

Evolution of SUMO's Simulation Model

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Abstract: This text gives a short account on DLR's open source micro-simulation tool SUMO. It does so mostly by reporting some of the applications cases that had been performed with the help of SUMO. These application cases show that SUMO is a very versatile, timely, and mature research tool which nevertheless is continuously developed further.

1 INTRODUCTION – A SHORT ACCOUNT OF SUMO

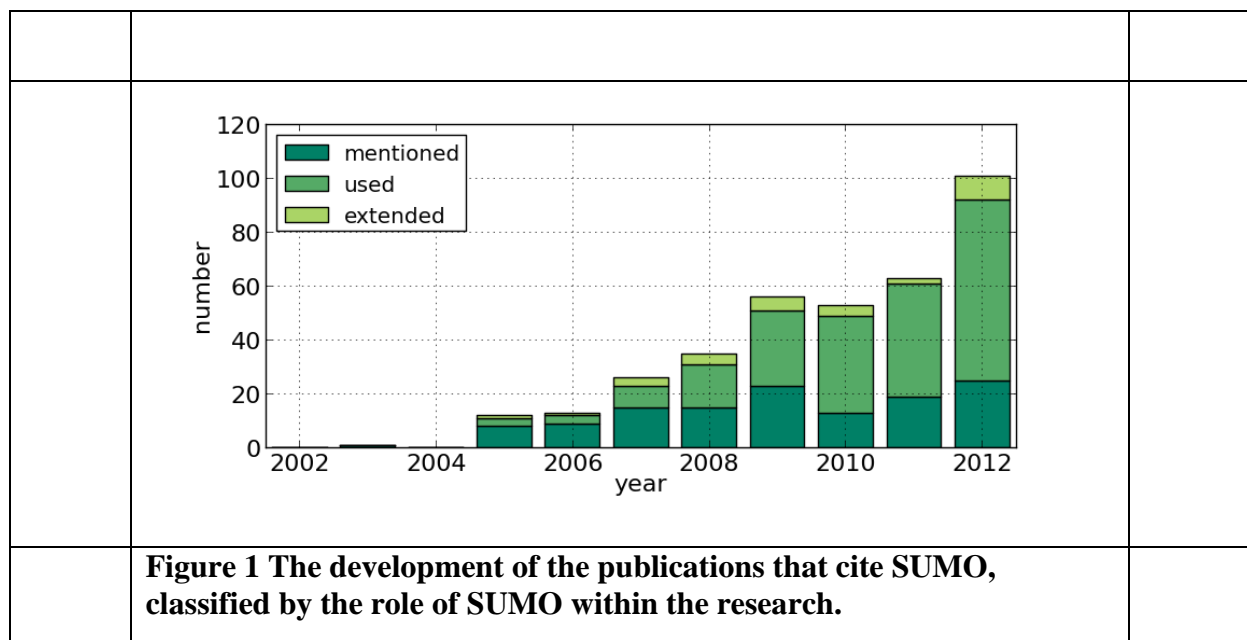
Arguably the first micro-simulation model that made it into a journal article was the one introduced by Reuschel in 1950 [1]. Ever since, a continuous string of new microscopic traffic flow models has been invented, see the reviews [2], [3], [4] for more details. Today, still new models are invented or older ones are improved, and there seems to be not end in sight to this process. Also, since the late of the 1980, first implementations of such models into micro-simulation packages have been reported. The first tools have mainly being used to help with the design and optimization of traffic signals at intersections, but today even large scale simulations are to be performed by such tools. Of course, when going truly large-scale, simplifications of the underlying dynamics is needed which is often done with so called queueing models. An example of this is the MATSim project [5].

The implementation of the microscopic traffic simulation SUMO [6] [7] started in 2001 as a co-operation project between the DLR and the Centre for Parallel Computing at the University of Cologne. SUMO was from the beginning designed as an open source project. The major reason for supplying an open source tool was the observation that many similar applications were built as an intermediate tool needed to evaluate a developed traffic management application or a model of traffic. After closing such a project, the used traffic simulation was usually abandoned. Having a common test bed makes the implementation of an own evaluation system unnecessary, saving time and allowing to concentrate on the application, not on the evaluation system. Additionally, it was assumed that the usage of a common test bed increases the comparability of different traffic management applications. Since 2002, SUMO has been used within many of the projects the German Aerospace Centre participated in. We have to admit in addition that we have learned a lot about traffic and traffic flow itself by writing and testing the software.

The initial purpose of the simulation was to deliver travel times of a synthetic population of the city of Cologne. The major requirement was therefore to simulate large urban areas, of course as fast as possible. Albeit SUMO has been used for other purposes as well, the requirement for a fast simulation of large networks had a strong influence on the design of the simulation suite; a more detailed explanation is given in section 3.3. The available hardware was heterogeneous, including desktop computers running the MS Windows operating system, as well as Linux and even Solaris systems. This dictated a strong focus on portability. Nowadays, the SUMO can be run under all major operating systems, including the named ones and additionally MacOS.

Originally, just one microscopic traffic flow was built into SUMO that was the model of Krauß [8]. This model bears a strong similarity with the Gipps model [9], however it has been radically designed for simplicity. Meanwhile, SUMO hosts a small number of well-known traffic simulation models, like the Intelligent Driver Model (IDM), the Wiedemann model, one of Kerner’s three phase models, and a few less well-known experimental models.

But making software available as open source matters only if groups interested in such a software exist. Meanwhile, SUMO is routinely being used in a considerable number of internal projects as well as by a world-wide community. In [10], the evaluation of 362 papers that cite or at least mention SUMO is given. It shows that the number of such publications increases – almost continuously, as visualised in Figure 1. From this analysis, it is known that the majority of the research with SUMO is done within “sole projects”, such as Master theses. But on the other hand, long-term single users are known as well as organisations, mainly universities, which start to use SUMO for teaching purposes.



2 SOFTWARE DESIGN AND MODEL DEVELOPMENT

Models like the Gipps and IDM are constructed as car-following models. To make them useable for the simulation of traffic flow in a realistic environment (urban or motorway), they

need to be extended by more complex tasks. In the following sections 2.1 and 2.2 the intersection and the lane changing model, respectively, will be discussed. Together with car-following, these three form the heart of the microscopic simulation.

However, this is not all. To run a microscopic simulation, not only the behaviour of all traffic participants must be defined, the participants and their environment must be defined as well. In other words, the simulation road network including traffic lights, the traffic demand and also the fleet composition must be declared. Modelling the scenario is a task left to the end user and it is by no means trivial. To aid and empower the user, SUMO is designed as a suite of applications to support these preparatory tasks. An overview over these supporting applications is given in section 2.3.

Finally, there are a number of simulation tasks which require dynamic control of a running simulation. In section 2.4 the TraCI API of SUMO is described which allows client programs written in different programming languages to control a running SUMO simulation. Usage examples for this type of control are given in section 3.3

2.1 Intersection Model

The behaviour of vehicles when approaching and crossing an intersection is of immense importance when simulating traffic microscopically in urban environments. Here, vehicles need to avoid collision with any vehicle that crosses their path. This requires dealing with a number of different schemes for intersection control which are found in reality such as priority intersections, right-before-left rules and traffic lights. In contrast to car-following models where the ego vehicle typically has no influence on the behaviour of its leader vehicle, a vehicle passing an intersection can assume that its presence on the intersection will cause oncoming vehicles to adapt their behaviour. For this reason, the intersection model in SUMO is considerably more complex than any of the car-following models. The complexity of intersection models in general is also the reason why this part of the simulation architecture cannot be as easily exchanged as the car-following model.

