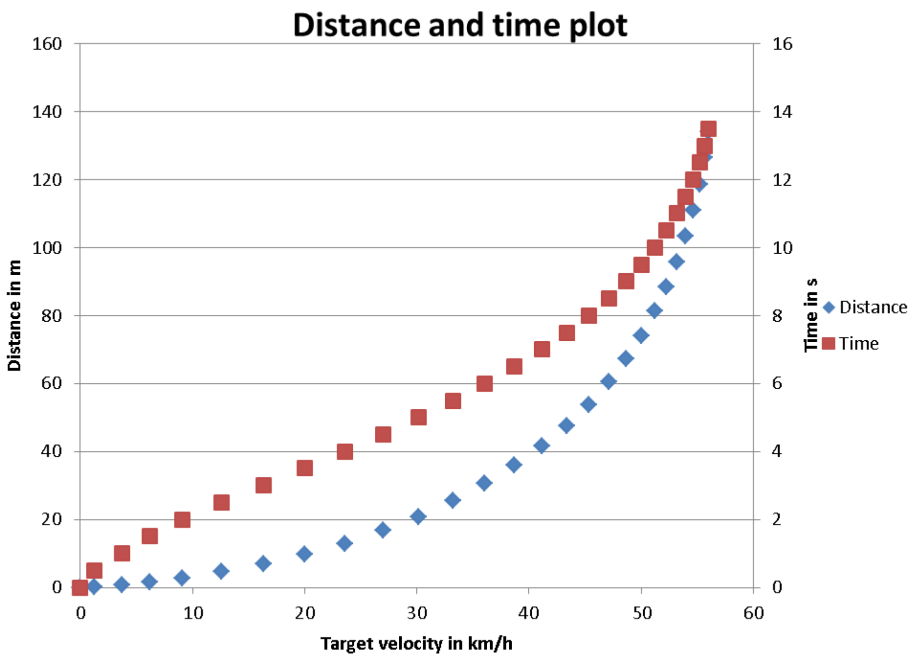

Figure 4.5: Distance and time plot from NITRA.

The acceleration behavior shown in Figure 4.5 was approximated by polynomial equations as shown below.

Distance over target velocity:

$$l_{vt} = 1.0796 \cdot 10^{-7} \cdot {v_t}^6 - 1.5728 \cdot 10^{-5} \cdot {v_t}^5 + 8.6369 \cdot 10^{-4} \cdot {v_t}^4 - 2.1519 \cdot 10^{-2} \cdot {v_t}^3 + 2.5100 \cdot 10^{-1} \cdot {v_t}^2 - 6.8842 \cdot 10^{-1} \cdot v_t \quad \textbf{[2]}$$

Time over target velocity:

$$t_{vt} = 5.1499 \cdot 10^{-9} \cdot {v_t}^6 - 6.6863 \cdot 10^{-7} \cdot {v_t}^5 + 2.9413 \cdot 10^{-5} \cdot {v_t}^4 - 3.7411 \cdot 10^{-4} \cdot {v_t}^3 - 5.3678 \cdot 10^{-3} \cdot {v_t}^2 + 2.8539 \cdot 10^{-1} \cdot v_t \quad \textbf{[3]}$$

where:

l_{vt}	[m]	Covered distance to accelerate to target velocity
v_t	[m/s]	Target velocity
t_{vp}	[s]	Time to accelerate to target velocity

These equations are used for the calculation of the basic offset value later on in this study.

The calculation of the complete time offset between two intersections where acceleration from zero speed is required is done in two steps:

1. Calculate the time till a vehicle reaches its target velocity
2. Calculate the time the vehicle needs to drive the rest of the length between the intersections with constant (target) speed.

$$t_{offset,acc} = t_{vt} + \frac{l_{intersection} - l_{vt}}{v_t} \quad \textbf{[4]}$$

where:

$t_{offset,acc}$	[s]	Offset between the intersections (vehicles accelerate from standstill)
$l_{Intersection}$	[m]	Length between the intersections

In both calculation cases (equation [1] and [4]) a safety time (t_{safety}) should be used to consider that driver's only hold the velocity if they see that the traffic light turns green before they are too close to the traffic light. The analyses show that the best results were calculated if a safety length from 30 meters was used. The calculation of the safety time follows then equation [5]:

$$t_{safety} = \frac{30}{v_t} \quad \textbf{[5]}$$

With the consideration of the side traffic both formulas need to be extended. The influence of the side traffic is that these vehicles stand in front of the traffic light. Not to disturb the vehicles arriving from the green wave from the upstream junction, the vehicles standing in front of the traffic light have to accelerate to target speed when the last of these vehicles is caught up by the arriving green wave group. This leads to an update for the offset time and for the green duration of the traffic light. The traffic light must turn green earlier so that all accumulated vehicles are away or on the same velocity when the approaching vehicles reach their position. The green duration update is needed because the vehicles driving on the green wave route needs the same time like before to pass the intersection length. The offset shortening time and the green duration prolongation time are hence the same.

