Friederike Hülsmann, Regine Gerike, Benjamin Kickhöfer, Kai Nagel,
Raphael Luz

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Towards a multi-agent based modeling approach for air pollutants in urban regions

Entwicklung eines Ansatzes zur multi-agentenbasierten Modellierung von Luftschadstoffemissionen in urbanen Regionen

Friederike Hülsmann, Regine Gerike
mobil.TUM, Technische Universität München
Correspondence address: friederike.huelsmann@mobil-tum.de

Benjamin Kickhöfer, Kai Nagel
FG Verkehrssystemplanung und Verkehrstelematik, Technische Universität Berlin
Correspondence address: kickhoefer@vsp.tu-berlin.de

Raphael Luz
Institut für Verbrennungskraftmaschinen und Thermodynamik, Technische Universität Graz

Abstract

Urban environments are often associated with high traffic density. Especially road traffic is a major source for air pollution in cities. The cause-and-effect chain from the traffic activity towards the concentration of air pollutants is complex. Modeling the outcome needs a lot of inputs in terms of methodology and data. Against this background, an approach is developed that links the agent-based transport model MATSim with the emission factors and traffic situations of HBEFA. The goal is to approximate link travel times as well as the resulting emissions of air pollutants while still being applicable to large-scale scenarios. This paper aims at laying down the foundations for this innovative approach. A test case is developed where link travel times are simulated and the resulting emissions are calculated for MATSim test vehicles. The results are then compared to real-world data. Further, it is discussed how to extend this approach to a large-scale scenario and what prerequisites are needed. Finally, it is analyzed what additional information the model provides in order to achieve a more sustainable transport and urban planning.

Kurzfassung

Urbane Regionen weisen zumeist eine hohe Verkehrsdichte auf. Die durch den Straßenverkehr hervorgerufenen Luftschadstoffemissionen tragen in einem großen Maße zur Luftverschmutzung bei. Der Ursache–Wirkungspfad von der Verkehrsaktivität bis hin zu den Auswirkungen auf die Luftschadstoffkonzentration ist komplex. Seine Abbildung ist methodisch aufwendig und geht mit einem erheblichen Datenaufwand einher. Vor diesem Hintergrund wird ein Ansatz entwickelt, der das agentenbasierte Verkehrsmodell MATSim mit HBEFA Emissionsfaktoren und Verkehrssituationen koppelt. Ziel ist es straßenfeine Reisezeiten und die resultierenden Luftschadstoffemissionen zu approximieren ohne die Anwendbarkeit auf großräumige Szenarien zu verlieren. Diese Studie legt die Grundlagen für diesen innovativen Ansatz. Es wird eine Teststrecke simuliert, für die Reisezeiten und die resultierenden Emissionen eines Testfahrzeugs berechnet werden. Die Ergebnisse werden mit realen Daten verglichen. Des Weiteren wird diskutiert, wie dieser Ansatz auf großräumige Szenarien angewendet werden kann und welche Voraussetzungen dafür nötig sind. Abschließend wird analysiert, welchen Beitrag das Modell für eine nachhaltigere Transport- und Stadtplanung leisten kann.

1 Introduction

Environmental effects that are related to road traffic depend on various factors. The air pollutant concentration is particularly affected by the type of air pollutant, the emission level and the atmospheric conditions. In order to reduce the impacts on humans and the environment in a sustainable way, the polluter has to be identified. Furthermore, the air pollutants with high concentrations in urban areas should be focused on. These are nitrogen dioxide and particulate matter. In this context it is an important task to model and evaluate the impacts of transport policies to improve air quality.

For a detailed assessment of the environmental effects a transport model is needed that produces enough information about the travel behavior, but is able to model an entire urban area to assess transport policies. The multi-agent transport simulation MATSim[1] is able to simulate large-scale scenarios. It is particularly suitable for modeling the air pollution on a detailed level as complete daily plans are modeled and the traveler's identity is kept throughout the simulation process. The goal of this paper is to link the kinematic characteristics per traveler and road section obtained from the transport model MATSim with emission factors that fit to the travel behavior and the road category. The questions are how the parameters used in the MATSim simulation need to be set up, modified or adapted, what kinematic value serves best to calculate the emissions, what and how the emission factors should be applied.

The paper starts with a presentation of the transportation model in Section 2, followed by an exposure of the emission calculation tool in Section 3. This basically gives an overview of the two parts to be linked. In Section 4, a test case is developed. It aims at showing that link travel times can be approximated in a meaningful way for each traveler on this road section. The resulting emissions of air pollutants are analyzed in Section 5. Section 6 discusses what extensions of the emission calculation tool are possible and how to adapt the modeling and calculation process to a large-scale real-world scenario of the Munich metropolitan area. The paper ends with a conclusion.

2 Simulation approach

This section (i) gives a brief overview of the general simulation approach the software tool MATSim uses and (ii) describes in more detail the representation of traffic flow. The understanding of the general simulation approach presented in Section 2.1 is relevant for the outlook towards a real-world application, given in Section 6.2, in order to fully capture the possibilities that MATSim opens up for transport planners and decision makers. Section 2.2 is relevant for the simulation runs and emission calculations presented in this paper. For further information please refer to Raney and Nagel (2006) and Balmer et al. (2005) or to Charypar et al. (2007), respectively.

2.1 MATSim at a glance

In MATSim, each traveler of the real system is modeled as an individual agent. The approach consists of an iterative loop that has the following important steps:

1. **Plans generation**: All agents independently generate daily plans that encode among other things his or her desired activities during a typical day as well as the transportation mode. There is always one plan for each mode.

[1] "Multi-Agent Transport Simulation", see www.matsim.org

2. **Traffic flow simulation**: All selected plans are simultaneously executed in the simulation of the physical system.

