# Recent Development and Applications of SUMO – Simulation of Urban MObility

Daniel Krajzewicz, Jakob Erdmann, Michael Behrisch, and Laura Bieker
Institute of Transportation Systems
German Aerospace Center
Rutherfordstr. 2, 12489 Berlin, Germany
e-mail: Jakob.Erdmann@dlr.de, Daniel.Krajzewicz@dlr.de, Michael.Behrisch@dlr.de, Laura.Bieker@dlr.de

***Abstract*—SUMO is an open source traffic simulation package including the simulation application itself as well as supporting tools, mainly for network import and demand modeling. SUMO helps to investigate a large variety of research topics, mainly in the context of traffic management and vehicular communications. We describe the current state of the package, its major applications, both by research topic and by example, as well as future developments and extensions.**

***Keywords-microscopic traffic simulation; traffic management; open source; software***

## I. INTRODUCTION

SUMO ("Simulation of Urban MObility") [1][2] is a microscopic, inter- and multi-modal, space-continuous and time-discrete traffic flow simulation platform. The implementation of SUMO started in 2001, with a first open source release in 2002. There were two reasons for making the work available as open source under the gnu public license (GPL). The first was the wish to support the traffic simulation community with a free tool into which own algorithms can be implemented. Many other open source traffic simulations were available, but being implemented within a student thesis, they got unsupported afterwards. A major drawback – besides reinvention of the wheel – is the almost non-existing comparability of the implemented models or algorithms, and a common simulation platform is assumed to be of benefit here. The second reason for making the simulation open source was the wish to gain support from other institutions.

Within the past ten years, SUMO has evolved into a full featured suite of traffic modeling utilities including a road network importer capable of reading different source formats, demand generation and routing utilities, which use a high variety of input sources (origin destination matrices, traffic counts, etc.), a high performance simulation usable for single junctions as well as whole cities including a "remote control" interface (TraCI, see Section II. D.) to adapt the simulation online and a large number of additional tools and scripts. The major part of the development is undertaken by the Institute of Transportation Systems at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR). External parties supported different extensions to the simulation suite.

In this paper, we will survey some of the recent developments and future prospects of SUMO. We start with an overview of the applications in the suite, showing how they help in preparing and performing a traffic simulation. Then, major research topics, which can be addressed using SUMO are presented. We then outline the usage of SUMO within some recent research projects. Finally, we present recent extensions and discuss current development topics.

## II. THE SUMO SUITE

SUMO is not only a traffic simulation, but rather a suite of applications, which help to prepare and to perform the simulation of a traffic scenario. As the simulation application "*sumo*", which is included in the suite, uses own formats for road networks and traffic demand, both have to be imported or generated from existing sources of different kind. Having the simulation of large-scale areas as the major application for *sumo* in mind, much effort has been put into the design and implementation of heuristics which determine missing, but needed attributes.

In the following, the applications included in the suite are presented, dividing them by their purpose: network generation, demand generation, and simulation.

### *A. Road Network Generation*

SUMO road networks represent real-world networks as graphs, where nodes are intersections, and roads are represented by edges. Intersections consist of a position, a shape, and right-of-way rules, which may be overwritten by a traffic light. Edges are unidirectional connections between two nodes and contain a fixed number of lanes. A lane contains geometry, the information about vehicle classes allowed on it, and the maximum allowed speed. Therefore, changes in the number of lanes along a road are represented using multiple edges. Such a view on road networks is common; though some other approaches, such as Vissim's [3] network format or the OpenDRIVE [4] format, exist. Besides this basic view on a road network, SUMO road networks include traffic light plans, and connections between lanes across an intersections describing which lanes can be used to reach a subsequent lane.

SUMO road networks can be either generated using an application named "*netgenerate*" or by importing a digital road map using "*netconvert*". *netgenerate* builds three different kinds of abstract road networks: "manhattan"-like grid networks, circular "spider-net" networks, and random networks. Each of the generation algorithms has a set of options, which allow adjusting the network's properties. Figure 1 shows examples of the generated networks.

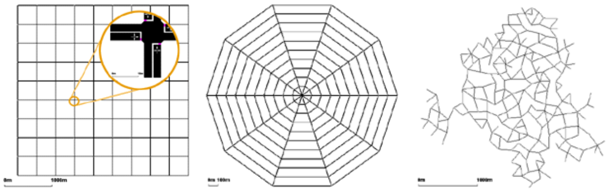


Figure 1. Examples of abstract road networks as built using "netgenerate"; from left to right: grid ("manhattan", spider, and random network)

The road network importer *netconvert* converts networks from other traffic simulators such as VISUM [5], Vissim, or MATSim [6]. It also reads other common digital road network formats, such as shapefiles or OpenStreetMap [7]. Besides these formats, *netconvert* is also capable to read less known formats, such as OpenDRIVE or the RoboCup network format. Figures 2 and 3 show the capabilities to import road networks from OpenStreetMap by example, comparing the original rendering on OpenStreetMap's web pages against SUMO rendering of the imported network.

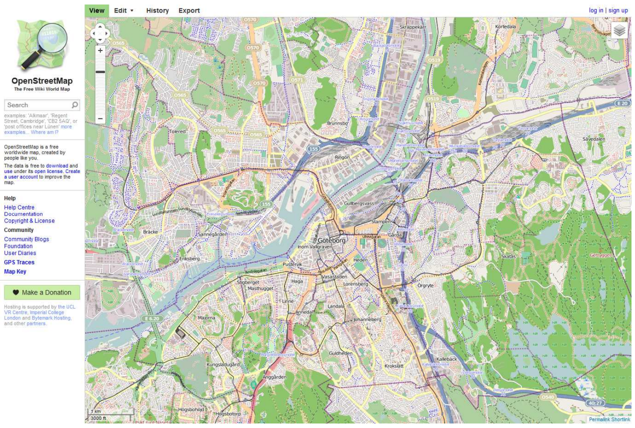


Figure 2. Original OpenStreetMap network of Gothenborg.

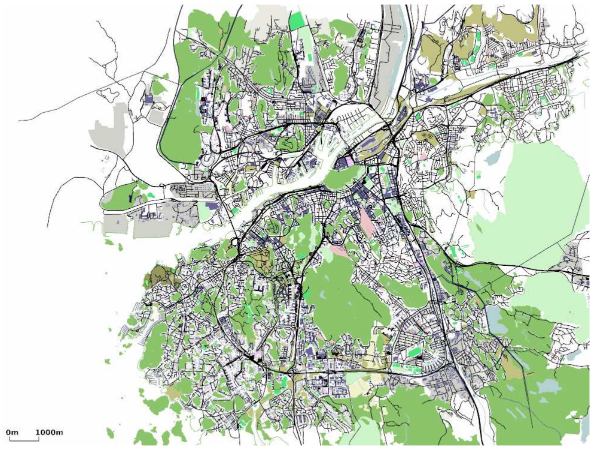


Figure 3. Gothenborg network imported into SUMO.