For the calculation of this time the time curve for vehicles accelerating in NITRA to the target speed are plotted over the distance. This leads to the equation [6], which calculates the time the vehicle queue from the side traffic needs to cover the accumulated distance by accelerating:

$$t_{side} = -9.8087 \cdot 10^{-11} \cdot l_{side}{}^{6} + 4.2752 \cdot 10^{-8} \cdot l_{side}{}^{5} - 7.2059 \cdot 10^{-6} \cdot l_{side}{}^{4} + 5.9098 \cdot 10^{-4} \cdot l_{side}{}^{3} - 2.4497 \cdot 10^{-2} \cdot l_{side}{}^{2} + 5.6276 \cdot 10^{-1} \cdot l_{side} \qquad [6]$$

where:

t_{side}	[s]	influence of side traffic on offset time
l_{side}	[m]	accumulated length of vehicle queue from side traffic

With this formula the emission optimal green wave offset by consideration of side traffic can be calculated with equation [7] in case vehicles arrive at constant speed or with equation [8] incase vehicles have to accelerate from standstill.

$$t_{offset,const} = \frac{l_{intersection}}{v_t} - t_{safety} - t_{side} \qquad [7]$$

$$t_{offset,acc} = t_{vt} + \frac{l_{intersection} - l_{vt}}{v_t} - t_{safety} - t_{side} \qquad [8]$$

In both cases the green duration has to be increased by t_{side}.

For the calculation of t_{side} the length of the accumulated vehicles before the traffic light l_{side} at the specific traffic volume is needed. The length of the queue is dependent on the amount of vehicles entering from the side. If not known, the calculation can be done by the green duration time of the side traffic light, the length of the vehicles, an average time gap between two vehicles passing a traffic light and the amount of lanes. The accumulated length can be calculated by equation [9].

$$l_{side} = \frac{l_{veh} \cdot \left(\frac{t_{sideTraff}}{t_{vehPass}} \cdot n_{lanes,SR}\right) \cdot FR}{n_{lanes,MR}} \qquad [9]$$

where:

l_{veh}	m	Length of a standard vehicle (4.5m)
FR	-	ratio of vehicles entering from a side road to the maximal possible number of vehicles which could pass the green light on the side road
$n_{lanes,SR}$	#	number of lanes before the traffic light (Side Road)
$n_{lanes,MR}$	#	number of lanes before the traffic light (Main Road)

The standard length for a LDV with safety gap to the front vehicle is set here to 4.5m while the gap between two vehicles passing the traffic light was set to 2 seconds.

The test of the equations elaborated was done at the last two intersections in the "Wiener Straße" (see Figure 4.4) marked with the ID "303" and "302". The values given for this intersection are shown in Table 4.5.

Table 4.5: Control area data

Name	Unit	Value
v_t	km/h	55
$l_{intersection}$	m	306
l_{veh}	m	4.5
$t_{sideTraff,303}$	s	12
$t_{vehPass}$[20]	s	2
$n_{lanes,SR,303}$	#	2
$n_{lanes,MR}$	#	2
FR	%	100

With these values the following offsets for constant driving are calculated by using the equations [5]-[7] and [9]:

$t_{safety} = 1.96s$

$l_{side} = 27m$

$t_{side} = \underline{\underline{5.7s = t_{green,prolong}}}$

$\underline{\underline{t_{offset,const} = 12.4s}}$

For acceleration driving the offset can be calculated with the equations [5]-[6] and [8]-[9]:

$t_{safety} = 1.96s$

$l_{side} = 27m$

$t_{side} = \underline{\underline{5.7s = t_{green,prolong}}}$

$l_{vt} = 117.24m$

$t_{vt} = 12.41s$

$\underline{\underline{t_{offset,const} = 17.1s}}$

These offsets were used to parameterize the street network "Wiener Straße" in NITRA as standard scenario and simulate 30 minutes of traffic. The traffic volume has been set according to the morning peak. For each vehicle driving on the green wave route in this network dynamic parameters (driving time, average velocity …) and emissions (FC, NO_x, CO_2 etc.) are calculated and averaged. To look if this parameterization leads already to minimum emission levels and efficient driving conditions a sensitivity analysis was done afterwards. In this analysis the offset (from 0s to ±4s) and the green duration time of the traffic light (±1s to ±3s) have been varied (see Table 4.7). For the assessment of the emission reduction potential a weighted emission index was calculated for every test. The weights used are shown in Table 4.6. Depending on local conditions, the best weighting may be different. E.g. severe NO_2 air quality problems would give NO_x a higher

[20] Gap between two vehicles passing the traffic light [s]

weight. To test the effect of the weighting two scenarios were run. Scenario (a) weights for CO_2 and fuel consumption optimization while scenario (b) weights for pollutant emissions and CO_2 with more weighting for the sum of pollutants (3:1). The weighting is used to calculate a weighted change of emissions against the base case traffic light control settings. Thus the different absolute emission quantities from each exhaust gas component are not relevant.

