Investigating emissions of traffic by simulation

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Keywords

transportation, traffic simulation, queuing model, emission inventory, air–quality management

Abstract

The applicability of a microscopic traffic simulator for the calculation of environmental impacts is discussed. This simulator is based on a queuing model approach (Q–model). Arguments will be given in terms of comparison to a simulator that models single vehicular dynamics. Simulation results show the importance of modelling dynamic effects to achieve high accuracy. Finally, an example for the application of the Q–model in air–quality management is presented.

1 Introduction

Street traffic represents one of the main polluters of air whose impact on environment is constantly increasing due to the rapid growth of traffic volumes in industrial conurbation. It is not even clear if the improvement in motor technology will be able to even up this development.

To analyse the effects of certain strategies to reduce air pollution, simulation models are useful and needed [1, 2]. They have to combine the modeling of different sources of pollution, e.g. industry and traffic, as well as the pollutants' transport and transformation by air chemistry. The work described here is focused on the problem of modeling air pollution due to road traffic. A microscopic dynamic traffic simulator (Q–model) used for this purpose will be described in section 2. Due to its computational efficiency it is suitable to calculate car emissions on the basis of individual vehicle units in a reasonable time, even for huge networks (about 10^6 cars). Recent investigations by means of simulation underline the necessity to take into account the dynamical properties of traffic flow, namely the "queuing up in jams", to properly map the strong temporal variability of car emissions. The applicability of the Q–model for the calculation of car emission inventories is discussed.

Moreover, results of simulations of air pollution concerning the area around the city of Cologne are presented in the last section. The intention of the interdisciplinary cooperation with metereologists is to combine the different models to investigate the causal chain emission – transmission – immission of air pollutants. By computing different scenarios, reduction potentialities are evaluated, in particular the impacts of emission sources that strongly vary in space and time as given for street traffic.

2 Emission calculation using a queuing model

The Q–model [3] is a vehicle oriented traffic flow model which was originally introduced to solve the dynamic traffic assignment problem (DTA) by simulation. One of its major features is its compu-

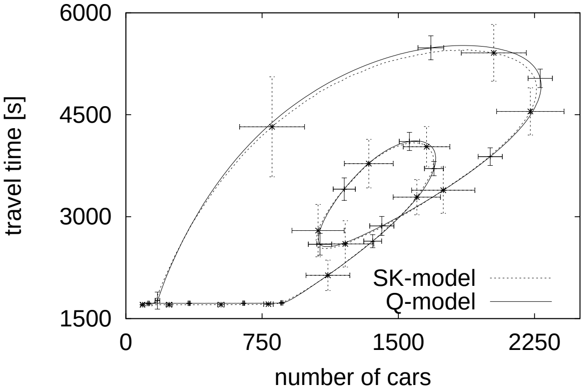

Figure 1: Comparison of travel time versus number of cars for the queuing model and SK–model. The dynamic changes in the length of the queue at the bottleneck are well reproduced. Data points are averages over 100 runs.

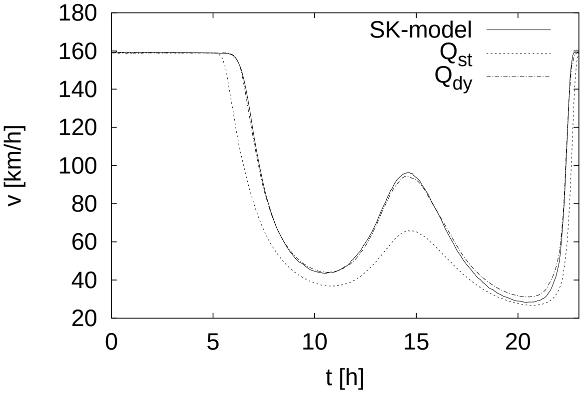

Figure 2: Mean velocity over time in front of the bottleneck. In the case of a constant capacity ($\mathtt{Q}_{\mathrm{st}}$), there is a shift to lower values compared to the SK–model. With a dynamic modelling of the capacity ($\mathtt{Q}_{\mathrm{dy}}$) an excellent agreement is achieved.

tational efficiency which allows the computation of traffic flows in large networks still being microscopic and dynamic. Microscopic here means that its input is a set of drivers with specified routes. This set is the solution of the assignment step in which the route choice for a given travel demand is calculated [4, 5].

In the Q–model the links of the network are primarily characterized by their maximum flow (capacity), length and maximal velocity. Each link is represented by a priority queue and an output queue. For each car entering a link the travel time is calculated under the assumption of free flow conditions. They are stored in the priority queue according to their travel time and are transmitted to the next link via the output queue when this time is elapsed. The number of cars that can leave a link is constrained by its capacity and by the maximum number of cars which fit into the next link. If more cars than the link capacity arrive, a queue starts to build at this link in the output queue. In doing so the model allows to take into account dynamic effects like spill–back.