Additionally, *netconvert* reads a native, SUMO-specific, XML-representation of a road network graph referred to as "plain" XML, which allows the highest degree of control for describing a road network for SUMO. This XML representation is broken into five file types, each for description of nodes, edges, optionally edge types, connections, and (fixed) traffic light plans. Edge types name sets of default edge attributes, which can be referenced by the later loaded edges. Nodes describe the intersections, edges the road segments. Connections describe which lanes incoming into an intersection are connected to which outgoing lanes. The simulation network created by *netconvert* contains heuristically computed values wherever the inputs are incomplete as well as derived values such as the exact geometry at junctions. It is also possible to convert a simulation network back into the "plain" format. Multiple input formats can be loaded at the same time and are automatically merged. Since the "plain" format allows specifying the removal of network elements and the adaption of single edge and lane parameters, it can be used for a wide range of network modifications. To support such modifications SUMO additionally provides the python tool *netdiff.py*, which computes the (human-readable) difference D between two networks A and B. Loading A and D with *netconvert* reproduces B.

Most of the available digital road networks are originally meant to be used for routing (navigation) purposes. As such, they often lack the grade of detail needed by microscopic road traffic simulations: the number of lanes, especially in front of intersections, information about which lanes approach which consecutive ones, traffic light positions and plans, etc., are missing. Sharing the same library for preparing generated/imported road networks, see Figure 4, both, *netgenerate* and *netconvert*, try to determine missing values using heuristics. A coarse overview on this preparation process can be found in [8]. However, most of the algorithms described in [8] have been reworked since its publication. Additional, optional heuristics guess locations of highway on- and off-ramps, roundabouts, traffic lights, etc.

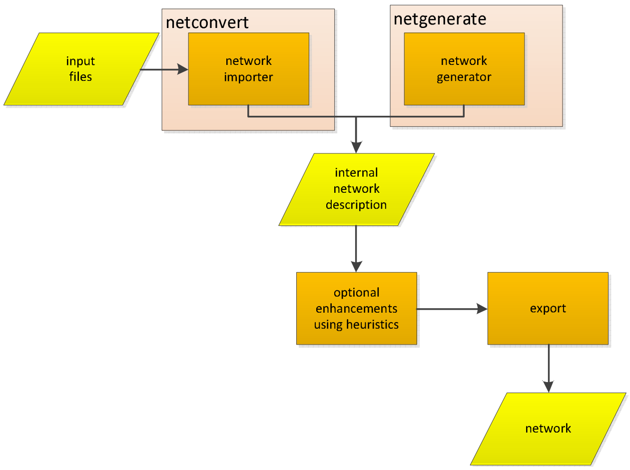


Figure 4. Common network preparation procedure in *netconvert* and *netgenerate*.

Even with the given functionality, it should be stated that preparing a real-world network for a microscopic simulation is still a time-consuming task, as the real-world topology of more complicated intersections often has to be improved manually. A new tool named "*netedit*" allows editing road networks graphically. This is in many cases simpler and faster than preparing XML input files. It also combines the otherwise separate steps of network generation and inspection with *netconvert* and the simulation GUI. *netedit* is not yet available for public use.

### B. *Vehicles and Routes*

SUMO is a purely microscopic traffic simulation. Each vehicle is given explicitly, defined at least by a unique identifier, the departure time, and the vehicle's route through the network. By "route" we mean the complete list of connected edges between a vehicle's start and destination. If needed, each vehicle can be described in a finer detail using departure and arrival properties, such as the lane to use, the velocity, or the exact position on an edge. Each vehicle can get a type assigned, which describes the vehicle's physical properties and the variables of the used movement model. Each vehicle can also be assigned to one of the available pollutant or noise emission classes. Additional variables allow the definition of the vehicle's appearance within the simulation's graphical user interface.

A simulation scenario of a large city easily covers one million vehicles and their routes. Even for small areas, it is hardly possible to define the traffic demand manually. The SUMO suite includes some applications, which utilize different sources of information for setting up a demand.

For large-scale scenarios usually so-called "origin/ destination matrices" (O/D matrices) are used. They describe the movement between so-called traffic analysis zones (TAZ) in vehicle numbers per time. For use in SUMO these matrices must be disaggregated into individual vehicle trips with depart times spread across the described time span. Unfortunately, often, a single matrix is given for a single day, which is too imprecise for a microscopic traffic simulation since flows between two TAZ strongly vary over the duration of a day. For example, people are moving into the inner-city centers to get to work in the morning, and leave the inner-city area in the afternoon or evening. Such direction changes cannot be retrieved from an aggregated 24h matrix. Much more useful but only sometimes available are matrices with a scale of 1h. The SUMO suite includes "*od2trips*", an application for converting O/D matrices to single vehicle trips. An hourly load curve can be given as additional input for splitting the daily flows into more realistic hourly slices. Besides disaggregating the matrix, the application also optionally assigns an edge of the road network as depart/arrival position, respectively. The mapping from traffic assignment zones to edges must be supplied as another input.

The resulting trips obtained from *od2trips* consist of a start and an end road together with a departure time. However, the simulation requires the complete list of edges to pass. Such routes are usually calculated by performing a dynamic user assignment (DUA). This is an iterative process employing a routing procedure such as shortest path calculation under different cost functions. Details on the models used in SUMO can be found in Section III.B.

SUMO includes two further route computation applications. The first, "*jtrrouter*", uses definitions of turn percentages at intersection for computing routes through the network. Such an approach can be used to set up the demand within a part of a city's road network consisting of few nodes. The second, "*dfrouter*", computes routes by using information from inductive loop or other cross-section detectors. This approach is quite successful when applied to highway scenarios where the road network does not contain rings and the highway entries and exits are completely covered by detectors. It fails on inner-city networks with rings or if the coverage with detectors is low.

It should be noted, that, while digital representations of real-world road networks became available in good quality in recent years, almost no sources for traffic demand are freely available. Within most of our (DLR's) projects, a road administration authority was responsible for supporting the demand information, either in form of O/D-matrices or at least by supplying traffic counts, which were used to calibrate a model built on rough assumptions.

Two tools enclosed in the SUMO package try to solve this problem by modeling the mobility wishes of a described population. "*SUMO Traffic Modeler*" by Leontios G. Papaleontiou [9] offers a graphical user interface allowing the user to set up demand sources and sinks graphically. "*activitygen*" written by Piotr Woznica and Walter Bamberger from TU Munich has almost the same capabilities, but has no user interface. Both tools are included in the suite and both use own models for creating mobility wishes for an investigated area, requiring different data. They are both under evaluation, currently.

Figure 5 summarizes the possibilities to set up a demand for a traffic simulation using tools included in the SUMO package.

