Toward Realistic Simulation of Intervehicle Communication: Models, Techniques and Pitfalls

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***Abstract*—The quality of Intelligent Transportation Systems strongly depends on the underlying communication protocols and techniques. In this article, we discuss the current state of the art, trends, and open problems in the area of simulation techniques used to study Inter-Vehicle Communication (IVC). Complementary to testbed experiments that are often limited in scale and variety, simulation is one of the most important methods for performance evaluation of IVC applications. In the last couple of years, the quality of used simulation models has seen tremendous improvement, yet there are still open issues regarding the accuracy of typical simulation experiments. In this article, we touch on a broad range of topics but focus on three aspects that have a strong influence on the degree of realism and hence the reliability of simulation results: the need to integrate microscopic mobility models, the used evaluation metrics, and the impact of human driver behavior on a macroscopic scale. Based on selected example settings, we first demonstrate the strong influence of these aspects on the quality of simulation experiments and then describe available models and tools that can be used for IVC simulation.**

I. Introduction

We study and discuss the state of the art of simulation-based performance evaluation of Inter-Vehicle Communication (IVC) protocols and applications. In the scope of this article, we concentrate on the most recent advances and findings by outlining selected models, techniques, and issues that are specifically related to IVC, with a strong focus on aspects beyond network simulation issues. The main objective is to determine the degree to which available simulation techniques produce realistic results.

In the last years, there has been significant progress in the development of IVC protocols [1], [2]. Typically, two application scenarios are distinguished: efficiency and comfort applications (such as Traffic Information Systems (TIS), multiplayer games, or location based services) and safety applications (including emergency brakes, accident warning, or lane change control). All these applications demand for a wide variety of characteristics of the used communication protocols. In the IVC community, protocols have been developed using centralized or completely distributed approaches exploiting many different communication channels. For direct communication among vehicles, and also multi-hop transmissions, infrastructure-less approaches started using consumer WLAN, which is being succeeded by the emerging IEEE 802.11p/WAVE standard. Furthermore, infrastructure-based communication is assumed to employ WiFi or 3G/3.5G solutions in many application scenarios.

Besides real world experiments, simulation is used as a tool to evaluate developed information exchange protocols in vehicular networks.

A. Challenges in Simulating IVC

Simulation of IVC applications and protocols is typically based on classical network simulation used to evaluate the performance of network protocols [3]. There has been much progress in this field both in terms of improving the accuracy of the simulation results and of improving the simulation speed. There are, however, a number of issues specific to IVC that need to be considered in such simulation experiments.

For evaluating the communication network in IVC, there are two major challenging questions: how to integrate the mobility aspects of vehicles and how to exactly estimate the characteristics of the wireless channel. Mobility modeling started using simple random waypoint or Manhattan grid models, but there is the need to have more realistic models incorporating the microscopic behavior of individual vehicles as well as the macroscopic behavior of entire road traffic flows. Furthermore, exact physical layer models are required [4], [5]. This issue is currently being addressed in many research projects, but still encounters problems related to the availability of highly detailed environment models.

Beyond those aspects, there are a number of additional challenges. This includes for example the behavior of human drivers. Partially, this is relevant to the microscopic mobility of cars, e.g., using car following and lane change models, but also to macroscopic effects caused by the individual reaction on presented traffic information.

Finally, the appropriateness of the evaluation criteria used in classical (communication) network simulation need to be reconsidered for IVC performance evaluation. In many cases, the raw number of wireless communication attempts or the achieved end-to-end latency is not sufficient. IVC specific metrics have to be developed.

B. Contributions

In this article, we discuss three key aspects that strongly influence the simulation quality, the degree of realism, and thus the significance of obtained results:

- *Use of accurate mobility models* (Section II) – technical aspects of vehicles' mobility such as mass, acceleration as well as non-technical aspects on a microscopic level like car-following and lane-change models.
- *Impact of human driver behavior* (Section III) – human driver behavior on a macroscopic scale such as route choice influencing the efficiency of TIS applications.
- *Adequate evaluation metrics* (Section IV) – travel times and emission models (when focusing on TIS applications) besides typical communication related metrics, e.g., congestion on the wireless channel, delays, and throughput.

