FUEL CONSUMPTION AND EMISSION MODELING FOR URBAN SCENARIOS

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ABSTRACT

Traffic simulation systems are widely used for the prediction of certain effects like traffic jam formation or the analysis of performance for new traffic light systems. Fuel consumption and CO_2 emissions are important measurements. This work integrates a physical model for fuel consumption into a microscopic traffic simulation system for urban scenarios. The parameters of the model are discussed and practical values are given. The model is evaluated on different scenarios with focus on innercity simulation. The results indicate that the simulation of bicycles and pedestrians as well as the usage of a Digital Terrain Model (DTM) increase fuel consumption of simulated cars. A map of CO_2 emissions for the chosen simulation area is calculated and provides an insight on how emissions are distributed in cities.

INTRODUCTION

The increasing amount of road users has led to the situation that road network capacities seem to be exceeded in many areas due to high traffic load. Besides economic disadvantages as well as personal inconveniences of road users being stuck in traffic, the ecological facet has recently gained more attention. Potential effects of air pollution on the Earth's atmosphere like global warming as well as impacts on health are subject of many discussions.

Simulation is widely used to study traffic effects or to get insights on how certain traffic strategies can have influence on a specific situation. However, most studies address consequences regarding the emergence (or avoidance) of congestions or deal with aspects on how to arrange and configure road networks in a way that travel times can be optimized.

Another field of study is the dispersion of gases under certain atmospheric conditions. Using this kind of simulation, it can be estimated how certain gases disperse, e.g., if certain wind directions and wind speeds are present. If information about CO_2 emission of cars was used in combination with such gas dispersal simulations, it would be possible to gain valuable information concerning what regions are likely to have a high pollution due to traffic and atmospheric situations. It could be identified if there are certain regions where it is expected that critical values for toxicity will frequently be exceeded or how high gas concentration is in particular regions of interest.

In this paper, we present a first step towards such a combined simulation. Based on the traffic simulation model presented in (Dallmeyer et al., 2011), we introduce a fuel consumption model and provide means to capture CO_2 emissions at specific positions. With this information at hand, it is possible to generate "emission maps" for different road network configurations. In order to have a more realistic fuel consumption model, the approach also takes into account elevation of the region, i.e., consumption in dependence of the slope can be computed.

The paper is structured as follows. In the next section, we present a selection of related approaches addressing traffic simulation as well as models for fuel consumption. In the subsequent section, we describe the used traffic simulation system. The fuel consumption model and its integration to the simulation system are then presented. The evaluation of the approach is described subsequently. In the final section we draw conclusions and discuss some ideas for future works.

TRAFFIC SIMULATION AND FUEL CONSUMPTION

Traffic simulation systems are used for different purposes like, e.g., traffic jam prediction (Sugiyama et al., 2008) or traffic light optimization (Brockfeld et al., 2001). The range of fidelity differs from macroscopic models (e.g., gas kinetic models) to high fidelity microscopic models (e.g., the Wiedemann model, used in VISSIM (Wiedemann, 1974)).

In order to predict the effects of different influencing actions (e.g., modifications on the course of road or alterations on traffic light circuits) on traffic with respect to fuel consumption and CO_2 emissions, road traffic models need to be extended by a model for fuel consumption. This has been done in several studies (Carten et al., 2010; Karathodorou et al., 2010; Pelkmans et al., 2005; Ahn et al., 2002). To the best of our knowledge, no study investigates the influence of multimodality in urban scenarios on fuel consumption.

Fuel consumption models discussed in literature are

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based on rolling, aerodynamic, frictional, and acceleration resistance. The physical coherences to calculate the driving resistance and the needed engine power for vehicle movement is discussed in literature, e.g., (Treiber and Kesting, 2010; Heißing et al., 2011). (Ross, 1997) compares an amount of modeled cars with respect to fuel consumption and discusses some strategies for reduction of fuel consumption with new car design strategy or hybrid engine power. The fuel consumptions of four simulated cars are shown to deviate less then 1% from measured data in the study of (An et al., 1997). The functionality of the catalytic converter is analyzed with respect to toxic substances produced by vehicles for the development of an emission model (Cappiello et al., 2002).

The literature shows that the simulation of fuel consumption and emissions is possible. This work focuses on the simulation of the traffic of whole cities with help of MAINS^{2}IM. Thus, the extension by a fuel consumption model based on technologies described in literature will lead to a system being able to undertake innovative simulation studies with respect to multimodality and size of study. We have available a Digital Terrain Model (DTM) with resolution of 10m for our evaluation simulation area and thus, can investigate the influence of downhill-slope force on fuel consumption.