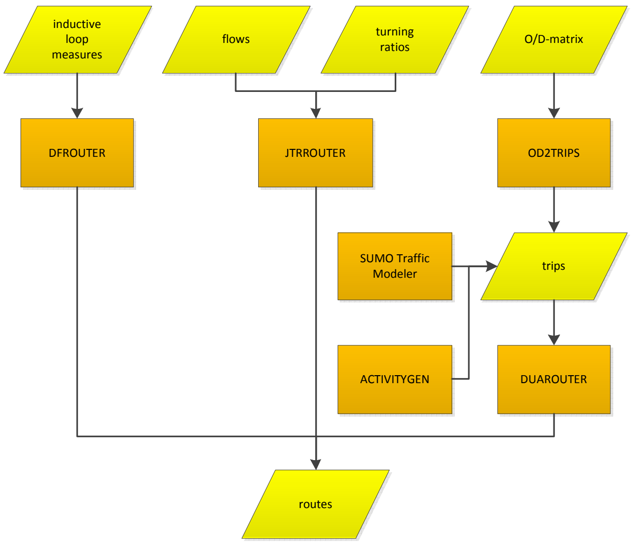


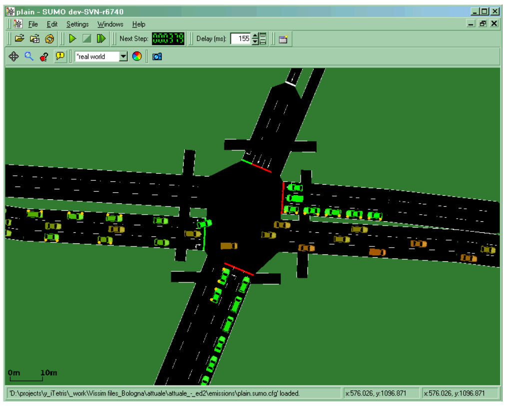
Figure 5. Supported methods for demand generation.

### *C. Simulation*

The application "*sumo*" performs a time-discrete simulation. The default step length is 1s, but may be chosen to be lower, down to 1ms. Internally, time is represented in microseconds, stored as integer values. The maximum duration of a scenario is so bound to 49 days. The simulation model is space-continuous and internally, each vehicle's position is described by the lane the vehicle is on and the distance from the beginning of this lane. When moving through the network, each vehicle's speed is computed using a so-called car-following model. Car-following models usually compute an investigated vehicle's (ego) speed by looking at this vehicle's speed, its distance to the leading vehicle (leader), and the leader's speed. SUMO uses an extension of the stochastic car-following model developed by Stefan Krauß [10] per default. Krauß' model was chosen due to its simplicity and its high execution speed.

The model by Krauß has proved to be valid within a set of performed car-following model comparisons [11][12][13]. Nonetheless, it has some shortcomings, among them its conservative gap size, yielding in a too low gap acceptance during lane changing, and the fact that the model does not scale well when the time step length is changed. To deal with these issues, an application programmer interface (API) for implementing other car-following models was added to *sumo*. Currently, among others, the following models are included: the intelligent driver model (IDM) [14], Kerner's three-phase model [15], and the Wiedemann model [16]. It must be stated, though, that different problems were encountered when using these models in complex road networks, probably due to undefined side-constraints and/or assumptions posed by the simulation framework. For this reason, the usage of different car-following models should be stated to be experimental only, at the current time. Being a traffic flow simulation, there are only limited possibilities to reflect individual driver behavior; it is however possible to give each vehicle its own set of parameters (ranging from vehicle length to model parameters like preferred headway time) and even to let different models run together. The computation of lane changing is done using a model developed during the implementation of SUMO [17].

Two versions of the traffic simulation exist. The application "*sumo*" is a pure command line application for efficient batch simulation. The application "*sumo-gui*" offers a graphical user interface (GUI) rendering the simulation network and vehicles using openGL. The visualization can be customized in many ways, i.e., to visualize speeds, waiting times and to track individual vehicles. Additional graphical elements – points-of-interest (POIs), polygons, and image decals – allow to improve a scenario's visual appearance. The GUI also offers some possibilities to interact with the scenario, e.g. by switching between prepared traffic signal programs, changing reroute following grades, etc. Figure 6 shows a single intersection simulated in *sumo-gui*. *sumo-gui* offers all features the command line version *sumo* supports.



Delay (ms): 155

*real world

'D:\projects\y_iTetris_work\Vissim files_Bologna\attuale\attuale_-_ed2\emissions\plain.sumo.cfg' loaded.

x:576.026, y:1096.871

x:576.026, y:1096.871

Figure 6. Screenshot of the graphical user interface coloring vehicles by their $CO_2$ emission.

SUMO allows generating various outputs for each simulation run. These range from simulated inductive loops to single vehicle positions written in each time steps for all vehicles and up to complex values such as information about each vehicle's trip or aggregated measures for all streets and/or lanes. Besides conventional traffic measures, SUMO was extended by a noise emission and a pollutant emission / fuel consumption model, see also Section V.A. All output files generated by SUMO are in XML-format.

### *D. On-Line Interaction*

In 2006, the simulation was extended by the possibility to interact with an external application via a socket connection. This API, called "TraCI" for "Traffic Control Interface" was implemented by Axel Wegener and his colleagues at the University of Lübeck [18], and was made available as a part of SUMO's official release. Within the iTETRIS project, see Section IV.B, this API was reworked, integrating it closer into SUMO's architecture.

To enable on-line interaction, SUMO has to be started with an additional option, which obtains the port number to listen to. After the simulation has been loaded, SUMO starts to listen on this port for an incoming connection. After being connected, the client is responsible for triggering simulation steps in SUMO as well as for closing down the connection what also forces the simulation to quit. The client can access values from almost all simulation artifacts, such as intersections, edges, lanes, traffic lights, inductive loops, and of course vehicles. The client may also change values, for example instantiate a new traffic light program, change a vehicle's velocity or force it to change a lane. This allows complex interaction such as online synchronization of traffic lights or modeling special behavior of individual vehicles.

While DLR uses mainly a client-library written in Python when interacting with the simulation, the client can be written in any programming language as long as TCP sockets are supported. A Python API as well as a freely available Java API [19] are included with SUMO and support for other programming languages may follow.

## III. RESEARCH TOPICS

In the following, the major research topics addressed using SUMO are presented. The list is mainly based on observations of published papers which cite SUMO.

### *A. Vehicular Communication*

The probably most popular application for the SUMO suite is modeling traffic within research on V2X – vehicle-to-vehicle and vehicle-to-infrastructure – communication. In this context, SUMO is often used for generating so-called "trace files", which describe the movement of communication nodes by converting the output of a SUMO simulation into a format the used communication simulator can read. Such a post-processing procedure allows feeding a communication simulator with realistic vehicle behavior, but fails on simulating the effects of in-vehicle applications that change the vehicles' behavior. To investigate these effects, a combined simulation of both, traffic and communication is necessary [20]. For such research, SUMO is usually coupled to an external communication simulation, such as ns2 or ns3 [21] using TraCI. For obtaining a functioning environment for the simulation of vehicular communications, a further module that contains the model of the V2X application to simulate is needed. Additionally, synchronization and message exchange mechanisms have to be involved.