During the evolution of SUMO the model has experienced a growing increase in complexity. In the beginning, the model only answered the question whether a vehicle should pass an intersection and this vehicle would then instantly continue driving on the other side of the intersection, seemingly “jumping” across. In later stages of the model, the driving dynamics on the junction were also modelled. This prompted considerations such as the stopping position of left-turning vehicles within the intersection while waiting for a gap in oncoming traffic. Another aspect where the complexity of the model has grown is the acceptance of safe time gaps when crossing an intersection without having the priority. In older versions of the model, vehicles would not enter an intersection if it meant that other vehicles had to adapt their speed at all. In the current versions, a concept of “impatience” is implemented where vehicles may enter the junction even if it means that vehicles with priority have to slow down a bit.

For the future evolution of the intersection model it would be desirable to increase the modularity to allow research on alternative models. This might be achievable by dividing the intersection model into smaller parts with well-defined interfaces.

2.2 Lane-Changing Model

Another core component of the vehicle dynamics is the lane-changing behaviour. This is needed to simulate behaviour on multi-lane roads which occur frequently in urban environments and on motorways. Vehicles change their lane for multiple reasons including mandatory as well as optional manoeuvres. The lane changing model in SUMO currently recognizes four reasons for lane-changing:

- Strategic (another lane must be used to continue the current route)
- Cooperative (the vehicle would like to clear the lane for another vehicle)
- Speed gain (the vehicle speed up its travel by changing to a faster lane)
- Keep right (the vehicle should keep the left lanes clear for faster vehicles)

The lane-changing model not only governs the “motivation” for changing lanes, it is also responsible for adapting vehicle speeds to allow lane-changing manoeuvres to take place. This is of immense importance in dense traffic flow because the vehicles need to maintain safe distances to all vehicles on the target lane to avoid collisions later on. Achieving safe distances often require speed changes by the ego vehicle as well as by vehicles on the target lane. Among the questions that typically need to be answered by the lane-change model is whether a blocking vehicle on the target lane should be overtaken or whether it is better to slow down and take this vehicle as the leader.

Due to the different motivations for lane-changing and the large number of traffic situations that must be dealt with (in regard to urgency of lane-changing and occupancy of the target lane) the lane-changing model in SUMO is arguably even more complex than the intersection model. Nevertheless, the model is already compartmentalized from the rest of the simulation and different lane-changing models can be selected. The enormous impact of the lane-changing model on simulation behaviour could be seen recently when a new model was implemented in SUMO. Motorway scenarios that experienced strong congestion using the older model exhibited freely-flowing traffic when run again with the new model (see section 3.6). One important aspect

that was changed was the way how vehicles ensure the success of strategic lane-changes and the avoidance of dead-locks when two vehicles need to change in opposite directions and thus block each other. An example of this situation to be avoided can be seen in Figure 2.

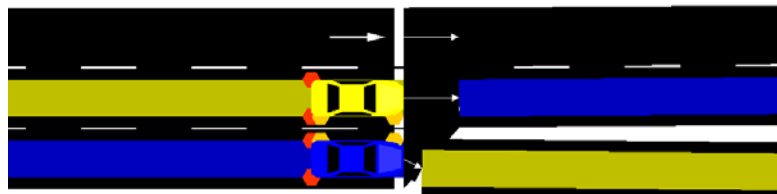


Figure 2 Deadlock on a motorway. Two vehicles need to change in opposite directions and block each other's path. In reality drivers might even change their route to avoid blocking the motorway.

For the future it is planned to increase the configurability of the implemented lane-changing models by exposing more calibration variables to the end user.

2.3 Applications for Scenario Modelling

One of the first major applications was the simulation of large cities, mainly the city of Cologne for supplying travel times to a demand model based on a synthetic population model that was developed in parallel. Quite early, the need to extend available road network representations by simulation-specific information, such as proper right-of-way representations, simulation-specific representations of traffic lights, etc. got obvious. As this information was not given within the available digital road networks, heuristics for computing them had to be implemented. This computation has to be performed only once for every "imported" road network and as it may take some minutes for large road networks, it was decided to embed it into a dedicated application, not directly into the simulation.

Similar constraints and assumptions about simulation usage apply for the computation of vehicle routes. In most cases, the simulation is used to evaluate some kind of a system that changes the behaviour of traffic by changing infrastructure elements, such as traffic lights or by changing the behaviour of vehicles. The simulation is used to compare the performance of traffic with such a change against the initial (original) behaviour. Usually, the same demand is used to simulate both variants. For larger scenarios, the demand is usually imported from O/D matrices and a traffic assignment is performed. This is usually very time-consuming, since it requires running the same simulation (with a changed set of routes) over and over again until equilibrium is reached. Therefore, the computation of routes is not performed within the simulation either, but by an additional application. This application is responsible for computing routes using travel times obtained from the traffic simulation.

Summarizing, to run a SUMO simulation the user must prepare at least a simulation network file and a demand definition file in a specific XML format. SUMO's approach is to support this work by providing additional tools with a certain purpose. Overall, the suite supplies the following applications:

- **NETCONVERT:** Imports digital road networks in commonly used formats such as OpenStreetMap, VISUM, Vissim, Shapefile, OpenDrive and many more. Information missing in the source networks such as traffic light plans and lane-to-lane connectivity are supplemented heuristically. Road networks can be modified in various ways (i.e. by removing edges, adding more traffic lights, etc).
- **OD2TRIPS:** Disaggregates origin/destination matrices into individual vehicles departing at specific points in time.
- **DUAROUTER:** Computes fastest paths based on given travel times and implements route choice models for route alternatives. When iterating simulation and routing this can be used to compute the Dynamic User Assignment.
- **DFROUTER:** Computes routes matching given detector flow measurements
- **JTRROUTER:** Computes routes matching given junction turn ratios.
- **TOOLS:** More than 40 additional applications to process simulation outputs, prepare input files, compare networks, etc.

The tools allow using a large variety of available data to set up simulation scenarios. Nonetheless, we observe that some user needs are not covered properly, yet. This mainly

concerns the generation of a demand for a given area. For instance, when using the JTRROUTER on large areas where only turning ratios at intersections are given, then the routes generated have unrealistic loops. The DFROUTER can only be applied on highway networks, and the O/D matrices that are usually used by DUAROUTER are not always available. Two attempts are followed to close the gap, supporting complete simulation scenarios and the implementation of further tools that estimate a demand for a given area.

2.4 TraCI

In many use cases for microscopic traffic simulation, the behaviour of the simulation must be adjusted dynamically while the simulation is running. A typical example is the simulation of applications based on vehicular communication (V2X). These V2X applications as well as the communication are not part of SUMO but are controlled and provided by external programs. However, they use information from the simulation such as the proximity of vehicles and they influence the simulation dynamically i.e. by altering vehicle speeds or routes. The same holds true for the development of new traffic control algorithms in general, like ramp metering, traffic signal controls algorithms, or freeway applications.

