SUMO – Simulation of Urban MObility

An Overview

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***Abstract*— SUMO is an open source traffic simulation package including net import and demand modeling components. We describe the current state of the package as well as future developments and extensions. SUMO helps to investigate several research topics e.g. route choice and traffic light algorithm or simulating vehicular communication. Therefore the framework is used in different projects to simulate automatic driving or traffic management strategies.**

Keywords- microscopic traffic simulation, software, open source

I. INTRODUCTION

The German Aerospace Center (DLR) started the development of the open source traffic simulation package SUMO back in 2001. Since then SUMO has evolved into a full featured suite of traffic modeling utilities including a road network capable to read different source formats, demand generation and routing utilities from various 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) to adapt the simulation online.

In this paper, we will survey some of the recent developments and future prospects of SUMO including multimodal simulation and emission modeling. We start with an overview of recent projects, then give a more detailed description of the two topics mentioned before and finish with an outlook on the extensibility especially regarding simulation models and online interaction.

II. THE SUMO SUITE

SUMO was started to be implemented in 2001, with a first open source release in 2002. There are two reasons for making the work available as open source. The first is the wish to support the traffic simulation community with a free tool into which own algorithms can be implemented. While there are some open source traffic simulations available, most of them have been implemented within a student thesis and got unsupported afterwards. A major drawback – besides reinventing the wheel – is the almost non-existing comparability of the implemented models or algorithms. A common simulation platform should be of benefit here. The second reason for making the simulation open source was the wish to gain support from other institutions.

SUMO is not only a traffic simulation, but rather a suite of applications which help to prepare and to perform the simulation of traffic. As the traffic simulation “sumo” requires the representation of road networks and traffic demand to simulate in an own format, both have to be imported or generated using different sources.

SUMO road networks can be either generated using an application named “*netgen*” or generated by importing a digital road map. The road network importer “*netconvert*” allows to read networks from other traffic simulators as VISUM, Vissim, or MATsim. It also reads other common formats, as shapefiles or Open Street Map. Due to the lack of applications, the support for TIGER networks was dropped. But TIGER networks are also available as shapefiles and were included in the OSM data base. Besides these formats, “netconvert” is also capable to read less known formats, as RoboCup network format, or openDRIVE.

(a)

(b)

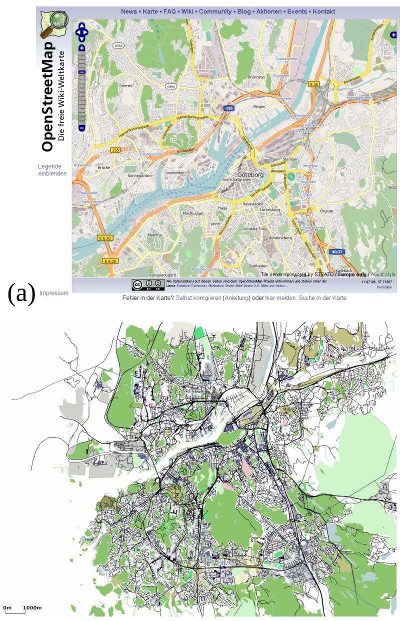

Figure 1. Example conversion of an OpenStreetMap; a) original OpenStreetMap view, b) network imported into SUMO.

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SUMO is a purely microscopic traffic simulation. Each vehicle is given explicitly, defined at least by an identifier (name), the departure time, and the vehicle's route through the network. If wanted, each vehicle can be described more detailed. The departure and arrival properties, such as the lane to use, the velocity, or the position can be defined. 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.

The definitions of vehicles can be generated using different sources. For large-scale scenarios usually so-called "origin/destination matrices" (O/D matrices) are used. They describe the movement between traffic assignment zones in vehicle number per time. Often, a single matrix is given for a single day what is insufficient for microscopic traffic simulations as the direction changes over time are not represented. Sometimes, matrices with a scale of 1h are available. For large-scale traffic simulations, they are the most appropriate source. The SUMO suite includes "*od2trips*", an application for converting O/D matrices to single vehicle trips. Besides disaggregating the matrix, the application also assigns an edge from the road network as depart/arrival position. The map from traffic assignment zones into edges is to be given to application as one input.

The resulting trips consist of a start and end road together with a departure time but no explicit route information. Routes are usually calculated by performing a traffic assignment employing a routing procedure such as shortest path calculations under different cost functions. Details on the models in SUMO can be found in section III.B.

A further route computation application, "*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 up to ten nodes. A further application, "*dfrouter*", computes routes by using information from loop 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 and if the coverage with induction loops is low.

The simulation is time-discrete with a default simulation step length of 1s. It 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. SUMO uses an extension of the car-following model developed by Stefan Krauß [1]. Changing the lane is done using a model developed during the implementation of SUMO [12]. Two versions of the traffic simulation exist. The first is a pure command line application for efficient batch simulation. The second version is a graphical application which renders the performed simulation using openGL.