SIMULATION SYSTEM

The model for fuel consumption and CO_2 emissions applied in this work is part of the traffic simulation system MAINS^{2}IM (MultimodAl INnercity SIMulation). Cartographical material from *OpenStreetMap*[1] (OSM) can be used to automatically generate a simulation model from a user defined area. A discussion of map quality of OSM can be found, e.g., in Haklay (2010). The information in this material is split into several logical layers and a simulation graph data structure is calculated. Geographical operations as well as the rendering of the map section are done with help of a geographical information system on basis of *GeoTools*[2]. A number of analysis and correction steps extract information from the map layers and refine the simulation graph.

The simulation system applies microscopic traffic simulation models for cars (passenger cars, trucks and buses), bicycles and pedestrians. The models are continuous in space and discrete in time with simulation time steps of $1s$ real time.

The simulation system is written in Java and can be used on a workstation computer. More detailed information about the basic concept, the developed models and applications for the simulation system can be found in (Dallmeyer et al., 2011; Lattner et al., 2011; Dallmeyer et al., 2012a,b) and on the website `www.mainsim.eu`.

[1] http://www.openstreetmap.org
[2] http://www.geotools.org

MODEL FOR FUEL CONSUMPTION AND CO_2 EMISSIONS

The fuel consumption and emission model is built as a separate simulation extension. In exchange with the new extension only a few parameters are provided by the simulation: position, type, velocity v, acceleration $\dot{v}$ and length l of the vehicle as well as the gradient angle α of the street. Other parameters are defined from the extension itself according to statistical rules.

The physical power P depends on the minimum power demand P_0, instantaneous power F and the velocity v:

$$P = P_0 + \max\left(F \cdot v, 0\right)$$

The value of F may become negative, when the vehicle decelerates or drives downhill. Anyhow, the car spends power P_0 for, e.g., light, radio or the power to overcome friction within the pistons of the motor during idling of the engine.

F depends on the inertial force $m \cdot \dot{v}$, the frictional force $m \cdot g \cdot \mu$, the downhill-slope force $m \cdot g \cdot \sin(\alpha)$ and the air resistance $\frac{1}{2} \cdot c_w \cdot \rho \cdot A \cdot v^2$. This leads to

$$F = m \cdot \dot{v} + \left[\mu + \sin(\alpha)\right] \cdot m \cdot g + \frac{1}{2} \cdot c_w \cdot \rho \cdot A \cdot v^2$$

Several parameters for the model need to be defined: The mass of car m, the frictional coefficient μ, the air resistance factor c_w (a measure for aerodynamic), the air density ρ and the cross-section surface A.

Therefore, detailed statistical data of (Kraftfahrt-Bundesamt, 2009) is used that describe the distribution of vehicles and fuel types as well as the loading of trucks in Germany. In order to calculate m, a significant factor for fuel consumption, the defined length of the car l is multiplied with a factor which is measured by a collection of 50 typical cars and their length-mass ratio.

Parameters like the frontal area of a car A and the air drag coefficient c_w are normally distributed on a statistically determined arithmetical mean. Further undefined parameters are supposed constant: the coefficient of rolling resistance of the tires, air density, lower heating value of the gasoline depending on the fuel type and engine efficiency.

Let $\mathcal{N}_a^b(\mu, \sigma) = \min\left(\max\left(\mathcal{N}(\mu, \sigma), a\right), b\right)$ be a Gaussian distributed random number with μ and σ bounded to the interval $[a \cdots b]$. Table 1 shows the estimated values for the fuel consumption model. The values of μ, ρ[3] are taken from (Ross, 1997), the values of P_0 from (Treiber and Kesting, 2010).

During initialization of the simulation, the individual car characteristics needed for the fuel consumption and emission model are calculated and assigned to each vehicle. The values for v, $\dot{v}$ and α of the current street are forwarded to the new extension and are used to calculate the consumption and emission during a simulation on every simulation step for every single vehicle. Therewith,

[3] Typical value for normal height null and 20 °C.