To demonstrate that the Q–model is well suited to compute car emissions, its results are compared to calculations using a microscopic car–following model (SK–model [6]) which is a further improvement of the well known Nagel–Schreckenberg–model [7]. The SK–model describes jam formation and changes of vehicle speeds in a "realistic" manner.

A system with a merging of two lanes into one was set up. It consists of two road sections (one with two lanes, the other with one) of $37.5\,km$ length each which are connected with a short merging region. While in the SK–model the lane changes in that region are modeled explicitly by a set of rules, in the Q–model it is represented by an additional road–section with a maximum throughput. A periodic input flow showing the typical structure of two "rush-hours" per day was used. During the rush-hour peaks the inflow exceeds the maximum throughput of the merging region. Therefore, it behaves like a dynamic bottleneck with queuing of cars. The crucial question is whether the simple queuing model is able to map dynamic effects like spill–back properly. In favour to compare the two models with more statistical confidence, averages over 100 simulations runs have been taken for each situation.

In figure 1 the relation between travel time and the number of cars in the system for both systems

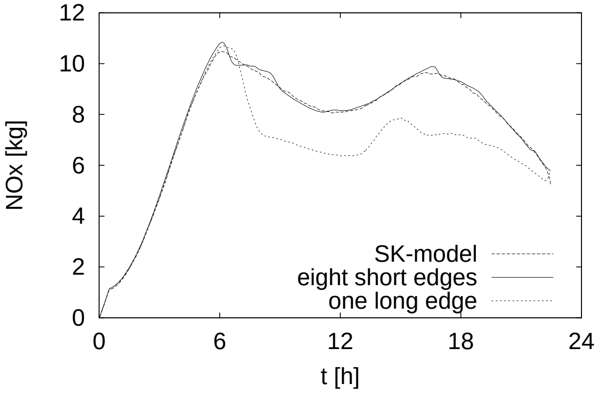

Figure 3: Comparison of NO_x emission for the same scenario as in figure 1. If the average edge–length in the queuing model is on the order of 4 km or smaller (as for city networks) the time dependence of the emission is quantitatively well reproduced.

is shown. The dynamics is very well reproduced including the temporal development of the length of the queues (loop structure). The same applies for the flow through the bottleneck and the development of the travel time over simulation time whose absolute error stays below 2% (not shown). Simulation results show that the throughput of the bottleneck is not a constant. Therefore the capacity of the bottleneck in the Q–model was modelled as a function of the number of queued cars in order to achieve high accuracy [8]. The effect of using just a constant capacity on the mean speed in the system can be seen clearly in figure 2. There is a shift towards lower velocities, since a constant capacity does not allow short periods of high metastable flows which are found in real traffic.

A comparison between the emission of NO_x (just to choose an example) is shown in figure 3. For both models they were calculated using a "table of emission factors" that relates individual vehicle speed to the amount of emission. However, as one can see, just to reproduce the mean behaviour of the traffic system in term of velocity is not enough to achieve good results in the calculation of emissions. Even though the mean velocities are the same in both systems, the queuing model underestimates the total emission of NO_x.

The reason is that the queuing takes place at the end of the edge while in the remaining part of the edge the cars flow freely. With the growth of the queue the free-flow part of the edge is reduced more and more. A solution to this problem is to subdivide the edge into several pieces so to have periods of free flows interlaced with the formation of queues. The maximum number of cars that fit into each piece has been adjusted respectively. Indeed, using pieces of around $4km$ length, the results are much better, with small discrepancies around the sixth hour when the queue starts to build (see figure 3). Fortunately, this splitting of the edges is already given in city networks due to their typical shortness. The important point is that if the network structure is chosen in a way that free-flow and congested parts in front of bottlenecks can be separated appropriately, the Q–model is appropriate for an accurate calculation of street traffic emissions.

It is important to stress that one time step in the queuing model is 10 times larger than for the SK-model. This fact, together with its algorithmic details, makes it noticeable faster. Computational efficiency is an important factor regarding the iterative approach needed in the assignment step (see section 3) and may be crucial when using the model to simulate a large number of scenarios.

3 Example of use: NO_x around Cologne

As already mentioned in section 1, the methods presented here are being used in a joint work to investigate possible reduction–scenarios concerning air quality [9]. At present the work focus on the comparison of simulation results with measured data (due to availability, the year 1997 has been chosen) to validate the modelling of the causal chain emission – transmission – immission of air pollutants in conurbations.