To allow for these use cases, SUMO provides the **TrafficControlInterface** (TraCI) which allows client programs to retrieve information and to influence the simulation over a network socket. To use this functionality, libraries are provided in various programming languages which can be used to write control programs for the simulation. Among the currently supported languages are python, C++, and Java. Exemplary functions from the python library are

- `traci.vehicle.getSpeed(vehID)` and
- `traci.vehicle.setRoute(vehID, edgeList)`

The socket interface is well documented and the Java-libraries are maintained outside the DLR. Likewise, Matlab-libraries for TraCI are currently being developed outside the DLR and expected to be included in the next release of SUMO.

3 SELECTED SUMO CASE-STUDIES

This section will describe more detailed some of the case studies that have been done with SUMO. Some of the scenarios can be found on SUMO's homepage [7].

3.1 Comparison of intersection control algorithms

In [11], a case study can be found that demonstrates how such a comparison works. There, a new traffic control algorithm named delay-based control was tested against an idealized fixed-time control and against a standard traffic-actuated control that worked with loop detectors. Albeit the intersection used was a highly abstracted (but fairly generic) one with four arms and two phases, the simulation tested a whole range of demands (in fact all possible ones). This is done as follows. From the range of demands (e.g. 100, 200, ..., 1000 veh/h) pick a pair (q_1, q_2) and compute for this pair the optimum fixed cycle parameters, i.e. the cycle length and the green times. Run a simulation with this set-up which works as the base scenario, and

then run two additional simulations with the same demand, but with a different control strategy. Now, the three simulations can be compared with each other, leading to a fair comparison. Note, that the delay-based control runs with input via vehicle-to-infrastructure communication, so there is a dependency on the equipment rate as well, which can be measured via simulation. A typical result is shown in Figure 3.

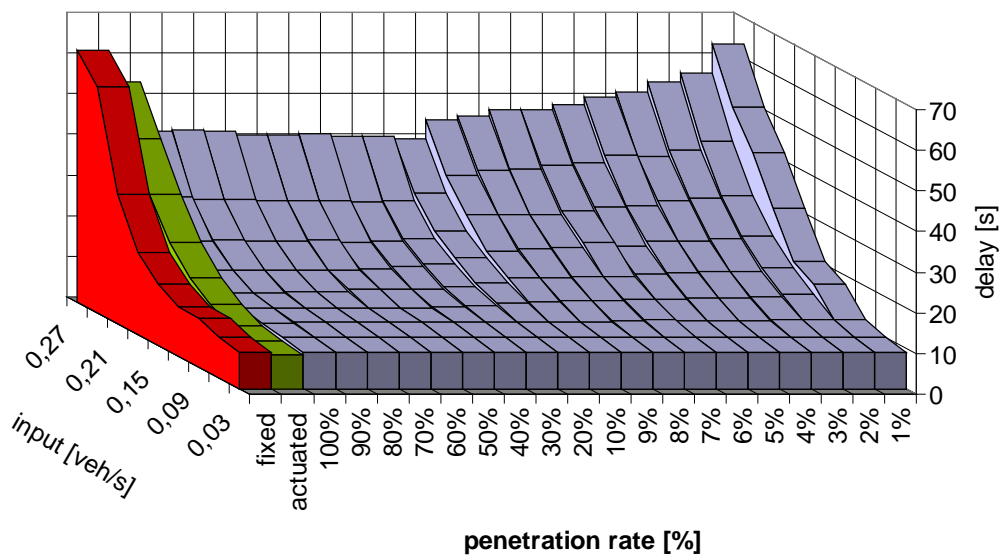


Figure 3 Average delay times of the fixed time control (red), the traffic actuated control (green) and the delay-based control (grey) as function of ratio of equipped vehicles and traffic flow.

Recently [12], this approach has been extended by using a combination of GLOSA (Green-Light-Optimal-Speed-Advisory, see section 3.3.2) and a dynamic programming approach to create an intersection control strategy that minimize energy consumption at a single intersection.

3.2 Emission modelling

The computations of vehicular emissions and of fuel consumption were first targeted in 2008, in the scope of the “iTETRIS” project, co-funded by the European Commission [13]. The task was to extend SUMO by according models to determine whether the developed V2X-applications besides improving traffic flow also reduce the environmental impact of traffic. The resulting model should have computed the pollutants CO, CO₂, NO_x, HC, and PM_x as well as fuel consumption. Additionally, a noise model had been implemented that will not be discussed here. Please note, that SUMO hosts emission models only. No attempt has been made to work on the effect of such emissions, i.e. to have an immission model.

The model should have worked on a “microscopic scale” for different reasons. The first is SUMO’s microscopic nature – aggregating the simulation state into a kind of macroscopic states as required by inventory models would add an unnecessary error. The second is grounded in the major scope of most investigations, namely vehicular communications (see

also section 3.3). As usually only a fraction of the vehicles is assumed to be equipped with such a technology, the emission model should allow to investigate the emissions of both equipped and unequipped vehicles, and to compare them against each other. But this is only possible, if each vehicle can be accessed individually. The third reason is the granularity of the effects of the investigated applications. Some of them affect the acceleration behaviour of single vehicles rather than changing the macroscopic state of traffic. The accelerations are but one of the major factors influencing the amount of emitted pollutants. As a result, a model was assumed to be needed that takes into account the acceleration behaviour of vehicles.

After evaluating 15 emission models, the decision to use the inventory model HBEFA ([14], at that time available in version 2.1) as the input for an own model was taken. HBEFA is a macroscopic inventory model and covers a large part of nowadays' vehicle fleet (for European countries such as Germany or Austria). HBEFA does not include information about the influence of a vehicle's acceleration on emissions. This was substituted by using the influence of the road slope on emissions that is given in HBEFA. To integrate the HBEFA into SUMO, the tables have been fitted with a function $e(v, a) = c_0 + b_1va + c_1v + c_2v^2 + c_3v^3$. During a simulation run, SUMO inserts in any time-step the current speed and acceleration into this expression to compute the amount of emissions produced. To ease the set-up of scenarios by avoiding the need to explicitly give the distribution of vehicle emission classes on vehicles, the obtained coefficient sets (for 93 vehicle classes) were classified using a clustering algorithm. Finally, three different classification schemes for heavy duty vehicles and two for light vehicles were chosen. Incrementing the number of clusters does not significantly increase the quality of the fit as could be measured by, e.g. the residual sum of squares.

The implementation of the emission model allowed benchmarking the emission behaviour of the applications developed in iTETRIS. In addition, some research has been performed that used the ability to compute emissions. The first of those to name is "emission-based routing". In [6], results are reported where a traffic assignment used the amount of emitted pollutants instead of the travel time for the road network's edge weights. Further tests of similar kind but have shown unstable behaviour of such an emission-based assignment processed. Digging deeper, it turned out that such an assignment lacks a unique user equilibrium solution. This is due to the effect that the energy consumption of vehicles has a minimum at speeds around 60 km/h. It can be shown, that this carries over to a link performance function whose cost function (energy) is dependent on demand, but now with a non-monotonous link performance function: for small and large demands, the energy consumption is big, while it is minimal in between. This may be an explanation of the observed instabilities.

European laws force real-world traffic management to cope with vehicular emissions by enforcing thresholds for pollutant concentrations (EC-Directive 2001/81/EC). Some cities instantiate certain traffic management actions that aim at reducing the amount of emitted pollutants.