Table 4.6: Emission index weights.

Emission	Weight (a)	Weight (b)
CO_2	1	1
NO_x	0	1
HC	0	0.5
PM	0	1
CO	0	0.5

The assessment of the dynamic driving parameters "Driving Index" was done by averaging all traffic parameters calculated. An option which shall be implemented in a next version of the evaluation algorithm is the "Time Loss" which describes the difference of travel time against the ideal trip without stops due to red lights. The results of the simulations are shown below. The "baseline" simulation was performed in NITRA with the offset times and green light durations calculated with the basic equations shown before. Lines marked green are variants, which achieved better results both fort emissions and for the traffic parameters.

In the simulation first the acceleration of the vehicles was done outside of the control area and the vehicles moved around target speed on the main road when entering the relevant junctions.

Table 4.7: Overall results for driving dynamics and emissions for vehicles entering at constant speed.

	Driving Time	Still Stand Time	Average Velocity	Average Velocity 0-30km/h	Average Velocity >30km/h	Acc	Stops	RPA	Emission index (a)	Emission index (b)	Driving index
Description	[s]	[s]	[m/s]	[m/s]	[m/s]	[m/s²]	[#]	[m/s²]	[-]	[-]	[-]
CD "baseline"	36.80	0.00	14.94	0.51	15.04	0.0365	0.00	0.0940	base	base	base
CD, offset -0.5s	40.56	1.80	14.26	0.19	14.95	0.0185	0.09	0.1035	3.42%	18.59%	9.56%
CD, offset -1s	38.89	0.98	14.50	0.56	14.87	0.0271	0.05	0.1032	2.45%	11.80%	5.13%
CD, offset -1.5s	37.62	0.00	14.64	0.74	14.81	0.0243	0.00	0.1089	3.08%	14.71%	0.99%
CD, offset -2s	38.94	0.94	14.54	0.22	14.95	0.0051	0.06	0.0936	0.24%	2.05%	5.21%
CD, offset -2.5s	37.25	0.50	14.98	0.03	15.18	0.0080	0.03	0.0803	-3.75%	-18.79%	1.88%
CD, offset -3s	39.97	1.50	14.36	0.08	14.96	0.0058	0.09	0.0969	1.54%	7.54%	7.99%
CD, offset -3.4s	40.94	1.53	14.02	0.67	14.80	0.0265	0.10	0.1206	8.12%	42.06%	9.37%
CD, offset -4s	39.19	1.10	14.49	0.32	15.03	0.0143	0.06	0.1025	3.25%	17.06%	5.96%
CD, offset +0.5s	38.37	0.39	14.58	0.44	14.84	0.0264	0.02	0.1135	3.90%	21.71%	3.14%
CD, offset +1s	37.98	0.35	14.64	0.64	14.86	0.0376	0.02	0.1210	6.54%	33.14%	2.45%
CD, offset +1.5s	36.36	0.00	15.11	0.13	15.16	0.0156	0.00	0.0855	-3.21%	-15.49%	-0.58%
CD, offset +2s	36.47	0.00	15.02	0.57	15.06	-0.0068	0.00	0.0849	-3.37%	-16.14%	-0.59%
CD, offset +2.5s	36.90	0.00	14.91	0.40	15.02	0.0101	0.00	0.0952	-0.29%	-2.23%	0.07%
CD, offset +3s	37.26	0.00	14.75	0.50	14.85	0.0152	0.00	0.1066	2.57%	13.34%	0.49%
CD, offset +3.4s	37.27	0.00	14.75	0.17	14.76	0.0107	0.00	0.1034	0.39%	2.27%	0.51%
CD, offset +4s	36.44	0.00	15.07	0.16	15.09	-0.0074	0.00	0.0740	-6.51%	-32.54%	-0.58%
CD, GD +1s	36.95	0.00	14.88	0.52	14.96	0.0242	0.00	0.0983	0.97%	5.12%	0.16%

Description	Driving Time [s]	Still Stand Time [s]	Average Velocity [m/s]	Average Velocity 0-30km/h [m/s]	Average Velocity >30km/h [m/s]	Acc [m/s^2]	Stops [#]	RPA [m/s^2]	Emission index (a) [-]	Emission index (b) [-]	Driving index [-]
CD, GD +2s	37.23	0.00	14.78	0.54	14.85	0.0218	0.00	0.1023	2.04%	11.17%	0.51%
CD, GD +3s	37.22	0.00	14.79	0.51	14.86	0.0194	0.00	0.1001	1.32%	7.42%	0.49%
CD, GD -1s	36.49	0.00	15.05	0.13	15.08	0.0132	0.00	0.0910	-2.00%	-10.02%	-0.44%
CD, GD -2s	35.94	0.00	15.26	0.00	15.26	-0.0008	0.00	0.0741	-6.84%	-34.10%	-1.17%
CD, GD -3s	47.22	4.68	13.18	0.53	14.43	0.0231	0.20	0.1454	16.83%	84.01%	26.16%