This article surveys, and gives recommendations on, available simulation techniques and models. In addition, Section V outlines some of the most commonly used simulation tools and their properties.

II. Coupling with Microscopic Mobility Models

Aside from the influence of the wireless channel, one of the most critical issues in realistic simulation of IVC protocols and applications is the mobility of the vehicles. A Vehicular Ad Hoc Network (VANET) is characterized by its inherent dynamic nature due to the mobility of the cars. This aspect needs to be carefully modeled for simulation experiments [3].

A. Problems

Early approaches to study vehicles' mobility using simple random waypoint or Manhattan grid mobility models have been proven to produce inaccurate or at least misleading results [6].

To overcome these problems, data on vehicles moving in urban (but also in freeway) scenarios has been collected in many research projects, resulting in very accurate mobility traces. These can then be fed into simulations to represent nodes' mobility. The key advantage is that such simulations can easily be reproduced using the same traces. The main drawback, however, is that no arbitrary scenarios can be modeled in the transportation domain: the experiments need to be done based on available traces. At the same time, models of the micro mobility of vehicles have been developed that very accurately simulate the mobility of individual vehicles. Using this type of microsimulation, scenarios can be described and simulated according to the needs of an evaluation experiment. Today, very accurate models of the vehicle movement are available. These take into account the characteristics of the vehicle itself (e.g., mass, acceleration), its environment (e.g., speed limits, neighboring cars), but also the driver's behavior (e.g., aggressiveness for lane changes). Two of the best known implementations of such models are VISSIM and SUMO [7]. The outcome of the vehicle microsimulation is then a synthetic trace for an arbitrary scenario.

However, the key problem is that the interaction between the IVC protocol and the vehicle's mobility is still not considered [3]. For example, after receiving information about a traffic congestion, a vehicle can be expected to change its route to bypass this problematic zone.

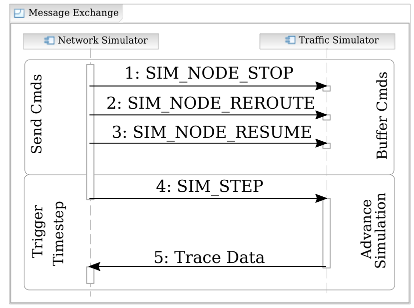

Fig. 1. Message exchange and time control between OMNeT++ and SUMO

B. Solutions

Most recently, bidirectional coupling of road traffic microsimulation and network simulation has been proposed to overcome this issue [8], [9]. This allows the incorporation of IVC based control, e.g., in the route planning of the vehicles. For example, network simulators such as OMNeT++ or ns-2 have been coupled with SUMO, controlling the time progress in the mobility model and continuously updating the positions of all vehicles. In this context, the concept of using cellular automata for modeling the microscopic mobility needs to be mentioned, which can easily be integrated with a typical network simulator [10]. The principle of the bidirectional coupling is outlined in Figure 1 using the *Veins* simulation framework as an example [8].

This simulation framework has also been used to generate the simulation results presented in the following to show the impact of the bidirectional coupling. A simple broadcast-based TIS protocol has been investigated: blocked vehicles broadcast information about a potential congestion to neighboring vehicles, which, in turn, re-broadcast this information for a given number of hops. If the network simulation determines that such an incident warning has been received by a node's wireless interface, it stores both the timestamp and the contents of the warning message. Using the bidirectional coupling to the road traffic simulator, it also triggers an adjustment of the affected road segments' estimated travel times for this vehicle. Finally, the vehicle recalculates its route to the destination. Later, when the originating vehicle resumes its journey, it notifies other vehicles that the lane can be used again, allowing them to restore their original routes.