$\mu = 0.01$
$P_0^{\text{car}} = 3\text{kW}$ $P_0^{\text{truck}} = 6\text{kW}$
$c_w^{\text{car}} = 0.3$ $c_w^{\text{truck}} = 0.8$
$\rho = 1.2\text{kg} \cdot \text{m}^{-2}$
$m^{\text{car}} = 1000 \cdot l \cdot \mathcal{N}_{0.26}^{0.49}\,(0.339\text{kg}, 0.34)$
$A^{\text{car}} = \mathcal{N}_{2.3}^{2.81}\left(2.5\text{m}^2, 0.1\right)$ $A^{\text{truck}} = \mathcal{N}_{6.0}^{10.0}\left(8.0\text{m}^2, 0.25\right)$

Table 1: Estimated parameters for the fuel consumption model.

it is possible to retrieve the current and overall consumption and emission for every car.

The amount of carbon dioxide is calculated directly proportional to the vehicle's fuel consumption (Treiber and Kesting, 2010; Schreiner, 2011). The emissions vary for diesel (2.68 kg/l) and gasoline-powered vehicles (2.32 kg/l). In order to calculate other emissions like nitrogen and carbon hydride, it would be necessary to take into account dependencies and the functionality and effectiveness of the vehicles catalyst. For that reason only carbon dioxide will discussed in this article.

In order to generate an emission map for a selected area, the simulation map extract is divided in a variable number of subareas. Each subarea cumulates the emissions of all vehicles within in the current simulation step. The emissions are cumulated during the simulation. After finishing a simulation run, the emission module exports a matrix with the summarized emissions of all subareas.

EVALUATION & CASE SCENARIOS

In this section we present the evaluation of the model for fuel consumption and CO_2 emissions. The extended simulation system is applied to a number case studies investigating impacts of multimodal traffic and elevation information.

Evaluation of the Simulation Model

In order to determine the fuel consumption of a new car, the European Union has established the NEDC (New European Driving Cycle). Thereby a car has to pass different traffic situations on a roller dynamometer test bench to log fuel consumption and emissions. Every car manufacturer is obliged to publish these key data.

These data is ideally suitable for comparison with data obtained from simulation. For this purpose some cars are simulated in NEDC-similar conditions in an urban and a mixture of urban and country road scenario. The amount of cars is held constantly at 1. The simulation duration is 86,400 iterations. Whenever the simulated car has reached its destination of travel, a new one gets inserted into the simulation. The vehicle fuel consumptions are protocolled. The experiment is repeated for four modeled car types. Table 2 shows the results of the simulation in comparison with the NEDC values.

vehicle	NEDC city	NEDC mix	SIM city	SIM mix
Smart ForTwo	4,6 l	4,3 l	5,2 l	4,3 l
Audi A4	8,8 l	7,0 l	9,5 l	7,0 l
Porsche 987	13,8 l	9,4 l	13,5 l	9,8 l
Mercedes C180	6,3 l	4,7 l	6,5 l	4,7 l

Table 2: NEDC and simulated fuel consumption in comparison.

The next step to verify the fuel consumption and emission model described in the preceding section is to simulate scenarios with a typical number of cars in various regions. The first test simulates an urban area with a road network of 150 km and 500 cars. Therefore, the mean fuel consumption for all cars in this simulation run is calculated and compared with the mean NEDC value for urban areas out of 50 reviewed state-of-the-art cars. As there is no interaction and influence between cars in the NEDC, it is expected that the simulated consumption is higher. The simulation results confirm this assumption. While the NEDC calculates about 9 liters per 100 km the simulation computes a consumption of 11,2 liters.

A second test simulates a mixture scenario of urban and non-urban areas on a road network of 65 km and 250 cars. The mean NEDC consumption for mixture areas is 6,7 l. The result of the simulation is 8,1 l.

The comparison to NEDC showed feasible results. The next experiments focus on fuel consumption on motorways under consideration of car-to-car interactions.

Fuel Consumption on Motorways

Fuel consumption on motorways is investigated with periodically boundary conditions on a two-lane motorway with length of 6km. In a first experiment, only cars are simulated. The number of cars is set to 5 and is increased with an increment of 5 for 310 simulation runs. The results of each simulation run are average values over 3 replications. Each replication starts with a settlement phase of 2,000 iterations. Then, each car protocols its fuel consumption during a measurement phase of 20,000 iterations. The result of each replication is the mean fuel consumption in l/100km for all cars. Figure 1 shows the resulting consumptions in relation to the mean velocities driven, with increasing traffic densities.