The sensitivity analysis shows for the constant speed start in comparison to the baseline scenario low reduction potentials in the driving dynamics (1%) while the CO_2 reduction by 7% and the pollutant reduction by more than 30% are quite high. The best results can be found by the scenario with a lower green duration time from two seconds. The five scenarios that produce better emission and driving results were then also tested under different conditions like vehicles starting from stand still and higher side traffic (see Table 4.8 to Table 4.10).

Table 4.8: Results for driving dynamics and emissions for entering at constant speed with higher green duration time from the side traffic.

Description	Driving Time [s]	Still Stand Time [s]	Ave. v [m/s]	Ave. v 0-30km/h [m/s]	Ave. v >30km/h [m/s]	Acc [m/s^2]	Stops [#]	RPA [m/s^2]	Emission index (a) [-]	Emission index (b) [-]	Driving index [-]
CD, GDT +10s	36.84	0.00	14.91	0.48	14.95	0.0022	0.00	0.0910	base	base	base
CD, GDT +10s, offset +1.5s	36.79	0.00	14.91	0.14	14.94	0.0250	0.00	0.1113	4.82%	25.27%	0.01%
CD, GDT +10s, offset +2s	37.44	0.00	14.68	0.71	14.72	0.0132	0.00	0.1149	4.54%	24.52%	0.78%
CD, GDT +10s, offset +4s	37.19	0.04	14.82	0.28	14.94	0.0387	0.03	0.1052	4.49%	22.65%	0.74%
CD, GDT +10s, GD -1s	42.14	2.23	13.80	0.54	14.77	0.0060	0.15	0.1029	6.29%	30.77%	12.71%
CD, GDT +10s, GD -2s	40.02	1.32	14.21	0.56	14.73	0.0134	0.07	0.1117	6.84%	34.50%	7.52%

Table 4.9: Results for driving dynamics and emissions for vehicles starting from zero speed.

Description	Driving Time [s]	Still Stand Time [s]	Ave. v [m/s]	Ave. v 0-30km/h [m/s]	Ave. v >30km/h [m/s]	Acc [m/s^2]	Stops [#]	RPA [m/s^2]	Emission index (a) [-]	Emission index (b) [-]	Driving index [-]
AD	40.46	0.00	13.65	1.78	13.86	0.0691	0.00	0.2010	base	base	base
AD, offset +1.5s	41.85	0.00	13.23	2.93	13.65	0.1124	0.00	0.2326	6.95%	36.08%	1.93%
AD, offset +2s	41.53	0.00	13.30	2.22	13.75	0.1032	0.00	0.2208	5.21%	25.48%	1.43%
AD, offset +4s	40.34	0.00	13.67	2.07	13.86	0.0776	0.00	0.1976	-1.10%	-3.58%	-0.17%
AD, GD -1s	39.80	0.00	13.86	1.68	14.09	0.1021	0.00	0.1950	-0.30%	-1.33%	-0.78%
AD, GD -2s	40.26	0.00	13.72	0.98	13.90	0.1241	0.00	0.2008	1.19%	5.09%	-0.14%

Table 4.10: Results for driving dynamic and emissions vehicles starting from zero speed with higher green duration time from the side traffic.

Description	Driving Time [s]	Still Stand Time [s]	Ave. v [m/s]	Ave. v 0-30km/h [m/s]	Ave. v >30km/h [m/s]	Acc [m/s²]	Stops [#]	RPA [m/s²]	Emission index (a) [-]	Emission index (b) [-]	Driving index [-]
AD, GDT +10s	40.22	0.00	13.72	1.37	14.04	0.1143	0.00	0.2158	base	base	base
AD, GDT +10s, offset +1.5s	40.15	0.00	13.75	1.67	13.98	0.1127	0.00	0.2166	-0.57%	-0.24%	-0.09%
AD, GDT +10s, offset +2s	40.42	0.00	13.70	1.79	13.90	0.0834	0.00	0.2009	-3.23%	-13.63%	0.23%
AD, GDT +10s, offset +4s	41.68	0.00	13.35	1.73	13.90	0.0997	0.00	0.2132	-0.52%	-2.13%	1.97%
AD, GDT +10s, GD -1s	41.14	0.00	13.49	1.89	13.94	0.0811	0.00	0.1988	-1.89%	-10.89%	1.16%
AD, GDT +10s, GD -2s	39.88	0.00	13.79	1.54	14.05	0.1200	0.00	0.2073	-1.18%	-4.86%	-0.53%

The analysis shows under different boundary conditions other control parameter settings leading to minimum emission and best traffic flow. However the baseline scenarios, which are calculated with the equations shown before, always were close to the best case. This shows that the formulas are useful for a basic parameterization of traffic lights for low emissions. Certainly, to obtain local optima, individual analyses for each intersection can be performed using NITRA software instead of the simple equations or using more sophisticated traffic models.