3. **Scoring**: All executed plans are scored by an utility function which is, in this paper, personalized for every individual by individual income.

4. **Learning**: Some of the agents obtain new plans for the next iteration by modifying copies of existing plans. This is done by several modules that correspond to the choice dimensions available: time choice, route choice and mode choice. Agents choose between their plans with respect to a Random Utility Model (RUM).

The repetition of the iteration cycle coupled with the agent database enables the agents to improve their plans over many iterations. This is why it is also called **learning mechanism** which is described in more detail by Balmer et al. (2005). The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; we just allow the cycle to continue until the outcome is stable.

2.2 Traffic flow simulation

For the simulation runs in this paper that will focus on a single test road, only the first two steps of the overview above are relevant. For the test road, even the first step is done in a very basic way since there is no need of constructing activity locations and transportation modes based on real-world data. The mental layer within MATSim that describes the planning of activities and the behavioral learning of agents does not add additional information for the test road scenario since there are no alternatives to choose from. Therefore, only the physical layer that is responsible for traffic flow simulation is now of special interest.

MATSim currently implements a so called queue-based traffic flow simulation (Charypar et al., 2007). This implies the following characteristics:

- Instead of traveling cars, the *links* (= roads) of a road network are simulated.

- Links are among others represented by parameters like flow capacity, storage capacity (deduced from length), maximum velocity and number of lanes. The flow capacity defines how many cars can leave the link in a time step. The storage capacity defines how many cars can be on the link at the same time.

- The cars that enter a link are stored in a first-in-first-out queue with their individual entry time.

- A car can only leave the link if it was at least in the queue for the free speed travel time of the link, all other cars that entered earlier already left the link and if the next link has enough storage capacity.

The reason for this rather abstract model is that it considerably reduces computation complexity and time. It therefore allows modeling large-scale scenarios with several million agents while considering upstream moving traffic jams and gridlock effects. However, its major drawback in the context of emission modeling is that there is very little information available about an agent's position during his or her time spent on a link. This makes it difficult to directly deduce driving patterns which do have big impacts on the emission level. This issue is addressed in Section 3.2.

3 Emission calculation tool

3.1 Overview of air pollutants and emission sources

The two air pollutants that exceed the limiting values prescribed by the European Union in several municipalities in Germany to a large extent are nitrogen dioxides (NO_2) and particulate matters (PM). The concentration of PM is composed of engine exhaust gas emissions as well as abrasion and suspension. Regarding health effects, the smaller the particle the worse the impact on humans. The effects range from damages of the respiratory system to carcinogenic effects. Only small amounts of NO_2 are emitted directly from fuel burning. However, the larger part originates from the reaction of nitrogen monoxide (NO) with oxygen. Even though the nitrogen oxide concentration has been found to show lower levels nowadays than in recent years, the concentration of NO_2 in the urban area is still increasing. Such development results from a mixture of effects, one being the introduction of oxidation catalyst and particle filters and another one being the increased ozone concentration in urban regions. A trade-off effect between NO_2 and PM can therefore be identified. NO_2 has a negative impact on the environment and human health mainly with respect to irritations of the respiratory system. Beyond nitrogen oxides and particulate matter, hydrocarbons and benzol are emitted by road traffic (Becker et al., 2009).

According to the emission factors presented in the Handbook of Emission Factors for Road Transport (HBEFA, 2010), different traffic situations exhibit different emission levels. Whereas a free flow, heavy and saturated traffic situation shows relatively similar emission factors, the stop&go traffic situations comes along with considerably higher emission factors. The observation applies to both emission types described above, NO_2 and PM. With respect to the overall emission calculation, a focus should be, thus, on defining the stop&go fraction when driving.

There are several sources of air pollution that can be assigned to road traffic: Warm emissions are emitted when the vehicle's engine is already warmed-up, whereas cold-start emissions occur during the warm-up phase. They differ with respect to the distance travelled, the parking time, the average speed, the ambient temperature and the vehicle characteristics (Weilenmann et al., 2009). Furthermore, emission sources are caused by evaporation and air conditioning which are not further regarded in the modeling process. Cold start emissions that have a considerable impact on the total emission level cannot be included in this study since the test case refers to a road section not considering start and end location of the travel. Therefore, only warm emissions are analyzed. The other emissions types will be analyzed in consecutive studies. The emissions per distance travelled differ significantly with respect to driving speed, acceleration and stop duration as well as vehicle characteristics such as fuel type (André and Rapone, 2009).

3.2 Methodology of the emission calculation tool

The emission tool is composed of two main steps: first, the deduction of kinematic characteristics from MATSim simulations and, second, the generation of emission factors. As described in Section 2.1, the MATSim approach exhibits activity chains for every agent over the entire day. Using this information, kinematic information per agent and link can be deduced. The emission tool can be executed as a post processing step of the MATSim or directly integrated into the simulation. When an agent enters and leaves a link a timestamp is created. Thereby, it is possible to calculate the free flow travel time and the travel time in a loaded network for every agent and link. As MATSim keeps the demographic information until the system is relaxed, information about each agent's vehicle is available at any time.

This information comprises the vehicle type, age, engine size and fuel type and is therefore relevant for emission modeling.