The simulation results depicted in Figure 2 outline the impact of the IVC on the mobility of the vehicles. In particular, an urban scenario has been studied with 200 simulated cars leaving a parking lot in the city of Erlangen, on average one every 6 s, then heading to a business park along an individual, dynamically chosen route. Serving as the basis for the road layout in this scenario was map data publicly available from the OpenStreetMap project. Four sets of simulation runs have been performed. One set of runs simulated uninhibited road traffic, labeled with "free" in Figure 2. In the second set of runs, labeled with "none", an incident was simulated by stopping the lead vehicle of cars traveling along the major artery connecting the parking lot and the business park. In the final two sets, labeled with "5" and "25", all vehicles were equipped with IVC technology, so stopped vehicles

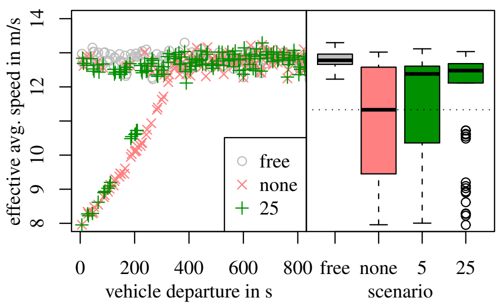

Fig. 2. Average speed of individual vehicles for free flowing traffic, traffic with an incident, and for broadcast-based IVC

could disseminate information about congested road segments. The difference between both settings is the dissemination range: it was configured to allow for 5 hops and 25 hops, respectively. Vehicles that received such notifications could often completely avoid traffic incidents.

Figure 2 (left) plots the effective average speed of each vehicle in relation to the time it entered the simulation for three sets of simulation runs. As can be seen, the recorded travel times vary widely for free flowing traffic, congested traffic, and, most importantly, traffic that has been re-routed using IVC. Enabling broadcast-based IVC over 25 hops led to a significant increase of vehicles' speeds, as vehicles that were not too close to the incident when it happened (and thus were caught in the resulting jam predicted by the microscopic mobility model) were now able to turn around before they reached the affected road segment, delaying them only slightly. Other cars managed to avoid the incident altogether. The increased variance and improvements of the average speed are summarized in the boxplot in Figure 2 (right). Based on the integrated (bi-directionally coupled) road traffic microsimulation and network simulation, we were able to produce realistic results explaining the advantages of IVC in the given scenario. In particular, the results outline the impact on each individual vehicle as well as the effects on the overall traffic flow.

III. Human Driver Behavior

Besides the more technical aspects of microscopic mobility of vehicles, higher layer decision systems about route planning and road traffic flow optimization are typically evaluated assuming a system that reacts optimally according to the available information. However, there is an additional aspect impacting the reactions: human driver behavior impacts a system not only on a microscopic level (as simulated by car following models), but also on a macroscopic level (impacting route planning and route changes): depending on the driver's knowledge and several additional aspects, either the recommendations of the IVC-based information system are considered, or no action is taken.

A. Problems

The impact of individual human driver behavior on overall road traffic is a topic of interest since the early days of traffic information systems. Actually, some of the most comprehensive psycho-physiological studies have been performed in the late 1980s and early 1990s. König et al. developed driver behavior model using AI techniques for the driver's route planning [11]. Basically, the authors considered four submodels that influence the driver's behavior as shown in Figure 3. Besides factors influencing the microscopic behavior of vehicles based on experience, the degree of aggressiveness, age, and gender, especially the reaction to received traffic information has been studied. The preferences of drivers generally influence both the selected route (a factor that is integrated into navigation systems today) and the motivation to accommodate changes to this route. Finally, the reaction to received messages and the local knowledge are key elements of the driver's behavior. Local knowledge is difficult to model and also somewhat related to the reaction to received messages. In this work, we primarily consider the reaction to received messages and develop a model taking into account all the related influences.