The next step in the optimisation work is the common optimisation of the lanes in both directions for low emissions. Also further road categories shall be tested. The „Wiener Straße“ is a radial arterial road with direction flow. For these streets within this category the optimisation strategy is likely to be generally valid but other street categories may need other settings for target speed and accelerations.

4.5 Isolated Intersections

An isolated intersection does not contribute in any kind of a green wave. The most common strategy for such an intersection is vehicle actuated control. With this method, a traffic light is simply kept green until the flow is interrupted or the maximum green time has expired. This can best be understood considering the detection field that is often used for this type of control and is depicted in Figure 4.6.

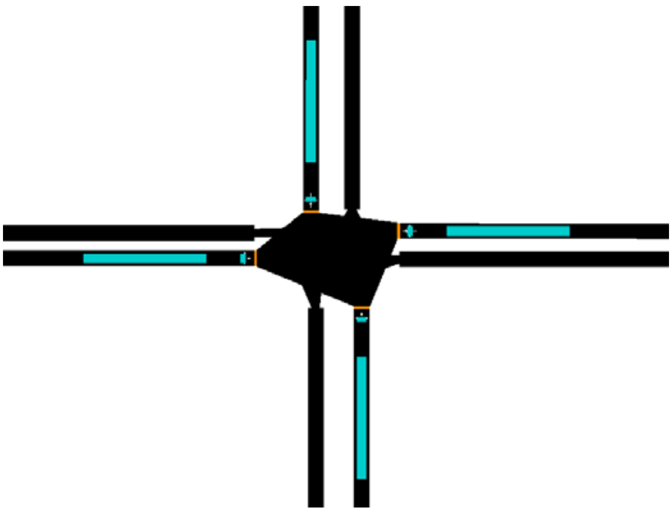

Figure 4.6: Simple vehicle actuated intersection layout.

The small loop at the stop line serves to detect if there are vehicles waiting for that signal group. The longer loop detects whether the flow is interrupted or not. This loop is dimensioned in such a way that the traffic light can achieve optimal throughput at minimal waiting time. The length takes two factors into account: a vehicle that leaves the loop at green will not stop anymore if the light is switched to amber right after it leaves the loop and a normal car following distance is smaller than the length of the loop. This also implies that the higher the speed of the traffic the longer the distance between this loop and the stop line and the length of the loop itself. Therefore, at higher speeds the single long loop is often replaced by several small loops, since extremely long loops are not practical.

Vehicle actuated control generally results in an acceptable control strategy and simply follows the maximum green phase durations in case the network is oversaturated. One of the main shortcomings, however, occurs when there is a gap that is just a bit larger than the size of the loop. This calls for a decision based on how large this gap is and how many vehicles are behind the gap. When there are many vehicles waiting at the other signal groups, it is probably not worth waiting for a single vehicle if there is a large gap. In case there is a platoon of 10 cars after this gap, then the situation is different. Two different situations that appear the same to a vehicle actuated controller, but require a different decision are depicted in Figure 4.7. The situation at the top would require further extension of the green, while the situation at the bottom should have switched green to the west-east direction already. Lastly, when the intersection is saturated, any gap means a loss of capacity and the signal group should be terminated, especially near the end of the maximum green time.