In the second step emission factors per air pollutant are identified. They can vary per vehicle type, road category and speed limit. Such emission factors are assigned to each agent and link the agent drives along. Emission factors are taken from HBEFA 3.1. The handbook provides emission factors depending on four traffic situation, free flow, heavy, saturated and stop&go. Such traffic situations show different kinematic characteristics depending on the road category and speed limit. The traffic situations are deduced from driving cycles which are described by time-velocity profiles. Typical driving cycles form the basis for the emission factor calculation in HBEFA 3.1. In order to adjust such driving cycles to the traffic situations in Munich, they are compared with a variety of driving cycles that were collected by GPS tracking on different road sections in Munich. In order to determine typical traffic situations for a specific road category and speed limit following the methodology developed by André (2004), a two-stage clustering approach is applied. A cluster represents a typical driving cycle. Important kinematic characteristics that determine the emission level are applied when clustering: stop duration, average driving speed, and relative positive acceleration. The parameter, relative positive acceleration, is chosen because it shows how steady the traffic flow behaves. By looking at the idling time an indication about the share of stop&go is given. In addition to these two parameters, the average speed has major influence on emission levels depending on the type of air pollutant. The resulting Munich specific traffic situations are compared with the ones in HBEFA 3.1 and adapted when the kinematic characteristics of the same road category and with the same speed limit differ.

In order to assign the emission factors to the traffic demand generated with MATSim, the driving behavior of an agent on a certain link in the MATSim simulation is linked to the respective HBEFA driving cycle. Beyond the traffic situation the emission factors in HBEFA are further varied by vehicle and fuel type, emission EURO-class and engine size corresponding to the attributes vehicle and fuel type, age and cubic capacity provided by MATSim. In this paper, only the fuel type is varied. The road categories of the Munich VISUM[2] road network (RSB, 2005) used in the traffic flow simulation differ from the categories defined in HBEFA. The road categories are differentiated by the number of lanes, speed limit and their function. These characteristics are used to link the road categories of the Munich VISUM road network with the HBEFA ones. The latter is less detailed, thus, a few road categories of the MATSim road network can be assigned to one HBEFA road category. HBEFA defines five road functions: a high-speed and high capacity road which can either be an urban motorway or a major arterial or ring road, a medium capacity road including arterial, distributor and district connectors, a local connector and a residential road. The test road in this paper corresponds with a major arterial.

Having identified the HBEFA road category, two approaches are developed to assign the emission factors to each agent and link. First, the four typical average speed values of one road category that represent the typical four traffic situations, free flow, heavy, saturated and stop&go are compared with the average speed an agent drives on a link in the MATSim road network. The corresponding emission factor is then calculated by interpolating the HBEFA emission factors. The second approach divides each link into fractions representing stop&go and free flow traffic following the methodology developed by Hatzopoulou and Miller (2009) with a few modifications. The difference between the actual travel time and the free flow travel time per link corresponds with travel time spent in stop&go. The average speed that represents a kinematic characteristic of the typical stop&go driving behavior can be obtained from HBEFA. It is used to calculate the fraction of the link the agent spends in the stop&go

[2] “Verkehr In Städten UMlegung“ developed by PTV AG (see www.ptv.de)

traffic situation. The respective emission factors can be assigned to the resulting stop&go and free flow fraction.

4 Test scenario: Frankfurter Ring, Munich

In order to test the correctness and plausibility of the emission tool implementation, a test scenario for a single road is set up in this section. The road is named Frankfurter Ring and is located in the north of Munich. There is some data available, on the one hand from counting stations and on the other hand for a test vehicle that was driving on this road several times per day. Based on this real world data, the traffic flow simulation in MATSim is set up and it is shown how to approximate the measured travel times with the simulation.

4.1 Input data and design

The test road is designed based on VISUM network information delivered by the municipality of Munich (RSB, 2005). Only one direction (east to west) along Frankfurter Ring is considered, between the counting station and the intersection Frankfurter Ring / Schleißheimer Straße, resulting in a total distance of 304 meter for this road. The network data also contains information about the total capacity of 36000 vehicles per day and the maximum speed of 60 km/h. Since VISUM is handling aggregated traffic flows for e.g. 24 hours and MATSim is a time-dependent micro-simulation model, the capacity was fine-tuned with information about traffic signals at the intersection Frankfurter Ring / Schleißheimer Straße (own calculations based on KVR, 2010). Based on this, the time-dependent flow capacities are defined as follows:

- midnight – 6am: 1900 veh/h
- 6am – noon: 2100 veh/h
- noon – 9pm: 2240 veh/h
- 9pm – midnight: 1905 veh/h

Counts data from counting stations that were provided by the municipality of Munich (KVR, 2006, 2009) give information about vehicle inflow patterns over time of day in two minutes time intervals as it is shown exemplarily in Figure 1 for July 07th, 2009. Based on this, individual agents are generated in MATSim format. An open question at this point is how to distribute these agents within the two minutes time bins. One could think – as a first approach – of distributing them randomly within these two minutes; as discussed further in Section 4.2, this seems to produce implausible results for the time-dependent link travel times. Therefore, following a second approach, the agents were told to depart all together at the end of their corresponding interval. It can be argued that this is more in line with reality since the upstream inflow is regulated by the upstream signaling system which does not let them drive on the link equally distributed but as a bulk when the signal turns green. For a better inflow modeling, one would need input data from the upstream signaling system. But since it is not part of this project to model signal systems for a large-scale scenario, this possibility is not further examined.