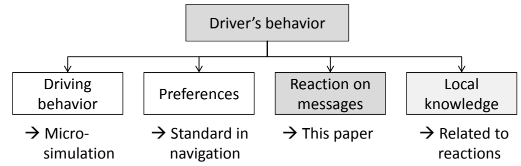

Fig. 3. Driver behavior submodels according to König et al. [11]

The most comprehensive literature study of human factors has been conducted by Dingus et al. [12] to provide guidelines for advanced traveler information systems and commercial vehicle operations. A very interesting aspect identified in this study is that human drivers tend to resist deviating from their present route to avoid congestions, i.e. they prefer following their "traditional" routes. This report also summarizes driver classes that have been identified earlier [13]. Based on cluster analysis techniques, it is possible to show that four commuter subgroups exist with respect to their willingness to respond to the delivery of real-time traffic information [12, section on driver acceptance and behavior].

In the field of IVC-based approaches, research has been conducted mainly on traffic signal control and its impact on the driver's route choice [14], as well as on intersection management [15]. It became obvious that a driver's behavior is of great interest for intelligent traffic light systems.

B. Solutions

Using the listed four basic classes of driver behavior as well as combinations thereof, we conducted a number of simulation experiments to study the impact of actions taken by individual drivers [16]. We implemented a decision system considering the typical behavior according to the published psychological studies and based on the following classes: A driver following all TIS recommendations falls into the class *always*. This is basically the kind of behavior that is being assumed for almost all simulation and experimental studies of IVC solutions. The second important class is *never*, in which the driver continues his every-day procedure and completely ignores the TIS (the ratio of drivers in class *never* must be clearly distinguished from the frequently used penetration rate: even though these

TABLE I
BEHAVIOR CLASSES

Class	Description	Mix
Always	route selection according to TIS recommendations	40.1 %
Never	drivers unwilling to change the route	23.4 %
$d < D$	route changes only if the distance to the congestion is less than D	20.6 %
$d > D$	route changes only if the distance to the congestion is larger than D	15.9 %
P	probabilistic decision whether to fall into class *always* or *never*	0 %

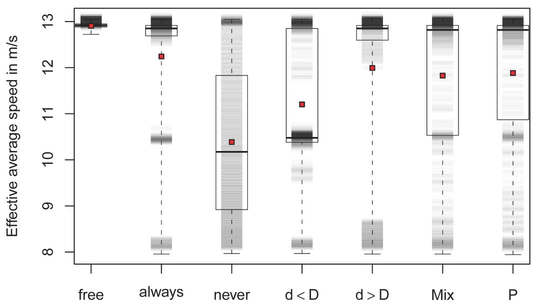

Fig. 4. Impact analysis of the driver behavior models for a TIS scenario

drivers do not follow any TIS advice, their cars certainly take part in the distributed TIS). The third class contains all drivers who only consider congestions that are within a certain range $d < D$ as relevant to their route – they simply assume that for obstructions that are further away there will be enough time for the congestion to clear before they will get there. Finally, a fourth class represents drivers who want to bypass a congestion using a long detour, but at the same time make sure that they will not have to stop in secondary jams due to short term detours; thus, this class is represented by $d > D$. All behavior classes are summarized in Table I, along with a *probabilistic* class that has drivers selecting either the *always* (with probability P) or the *never* model at the time of departure. Finally, the class *mix* is a representation of the driver model in [12].

For the evaluation, we again used the urban scenario [16] along with a simple broadcast-based IVC protocol for exchanging traffic information. In our example, we used $D = 1\,\mathrm{km}$ and $P = 0.7$. A more detailed discussion is presented in [16]. Figure 4 shows the statistical analysis of the impact different driver models have on the travel time of vehicles (normalized using the distance along the shortest route to derive an effective average speed). We present the results in the form of boxplots, indicating the median and the quartiles of all the measurements. Because the distribution of measurements is, by nature, multi-modal, we also display individual measurements, using light gray lines; thus, dark zones represent a significant number of cars in the same speed range. As the most obvious result, it can be seen that all the different models lead to a completely different overall behavior. Furthermore, as a second outcome, we observe that the mix according to [11], labeled with "Mix", can be closely approximated using the

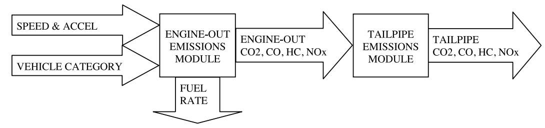

Fig. 5. Gas consumption and emission according to the EMIT model [18]

probabilistic model (P).