Now, given a certain city - what could be the best traffic management action to be instantiated? The combination of a microscopic emission model and a fast traffic simulation allows answering such questions, including the change in traffic participants' behaviour due

to changed travel times or restricted areas. In [15], three emission reduction actions have been investigated, a speed reduction to 30km/h in living areas, a permissive environment zone and a restrictive environment zone. This research was the first one that used the emission model PHEMlight (see below), which allows to distinguish EURO-Norms.

Emission modelling in SUMO is itself not yet finished. Within the COLOMBO project, the emission model PHEMlight was implemented and embedded into SUMO. It uses data obtained by re-sampling the emissions computed by PHEM [16], an instantaneous emissions model that is used for the development of HBEFA as well as of COPERT, an inventory emissions model. The inclusion of this second model was done by extending the available emission classes by the ones PHEMlight includes and deciding which model to use internally, depending on the emission class of the vehicle to compute emissions for. Within the project AMITRAN, also co-funded by the European Commission, SUMO is extended by a third emission model, derived from HBEFA v3.1. It uses new methods for fitting the used function to data and new vehicle classification schemes. In SUMO's vehicular emissions modelling capabilities, the influences of the load of a vehicle on its emissions as well as cold-start emissions are not yet regarded.

After having gained some initial insights into the work with emission models, we would like to state that neither the complexity of modelling emissions nor their implementation in software are the crucial points of such investigations. Rather than that the interpretation of such fine-grained results for which proper presentation and/or aggregation has to be found as well as a wise set-up of scenarios cause the major problems. Additionally, when looking at acceleration-dependent emission behaviour, the correct acceleration behaviour of the used car-following model gets into focus.

3.3 Vehicular communication

Figure 4 taken from [10] shows the development of the topics SUMO was used for, over years. There is a clear dominance of research on "V2X" – vehicular communication or vehicle-to-vehicle and vehicle-to-infrastructure communication. V2X is a technology: vehicles equipped with a communication device send information about their state, including their position, speed, acceleration, etc. Other equipped vehicles as well as equipped road-side units (RSUs) can receive this information and trigger certain actions, starting with a warning if the vehicle in front performs a hard brake.

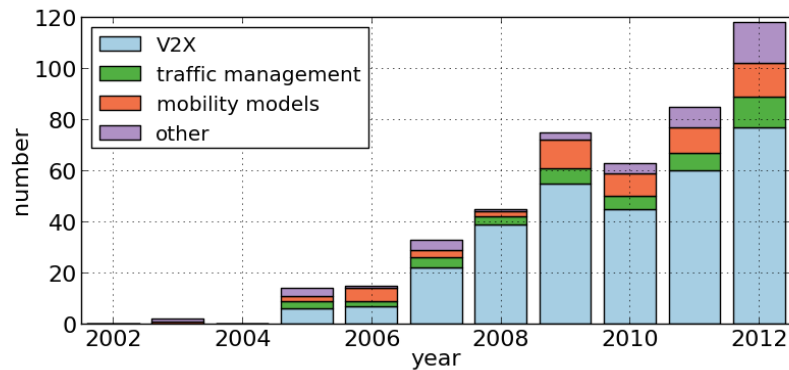


Figure 4 The distribution of research topics along publication years (multiple assignments possible).

Within the development of SUMO, a first communication model was directly embedded into the simulation in 2008. But the usage of SUMO for V2X-research is not mainly driven by DLR. In 2007, other groups have used SUMO to obtain “traces” – vehicle trajectories containing position and sometimes speed updates for each “equipped” vehicle that could be used as input to communication simulators. The usage of SUMO within the MOVE framework was probably the first step in making SUMO interesting for research on V2X. In 2008, the Technical University of Lübeck extended SUMO by a socket-based interface that allows to obtain values from SUMO and to control the behaviour of simulation structures, such as vehicles or traffic lights [17]. This extension allows interacting on-line with ns-2, a communication simulation. This extension was the first step towards opening SUMO for being usable in combination with a large number of other communication simulators and middleware solutions used for this purpose. In [18], it was showed that SUMO is getting to be the most popular traffic simulation used for evaluating vehicular communications.

The work performed using SUMO ranges from very low-level evaluation of the behaviour of the communication channel up to large-scale evaluations of the performance of a given application (mainly navigation) in city-wide scenarios. The model implemented in 2008 was removed from SUMO meanwhile, to concentrate on the task of simulating traffic. In the following, a brief description of three of the investigated applications is given.

3.3.1 Bus lane management

The increasing mobility is a major challenge for large cities. Therefore, public transport is often prioritized by traffic managers. Likewise, the city of Bologna has lanes which are restricted to be used by public transport only. Furthermore, the city of Bologna has small, narrow streets which are frequently used at a normal week day. But there are also big events like football matches when the traffic infrastructure is confronted with a huge additional traffic demand. The idea of the application investigated in the iTETRIS project was to open the lanes restricted to buses and allow private cars to use these lanes in case of an additional traffic demand. A detailed description of the application can be found in [19]. The simulation scenario is showed in Figure 5.

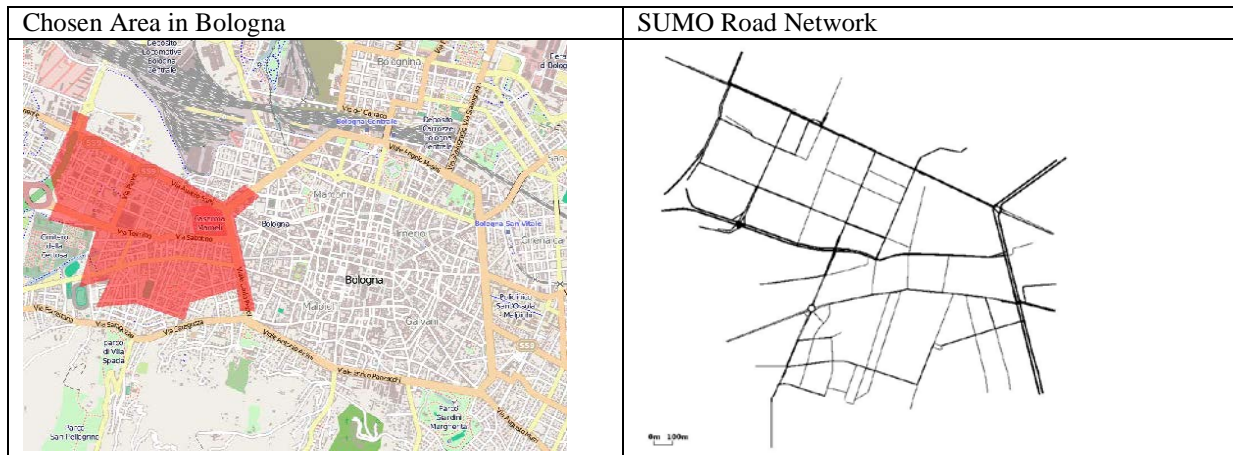


Figure 5 Simulation scenario city of Bologna.

For implementing this application two steps were necessary:

1. Determining an unusual high traffic demand:
Road side units (RSUs) have been placed at major intersections in the simulation scenario. The RSUs are collecting the cooperative awareness messages (CAMs) send by all equipped vehicles in communication range.
2. Open bus lanes for private cars:
If the average speed of the collected CAMs falls under a specific threshold an additional traffic demand was assumed. Therefore, the RSUs send messages to all equipped vehicles which inform the car that the bus lanes are open to private cars, too. The vehicles which receive this message are calculating the best route according to the new traffic situation.