TraNS [22] was a very popular middleware for V2X simulation realizing these needs. It was build upon SUMO and ns2. Here, TraNS' extensions to ns2 were responsible for synchronizing the simulators and the application had also to be modeled within ns2. TraNS was the major reason for making TraCI open source. After the end of the projects the original TraNS authors were working on, TraNS was no longer maintained. Since the TraCI API was changed after the last TraNS release, TraNS only works with an outdated version of SUMO.

A modern replacement for TraNS was implemented within the iTETRIS project [23]. The iTETRIS system couples SUMO and ns2's successor ns3. ns3 was chosen because ns2 was found to be unstable when working with a large number of vehicles. Within the iTETRIS system, the "iTETRIS Control System", an application written in c++ is responsible for starting and synchronizing the involved simulators. The V2X applications are modeled as separate, language-agnostic programs. This clear distribution of responsibilities allows to implement own applications conveniently in the user's favorite programming language.

The Veins framework [20] couples SUMO and OMNET++ [24], a further communication simulator. A further, very flexible approach for coupling SUMO with other applications is the VSimRTI middleware developed by Fraunhofer Fokus [25]. Its HLA-inspired architecture not only allows the interaction between SUMO and other communication simulators. It is also able to connect SUMO and Vissim, a commercial traffic simulation package. In [25], a system is described where SUMO was used to model large-scale areas coarsely, while Vissim was used for a fine-grained simulation of traffic intersections.

Many vehicular communication applications target at increasing traffic safety. It should be stated, that up to now, microscopic traffic flow models are not capable of modelling real collisions and thus derive safety-related measures indirectly, for instance by detecting full braking. SUMO's strength lies in simulation of V2X applications that aim at improving traffic efficiency. Additionally, evaluating concepts for forwarding messages to their defined destination ("message routing") can be done using SUMO, see, for example, [26] or [27].

### *B. Route Choice and Dynamic Navigation*

The assignment of proper routes to a complete demand or a subset of vehicles is investigated both, on a theoretical base as well as within the development of new real-world applications. On the theoretical level, the interest lies in a proper modeling of how traffic participants choose a route – a path through the given road network – to their desired destination. As the duration to pass an edge of the road graph highly depends on the numbers of participants using this edge, the computation of routes through the network under load is a crucial step in preparing large-scale traffic simulations. Due to its fast execution speed, SUMO allows to investigate algorithms for this "user assignment" or "traffic assignment" process on a microscopic scale. Usually, such algorithms are investigated using macroscopic traffic flow models, or even using coarser road capacity models, which ignore effects such as dissolving road congestions.

The SUMO suite supports such investigations using the *duarouter* application. Two algorithms for computing a user assignment are implemented, c-logit [28] and Gawron's [29] dynamic user assignment algorithm. Both are iterative and therefore time consuming. Possibilities to reduce the duration to compute an assignment were evaluated and are reported in [30]. A further possibility to reduce the computational effort is given in [31]. Here, vehicles are routed only once, directly by the simulation and the route choice is done based on a continuous adaptation of the edge weights during the simulation.

Practical applications for route choice mechanisms arise with the increasing intelligence of navigation systems. Modern navigation systems as Tom Tom's IQ routes ([32]) use on-line traffic information to support the user with a fastest route through the network regarding the current situation on the streets. One research topic here is to develop new traffic surveillance methods, where vehicular communication is one possibility. With the increased penetration rate of vehicles equipped with a navigation device, further questions arise: what happens if all vehicles get the same information? Will they all use the same route and generate new congestions? These questions are not only relevant for drivers, but also for local authorities as navigation devices may invalidate concepts for keeping certain areas calm by routing vehicles through these areas. SUMO allows addressing these topics, see, e.g., [33].

### *C. Traffic Light Algorithms*

The evaluation of developed traffic light programs or algorithms for making traffic lights adaptable to current traffic situation is one of the main applications for microscopic traffic flow simulations. As SUMO's network model is relatively coarse compared to commercial applications such as Vissim, SUMO is usually not used by traffic engineers for evaluating real-life intersections. Still, SUMO's fast execution time and its open TraCI API for interaction with external applications make it a good candidate for evaluating new traffic control algorithms in abstract scenarios.

The first investigation in traffic lights was performed within the project "OIS" [34] where a traffic light control algorithm, which used queue lengths determined by image processing should have been evaluated. As a real-world deployment of the OIS system was not possible due to legal constraints, the evaluation had to be done using a simulation. The simulation was prepared by implementing a real-world scenario, including real-world traffic light programs. The simulation application itself was extended by a simulated sensor, which allowed retrieving queue lengths in front of the intersection similar to the real image processing system. The traffic light control was also implemented directly into the simulation. At the end, the obtained simulation of OIS-based traffic control was compared against the real-world traffic lights, [34] shows the results.

In ORINOKO, a German project on traffic management, the focus was put on improving the weekly switch plans within the fair trade center area of the city of Nürnberg. Here, the initial and the new algorithm for performing the switch procedure between two programs were implemented and evaluated. Additionally, the best switching times were computed by a brute-force iteration over the complete simulated day and the available switch plans.

By distinguishing different vehicle types, SUMO also allowed to simulate a V2X-based emergency vehicle prioritization at intersections [35]. Other approaches for traffic light control were also investigated and reported by other parties, see, e.g., [36], or [37].

As mentioned before, the first investigations were performed by implementing the traffic light algorithms to evaluate directly into the simulation's core. Over the years, this approach was found to be hard to maintain. Using TraCI seems to be a more sustainable procedure currently.

### D. *Evaluation of Traffic Surveillance Systems*

Simulation-based evaluation of surveillance systems mainly targets on predicting whether and to what degree the developed surveillance technology is capable to fulfill the posed needs at an assumed rate of recognized and/or equipped vehicles. Such investigations usually compare the output of the surveillance system, fed with values from the simulation to the according output of the simulation. An example will be given later, in Section IV.A. on the project "TrafficOnline".

A direct evaluation of traffic surveillance systems' hardware, for example image processing of screenshots of the simulated area, is uncommon, as the simulation models of vehicles and the environment are too coarse for being a meaningful input to such systems. Nonetheless, the simulation can be used to compute vehicle trajectories, which can be enhanced to match the inputs needed by the evaluated system afterwards. An example of such an investigation is the evaluation of hyperspectral sensors reported in [38].

Besides evaluating developed surveillance systems, possibilities to incorporate traffic measurements of various kinds into a simulation are evaluated, see for example Section IV.C. on "VABENE".

## IV. RECENT AND CURRENT PROJECTS

SUMO was used in past research projects performed by the DLR and other parties. In the following, some of the recently performed projects are described.

### A. *TrafficOnline*

Within the TrafficOnline project, a system for determining travel times using GSM telephony data was designed, implemented, and evaluated. SUMO was used to validate this system's functionality and robustness. In the following, we focus on the simulation's part only, neither describing the TrafficOnline system itself, nor the evaluation results.