IV. Evaluation Metrics

The performance evaluation of IVC protocols frequently relies on communication network-related parameters such as network load, congestion of the wireless channel, or end-to-end transmission delays. This is, with some limitations, adequate to evaluate safety applications requiring low-latency (or even guaranteed real-time) communication. However, efficiency applications cannot easily be analyzed this way.

A. Problems

As a solution, the travel time of the cars is frequently used as a more descriptive metric. The travel time reveals the ability of the TIS to efficiently re-route cars in case of congestions.

It should be noted that the travel time only provides measures of the microscopic behavior of individual cars and, thus, to what extent the individual driver benefits from the system. A completely different view would be to analyze the overall behavior, i.e. the ability of the system to smoothen entire traffic flows. This can either be provided by looking at the variance of vehicle speeds or, as a combined metric with the distance traveled and revealing further interesting aspects, by looking at the resulting emissions (frequent accelerations result in a sharp increase of CO_2 emissions) [17].

B. Solutions

Very accurate modeling of the gas consumption and emissions is provided by the EMIT model, which has been calibrated for a wide range of different emissions including CO_2, CO, hydrocarbon (HC), and nitrous oxide (NO_x) [18]. The basic operation is depicted in Figure 5. Speed, acceleration, and the characteristics of the particular vehicle are used to calculate the gas consumption using an engine model. Based on these results, emissions after passing through a catalytic converter, which is assumed to have reached operating temperature, can be estimated very precisely.

The EMIT model uses a two step approach for such an engine model, first estimating the tractive power requirement at a vehicle's wheels P_{tract}. This is calculated using the following polynomial:

$$P_{tract} = Av + Bv^2 + Cv^3 + Mav + Mgv \sin\vartheta$$

Based on the tractive power requirement, the gas consumption can be estimated and, consequently, tailpipe emissions of CO_2 calculated according to a second polynomial:

$$TP_{CO_2} = \begin{cases} \alpha + \beta v + \delta v^3 + \zeta av & \text{if } P_{tract} > 0 \\ \alpha' & \text{else} \end{cases}$$

TABLE II
EMIT FACTORS FOR A CATEGORY 9 VEHICLE

factor		value	unit
v	vehicle speed		$\mathrm{m/s}$
a	vehicle accel.		$\mathrm{m/s^2}$
A	rolling resistance	0.132 6	$\mathrm{kW\,s/m}$
B	speed-correction to rolling resistance	$2.738\,4 \times 10^{-3}$	$\mathrm{kW\,s^2/m^2}$
C	air drag resistance	$1.084\,3 \times 10^{-3}$	$\mathrm{kW\,s^3/m^3}$
M	vehicle mass	$1.325\,0 \times 10^{3}$	kg
g	gravitational const.	9.81	$\mathrm{m/s^2}$
ϑ	road grade	0	degrees
α		1.110 0	$\mathrm{g/s}$
β		0.013 4	$\mathrm{g/m}$
δ		$1.980\,0 \times 10^{-6}$	$\mathrm{g\,s^2/m^3}$
ζ		0.241 0	$\mathrm{g\,s^2/m^2}$
α'		0.973 0	$\mathrm{g/s}$