On the basis of a time–dependent travel demand matrix for the city of Cologne the traffic assignment

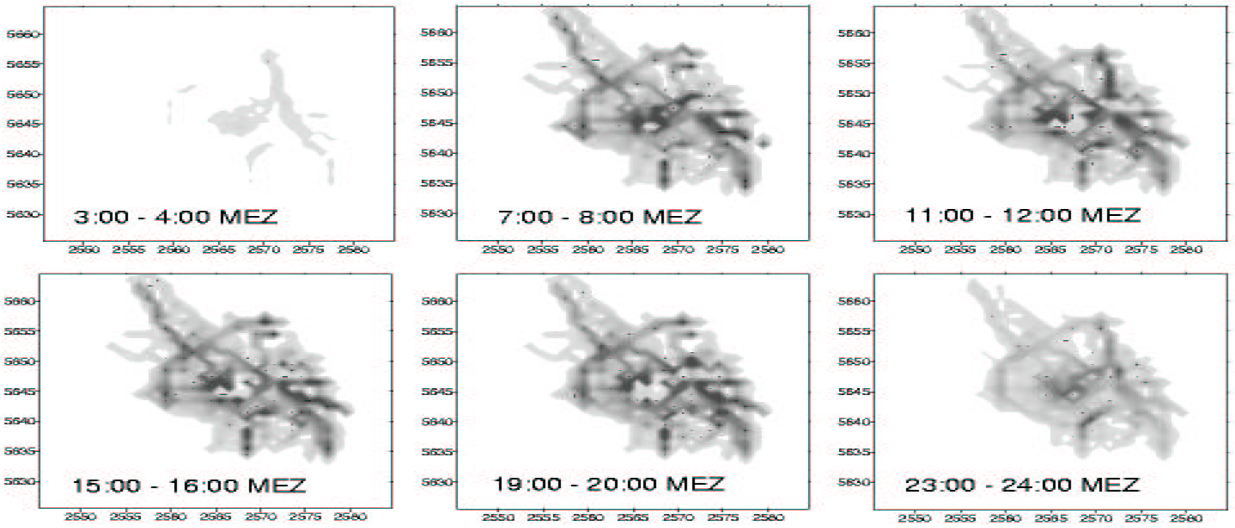

Figure 4: Computed spatio-temporal concentration of NO_x emitted by street traffic on a typical workday around the city of Cologne at different daytimes. Higher concentrations are indicated using darker colours. Transit traffic for that region has not been included.

step is performed. A simulation based approach is used for this step, in which the individual travellers learn about the travel times on different routes within an iterative process [4]. Since this approach is dynamic, the dependence of the travel time on the history of the system is taken into account in contrast to widely–used static assignment models.

Using the calculated routes the emission of several pollutants have been computed using the queuing model (see figure 4). One can see the strong variation of the amount of pollutants over the day which corresponds to the dynamic variation of traffic patterns. The resulting emission inventories entered the simulation models of meteorology to calculate their spreading and spatial impact. The results for NO_x are shown in figure 5 together with annual averages taken at measurement spots. It can be seen that calculated concentrations are too low in particular at spots located close to highways. However, this may be due to the fact that up to now transit traffic has not been taken under consideration in the input data. This will be done in a future step. However, the combination of the different models will be computationally efficient and accurate enough to investigate different reduction strategies.

4 Summary

We have shown that a simple queuing model is able to reproduce the dynamic effects of traffic compared to more a detailed model [6]. Therefore, it is applicable to an accurate calculation of the emissions of street traffic. For sake of computational efficiency the choice of the time step and corresponding parameterizations in the queuing model has still to be investigated to improve its use for scenario calculations. To investigate a large number of scenarios with the combination of different models, efficiency and accuracy are mandatory.

The authors wish to thank the Deutsche Forschungsgemeinschaft (DFG) for supplying their work within the Collaborative Research Centre (SFB) 419 at the University of Cologne. The time dependent travel demand was kindly provided by the Institut für Stadtbauwesen (RWTH Aachen).

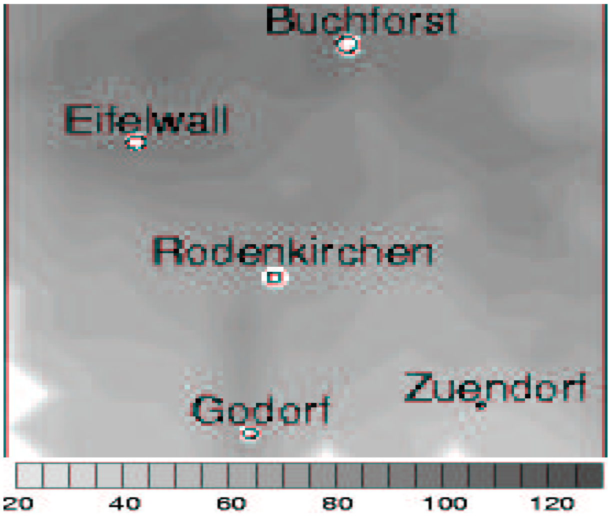

Figure 5: NO_x–Immission [$\mu g/m^3$] around the city of Cologne calculated using the emission pattern of figure 4. The white spots indicate given annual average values of 1997 taken from measurment stations; black circles correspond to simulation results. The size of the circles correspond to the amount of NO_x.

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