The outline for using the simulation was as follows. Real-world scenarios were set up in the simulation. When being executed, the simulation was responsible for writing per-edge travel time information as well as simulated telephony behavior values. The TrafficOnline system itself obtained the latter, only, and computed travel times in the underlying road network. These were then compared to the travel times computed by the simulation. The overall procedure is shown in Figure 7.

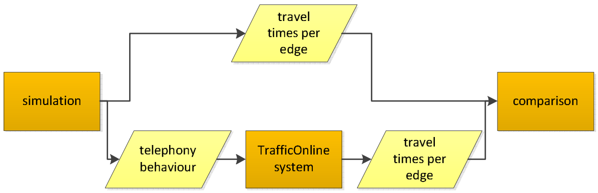


Figure 7. Overall process of TrafficOnline validation.

The evaluation was performed using scenarios located in and around Berlin, Germany, which covered urban and highway situations. The road networks were imported from a NavTeq database. Manual corrections were necessary due to the limits of digital road networks described earlier in Section II.A.

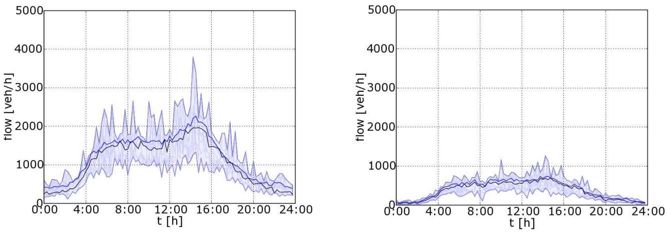


Figure 8. Validation of the traffic flows in TrafficOnline.

Measurements from inductive loops were used for traffic modeling. Figure 8 shows two examples of validating the traffic simulation by comparing simulated (black) and real-world inductive loop measures (blue, where dark blue indicates the average value). For validating the robustness of the TrafficOnline system, scenario variations have been implemented, by adding fast rail train lines running parallel to a highway, or by implementing additional bus lanes, for example. Additionally, scenario variations have been built by scaling the simulated demand by +/- 20%.

For validating the TrafficOnline system, a model of telephony behavior was implemented, first. The telephony model covered the probability to start a call and a started call's duration, both retrieved from real-world data. For an adequate simulation of GSM functionality, the real-world GSM cell topology was put onto the modeled road networks. It should be noted, that dynamic properties of the GSM network, such as cell size variations, or delays on passing a cell border, have not been considered. Figure 9 shows the results of validating the simulated telephone call number (black) against the numbers found in real-world data (green, dark green showing the average call number) over a day for two selected GSM cells.

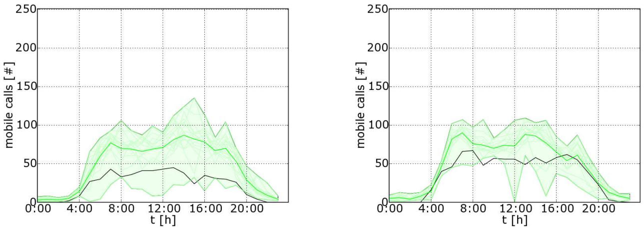


Figure 9. Validation of the telephony behavior in TrafficOnline.

### B. *iTETRIS*

The interest in V2X communication is increasing but the deployment of this technology is still expensive, and ad-hoc implementations of new traffic control systems in the real world may even be dangerous. For research studies where the benefits of a system are measured before it is deployed, a simulation framework, which simulates the interaction between vehicles and infrastructure is needed, as described in III.A. The aim of the iTETRIS project was to develop such a framework, coupling the communication simulator ns3 and SUMO using an open source system called "iCS" – iTETRIS Control System – which had to be developed within the project. In contrary to other, outdated solutions such as TraNS, iTETRIS was meant to deliver a sustainable product, supported and continued to be developed after the project's end.

Besides implementing the V2X simulation system itself, which was already presented in Section III.A., the work within iTETRIS included a large variety of preparation tasks and – after completing the iCS implementation – the evaluation of traffic management applications as well as of message routing protocols.

The preparations mainly included the investigation of real world traffic problems and their modelling in a simulation environment. The city of Bologna, who was a project partner in iTETRIS, supported traffic simulation scenarios covering different parts of the town, mainly as inputs for the simulations Vissim and VISUM, both commercial products of PTV AG. These scenarios were converted into the SUMO-format using the tools from the SUMO package. Besides the road networks and the demand for the peak hour between 8:00am and 9:00am, they included partial definitions of the traffic lights, public transport, and other infrastructure information.

One of the project's outputs is a set of in-depth descriptions of V2X-based traffic management applications, including different attempts for traffic surveillance, navigation, and traffic light control. In the following, one of these applications, the *bus lane management*, is described, showing the complete application design process, starting at problem recognition, moving over the design of a management application that tries to solve it, and ending at its evaluation using the simulation system. A more detailed report on this application is [39].

Public transport plays an important role within the city of Bologna, and the authorities are trying to keep it attractive by giving lanes, and even streets free to public busses only. On the other hand, the city is confronted with event traffic – e.g., visitors of football matches, or the fair trade centre – coming in the form of additional private passenger cars. One idea developed in iTETRIS was to open bus lanes for private traffic in the case of additional demand due to such an event. The application was meant to include two sub-systems. The first one was responsible for determining the state on the roads. The second one used this information to decide whether bus lanes shall be opened for passenger cars and should inform equipped vehicles about giving bus lanes for usage.

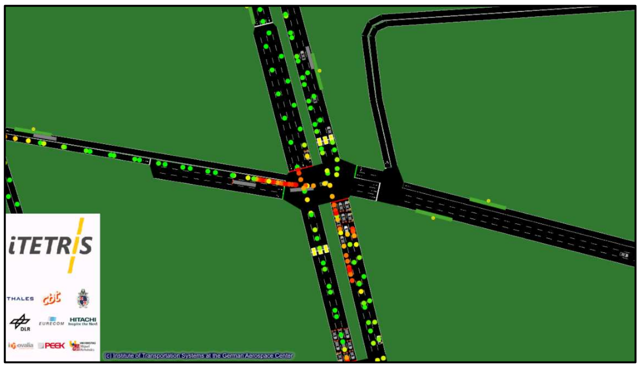


Figure 10. Speed information collection by RSUs. Each dot represents one data point, the color represents the speed (green means fast, red slow).

In order to use standardised techniques, traffic surveillance was implemented by collecting and averaging the speed information contained in the CAMs (cooperative awareness messages) at road side units (RSUs) placed at major intersections (see Figure 10). As soon as the average speed falls below a threshold, the application, assuming a high traffic amount, gives bus lanes free for passenger cars. The RSU sends then the information about free bus lanes to vehicles in range.

The evaluations show that the average speed was usable as an indicator for an increase of traffic demand. Though, as the usage of this measure is rather uncommon, further investigations and validations should be performed. When coming to measure the benefits of using bus-lanes for private vehicles, the application did not prove its benefits at all. At higher penetration rates, the average travel time of all distinguished transport modes – busses, vehicles not equipped with V2X devices, equipped vehicles, as well as rerouted vehicles – climbs above the respective average travel times without the application. The main reason is that vehicles, which use bus lanes tend to either decelerate the busses or are blocked by busses.