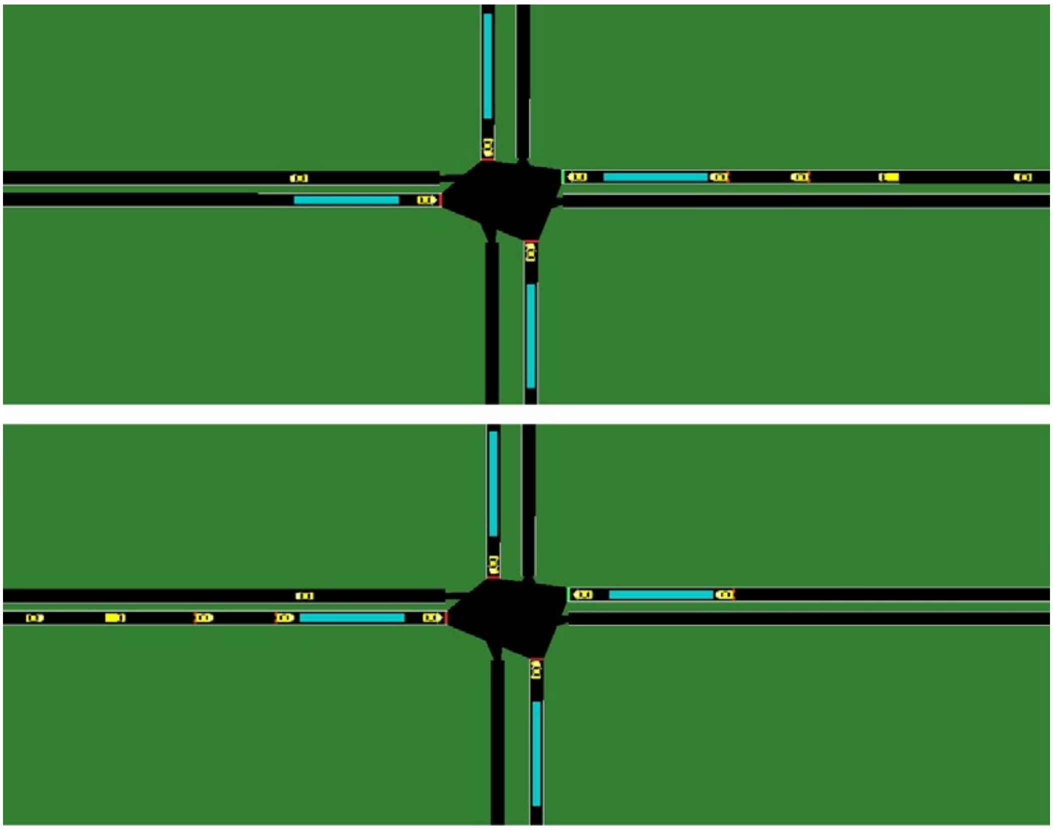

Figure 4.7: Two situations that appear the same to a vehicle actuated controller, but require a different emission optimal decision.

When knowing the pattern of arriving vehicles and the queue lengths, better informed decisions can be made. This is the main advantage of traffic adaptive control; an entry detector located upstream at a given incoming lane enables the controller to determine the positions of approaching vehicles. From the PHEMlight model it could be derived that five seconds of waiting time with the engine running stationary causes the same amount of extra emissions as stopping and accelerating back to 50 km/h as compared to travelling at a constant speed. Using this ratio between cost of delay time and stops for configuring the optimization of a traffic adaptive controller, should therefore result in the least emissions possible.

To test this theory, a simulation of the networks shown above was carried out with both a vehicle actuated controller and the traffic adaptive controller as designed by Imflow. The results are shown in the charts of Figure 4.8.

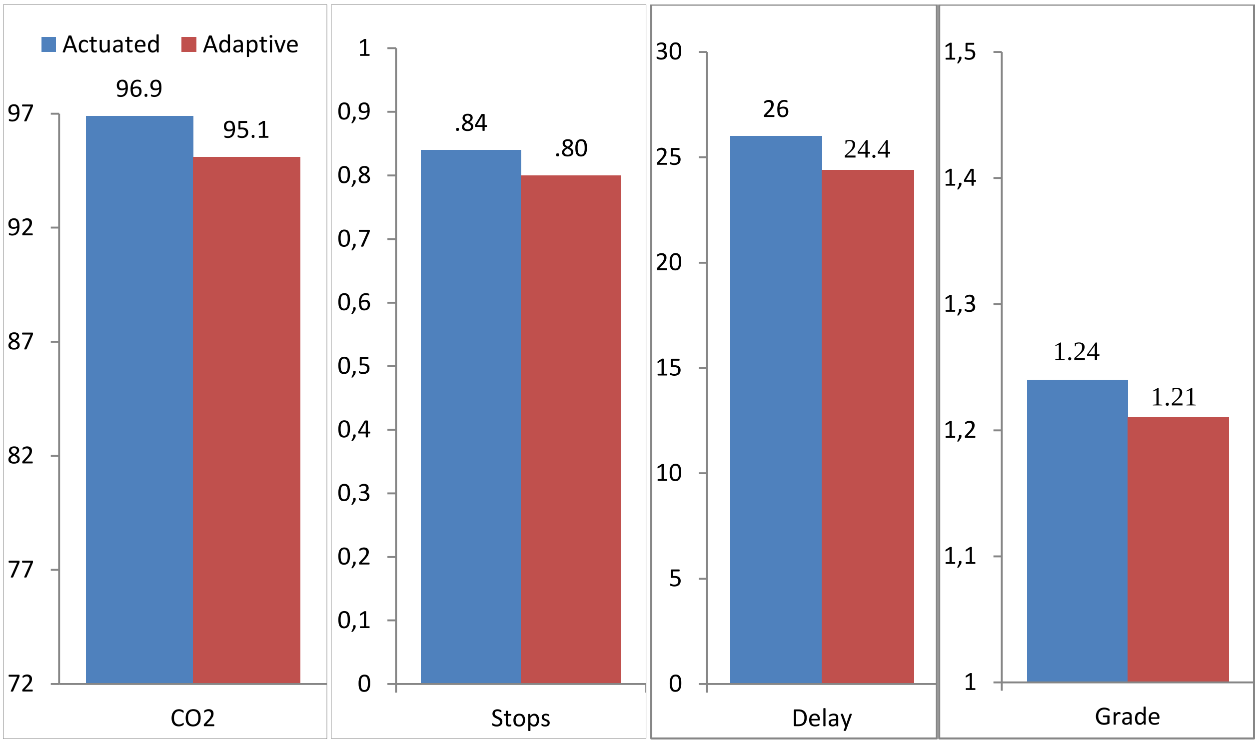

Figure 4.8: Comparison between vehicle-actuated and traffic adaptive (Imflow) control.