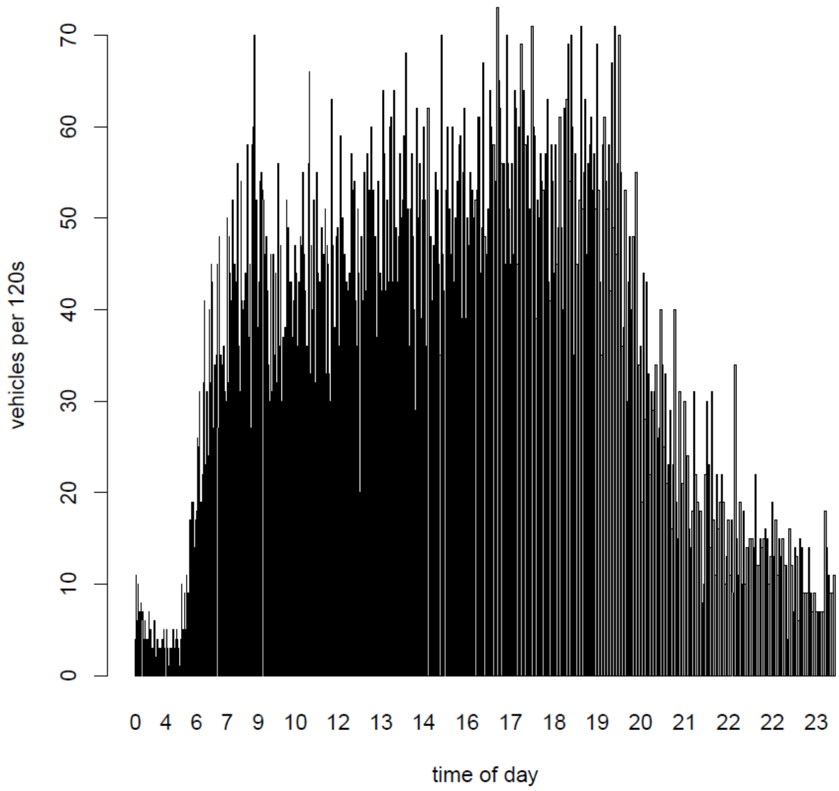


Figure 1: Inflow of vehicles onto the test road over time of day in 120 seconds intervals for July 07th 2009.

Data for test vehicles were recorded by the Chair of Traffic Engineering and Control at Technical University of Munich (VT, 2009). It includes GPS data of the test vehicles driving through the city of Munich and recording information over time of day and for several days. Time-velocity profiles are of special interest in the case of emission modeling since driving patterns – including distance, travel time, acceleration and breaking between arbitrary locations – can be deduced. In a first step, this gives insights into the time-dependent traffic conditions in the network. In a second step, emissions can be calculated e.g. by the software tool PHEM[3] and serve as benchmarks for the model. Thus, test vehicles are also generated as MATSim agents, setting their departure times equal to the real-world inflow times taken from the time-velocity profiles onto the test road. Due to the need of having data from counting stations and test vehicles available for the same days, the following eight days were selected and taken into account for analyzing the simulation results: January 27th and 31st 2006, March 17th, 18th and 19th 2009 and July 07th, 08th and 09th 2009.

4.2 Goals and configuration

The two goals of analyzing the test road are to find out (i) whether and under what conditions a plausible approximation of the link travel times is possible with MATSim and (ii) whether plausible results for emissions of diesel / gasoline cars can be obtained. For answering the first question, simulation data for the test vehicles is now compared to real-world data. The

[3] "Passenger Car and Heavy Duty Emission Model", developed at TU Graz (see http://ivt.tugraz.at)

real-world data was taken from GPS tracks; it is shown in Figure 2a. Different configurations are tested for the simulation runs as shown in Table 1. For all of these configurations, the road is always assumed to have two lanes. In MATSim, where cars cannot overtake other cars, this mainly influences the storage capacity of the link and thus, in case of a traffic jam, the maximum travel time on the link. For example, when a car is driving onto a two lane link, there are double as many cars in front of it compared to a jammed single lane road. Thus, the maximum travel time is (as long as the flow capacity remains the same) exactly double as high as for a single lane road. All test scenario configurations are indexed with upper case characters (A to H) and are distinguished by (i) the flow capacity of the test road in vehicles per hour, (ii) the maximum velocity v_{max} in kilometers per hour and (iii) the distribution of departure times for all vehicles that is assumed within the two minutes time intervals of the counting stations.

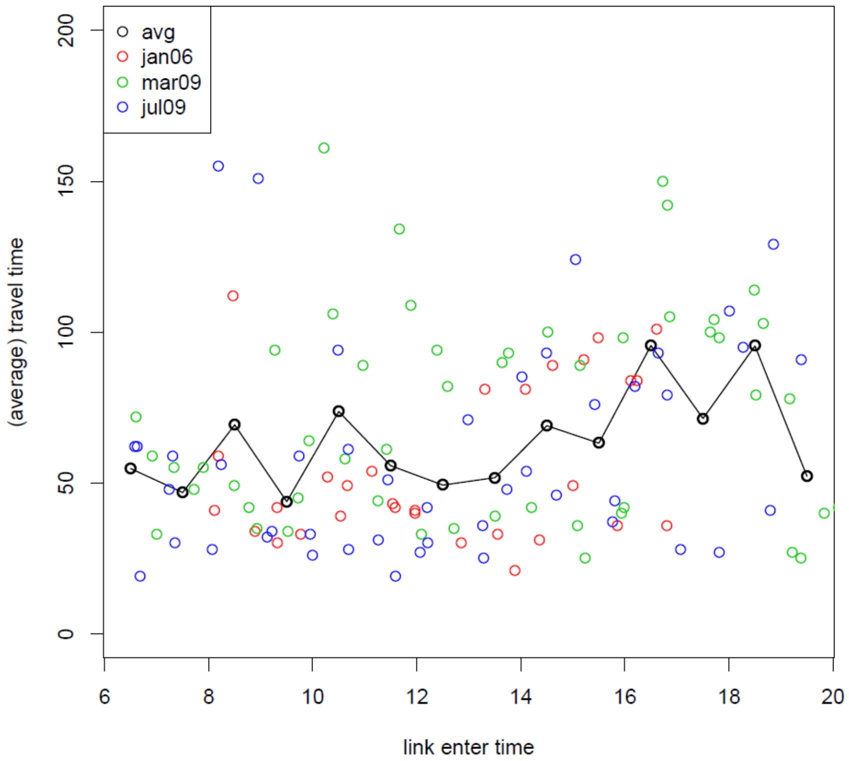
Departure Times	Initial flow capacity 1900 veh/h		Initial flow capacity 1400 veh/h	
	v_{max} = 30 km/h	v_{max} = 60 km/h	v_{max} = 30 km/h	v_{max} = 60 km/h
Randomly distributed	A.	B.	C.	D.
End of interval	E.	F.	**G.**	H.