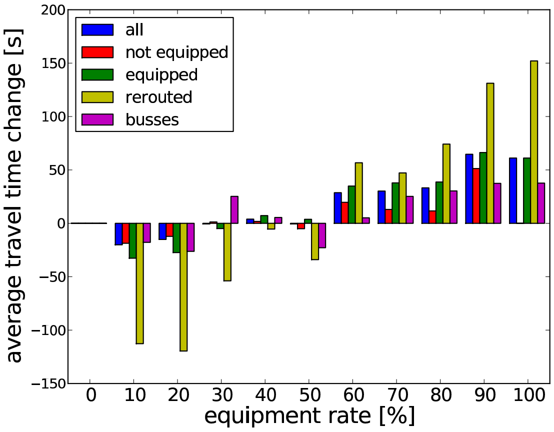


Figure 11. Average travel times changes per vehicle class over equipment rates.

The results show, that a naive implementation of the application does not take into account traffic behaviour and degrades with increasing penetration rate. This effect was observed in studies on other V2X-based traffic management applications as well. It also shows that proper design and a fine-grained evaluation of developed applications are needed.

### *C. VABENE*

Big events or catastrophes may cause traffic jams and problems to the transport systems, causing additional danger for the people who live in the area. Public authorities are responsible for taking preparatory actions to prevent the worst case. The objective of VABENE is to implement a system that supports public authorities to decide which action should be taken. This system is the successor of demonstrators used during the pope's visit in Germany in 2005 and during the FIFA World Cup in 2006.

One focus of VABENE lies on simulating the traffic of large cities. The system shows the current traffic state of the whole traffic network, helping the traffic manager to realize when a critical traffic state will be reached. To simulate the traffic of a large region such as Munich and the area around Munich at multiple real-time speed, a mesoscopic traffic model was implemented into SUMO. This model has not yet been released to the public and is available for internal proposes only.

Similar to the *TrafficOnline* Project (Section A), the road networks were imported from a NavTeq database and adapted manually where needed. The basic traffic demand was computed from O/D-matrices supplied by traffic authorities.

The simulation is restarted every 10 minutes, loads a previously saved state of the road network and computes the state for half an hour ahead. While running, the simulation state is calibrated using traffic measurements from various sources such as inductive loops, floating car data and (if available) an airborne traffic surveillance system. This calibration is performed by comparing simulated vehicle counts with measured vehicle counts at all network edges for which measurements are currently available. Depending on this comparison, vehicles are removed prematurely from the simulation or new vehicles are inserted. Also, the maximum speed for each edge is set to the average measured speed.

A crucial part of this calibration procedure is the selection of a route for inserted vehicles. This is accomplished by building a probability distribution of possible routes for each network edge out of the basic traffic demand and then sampling from this distribution.

The accuracy of the traffic prediction depends crucially on the accuracy of the basic traffic demand. To lessen this problem we are currently investigating the use of historical traffic measurements to calibrate the simulation wherever current measurements are not yet available. However, this approach carries the danger of masking unusual traffic developments, which might already be foreseeable from the latest measurements.

Both, the current traffic state as well as the prediction of the future state is presented to the authorities in a browser-based management interface. The management interface allows to investigate the sources of collected information, including inductive loops, airborne and conventional images, as well as to monitor routes or evaluate the network's current accessibility, see Figure 12.

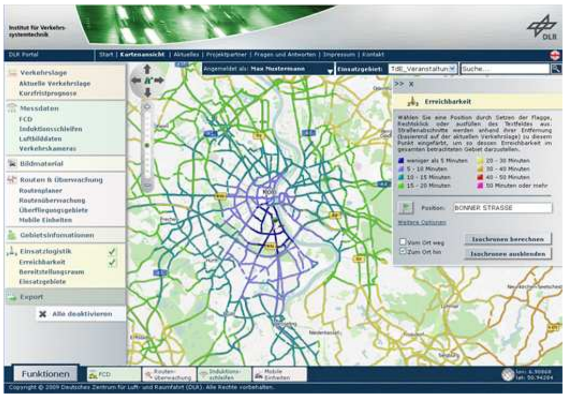


Figure 12. Screenshot of the "EmerT" portal used in VABENE showing travel time isochrones.

### *D. CityMobil*

Microscopic traffic simulations also allow the evaluation of large scale effects of changes in vehicle or driver behavior such as the introduction of automated vehicles or electromobility. The former was examined with the help of

SUMO in the EU project CityMobil where different scenarios of (partly) automated cars or personal rapid transit were set up on different scales, from a parking area up to whole cities.

On a small scale, the benefits of an autonomous bus system were evaluated. In this scenario, busses are informed about waiting passengers and adapt their routes to this demand. On a large scale, the influence of platooning vehicles was investigated, using the model of a middle-sized city of 100.000 inhabitants. Both simulations showed positive effects of transport automation.

## V. RECENT EXTENSIONS

### A. *Emission and Noise Modeling*

Within the iTETRIS project, SUMO was extended by a model for noise emission and a model for pollutant emission and fuel consumption. This was required within the project for evaluating the ecological influences of the developed V2X applications.

Both models are based on existing descriptions. 7 models for noise emission and 15 pollutant emission / fuel consumption models were evaluated, first. The parameter they need and their output were put against values available within the simulation and against the wanted output, respectively. Finally, HARMONOISE [40] was chosen as noise emission model. Pollutant emission and fuel consumption is implemented using a continuous model derived from values stored in the HBEFA database [41].

The pollutant emission model's implementation within SUMO allows to collect the emissions and fuel consumption of a vehicle over the vehicle's complete ride and to write these values into a file. It is also possible to write collected emissions for lanes or edges for defined, variable aggregation time intervals. The only available noise output collects the noise emitted on lanes or edges within pre-defined time intervals, a per-vehicle noise collecting output is not available. Additionally, it is possible to retrieve the noise, emitted pollutants, and fuel consumption of a vehicle in each time step via TraCI, as well as to retrieve collected emissions, consumption, and noise level for a lane or a road.

Besides measuring the level of emissions or noise for certain scenarios, the emission computation was also used for investigating new concepts of vehicle routing and dependencies between the traffic light signal plans and emissions [42].

### B. *Person-based Intermodal Traffic Simulation*

A rising relevance of intermodal traffic can be expected due to ongoing urbanization and increasing environmental concerns. To accommodate this trend SUMO was extended by capabilities for simulating intermodal traffic. We give a brief account of the newly added concepts.