Low traffic densities lead to low fuel consumptions, because of low interaction between cars. The abrupt rise of fuel consumption with increasing traffic densities is a consequence of the used micro model for car movement. The model is a continuous version of the Nagel-Schreckenberg model (Nagel and Schreckenberg, 1992) extended by a slow-start rule, anticipation and more realistic velocity values. The model has been calibrated for freeway and urban scenarios, leading to realistic density-flow-, density-velocity- and flow-velocity-relations. The

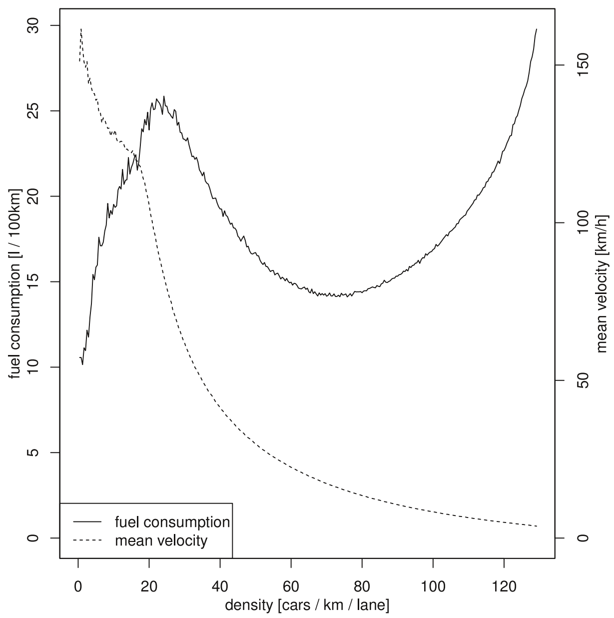

Figure 1: Fuel consumption on a motorway.

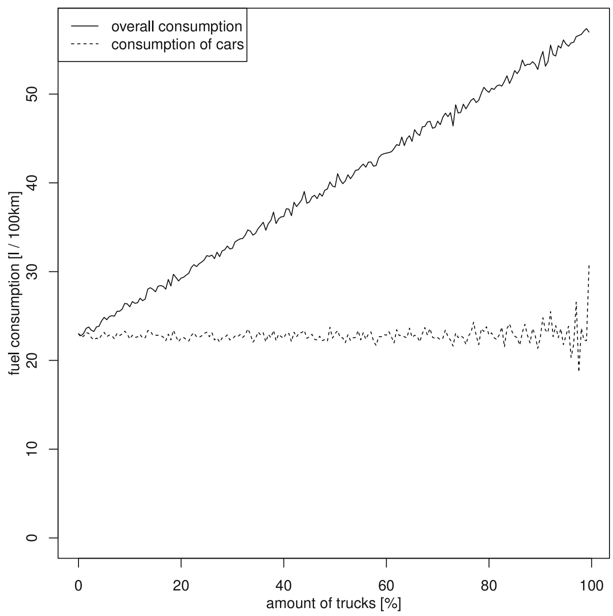

Figure 2: Fuel consumption on a motorway: Influence of trucks.

model gives realistic macroscopic results, but leads to a huge amount of velocity changes, due to lack of a smooth traffic flow.

Nevertheless, the shown maximum value for fuel consumption (in the density area lower than 80 cars/km) is lower than values discussed in literature between 80 l/100km (Yang et al., 2009), 30 l/100km (Madani and Moussa, 2012).

In a second experiment, the number of road users is fixed to 200 ($16.\overline{6}$ cars/km/lane) and the fraction of trucks in the simulation is varied from 0% to 99% with an increment of 1%. The result of each run is the average from 3

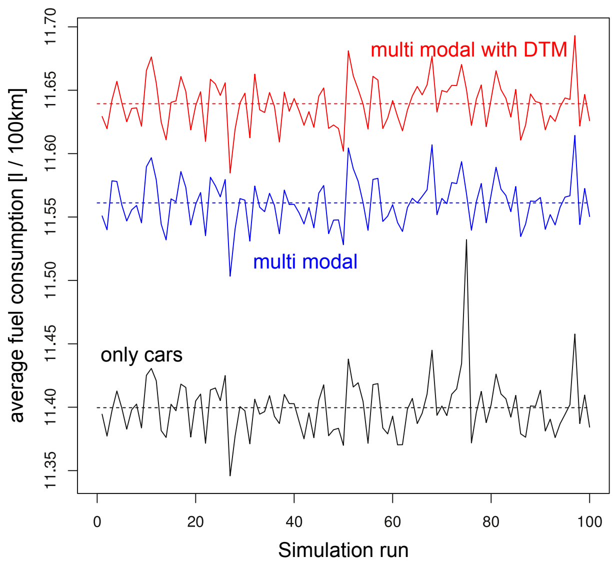

Figure 4: Comparison on fuel consumption in urban traffic. Results shown as lines, in order to simplify comparisons. Dashed lines represent mean values.

replications. The result of each replication is the average fuel consumption of the cars in the simulation and the overall consumption of all road users in the simulation. Figure 2 shows that the influence of the amount of trucks on car fuel consumption is small.