Table 1: Overview of the eight different test scenario configurations; the selected configuration G is highlighted in green.

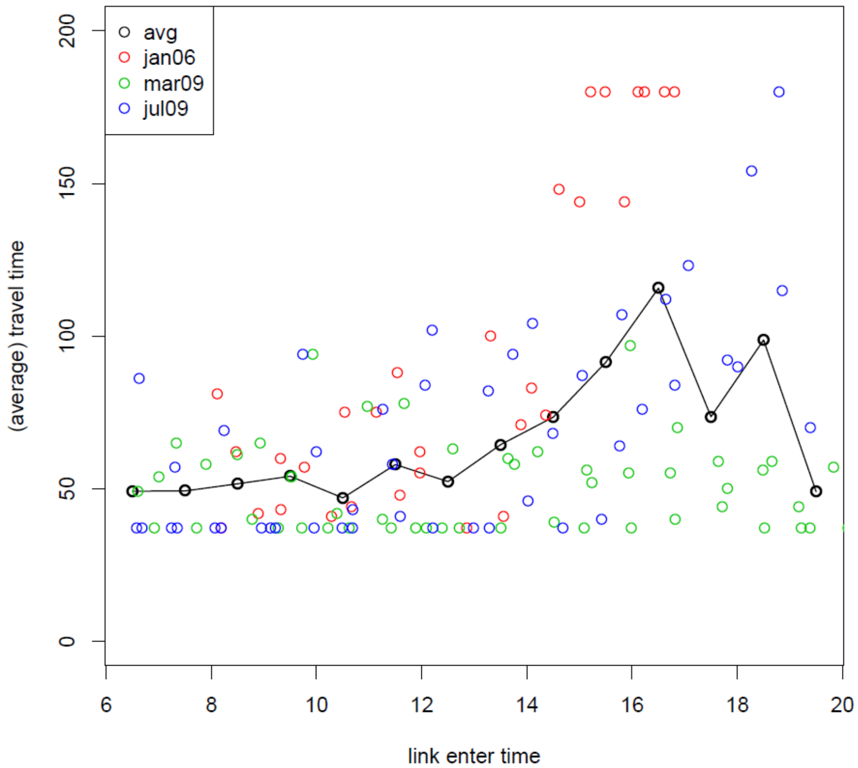
A discussion where the results of all configurations are compared to each other would exceed the scope of this paper. Therefore, the main findings are summarized here:

1. The random distribution of departure times (configurations A to D) within the two minutes time intervals defined by the counting stations produces too little variations in the time-dependent link travel times. One reason is probably that cars in reality do not enter the link randomly distributed due to the upstream signaling systems. It is more likely that they enter the link as bulks dependent on the upstream signaling cycle. Therefore, setting departure times at the end of the time interval (configurations E to H) seems to be a plausible approximation of the upstream signaling cycles.

2. Setting the initial flow capacity of the test road to 1900 veh/h with variations over the day also results in too little variation of the link travel times. Many agents leave the link after the minimal travel time of 19s (for 60 km/h) or 38s (for 30 km/h), respectively. There are two main reasons for this: on the one hand, MATSim does by default not implement time lags that occur when the first car of the queue leaves a link. On the other hand, capacities deduced from signaling plans only usually tend to be too high, since they assume that vehicles can leave the link if the signal is green. In reality, especially with mixed lanes (e.g. right and straight), cars that try to turn right might block the way of other cars wanting to go straight. This was actually observed during an inspection of this intersection. Therefore, a capacity of 1400 veh/h was chosen.



(a) Travel times taken from GPS data.



(b) Simulated travel times for scenario configuration G.

Figure 2: Comparison of real-world and simulated travel times on the test road; black dots indicate the average travel times over all eight days for every hour.

3. The real-world data in Figure 2a suggests that the minimal travel time is indeed 19s. However, due to the downstream traffic signal, the *expected* travel time with free flow road conditions is about double as high, e.g. when a car just misses the green phase, travel time directly adds up to about 60s. This effect is often called **phase failure** which is not represented by the default MATSim setup. In order to meet the expected travel time for vehicles traveling in free flow conditions, the maximum velocity for the test road is set to 30 km/h.

For these reasons, parameter configuration G in Table 1 and the resulting link travel times are selected for emission modeling in the next Section. In Section 6.2, the question will be discussed whether and – if yes – how the above findings need to be considered when applying this model to a large-scale scenario.

5 Results

This section compares emission levels based on MATSim output data to the emissions simulated by the emission model PHEM. Even though PHEM is a model itself and doesn't provide emission measurements there are two reasons why it is suited to be used in this analysis: it can compute the engine power demand in 1 Hz based on time-velocity profiles (Hausberger et al., 2009). Such modeling based on driving cycles provides a high level of detail since emissions per second are provided. The time-velocity profiles are segmented, according to the length of the test road, and can directly be used in PHEM. Beyond that, the emission factors of HBEFA 3.1 are mainly based on PHEM simulations. A validation of the emission calculation method applied in MATSim is therefore possible. PHEM uses driving cycles, driving resistance, losses in the transmission system and the road gradient as input parameters. The transmission ratios and a gear-shift model are used to simulate the 1 Hz course of engine speed. Transient correction functions are applied to adjust engine parameters, fuel consumption and emission levels. The HBEFA emission factors represent average values of vehicle categories and traffic situations and therefore PHEM creates models of "technology average" emission behavior. The resulting emission maps differ by fuel type, emission EURO-class, traffic situation and road gradient (Hausberger et al., 2009).