The CO_2 scale starts at 72 grams/kilometre, which is the minimal emission that can be achieved when all vehicles would be driving at a constant speed of 50 km/h. This means that the CO_2 reduction of the emissions due to the control is 7.6 % for traffic adaptive control with respect to vehicle actuated. This can mostly be explained by the delay reduction of 6.7 %. The last 0.9 % reduction can be explained by the 5.0 % fewer stops, which get on top of this (multiply the reduction of stops of 0.043 by 5 and add it to the delay reduction results in 0.9 % extra reduction) and validate the theory of 1:5 for waiting time vs. stops.

5 Summary

The Deliverable 4.3 described the progress made with the new microscopic vehicle emission model PHEMlight and the development of guidelines for emission optimum driver behaviour and traffic signal coordination.

The model PHEMlight was developed within COLOMBO to be integrated in microscopic traffic flow models. PHEMlight has several simplifications compared to the emission model PHEM. These simplifications allow computing a vehicle's emissions without knowing the time line of driving conditions before an actual emission event. Other features are similar to PHEM and a routine was added to the PHEM software which generates the input data for PHEMlight to guarantee comparability of the two models. Due to the simplifications made, the simulation of cool down and of heat up of exhaust gas aftertreatment systems is not possible in PHEMlight. Also effects of the cycle dynamic on the exhaust emissions are considered only as generic average effect. Thus, in extreme driving conditions such as very slow and/or steady state or very dynamic driving the deviations between PHEM and PHEMlight can be larger. In such situations PHEM will give more reliable emission results. Since already the speed trajectories and the corresponding cycle dynamics calculated by the traffic models include uncertainties, the simpler model set up of PHEMlight is not a disadvantage in typical applications but makes results less sensitive against some inaccuracies of the vehicle speed data.

A main target of the work described in deliverable 4.3 was the development of guidelines for traffic light coordination to achieve low emissions. Based on the basic dependencies between velocity, time and distance, basic functions for the offset time between consecutive traffic lights as well as for the green light duration have been produced. Starting with this baseline parameters simulation runs have been performed to identify the coordination settings for lowest emissions. For this analysis the software NITRA was produced, which combines a vehicle driver model (car following and target speed following) which virtually runs single cars over a street section with traffic lights. Traffic volumes, number of lanes, distances between traffic lights and number of vehicles entering from side roads etc. can be defined by the user. NITRA also includes PHEMlight and thus shows emissions resulting from different settings of the traffic light coordination. After review of deliverable 4.3, the guidelines will be extracted and shall be made available in a separate publication, possibly together with the software NITRA. This package is not seen as alternative to existing and more sophisticated tools for traffic light designing but shall motivate optimization towards low emissions as a reasonable potential for CO_2 and for pollutant emission reduction is expected.

Beside optimised traffic light coordination also the driver has a high influence on the emissions his car produces in street sections with junctions and traffic lights. Recommendations for emission optimal driver behaviour was elaborated which shows approx. 10 % lower emissions and energy consumption compared to "normal" driving. For the recommendations also equations to compute proper acceleration and deceleration behaviour were elaborated. This data set can be used in the traffic models to test effects of such eco-driving behaviour. In the future, a combined optimisation of traffic infrastructure, driver behaviour and consequently also emission relevant vehicle controllers shall lead to low energy consumption and pollutant emissions. Important basics for simulating these effects have been elaborated here.

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Appendix B – Vehicle Emission Fleet Composition Modelling

In most emission models the vehicle fleet is subdivided into vehicle groups with similar emission behaviour. A common method of fleet segmentation is to differentiate by the following criteria:

- vehicle category (e.g.: passenger cars, light duty vehicles, rigid trucks, …)
- engine concept (e.g. gasoline, diesel)
- size class (differentiating factor: capacity or maximum allowed gross weight) and
- emission standard (legislation which was applicable at the vehicles type approval, e.g. "EURO 5")

A vehicle segment is for example a "rigid truck with diesel engine, gross vehicle weight with more than 18 tons, emission standard EURO 5".