The conceptual center of intermodal traffic is the individual person. This person needs to undertake a series of trips where each may be taken with a different mode of transport such as personal car, public bus or walking. Trips may include traffic related delays, such as waiting in a jam, waiting for a bus or waiting to pick up an additional passenger. It is important to note that earlier delays influence later trips of a simulated person. The above concept is reflected in an extension of the SUMO route input. One can now specify a person as a list of rides, stops and walks. A ride can stand for any vehicular transportation, both private and public. It is specified by giving a starting edge, ending edge and a specification of the allowed vehicles. Stops correspond to non-traffic related activities such as working or shopping. A walk models a trip taken by foot but it can also stand for other modes of transport that do not interfere with road traffic. Another extension concerns the vehicles. In addition to their route, a list of stops and a line attribute can be assigned. Each stop has a position, and a trigger which may be either a fixed time, a waiting time or the id of a person for which the vehicle must wait. The line attribute can be used to group multiple vehicles as a public transport route.

These few extensions are sufficient to express the above mentioned person trips. They are being used within the TAPAS [43][44] project to simulate intermodal traffic for the city of Berlin. Preliminary benchmarks have shown that the simulation performance is hardly affected by the overhead of managing persons. In the future the following issues will be addressed:

- Online rerouting of persons. At the moment routing across trips must be undertaken before the start of the simulation. It is therefore not possible to compensate a missed bus by walking instead of waiting for the next bus.
- Smart integration of bicycles. Depending on road infrastructure bicycle traffic may or may not interact with road traffic.
- Import modules for importing public time tables.

## VI. CURRENT DEVELOPMENT

As shown, the suite covers a large variety of functionalities, and most of them are still under research. In the past, applications from the SUMO suite were adapted to currently investigated projects' needs, while trying to keep the already given functionality work. This development context will be kept for the next future, and major changes in functionality are assumed to be grounded on the investigated research questions. Nonetheless, a set of "strategic" work topics exist and will be presented in the following sub-sections. They mainly target on increasing the simulation's validity as well as the number of situations the simulation is able to replicate, and on establishing the simulation as a major tool for evaluation of academic models and algorithms for both traffic simulation as well as for evaluation of traffic management applications.

### A. *Car-Following and Lane-Change API*

One of the initial tasks SUMO was developed for was the comparison of traffic flow models, mainly microscopic car-following and lane-changing models. This wish requires a clean implementation of the models to evaluate. Within the iTETRIS project, first steps towards using other models than the used Krauß extension for computing the vehicles' longitudinal movement were taken by implementing an API for embedding other car-following models. Some initial implementations of other models exist, though not all of them are able to deal correctly with multi-lane urban traffic. What is already possible to do with car-following models is also meant to be implemented for lane-change models.

### *B. Model Improvements*

While evaluation of academic driver behavior models is one of the aimed research topics, most models are concentrating to describe a certain behavior, e.g., spontaneous jams, making them inappropriate to be used within complex scenarios which contain a large variety of situations. In conclusion, next steps of SUMO development will go beyond established car-following models. Instead, an own model will be developed, aiming on its variability mainly.

### *C. Interoperability*

SUMO is not the only available open source traffic simulation platform. Some other simulators, such as MATsim, offer their own set of tools for demand generation, traffic assignment etc. It is planned to make these tools being usable in combination with SUMO by increasing SUMO's capabilities to exchange data. Besides connecting with other traffic simulation packages, SUMO is extended for being capable to interact with driving or world simulators. Within the DLR project "SimWorld Urban", SUMO is connected to the DLR driver simulator, allowing to perform simulator test drives through a full-sized and populated city area.

## VII. SUMMARY

We have presented a coarse overview of the microscopic traffic simulation package SUMO, presenting the included applications along with some common use cases, and the next development steps. The number of projects and the different scales (from single junction traffic light control to whole city simulation) present the capabilities of the simulation suite. Together with its import tools for networks and demand and recently added features such as emission modeling and the powerful TraCI interface, SUMO aims to stay one of the most popular simulation platforms not only in the field of vehicular communication. We kindly invite the reader to participate in the ongoing development and implement his or her own algorithms and models. Further information can be obtained via the project's web site [2].

## REFERENCES

[1] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "SUMO - Simulation of Urban MObility: An Overview," in SIMUL 2011, The Third International Conference on Advances in System Simulation, 2011.

[2] DLR and contributors, SUMO Homepage [Online], http://sumo.sourceforge.net/, accessed July 03, 2012.

[3] PTV AG, Vissim homepage [Online], http://www.ptv-vision.com/en-uk/products/vision-traffic-suite/ptv-vissim/overview/, accessed July 03, 2012.

[4] OpenDRIVE consortium, OpenDRIVE homepage [Online], http://www.opendrive.org/, accessed July 03, 2012.

[5] PTV AG, VISUM homepage [Online], http://www.ptv-vision.com/de/produkte/vision-traffic-suite/ptv-visum/, accessed July 03, 2012.

[6] MATSim homepage [Online], http://www.matsim.org/, accessed July 03, 2012.

[7] OpenStreetMap homepage [Online], http://www.openstreetmap.org/, accessed July 03, 2012.

[8] D. Krajzewicz, G. Hertkorn, J. Ringel, and P. Wagner, "Preparation of Digital Maps for Traffic Simulation; Part 1: Approach and Algorithms," in Proceedings of the 3rd Industrial Simulation Conference 2005, pp. 285–290. EUROSIS-ETI. 3rd Industrial Simulation Conference 2005, Berlin (Germany). ISBN 90-77381-18-X.

[9] L. G. Papaleondiou and M. D. Dikaiakos, "TrafficModeler: A Graphical Tool for Programming Microscopic Traffic Simulators through High-Level Abstractions," in Proceedings of the 69th IEEE Vehicular Technology Conference, VTC Spring 2009, Spain, 2009.

[10] S. Krauß, "Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics," PhD thesis, 1998.

[11] E. Brockfeld, R. Kühne, and P. Wagner, "Calibration and Validation of Microscopic Traffic Flow Models," in Transportation Research Board [ed.]: TRB 2004 Annual Meeting, pp. 62–70, TRB Annual Meeting, Washington, DC (USA) 2004.

[12] E. Brockfeld and P. Wagner, "Testing and Benchmarking of Microscopic Traffic Flow Models," in Proceedings of the 10th World Conference on Transport Research, pp. 775-776, WCTR04 - 10th World Conference on Transport Research, Istanbul (Turkey) 2004.

[13] E. Brockfeld, R. Kühne, and P. Wagner, "Calibration and Validation of Microscopic Traffic Flow Models," Transportation Research Records, 1934, pp. 179–187, 2005.

[14] M. Treiber and D. Helbing, "Realistische Mikrosimulation von Strassenverkehr mit einem einfachen Modell," Symposium Simulationstechnik (ASIM), 2002.

[15] B. Kerner, S. Klenov, and A. Brakemeier, "Testbed for wireless vehicle communication: A simulation approach based on three-phase traffic theory," in Proceedings of the IEEE Intelligent Vehicles Symposium (IV'08), pp. 180–185, 2008.

[16] R. Wiedemann, „Simulation des Straßenverkehrsflußes," in Heft 8 der Schriftenreihe des IfV, Institut für Verkehrswesen, Universität Karlsruhe, 1974.