In this study NO_x emissions are calculated for the emission EURO-class 3 (HBEFA, 2010) and for both, diesel fuel and gasoline. For EURO-class 3 passenger cars, an average rated power of 82 kW is set in PHEM. Whereas PHEM simulates the emissions per second, the emission calculation tool of MATSim uses the HBEFA emission factors that measure emissions per distance. PHEM simulations are available for the driving cycles that are collected on three days, from July 07th to 09th, 2009, generating approximately one driving cycle for every hour between 6am and 8pm as described in Section 4.1.

Just by looking at the level of NO_x emissions based on PHEM and averaged over the three days (see Figure 3), it becomes obvious that at a few points in time the emission level deviates from expectations. A large deviation is found at 5pm, at which a higher traffic demand and therefore, a longer travel time resulting in a higher level of NO_x emissions is expected on average. A site inspection supports a high traffic demand at this hour. Thus, it can be stated that the NO_x emission level produced by PHEM for this hour is only based on an outlier in the data.

Emission levels based on MATSim output are calculated in two different ways:

1. Based on average speed (average speed approach)

2. Based on free flow and stop&go fractions (fraction approach)

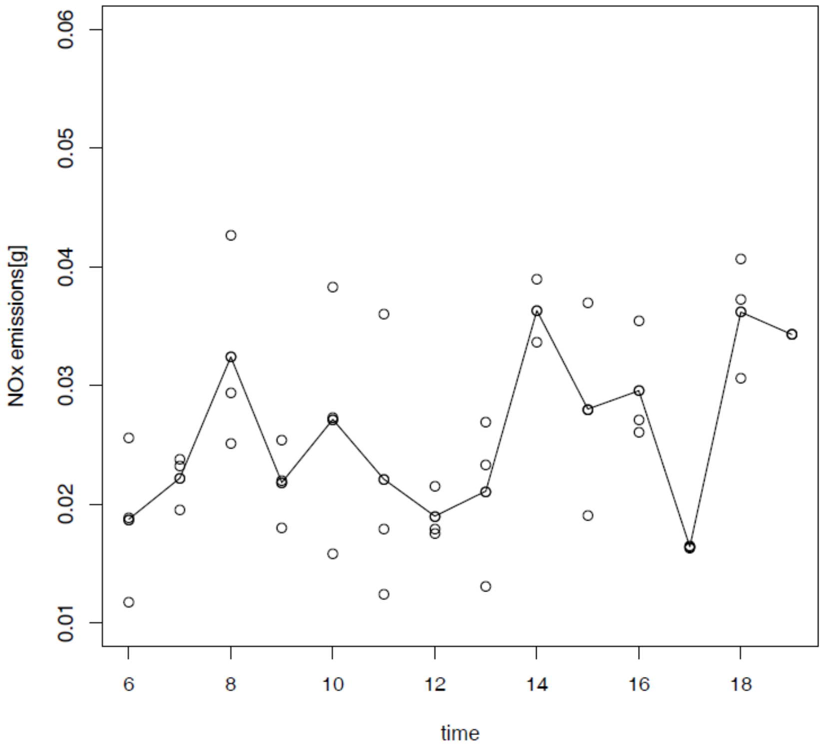


Figure 3: NO_x emission levels (gasoline) based on PHEM; average over three days.