For the overall emission output on the street network the shares of the different fleet segments on the overall mileage are relevant. As these numbers are usually not available from statistics or from traffic counts they have to be calculated by a fleet model. In these calculations the following steps are performed:

(1) Calculation of the vehicle stock one year after the other ("year I") for each vehicle segment according to the year of first registration (J_r) from the vehicle stock of the year before using vehicle survival probabilities.

$$stock_{\mathrm{Jr_i},\mathrm{year\,i}} = stock_{\mathrm{Jr_i},\mathrm{year\,i-1}} \times \text{survival probability}_{\mathrm{Jr_i}}$$

(2) Assessment of new registrations by difference of total vehicle stock from the registration statistics and the vehicle stock remaining from the previous year calculated in step (1)

(3) Assessment of the km per vehicle for each vehicle segment using age and size dependent functions of the average mileage driven.

(4) Calculation of the total mileage of each fleet segment. The total mileage of each "EURO-class" is computed from the sum of age groups for which the emission legislation (e.g. EURO 5) was valid. The factor $a_{(i,\ \mathrm{year}\ i)}$ considers that typically at the beginning of an emission legislation ("i") not all vehicles have to fulfil the new limits; similarly at the end of a EURO period already some vehicles fulfil the next legislation.

$$\text{total mileage}_{\mathrm{E_i}} = \sum_{\mathrm{Jr=start.}}^{\mathrm{end}} (a_{i,yeari}\,\mathrm{stock}_{\mathrm{Jr,year\,i}} \times \mathrm{km/vehicle}_{\mathrm{Jr_i},\mathrm{year\,i}})$$

In this project data on fleet composition is based on results from the model NEMO (Network Emission Model), e.g. [Dippold, 2012] and [Rexeis, 2008] which describes the Austrian fleet until the year 2050. Figure B.1 shows an example the composition of the passenger car mileage for the years 2010 to 2030. Due to the "natural" fleet renewal the fleet composition according to emission relevant fleet segments varies significantly over the years as old vehicles are replaced by new technologies in a permanent process.

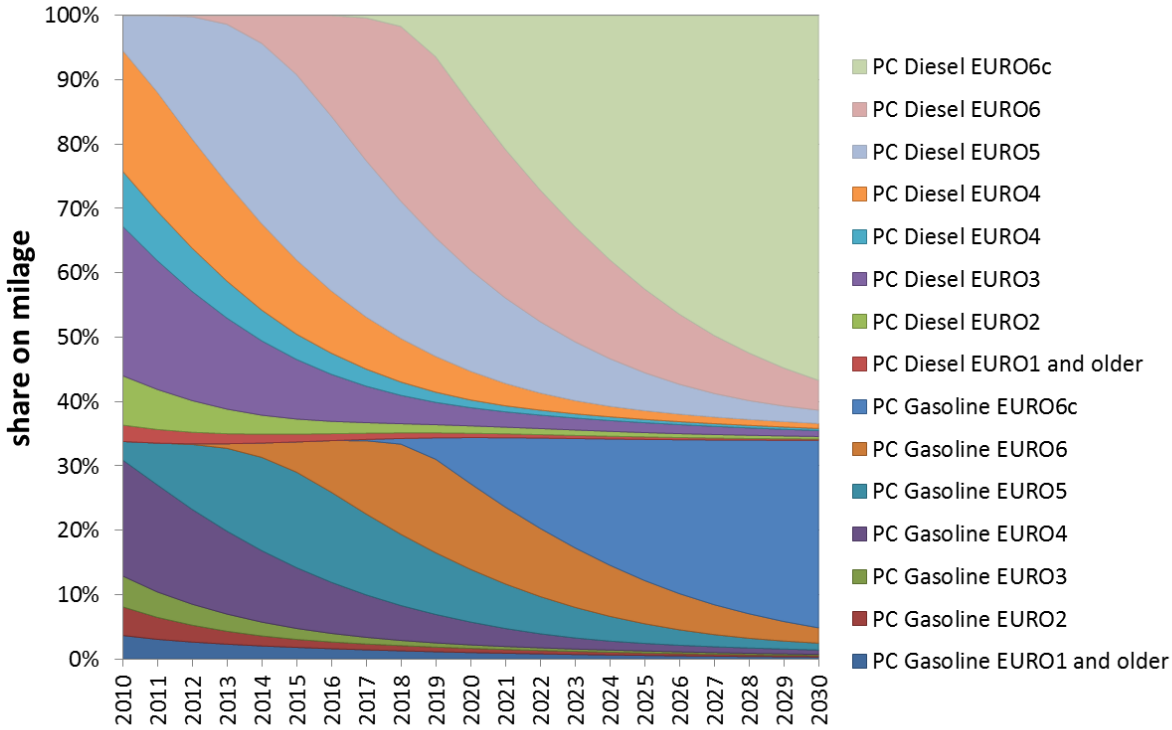

Figure B.1: Example for composition of passenger car mileage Austria 2010 to 2030.