Fuel Consumption in Urban Traffic

MAINS^{2}IM is a simulation system for urban traffic. Thus, the model's evaluation should also be done in a city scenario. Figure 3 (next page) shows the city used. In a first run, 750 cars are simulated on the road map (without DTM). After a settlement phase of 5,000 simulation iterations, a measurement phase of 50,000 iterations estimates the average fuel consumptions of all simulated cars. The simulated cars determine consumptions whenever driving within urban areas.

In the next setting, the simulation is reset and 1,750 bicycles and pedestrians (35% bicycles, 65% pedestrians) are put on the simulation graph. The simulated cars are copies of the cars from the former run, driving identical routes to identical starting times with identical behavior. The measurement is done, analogously.

A third setting uses identical road users of the former setting and enhances the fuel model with a Digital Terrain Model (DTM), enabling cars to determine their height above sea level and thus enabling downhill-slope force.

Every setting is repeated for 100 times in order to estimate the effects. Figure 4 shows the results.

Apparently, fuel consumption is the lowest, when only cars are simulated. Multimodality increases fuel consumption by $0.16\,\mathrm{l} \cdot (100\mathrm{km})^{-1}$ in this scenario. The usage of a DTM additionally increases fuel consumption by $0.08\,\mathrm{l} \cdot (100\mathrm{km})^{-1}$ in comparison to simulation with multimodal traffic and $0.24\,\mathrm{l} \cdot (100\mathrm{km})^{-1}$ overall. Statistical significance tests (t-tests with $\alpha = 0.05$) indicate higher

Figure 3: Extract of simulated map area, representing Hanau am Main (89,000 inhabitants), Germany with the corresponding extract of the DTM. Total length of roads: 548km, number of nodes in simulation graph: 4,201, number of edges: 5,758.

mean values for the multimodal setting against the setting with only cars and for the setting with DTM against the multimodal setting (in each case highly significant, taking into account multiple testing).

CO_2 emissions

The fuel consumption in the simulation system has been discussed in the previous subsections. This subsection analyses how the consumption is allocated in the simulated city. Thus, the popular measure of CO_2 emissions is used and a map layer for visualization of those is created. The map area is separated into 333 rows and 333 columns (110,889 cells). Each cell protocols the amount of CO_2 emitted by cars driving in the cell. This is done for all 100 simulation runs under consideration of multimodality and the DTM. Figure 5 shows the average results over all runs.

As in the urban fuel consumption experiments, only emissions in urban areas are captured. The main routes of travel are charged with CO_2 emissions, the most. The figure highlights two areas. The bridge over the river in the north of the map extract is a crucial point, because the road looses height above sea level to the east and two traffic lights on both sides of the bridge control traffic in this area. This leads to cars braking to standstill and afterwards accelerating against rising course of road and thus a high fuel consumption and high emissions rankings. The second highlighted area in the south is a part of the city with two lane roads with high volumes of traffic and traffic lights at each CO_2 hot spot.

SUMMARY AND PERSPECTIVES

This work has described the integration of a physical model for fuel consumption and CO_2 emissions into the traffic simulation system MAINS^{2}IM. The model parameters are set according to a review of current cars in Germany. An adaptation of these parameters would make the system work in other regions, too.

The model evaluation first compared simulation results without traffic to data from NEDC. Then, traffic on motorways has been examined. The main part of evaluation has been the simulation of an urban scenario in a medium sized city. A comparison between urban car traffic, and simulation runs with added pedestrians and bicycles has shown a significant increase in fuel consumption. The same effect could be observed when a DTM was added.