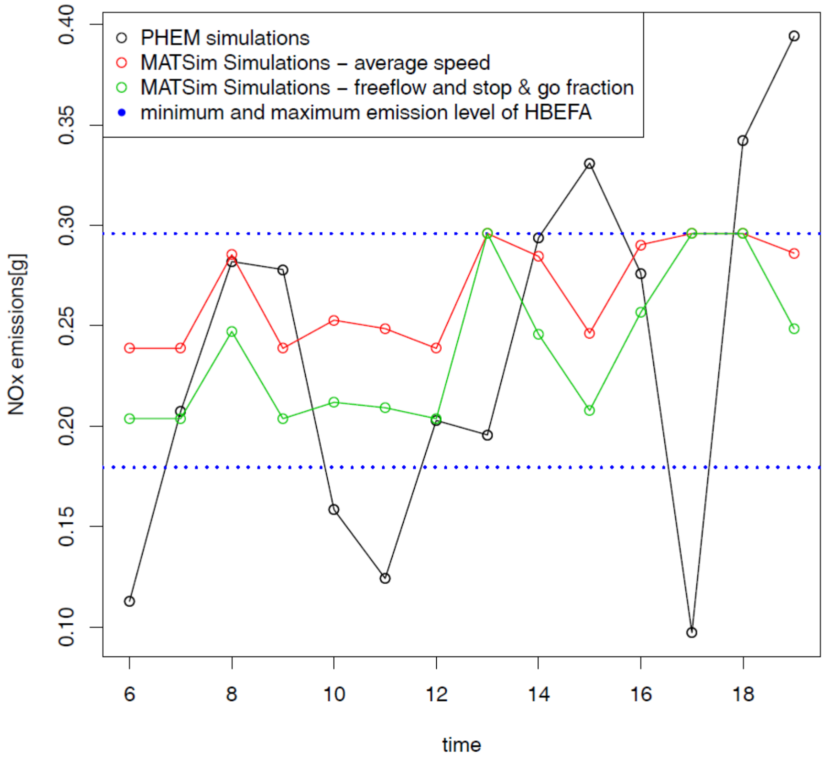
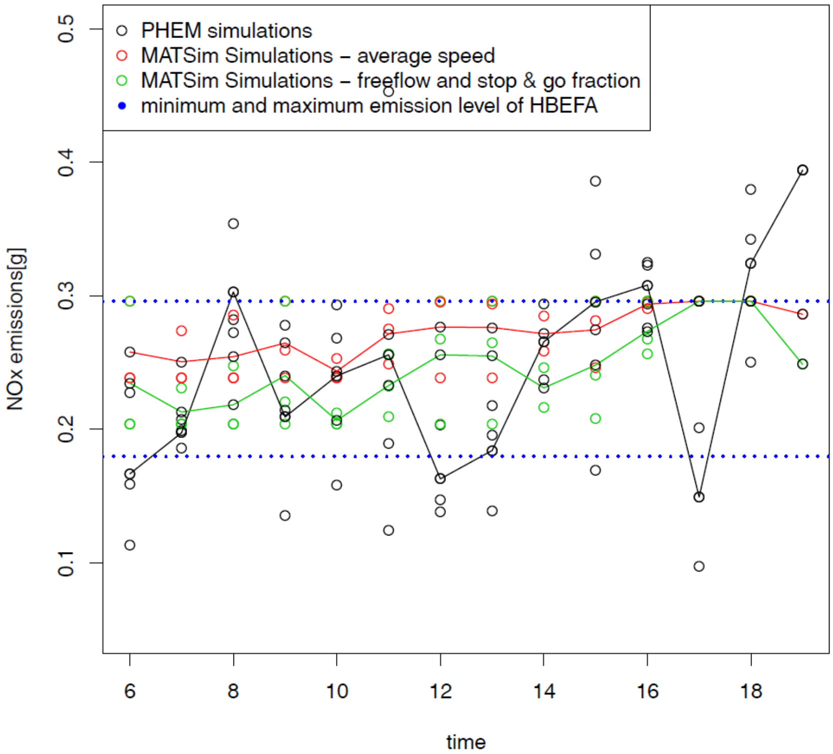
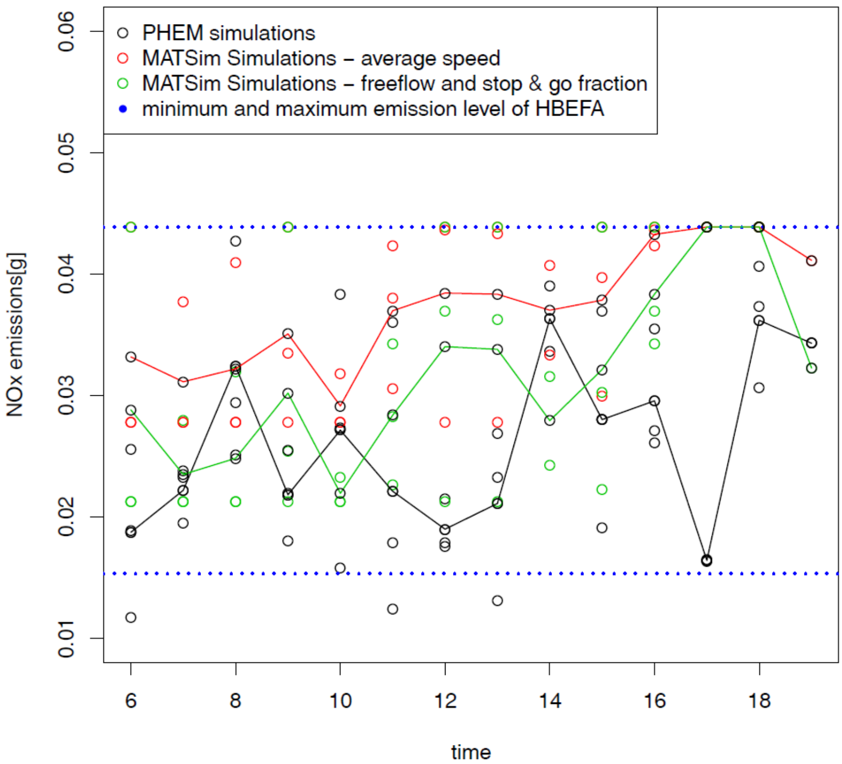


Figure 4: NO_x emission levels (diesel) for July 07th, 2009: in black PHEM data, in color the two MATSim-based approaches.



(a) Diesel fuel type



(b) Gasoline fuel type

Figure 5: NO_x emission levels for PHEM and the two MATSim-based calculations (average speed and fraction approach); average over three days.

Figure 4 and Figure 5 show the NO_x emission levels modeled by PHEM and the emission levels calculated by the two MATSim based approaches for one day and for all three days, respectively. With respect to one day, the main reason for the deviations between the curves is the difference in travel time. Overall the course over day is similar picking up the morning peak with higher emission levels, a decrease during late morning and midday and an increase towards afternoon and evening. Figure 5 differentiates between emissions levels for diesel and gasoline. The points represent MATSim and PHEM simulations for each day and the curves show the average over three days. Additionally, the blue, dotted lower and upper lines represent the minimum and maximum emission levels which can be calculated using the HBEFA emission factors. It is shown that it is not possible to simulate the emission levels that occur in reality with long travel times. Very low emission levels cannot be simulated as well. The reason is the distance based approach of HBEFA. A structural difference between the fraction approach and the average speed approach can be observed for both fuel types. The fraction approach generates on average lower emission levels than the average speed approach. Figure 5b shows that the fraction approach leads to a similar emission level as the PHEM results whereas the average speed approach generates on average higher emission levels than PHEM. This observation is partly supported by the course in Figure 5a. As it has been mentioned in Section 3, there is only a small difference between the emission factors of the free flow, heavy and saturated traffic situation. Therefore, it is important to determine the stop&go fraction which relatively contributes the most to the overall emissions. It can be observed that the fraction approach – due to the higher resolution of traffic situations– better approximates the emissions than the average approach which is based on one single emission factor for the entire link. Furthermore, the variations in the emission level are larger for gasoline than for the diesel fuel type. According to the HBEFA emission factors, the relative difference between emissions occurring in stop&go traffic situations and emissions resulting from the other three traffic situations is bigger for gasoline than for diesel.