Using speed as an indicator for recognising an increasing traffic demand is rather uncommon, but in the evaluation of the simulation scenario it produced usable results. Especially for small equipment rates it was possible to indicate additional traffic demand using this measure. Note, however, that speed is just a proxy for the demand, so scenarios are imaginable where

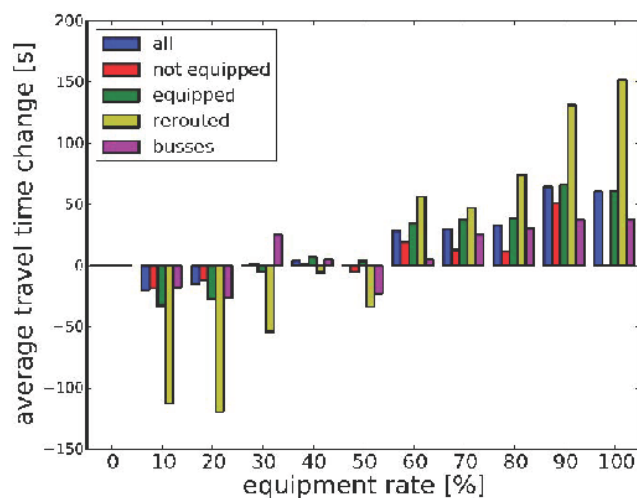


Figure 6 Average travel time changes per vehicle class over equipment rates.

this proxy can be misled. To avoid this, further research with other measures and simulation scenarios is needed.

The simulation results of the application can be seen in Figure 6. The application could not prove it benefits for all equipment rates. For small penetration rates up to approximately 25% all vehicle classes benefit from the application. But with higher equipment rates too many vehicle are rerouted. Consequently, the rerouted vehicles decelerate the busses on the bus lanes

and the vehicles are blocked by the busses and are forced to halt at every bus stop because no overtaking manoeuvre is possible in the traffic network.

3.3.2 Green light optimal speed advisory

One of the first V2X applications which are planned to be implemented in real life is the “Green light optimal speed advisory” (GLOSA) application. The aim of GLOSA is to improve the traffic efficiency and traffic safety at a controlled intersection. The driver of a car equipped with GLOSA will be informed about the recommended optimal speed to pass the next traffic light at a green light phase. The focus of the GLOSA evaluation was to predict real-world test for the EU co-founded project DRIVE C2X.

For the GLOSA application a simulation of the city of Helmond was set-up. The traffic lights within the scenario send the information about their program and timing to the equipped vehicles in communication range. The distance to the next traffic light is calculated using an internal map when a message is received by the vehicles. Using the calculated distance an advice for the speed needed to reach the traffic light in time can be given by a human-machine-interface display in the vehicle. In real life the driver has the choice to follow or ignore this advice. But in the simulation scenario the driver will always adapt her speed according to the recommendation. When the traffic light is red the driver is advised to drive slower than the speed limit (but never slower than 20 km/h) which led the driver pass the intersection after the traffic light turns green.

As a result, the GLOSA application can help vehicles to get through the traffic network without stopping at traffic lights. It turns out that the communication range is crucial for the success of the application. The driver is sometimes not able to adapt the speed early enough with a communication range of 300 m while the driver can pass the simulation without halt when a communication range of 1000 m is applied, see Figure 7.

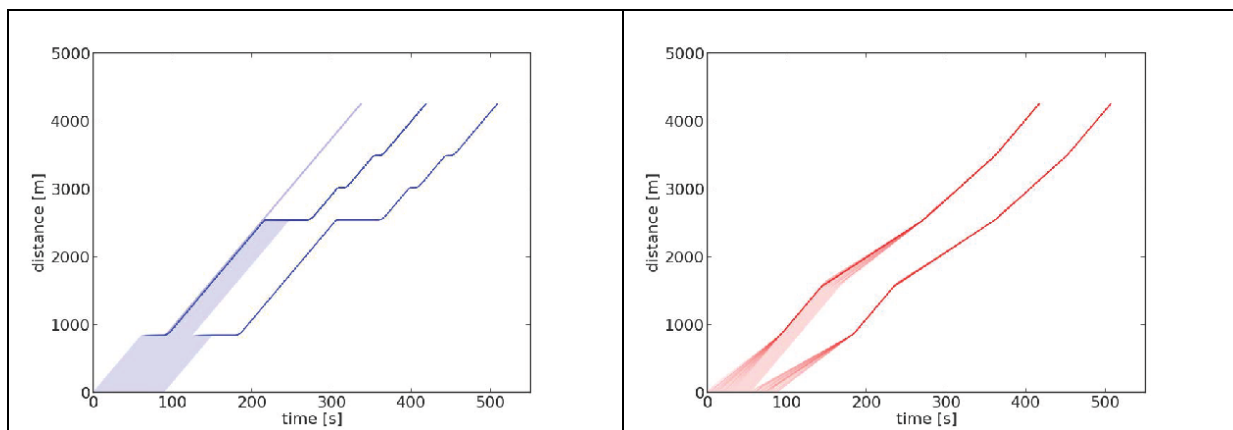


Figure 7 Trajectories of 90 simulated equipped vehicles with different departing times and with a communication range of 300 m (left) and 1000m (right).

3.4 Automatic Driving

One of the greatest benefits of dealing with traffic simulations is the possibility to implement traffic management strategies and new modes of traffic at an extremely low cost compared to a real world implementation. This makes it possible to evaluate things like “personal rapid transit”, an automated taxi cab which may operate on a dedicated infrastructure, for small

scenarios like a parking lot or to go for large scale evaluation of advanced cruise control systems and beyond.

SUMO was used on both scales to evaluate the effect of traffic automation in the context of EU project “CityMobil”. While the large scale evaluation involved mainly an adaption of vehicle parameters such as the aspired time gap to values which can be expected for automated vehicles, the PRT scenario did a fine grained control of every vehicle in the simulation and will be explained in further detailed in this section.

3.4.1 The agent controlled parking lot

A centralized yet flexible approach to the management of automated systems is to employ agent-based technologies where every stakeholder is represented by a (software) agent giving bids and orders for the services. The network layout for this system was inspired by the Rome demonstrator of the CityMobil project which included a shuttle service from a central parking lot to the new Rome fair ground.

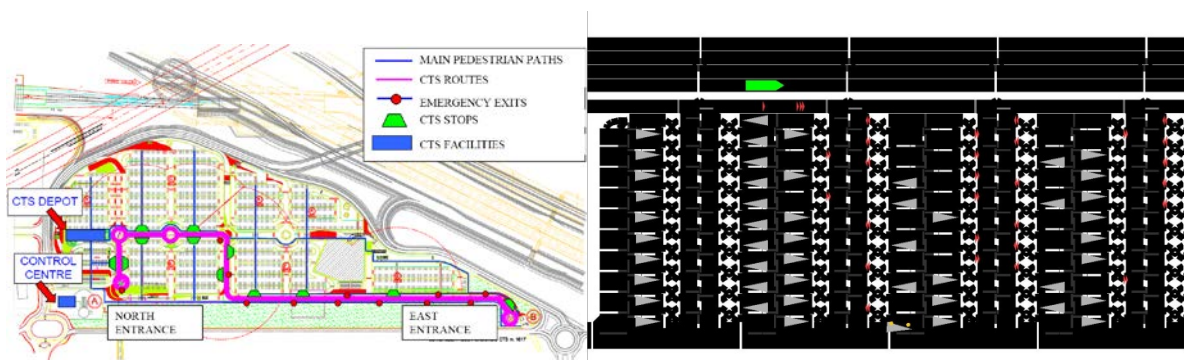


Figure 8 Network layout of the parking lot in Rome and its visualization in SUMO.