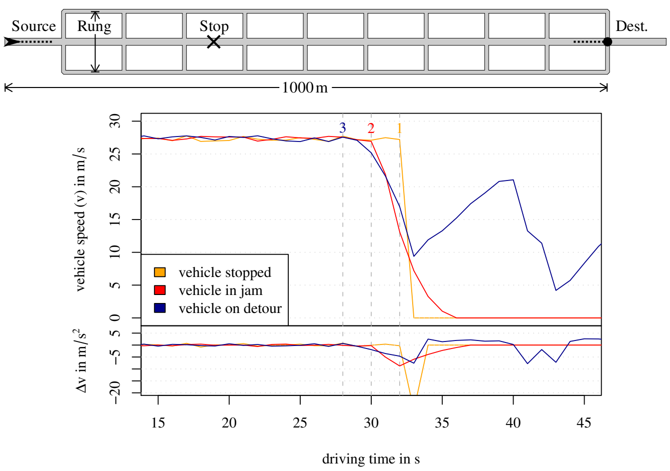

Fig. 6. Scenario description and speed / acceleration profile for vehicles approaching a congestion or taking a detour

Table II lists the used variables as well as the values of α to ζ, A to C, and M; fitted to match a *category 9 vehicle*, e.g. a '94 Dodge Spirit.

We implemented the EMIT model in the *Veins* simulation framework, using it to highlight the importance of considering both metrics, travel time and CO_2 emissions [17]. In this scenario, a single-lane trunk road with a speed limit of approx. 28 m/s (100 km/h) is supported by two parallel streets with speed limits of 22 m/s, all connected in the form of a ladder. This configuration is outlined in Figure 6 (top). Each simulation run consists of 101 cars driving on the main road, one departing every 5 s, then measuring both the cumulative time and the cumulative CO_2 emission of vehicles until all have left the simulation. We introduce an artificial incident, a vehicle stopping, on the trunk road and disallow overtaking this vehicle. Again, simple broadcast-based IVC takes place between the cars in order to exchange information about the blocked trunk road. If such a message successfully reaches a car heading towards an obstruction, it recalculates its path using one of the parallel streets if possible. We then modified the stop length in order to evaluate the appropriateness of the route recalculation with regard to the two selected metrics.

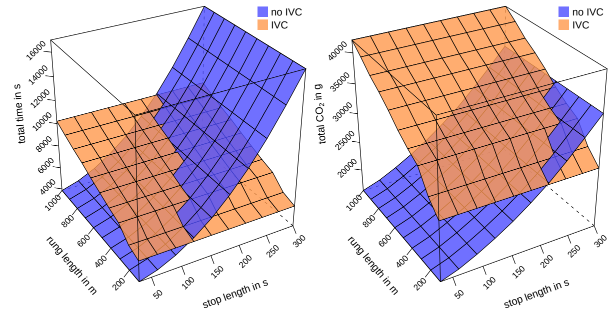

Fig. 7. Optimality of decision points according to travel time and CO_2 emission, respectively

Furthermore, we changed the length of the detour by modifying the rung length. This artificial setup is perfectly suited for analyzing the impact of the detour length, even though the road layout is certainly very abstract.

Figure 6 further shows a speed / acceleration profile for three different cars: the stopping car, a car caught in the resulting jam, and one taking a detour based on IVC-based traffic information. As can be seen, the necessary accelerations and decelerations for the detour are not negligible: in order to be able to yield to through traffic, each vehicle will have to brake slightly when leaving the rungs to and from the detour (visible in the figure as two pronounced drops in speed).

This effect can be studied in more detail by comparing the trade off between travel time and CO_2 emission metrics (because road grade is not currently modeled in SUMO, P_{tract} calculations assumed planar roads and, hence, $\vartheta = 0$). Figure 7 outlines the simulation results for varying stop times of the lead vehicle and different lengths of the detour, i.e. changed rung lengths. It plots the cumulative driving time, as well as the cumulative CO_2 emission, of all simulated vehicles. Serving as the baseline scenario in both cases is a setup with no IVC: we assume that in this scenario no vehicle is able to detect the traffic obstruction until after it passes the last chance to switch to the detour; thus, all vehicles will always stay on the main road. The plots show that the break-even points for the use of IVC (i.e., the lines where both graphs intersect) differ by a large margin. Thus, most interestingly, the optimal configuration of the overall TIS-based rerouting is different for both evaluation metrics, the travel time and the CO_2 emission. Considering the CO_2 emission, short stops are more appropriate compared to taking the respective detours, thus, optimizing the overall traffic flows. As can be seen, this decision is not necessarily optimal with regard to the travel times of an individual car.