[17] D. Krajzewicz, "Traffic Simulation with SUMO - Simulation of Urban Mobility," in J. Barceló, "Fundamentals of Traffic Simulation," International Series in Operations Research and Management Science. Springer, pp. 269–294, ISBN 978-1-4419-6141-9. ISSN 0884-8289, 2010.

[18] A. Wegener, M. Piórkowski, M. Raya, H. Hellbrück, S. Fischer, and J.-P. Hubaux, "TraCI: An Interface for Coupling Road Traffic and Network Simulators," in Proceedings of the 11th communications and networking simulation symposium, 2008.

[19] Politecnico di Torino, TraCI4J Homepage [Online], http://sourceforge.net/apps/mediawiki/traci4j/index.php?title=Main_Page, accessed July 09, 2012.

[20] C. Sommer, Z. Yao, R. German, and F. Dressler, "On the need for bidirectional coupling of road traffic microsimulation and network simulation," in Proceedings of the 1st ACM SIGMOBILE workshop on Mobility models, pp. 41–48, 2008.

[21] ns3 Homepage [Online], http://www.nsnam.org/, accessed January 26, 2011.

[22] M. Piórkowski, M. Raya, A. Lugo, P. Papadimitratos, M. Grossglauser, and J.-P. Hubaux, "TraNS: Realistic Joint Traffic and Network Simulator for VANETs," ACM SIGMOBILE Mobile Computing and Communications Review, pp. 31-33, 2008.

[23] iTETRIS Homepage [Online], http://www.ict-itetris.eu/10-10-10-community/, accessed July 09, 2012.

[24] OMNET++ Homepage [Online], http://www.omnetpp.org/, accessed July 09, 2012.

[25] D. Rieck, B. Schuenemann, I. Radusch, and C. Meinel, "Efficient Traffic Simulator Coupling in a Distributed V2X Simulation Environment," in SIMUTools '10: Proceedings of the 3rd International ICST Conference on Simulation Tools and Techniques, Torremolinos, Malaga, Spain, 2010. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, pp. 1-9, ISBN: 978-963-9799-87-5.

[26] D. Borsetti and J. Gozalvez, "Infrastructure-Assisted Geo-Routing for Cooperative Vehicular Networks," in Proceedings of the 2nd IEEE (*) Vehicular Networking Conference (VNC 2010), 2010, New Jersey (USA).

[27] M. A. Leal, M. Röckl, B. Kloiber, F. de Ponte-Müller, and T. Strang, "Information-Centric Opportunistic Data Dissemination in Vehicular Ad Hoc Networks," in International IEEE Conference on Intelligent Transportation Systems (ITSC), 2010, Madeira Island (Portugal).

[28] E. Cascetta, A. Nuzzolo, F. Russo, and A. Vitetta, "A modified logit route choice model overcoming path overlapping problems," in Transportation and traffic theory: Proceedings of the 13th International Symposium on Transportation and Traffic Theory. Pergamon Press, Lyon, France, 1996.

[29] C. Gawron, "Simulation-based traffic assignment – computing user equilibria in large street networks," Ph.D. Dissertation, University of Köln, Germany, 1998

[30] M. Behrisch, D. Krajzewicz, and Y.-P. Wang, "Comparing performance and quality of traffic assignment techniques for microscopic road traffic simulations," in Proceedings of DTA2008. DTA2008 International Symposium on Dynamic Traffic Assignment, Leuven (Belgien), 2008.

[31] M. Behrisch, D. Krajzewicz, P. Wagner, and Y.-P. Wang, "Comparison of Methods for Increasing the Performance of a DUA Computation," in Proceedings of DTA2008. DTA2008 International Symposium on Dynamic Traffic Assignment, Leuven (Belgien), 2008.

[32] R.-P. Schäfer, "IQ routes and HD traffic: technology insights about tomtom's time-dynamic navigation concept," in Proceedings of the the 7th joint meeting of the European software engineering conference and the ACM SIGSOFT symposium on The foundations of software engineering (ESEC/FSE '09). ACM, New York, NY, USA, 171-172. DOI=10.1145/1595696.1595698, 2009.

[33] D. Krajzewicz, D. Teta Boyom, and P. Wagner, "Evaluation of the Performance of city-wide, autonomous Route Choice based on Vehicle-to-vehicle-Communictaion," TRB 2008 (87. Annual Meeting), 2008, Washington DC, USA.

[34] D. Krajzewicz, E. Brockfeld, J. Mikat, J. Ringel, C. Rössel, W. Tuchscheerer, P. Wagner, and R. Woesler, "Simulation of modern Traffic Lights Control Systems using the open source Traffic Simulation SUMO," in Proceedings of the 3rd Industrial Simulation Conference 2005, pp. 299–302, EUROSIS-ETI, 3rd Industrial Simulation Conference 2005, Berlin (Germany). ISBN 90-77381-18-X.2005.

[35] L. Bieker, "Emergency Vehicle prioritization using Vehicle-to-Infrastructure Communication," Young Researchers Seminar 2011 (YRS2011), 2011, Copenhagen, Denmark.

[36] D. Greenwood, B. Burdiliak, I. Trencansky, H. Armbruster, and C. Dannegger, "GreenWave distributed traffic intersection control," in Proceedings of The 8th International Conference on Autonomous Agents and Multiagent Systems - Volume 2, pp. 1413–1414, 2009.

[37] O. H. Minoarivelo, "Application of Markov Decision Processes to the Control of a Traffic Intersection," postgraduate diploma, University of Barcelona, 2009

[38] J. Kerekes, M. Presnar, K. Fourspring, Z. Ninkov, D. Pogorzala, A. Raisanen, A. Rice, J. Vasquez, J. Patel, R. MacIntyre, and S. Brown, "Sensor Modeling and Demonstration of a Multi-object Spectrometer for Performance-driven Sensing," in Proceedings of Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XV, SPIE Vol. 7334, Defense and Security Symposium, Orlando, Florida, 2009, DOI: 10.1117/12.819265.

[39] L. Bieker and D. Krajzewicz, "Evaluation of opening Bus Lanes for private Traffic triggered via V2X Communication," (FISTS 2011), 2011, Vienna, Austria.

[40] R. Nota, R. Barelds, and D. van Maercke, "Harmonoise WP 3 Engineering method for road traffic and railway noise after validation and fine-tuning," Technical Report Deliverable 18, HARMONOISE, 2005.

[41] INFRAS. HBEFA web site [Online], http://www.hbefa.net/, accessed July 09, 2012.

[42] D. Krajzewicz, L. Bieker, E. Brockfeld, R. Nippold, and J. Ringel, "Ökologische Einflüsse ausgewählter Verkehrsmanagementansätze," In Heureka '11, 2011, Stuttgart, Germany.

[43] R. Cyganski and A. Justen, "Maßnahmensensitive Nachfragemodellierung in mikroskopischen Personenverkehrsmodellen," Deutsche Verkehrswissenschaftliche Gesellschaft, Schriftenreihe B, 2007.

[44] G. Hertkorn and P. Wagner, "Travel demand modelling based on time use data," in 10th International conference on Travel Behaviour Research, August 2004.