The setup consisted of 160 parking spaces organized in eight (double) rows each served by a single bus stop (Figure 8). People had to walk from the parking space of their vehicle to the bus stop where they are picked up and travel to the main entrance.

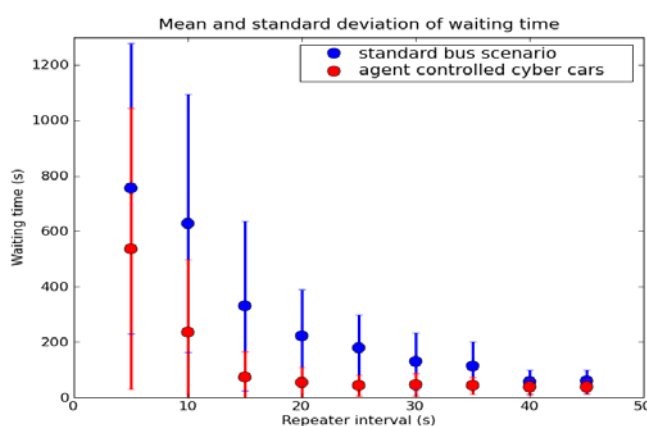


Figure 9 Waiting time depending on frequency of vehicle arrival

There the passengers request a ride to their destination (usually the main entrance of the fair) and the CyberCars serve the request in an optimized fashion minimizing the waiting times of the passengers. Not all of these control strategies needed to be implemented into the SUMO core but could be separated in to scripts which communicated

Streets and footpaths as well as the CyberCar (a small automatically driven vehicle that can carry up to 10 passengers) lanes are modelled without intersecting each other. The bus stops were served by a fleet of eight CyberCars.

The scenario involves a central control agency which assigns to every incoming vehicle a free parking space and directs the passengers to the

over the TraCI interface with the main simulation. Using this approach one could perfectly separate the car following logic from the central management which is possible for automated cars only. The results showed a significant reduction in waiting time compared to a traditional bus scenario involving fewer but larger busses, see Figure 9.

3.5 VABENE

The traffic situation has a major impact on the success of rescue measures during a major incident. The authorities need to get to the relevant places in a short period of time and have to find their places such that they do not hinder the transport of material or injured persons. Furthermore, many people on site may try to leave the place by means of individual transport. This situation calls for a tool which enables the authorities to have an overview of the current traffic situation as well as a prognosis how the traffic situation may evolve. The “EmerT” web portal provides such a system, backed by SUMO which was enhanced by a mesoscopic simulation model to give fast results even for large number of scenarios in big conurbations. These developments are part of the bigger project “VABENE” which deals with traffic management during big events and in catastrophes.

3.5.1 The model

For the type of scenarios within VABENE, the SUMO’s default micro-simulation model is too slow. The crisis scenarios need the computation of the traffic forecasts for the next 30 minutes to be completed in about five minutes. This led to the implementation of a different model, a so called mesoscopic queuing model by Eissfeldt [20]. In contrast to the microscopic model where each vehicle has an individual position and speed the vehicles queue up in edge segments of about 100 meters length and change between the queues. When changing to the next segment, it must be sure that there is space for the changing vehicle; in addition, the headway between subsequent vehicles leaving a segment depends on the traffic state of the current and the downstream segment. The basic model which gives good results for motorways was enhanced to reflect the special properties of city traffic. The resulting model is still about ten to twenty times faster than the microscopic one with small deviations in the measured speeds to the microscopic model.

As already shown in [20], the model reflects basic traffic properties such as back propagation of jams and the flow density relationship in the fundamental diagram. To model city traffic the following features were added:

- Lane queuing (to resolve blockings of cars with different destinations in front of junctions)
- Overtaking (to model different vehicle types without losing too much capacity)
- Junction control (especially for traffic light systems)

3.5.2 Multi scenario simulation

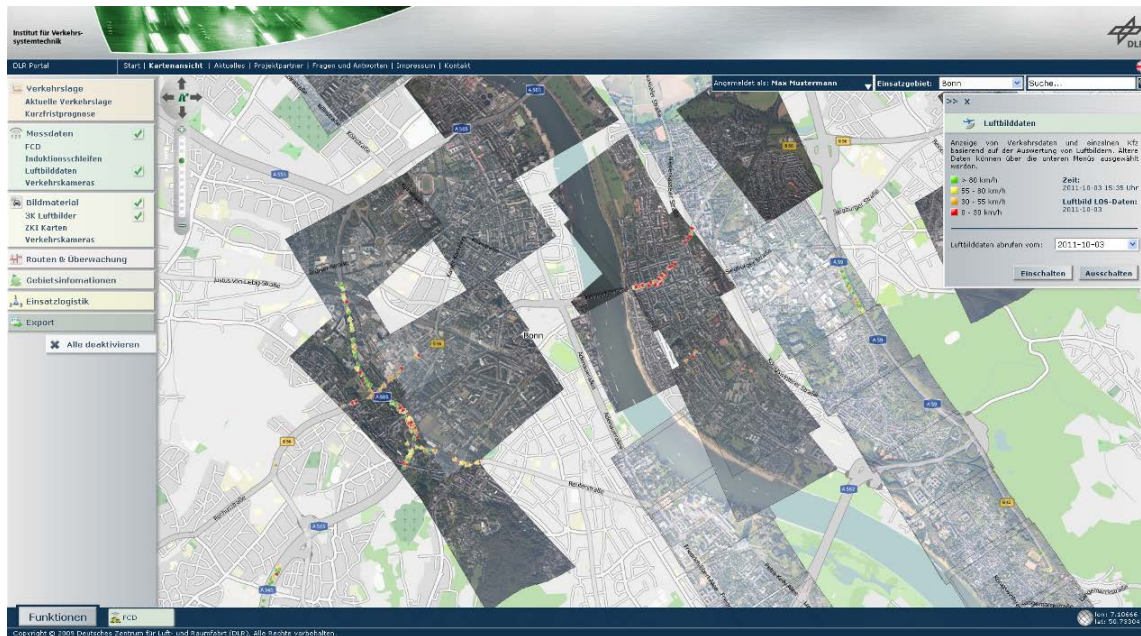


Figure 10 Presentation of enhanced map data in the EmerT portal.

The output of the model is fed into a web-based decision support system named “EmerT” (see Figure 10) that displays not only the simulation results but also induction loop data, floating car data and images from aerial photography. All of these data sources are used to drive, to calibrate, and to validate the simulation scenario so that the traffic situation and its prediction are reflected accurately.