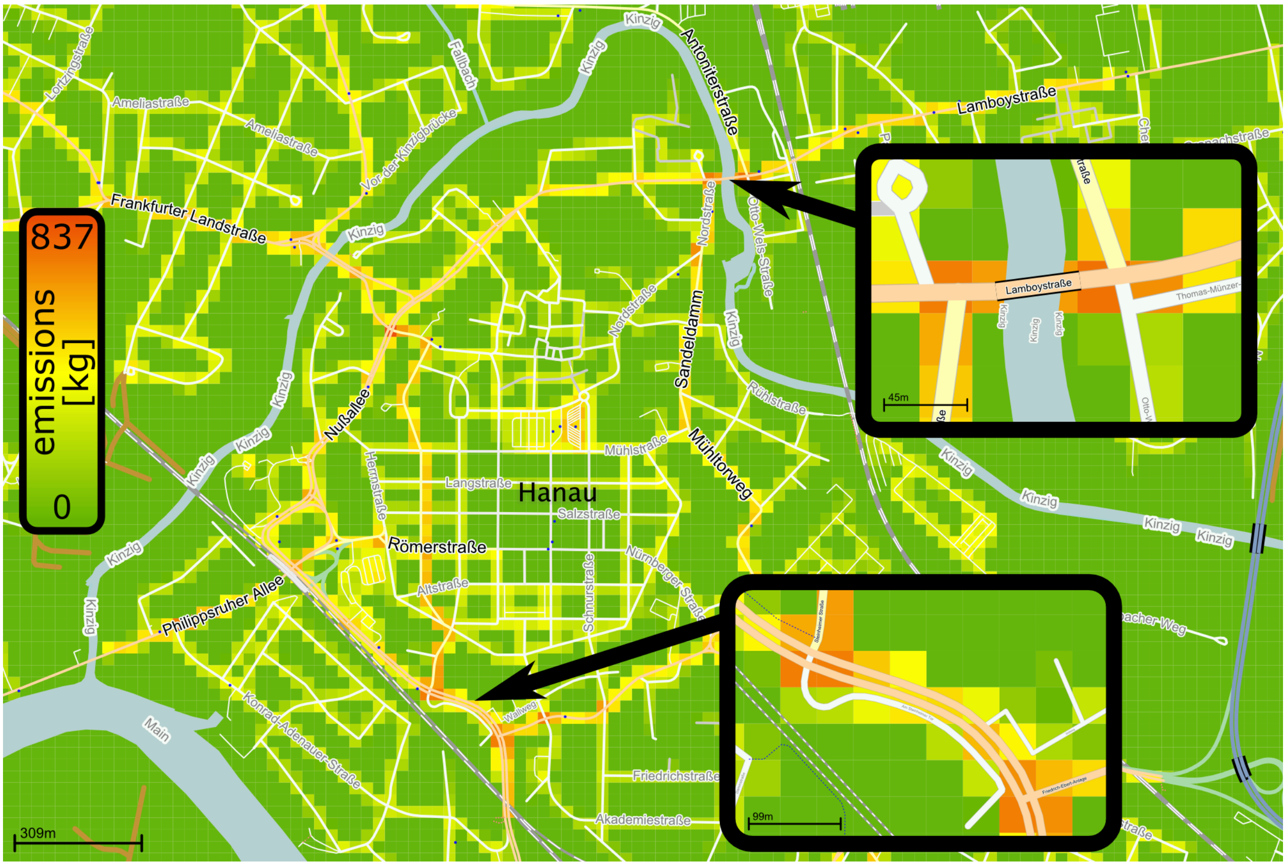

Figure 5: View on CO_2 emissions in case scenario in logarithmic scale.

CO_2 emissions are directly proportional to fuel consumption. A map showing CO_2 emissions in the simulation region was computed. The map shows emission hot spots over the regions of high traffic volumes. The CO_2 map currently assumes that there is no wind in the simulation area. Thus, this information needs to be integrated in the future. In further studies, MAINS^{2}IM has to be attached to a gas dispersion model with realistic wind input from the simulation area. Therefore, a calibration with help of measured origin destination matrices has to be done in order to have realistic traffic volumes. Then, the simulation could be used to determine places within a CO_2 hot spot, which should not have high emission ratios (e.g., positions of playgrounds or kindergartens) and test, which action (e.g., speed limits or other one-way road policies) could lead to an improvement.

Other scenarios like the implementation of a new car model with a certain fuel consumption behavior can be tested for efficiency in motorway, mixed or urban scenarios with help of the presented simulation system.

This could be an interesting problem for the invention of electrically powered cars, e.g., the identification of outstanding road map positions for charging stations or the opportunity to answer questions like "will this car reach its home position from work under given traffic conditions?". Additionally, the effect of electrically powered cars on the CO_2 map of a city could be tested.

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