V. TOOL SUPPORT

Quite a number of tools have been developed in the last couple of years that integrate support for realistic mobility models. Most of these tools can easily be extended to also cover emission and human driver behavior models, and some of them even provide initial support. Table III summarizes some of the most commonly used tools. The table can be used as a reference if specific IVC applications and protocols are to be investigated with the help of simulation.

TABLE III
SUMMARY OF SIMULATION FRAMEWORKS

Toolkit	Network simulation	Mobility modeling	Traffic metrics	Human driver behavior	Web site
Veins	OMNeT++	SUMO ★	EMIT and SUMO	multiple classes	http://veins.car2x.org/
TraNS	ns-2	SUMO ★	SUMO	partially	http://trans.epfl.ch/
iTETRIS	ns-3	SUMO ★	SUMO	partially	http://www.ict-itetris.eu/
VGSim	JiST/SWANS	Nagel-Schreckenberg	-	-	http://sourceforge.net/projects/vgsim/
VSimRTI	JiST/SWANS	VISSIM ✦	VERSIT+ ✦	partially	http://www.dcaiti.tu-berlin.de/research/simulation/
NCTUns	(Proprietary)	(Proprietary)	(Proprietary)	-	http://nsl10.csie.nctu.edu.tw/
SWANS++	JiST/SWANS	STRAW ✧	-	not applicable	http://www.aqualab.cs.northwestern.edu/projects/swans++/
GrooveNet	(Proprietary)	Roadnav ✧	-	not applicable	http://www.seas.upenn.edu/~rahulm/Research/GrooveNet/
ASH	JiST/SWANS	IDM/MOBIL ✳	-	not applicable	http://www.cs.odu.edu/~vanet/Software/Ash
vanet-highway	ns-3	IDM/MOBIL ✳	-	not applicable	http://www.cs.odu.edu/~vanet/Software/Ns3-highway

✳ self-generated scenarios that simulate micromobility on a linear stretch of road with nodes moving at highway speeds
✦ VISSIM (and its extensions) is commercial software, there exists no free academic license
✧ TIGER scenarios include most U.S. roads and a classification, e.g., "A31: Secondary and connecting road, state and county highways, unseparated"
★ SUMO scenarios can be based on OpenStreetMap, importing speed limits, lane counts, traffic lights, access and turn restrictions

VI. CONCLUSION

In this article, we outlined some of the aspects that strongly influence simulation experiments of IVC protocols. There is clear progress visible in this domain and quite a number of simulation tools have become available supporting at least some of the discussed issues. In conclusion, it can be said that in addition to encouraging the use of the described models for simulative evaluation of IVC protocols, we have shown that not using the following techniques, simulation results might be misleading and the evaluation might suggest a behavior deviating from what can be expected in reality:

- *Realistic mobility models* are of paramount importance for evaluating the microscopic mobility of vehicles when studying fine-grained communication aspects; bidirectional coupling of road traffic microsimulation and network simulation is a promising approach to overcome limitations from using traces or randomized mobility models.
- The *impact of the human driver behavior* on a macroscopic scale must be considered instead of assuming technically perfect reactions to IVC messages; this is of particular importance for the design and development of TIS applications.
- *Metrics appropriate for IVC evaluation* have an impact on the configuration of IVC-based applications, thus they provide deeper insights into the behavior of the system as a whole.

Of course, there are many other open issues in the field of realistic IVC simulation that need to be addressed. For example, realistic physical layer models rely on accurate 3D map information that includes buildings and other obstacles. Such maps are only available for a very small set of scenarios. Furthermore, there is still no set of standardized simulation setups available to be used for evaluation, thus, making the comparability of different studies an issue.

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