The simulation is already useful in itself by predicting traffic on roads not covered by real data and the evolution of the situation. But the major application is the support of reaction forces during the event or to train them before. Using the EmerT portal the users will have the possibility to study the potential traffic effects of different management measures (for instance road blockings) and adapt their strategies accordingly. They can also study in advance the weaknesses of the road network and identify critical roads in the case of emergencies at certain risky locations.

The simulation supports those endeavours by providing realistic traffic scenarios which give immediate feedback on the effectiveness of measurements. Unlike static analysis also spillback effects of jams and dynamic effects of traffic lights can be considered when optimizing scenarios.

3.6 The A92 scenario – lane changing

The investigations described in the following were set up to measure the quality of SUMO's lane changing model? To evaluate this, the freeway A92 had been set up. The basic reason for using this piece of freeway was an unprecedented coverage by loop detectors and another project that has already sampled the infrastructure data (especially the network) and put it into SUMO's format. It consists of nearly 20 km freeway which connects Munich with its airport.

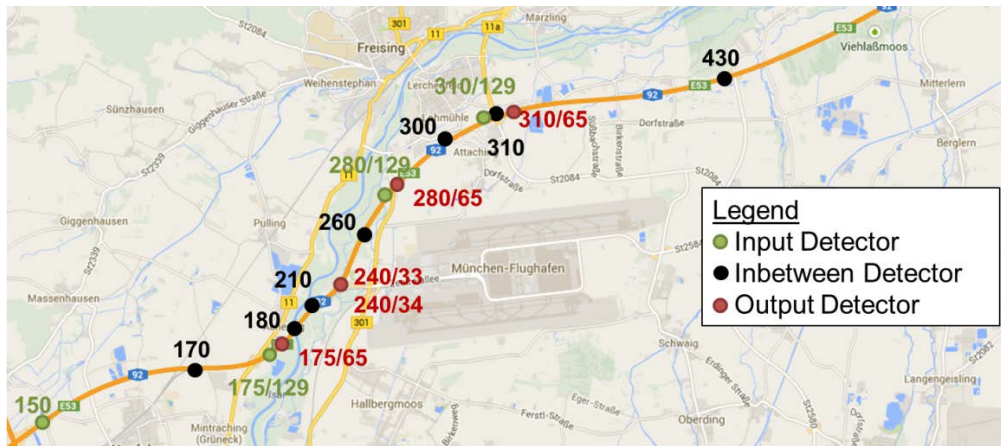


Figure 11 Freeway A92 (Munich, Germany) with loop detectors.

There are 4 on-ramps (green)-, 4 off-ramps (red), and a division at the airport where two lanes lead to the airport (240/33 and 240/34) and the two left lanes lead further north-east, see Figure 11. The inductive loop detectors placed in this area measure traffic flow (separately for trucks/ busses and passenger cars) and average speeds in five minutes intervals. Based on past projects, a large stock of data was available.

To use the detection values as input to the simulation, another tool from the SUMO suite is needed. The DFRouter uses those detector flow data as input and outputs the vehicles together with their routes. The resulting routes are put into the simulation which should lead to an exact fit between reality and simulation at the on-ramps. However, the off-ramps do not necessarily fit well, since there is a good chance, that a vehicle misses its off-ramp. Therefore, the results in Table 1 are not completely trivial.

Table 1 Difference between simulated and measured data. The largest error is 4.4%, while the smallest one is 0.2%.

	Exit #175/65	Exit #240	Exit #280(65)	Exit #310/65	Exit #430
Data	3718	27707	4103	6106	20632
Simulation	3556	28698	4112	6158	20616

However, when looking more detailed, new and different discrepancies show up. Especially the lane distribution is not reproduced correctly at some of the loop detectors, but not at all of them. In Figure 12, the results at detector 170 are shown, which is located closely behind (approximately 3 km) the entry point of the study area – almost 5000 vehicles per day do not use the correct lane. That could still indicate a problem with the lane selection.



Figure 12 Comparison between simulation and reality of the lane flows at detector 170.

But in fact there also exist detectors like detector 210 and 240 (located in the middle of the study area) in which the lane selection fits with a very small deviation, see Figure 13.

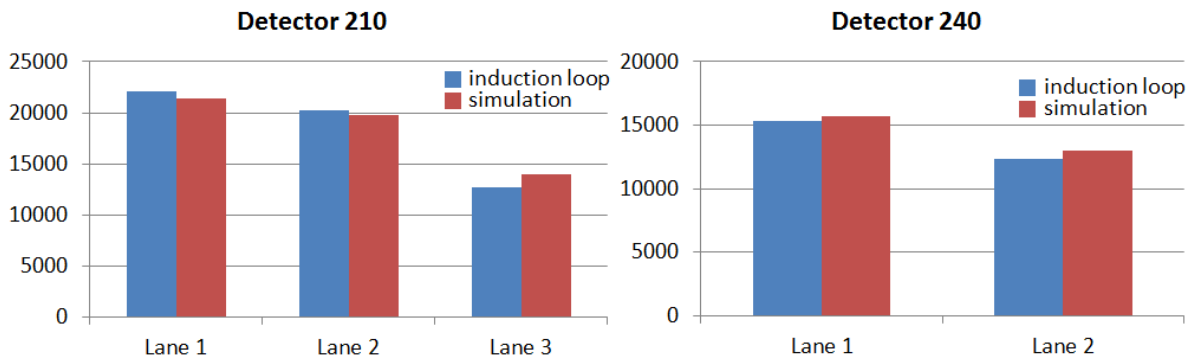


Figure 13 Comparison of the lane flows at detectors 210 (left) and 240 (right).

As could be imagined, the mismatch with the counts at detector 170 also comes with a mismatch in the speeds. In Figure 14 a comparison between the measured and the simulated speeds, for the right, middle, and left lane (from left to right) are shown. The bars represent the measured values and the blue line shows the simulated values.

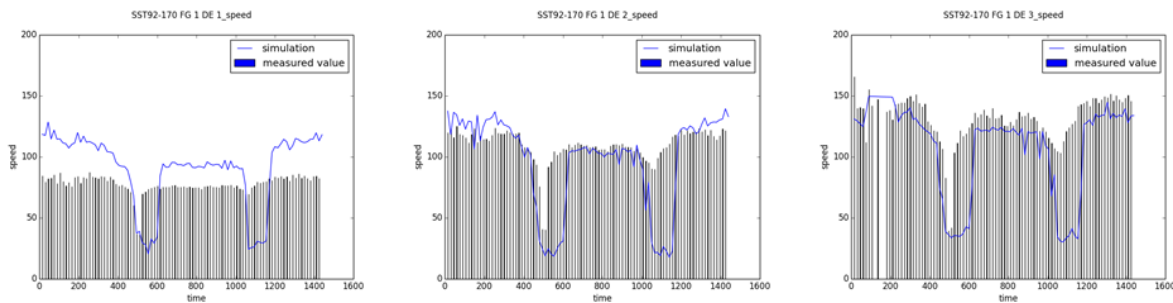


Figure 14 Speed at detector 170 as function of time of the day for the three lanes.

Unfortunately the speeds are not that precise, there are large differences between detector and simulation values on the slow lane. On the faster lanes the speed fits better. In addition, there is a different problem. Reality has just one short jam in the morning peak, but in the simulation there is an additional jam in the afternoon, while reality shows just the beginning

of such a jam. Repeating the simulation a couple of times with a different random number seed shows that the pattern to be seen in the simulation is robust, so there is definitely a difference between simulation and reality which will hopefully be made smaller by a subsequent calibration of the parameters of SUMO.