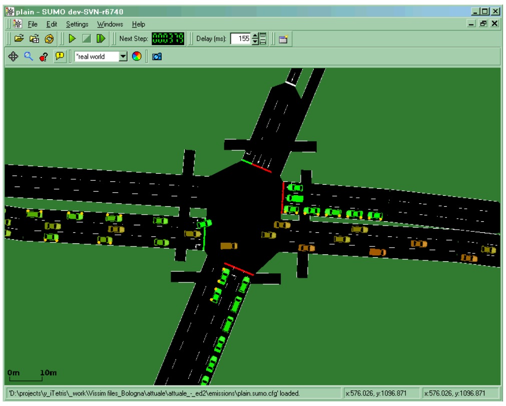

Figure 2. Screenshot of the graphical user interface coloring vehicles by their CO_2 emission.

SUMO allows to generate various outputs for each simulation run. These range from simulated induction loops to single vehicle positions written in each time steps for all vehicles and up to complex values as information about each vehicle's trip or aggregated measures along a street or lane. Besides conventional traffic measures, SUMO was extended by a noise emission and a pollutant emission / fuel consumption model, see also section V.A.

In 2006 the simulation was extended by the possibility to interact with an external application via a socket connection. This API was implemented by Axel Wegener and his colleagues from the University of Lübeck, and was made available as a part of SUMO's official release. Within the iTETRIS project, see section IV.A, this API was reworked, integrating it closer to SUMO's architecture and specification.

TraCI is not the only contribution to SUMO from other parties. SUMO Traffic Modeler [13] allows to define a population for a given area and compute this population's mobility wishes which can be used as an input for the traffic simulation. The same is done by "*activitygen*" written by Piotr Woznica and Walter Bamberger from TU Munich. eWorld [14] allows to set up further environmental characteristics, such as weather condition and visualizes a running, connected simulation.

III. Research Topics

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. Here, usually SUMO is coupled to an external communication simulation, such as ns2 or ns3 [2] using TraCI. For obtaining a functioning environment for the simulation of vehicular communications, an applications instance which models the V2X application to simulate is needed. Additionally, a synchronization and message exchange mechanism has to be involved.

TraNS [15] was a very popular middleware for V2X simulation which realizes these needs. It was build upon

SUMO and ns2. Here, the 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. With the end of the projects the original TraNS authors were working on, TraNS itself got no longer maintained and works with a very old SUMO version only, as the TraCI API was changed.

A modern replacement for TraNS was implemented within the iTETRIS project [7]. The iTETRIS system couples SUMO and ns2's successor ns3. ns3 was chosen, as 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 simulators. The V2X applications are modeled in own, language-agnostic programs. This clear distribution of responsibilities allows to implement own applications conveniently in ones favorite programming language.

A very flexible approach for coupling SUMO with other applications is the VSimRTI middleware developed by FhG Fokus [16]. Its HLA-based architecture does not only allow the interaction between SUMO and other communication simulators. It is also able to connect SUMO and Vissim, a commercial traffic simulation package. In [16], 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.

Besides the named possibilities to simulate vehicular applications, other implementations allow to use SUMO in combination with other communication simulators such as ns2 or ns3.

Many vehicular communication applications target at increasing safety. It should be stated, that up to now, microscopic traffic flow models are not capable to compute safety-related measures. SUMO's strength lies in simulation of V2X applications which aim at the improvement of traffic efficiency. Also, evaluating concepts for forwarding messages to their defined destination ("message routing") can be done using SUMO, see for example [17] or [18].

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 and as new 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" on a microscopic base. Usually, such algorithms are investigated using macroscopic traffic flow models, or even using coarser road capacity models which do not resemble dissolving road congestions.

The SUMO suite supports such investigations using the "*duarouter*" application. By now, two algorithms for computing a user assignment are implemented, c-logit and Gawron's dynamic user assignment algorithm. Both are iterative and due to this time consuming. Possibilities to reduce the duration to compute an assignment were evaluated and are reported in [19]. A further possibility to reduce the computational effort is given in [20]. 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. Navigation systems as Tom Tom's IQ routes ([21]) use on-line traffic information to support the user with a fastest route through the network regarding the current situation on the streets. A set of research is done on finding new ways of determining the state on the road network, where vehicular communication is one possibility. With the increased penetration rate of vehicles equipped with a navigation device, a further question arises: what happens if all vehicles get the same information? Will they all use the same route and generate new congestions? This question is 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 to address these topics, see, i.e., [9].

C. Traffic Light Algorithms

The evaluation of developed traffic light programs or algorithms for making traffic lights adaptable to the current traffic is one of the main applications for microscopic traffic flow simulations. As SUMO's network model is relatively coarse compared to commercial applications 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, both for controlling a single intersection ([22]) and for net-wide investigations. By distinguishing different vehicle types, SUMO also allows the simulation of public transport or emergency vehicle prioritization at intersections [5].