Overall, the course of the emission level based on MATSim simulations shows a similar tendency as the PHEM simulations. The emission levels are generally lower during the morning peak. Towards late afternoon, where demand rises, an increase in the emission levels is found. These differences between PHEM and MATSim simulations can mainly be explained by similar deviations in travel times. In order to compare the course of the emission levels more in detail, the MATSim simulation needs to be applied to some more days. At the same time PHEM data or actual emission measurements must be available to validate the MATSim simulations. Here, it is shown that the emission calculation tool implemented in MATSim is able to approximate emission levels that look similar to PHEM data and shows similar tendencies over time of day.

6 Discussion

In this paper, we proposed two approaches of how to link MATSim output data and HBEFA emission factors in order to calculate emission levels in a test scenario. We showed that the resulting emissions are a possible approximation of those calculated by the very detailed model PHEM.

6.1 Extension of the emission calculation tool

The results have shown that it is difficult to validate simulated emission levels due to the difference in travel times when only selected driving cycles are analyzed. A limitation of the emission calculation approach occurs which is based on the distance dependency of HBEFA emission factors. As a consequence it is not possible to picture the difference in emission levels between driving cycles from a certain critical value on at which stop&go prevails. As time-velocity profiles are available for some more days, there is actually scope for a more intensive analysis if PHEM or actual emission measurements are available. There are still several possibilities to further differentiate the emission analysis. As described in Section 3.2, HBEFA emission factors and the agent's attributes of the MATSim simulation differ both with respect to vehicle and fuel type, engine size as well as age and EURO-class, respectively. This is a major advantage of using MATSim output for emission modeling: it keeps the agent's identity throughout the simulation. Thus, these additional attributes can be used in the post processing, the emission calculation tool. In this paper we only differentiated between gasoline and diesel because we aimed at giving a general overview of the emission modeling. Beyond that, an interesting investigation would be to analyze the difference in emission levels with respect to the EURO-classes and cubic capacity, for example the impact of particle filters that are – for diesel vehicles – required for EURO-class 4 and newer.

Apart from warm emissions, cold start emissions need to be assessed as they play a significant role especially in urban areas as the distances driven are short. The engine is sometimes not even warmed-up when the destination is reached leading to higher emissions throughout the travel than when the engine is already warmed-up. We will extend our emission tool in this direction.

6.2 Opportunities and challenges for large-scale real-world applications

When aiming at applying the approach presented in this paper to a large-scale real-world scenario in the future, great opportunities open up in the context of policy analysis and in shifting towards a more sustainable transport and urban planning. However, there remain some challenges that need to be addressed.

When taking a closer look at the challenges, the assumptions made for the test road need to be discussed. It seems that for emission modeling in general, meeting the real-world link travel times is highly important. The need of reconstructing these in simulations of a single link test road, where agents cannot take any decisions about alternatives in terms of departure time, route or mode, led to three necessary adjustments: first, on the demand side, departure times had to be set to the end time of the counting stations intervals. Second and third, on the network side, flow capacity and maximum free speed had to be reduced in order to obtain enough heterogeneity in the link travel times. These adjustments are not applicable for large networks. Fortunately, the link travel times are correct if the system did convert to a Nash-equilibrium (Nash, 1951). Thus, we expect these problems to be minimized for large-scale applications. This we will verify for the test road in consecutive studies.

The opportunities of this approach can be characterized as follows: in a first step, it allows the mapping of emissions to households or individuals and additionally provides information *where* (on which link) and *when* (exact time of day) they are emitted. In a second step, desired policy measures can be simulated and the reactions of the whole population or different subgroups can be analyzed. An example for such a policy could be raising distance based user costs for cars that are EURO-class 3 or older. It is then possible to identify winners and losers of the policy similar to Kickhöfer et al. (2010). At the same time, one could see the impact on the level of car emissions on every link over the day. Still, the overall system reaction can be calculated by aggregating the data. Furthermore, the approach presented in this paper can easily be expanded to the modeling of external effects caused by noise emissions in urban transportation.

7 Conclusion

In this paper, a methodology is developed of how to link the traffic flow simulation of MATSim to an emission calculation tool based on HBEFA. The tool uses two different approaches, one is based on average speed, the other on free flow and stop&go fractions. It was applied to a test scenario; it was shown that the simulated average travel times approximate the average travel times derived from driving cycles appropriately. Travel times were found to have a major impact on the total emission level. However, it is not possible to picture the emission levels that occur in reality with long travel times. The reason therefore is the distance based approach of HBEFA. The comparison between PHEM and MATSim simulated emissions shows a similar tendency of the emission level especially with respect to the late afternoon and evening hours.

The methodology developed in this paper is a starting point to further refine the emission calculation by the integration of the test road into a large-scale application. Further emissions generated by other emission sources, such as cold start emissions, can be added. In addition, different vehicle characteristics can be obtained from the agent's identity in the MATSim simulation. Thereby, a variety of opportunities is created to analyze several transport policies, determine the impacts on subgroups and urban quarters or canyons and be able to internalize such external effects.

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