These preliminary results are encouraging but far from being satisfactory. At least, we have most of the basics correct and can now work out the details. Especially the lane-changing part, but also such problems like the correct speed and vehicle distribution. However, there are still a lot of things to do, like a distribution of the errors, and a detailed analysis of the lane distribution.

4 FUTURE PROSPECTS OF MICRO-SIMULATION

Despite the dramatic progress that has been made during the past 20 years or so, there are still a couple of dark corners left-over to be filled. This relates to micro-simulation models in general, but also to the modelling and to the software-engineering in software tools like SUMO.

4.1 How can we be sure that we have implemented the correct model?

Look at such complicated models as the ones of Wiedemann, Kerner, or the MITSIMLab model, which contain more than 10 parameters and an array of equations to advance the simulation by one time-step. The Wiedemann and one of Kerner's model had been implemented in SUMO. However, there is a big question here, and we use it to advocate a new culture: how can we ever be sure, that the code in SUMO implements the correct model? The answer is obvious: we do not.

Therefore, we think it might be a really good idea that the creator of a new traffic flow model should make all efforts to share his or her code with the rest of the scientific world. In this case, anybody who would like to use this model simply uses this source code; this reduces at least one possible error when trying to reproduce the results of other groups, which is at the heart of the scientific endeavour.

4.2 When do we actually need micro-simulation?

In general, this question is difficult to answer, and the answer is prone to rapid development. Instead of a general answer, just a nice example will be studied here which sheds some light on this question.

When it comes to the planning of a traffic light, most traffic engineers look into the HCM or the closely related national guidelines (HBS and RiLSA in Germany). There, a few formulas based on the work of Webster will be used, that tell the engineer the correct cycle time and the corresponding splits for such an intersection. Especially the HCM-approach is designed to handle additionally periods of over-saturation, which has been done by an extension of Webster's original work to handle non-equilibrium conditions – Webster's approach is essentially an equilibrium approach. Both Webster's approach and HCM's approach are based on queueing theory, however to arrive at the simple equation e.g. for the optimal cycle

time, a long and involved line of reasoning has to be followed, which involves more or less justifiable approximations. Note, that even the idea to describe an intersection by queueing theory is already an approximation, since traffic is definitely a spatio-temporal process.

Be that as it is. To simulate such an intersection as a queueing process is ridiculously simple. For one leg of the intersection, the core is just a seven line simulation program:

```
for (t=0.0; t<=tMax; t += deltaT) {
  if rand() < q(t)*deltaT and n<nMax then n = n + 1
  if mod(t,c)<=g and t>=tLast + tau and n>0 then {
    n = n - 1;
    tLast = t;
  }
}
```

Here, `rand()` is the call to a random number generator, `n` counts the number of vehicles currently in the leg, and `q(t)` is the demand function. In addition, the variable `tau` is just the inverse of the saturation flow `s`, and `deltaT` is the time-step size of this simulation. From a simulation of this simple source (of course with a lot of additional lines setting variables and collecting results) a very complete set of statistics can be drawn. It yields not only the delay itself, but in addition it also produces the whole delay distribution $p(d)$. The availability of this distribution has an important meaning for questions related to quality and reliability of the intersection at hand, and it is already beyond the capabilities of handbook methods. Of course, for this to happen require that the simulation is to be run multiple times to correctly arrive at averaged quantities and at the distributions.

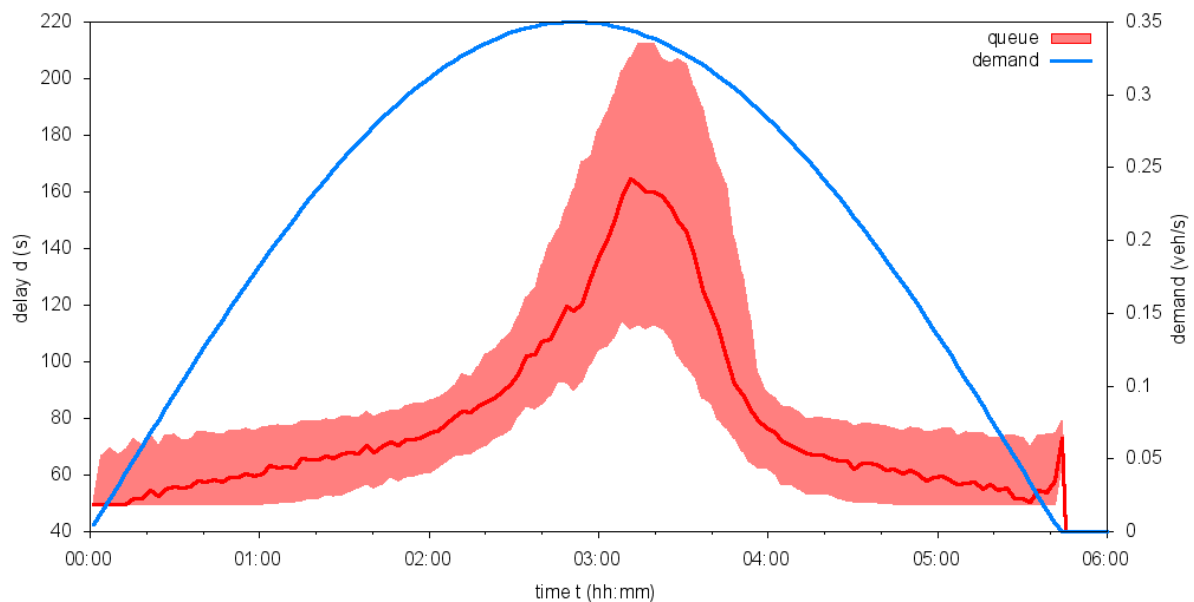


Figure 15 Simulation of a 6 h period with a sinusoidal demand function where peak demand exceeds capacity with the queueing model described above. Plotted are the median of the delay as function of time (red curve) and, as red area, the 25% and 75%-quantiles of the delay distribution.

It can even be run with hand-tailored (or data-driven) oversaturation periods (by specifying the demand function $q(t)$ accordingly), and it needs just three parameters s, g, c of which at least two of them are well-known (g, c) and the other one can be measured more or less

easily. Obviously, even the hand-book formulas in the HCM look more complicated than this, and it becomes even more dramatic for the equations that describe the time-depending queueing approach.

In our view, this is a beautiful example. A simulation of a six hour peak period with such a simple program needs a few seconds for 1000 repetitions, it runs at least a factor of 100 or even 1000 faster than any full-fledged micro-simulation tool, and one gets a wealth of data out of it. Of course, it is possible to alter the function $q(t)$ into a function that models a traffic light upstream. In this manner, co-ordination can be properly accounted for. Also, simple traffic actuated signal controls can also modelled by this approach, and the same hold true for the platoon dispersion.

As told already, this queueing approach is itself an approximation, therefore it might be better to switch either to a simplified microscopic approach like cellular automata or use directly a serious micro-simulation tool. Which, however, needs more simulation time to arrive at good answers, and it is very likely that the 1000 repetitions have to be reduced to 50 or so to arrive at bearable simulation times.

We pretty much think that such tools will be the future. Handbooks like the HCM will be superseded by such tools or even directly by the micro-simulation tools.

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