The first investigations were performed by implementing the traffic light algorithms to evaluate directly into the simulation's core. Over the years, this has showed to be hard to maintain. Using TraCI seems to be a more sustainable procedure currently.

D. Evaluation of Surveillance Systems

SUMO's capability to simulate large-scale scenarios allows the evaluation of new traffic surveillance systems. Within the VABENE project, a running traffic simulation was calibrated using conventional induction loop measures, and using vehicle densities and average velocities obtained from an airborne camera system which was mounted under a zeppelin. The taken pictures were processed on board of the zeppelin and the system sent the positions of vehicles to the ground center. Here, the number of vehicles running through the simulation was matched to the number of vehicles running on the observed street in reality.

Within the TrafficOnline project, a system for travel speed observation using GSM data was designed, implemented, and evaluated. SUMO's responsibility was to generate a virtual telephony behavior. For testing the travel speed recognition system, not only road traffic on both highways and within urban areas was modeled. Additionally, busses, light rail and fast rail were modeled to evaluate whether the system is able to detect the speeds on the roads even if additional moving participants exist.

IV. Recent Projects

SUMO was and is used and extended in several research projects. In the following, only some of the recent ones are named.

A. *iTetris*

The interest in V2X communication is increasing but it is expensive and may be even dangerous to implement such a system. For research studies which measure the benefits of a system before it is deployed into the real world, a simulation framework which simulates the interaction between vehicles and infrastructure of whole cities is needed. The aim of iTETRIS project was to develop such framework and to couple the communication simulator ns3 and SUMO using an open source system called "iCS" – iTETRIS Control System which was developed within the project. The iCS is responsible for starting the named simulators and additional programs which simulate the V2X applications. It is also responsible for synchronizing the participating simulators, and for the message exchange. Using this simulation framework it was possible to investigate the impacts on V2X communication strategies.

Within the project several traffic management strategies were simulated e.g. prioritization of emergency vehicles at controlled intersections [5] and rerouting vehicles over bus lanes using V2X communication [6].

B. *VABENE*

Traffic is more and more important for large cities. Big events or even catastrophes might cause traffic jams and problems to the transport systems and might even be dangerous for the people who live in the city. Public authorities are responsible to take the according action to prevent the worst case. The objective of VABENE is to implement a system which supports the public authority to decide which action should be taken.

The focus in this project lies on simulating the traffic of large cities. The system shows the current traffic state of the whole traffic network which helps the traffic manager to realize when a critical traffic state will be reached. To simulate the traffic of a large region like Munich and the area around Munich a mesoscopic traffic model was implemented into SUMO which is available for internal proposes only.

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 induction loop measures and measures collected from an airborne traffic surveillance system. Both, the current traffic state as well as the prediction of the future state is presented to the authorities. 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.

C. *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 the 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 [23] 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 [24].

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 this 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. Also, collected emissions, consumption, and noise level for a lane or a road can be retrieved.

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 [25].

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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 and report on our experience with person-based intermodal simulation.

The conceptual center of intermodal-traffic is the individual person. This person needs to undertake a series of trips each of which 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. While all trips may be simulated independently it is important to note that earlier delays influence later trips of the person. The above concept is reflected in an extension of the SUMO route input. One can now specify a person as 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 which 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 [10][11] 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 we would like to address the following issues:

- 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.
- Visualization of persons.
- 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

A. Car-Following and Lane-Change API

Within the iTETRIS project, first steps towards using other models than the used Krauß extension for computing the vehicles' longitudinal movement were taken. An API for implementing and embedding other car-following models was implemented. Some initial implementations of other models exist, though not all of them are able to deal correctly with multi-lane urban traffic. The work is assumed to continue, especially as the decision was taken to concentrate on extending the default model instead of sticking to a well-defined scientific model. What is already possible to do with car-following models is also meant to be implemented for lane-change models.

B. Model Improvements

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. On the other hand, 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.

As a recent 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. In a first step, the internal representation of road networks will be revalidated and cleaned. Then, the work will aim on coupling the car-following and the lane-changing models closer.

C. Interoperability

SUMO is not the only available open source traffic simulation platform. Some other simulations, such as MATsim [26], 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 the 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.

D. Network Editor

Since 2011, a graphical network editor is implemented. It allows to set up a complete road network for SUMO, including all needed information, such as correct lane number, speed limits, connections across intersections, and traffic lights. For now, this tool is not part of the open source package, but is held for internal purposes only.

VII. Summary

We have presented a coarse overview of the microscopic traffic simulation package SUMO, presenting the included application along with some common use cases, and the next steps within the development. We kindly invite the reader to participate in the development. Further information can be obtained via the project's web site [8].

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