Comparing Apples and Oranges? Trends in IVC Simulations

A Position Paper

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ABSTRACT

Looking back at recent years in Inter-Vehicle Communication (IVC) research, tremendous improvements in precision and realism of simulation models concerning all its aspects can be observed. These models offer a vast number of parameters, enabling investigations of a huge variety of different scenarios. Reviewing simulation studies published at major vehicular network conferences from 2009 to 2011, we reflect on the impact of these developments. We are glad to present a clear trend to conduct simulations based on a consolidated set of established standards, models, and tools. However, looking at individual papers, we commonly find key information (such as the used model) missing. We argue that this trend threatens to compromise both the reproducibility and the comparability of simulations conducted, but acknowledge that space constraints often make it impossible to describe current, complex simulations in full. We hope that the presented commonly used basic building blocks of simulations can serve as first step towards deriving an agreed-upon set to base IVC simulations on and, thus, ultimately, help keep future research reproducible and comparable.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*; C.4 [**Performance of Systems**]: Modelling Techniques

Keywords

vehicular networking, simulation, credibility, VANET, IVC

1. INTRODUCTION

Intelligent Transportation Systems (ITS) have become one of the fastest growing fields of research in mobile communications and networking, currently with a strong focus on Inter-Vehicle Communication (IVC) [14]. Such systems and protocols enable a wide variety of possible applications ranging from vehicular safety to traffic information systems and even to entertainment solutions, all requiring cooperative behavior [9]. Most recently, the community started conducting large scale field tests to assess the quality and performance of proposed solutions in realistic application scenarios. One example is the sim^{TD} project in Germany, where the deployment of up to 400 cars has been planned [13]. Yet, even such large experiments are not sufficient to evaluate all the possible options and parameters of the many proposed protocols. Therefore, simulation is still the primary tool for performance evaluation in vehicular networks [10].

Fortunately, there is already a variety of simulation tools and models available (e.g., Veins [12] or iTetris [6]) that support the evaluation of new ITS applications and IVC protocols. Even better newly developed models help continuously increase the degree of realism. Examples include new road traffic simulation tools, updated radio signal propagation models, and implementations of recent IVC standards such as IEEE 802.11p.

In order to get a better understanding of the used tools and models, as well as the degree of realism provided in recently published ITS solutions, we surveyed all related papers published between 2009 and 2011 which were presented at the following conferences:

- **ACM VANET** (Workshop on VehiculAr Inter-NETworking) is being held annually in conjunction with ACM MobiCom since 2004. The workshop initially focused on Vehicular Ad Hoc Network (VANET) topics, but soon widened its scope to vehicular networking in general, recently also including topics related to long-range cellular systems.
- **IEEE VNC** (Vehicular Networking Conference) is the youngest of the major vehicular networking centric events and has been taking place annually since 2009. This IEEE Communications Society conference focuses on vehicular networking in general and has a strong focus on IVC in particular.
- **IEEE VTC** (Vehicular Technology Conference) is being held semiannually (in spring and fall) as a flagship conference of the IEEE Vehicular Technology Society and dates back to 1950. In the last decade of vehicular networking research the conference focused on research topics regarding the physical layer and medium access.

This amounts to a literature body of more than 1000 papers out of which we selected the 116 simulation studies focusing on IVC using short range communication; we excluded all cellular networking approaches for this particular study.

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We found that there is a clear trend towards using standardized protocols developed specifically for IVC (most prominently IEEE 802.11p) instead of relying on common WiFi variants. Also, a consolidation of tools and models is taking place, which allows, in principle, to share setups and implementations for better comparability and reproducibility of simulation results.

At the same time, we observed that in a large number of cases the simulation setting and parameters are not fully clear. This includes precise information on the used models and tools as well as on the studied scenarios. In this paper, we describe, based on the large body of reviewed papers on IVC, what network simulation and road traffic simulation tools or models have been used, what scenarios have been considered, and to what degree simulation experiments can be considered reproducible.

Our main contributions can be summarized as follows:

- We reviewed a large body of recent publications in ACM VANET, IEEE VNC, and IEEE VTC to assess typical simulation studies in IVC related performance studies.

- We show that substantial improvements are being made in the use of state of the art tools and models, and, furthermore, a clear consolidation towards integrated simulation frameworks supporting both wireless network and vehicular mobility simulation takes place.

- We present and discuss a set of selected aspects that need to be addressed in each and every performance study to support both the reproducibility and the comparability of simulation results.

- We thus aim to motivate the vehicular networking community to work on a set of standard scenarios that can be used for simplified assessment of new concepts and applications.

2. DEMANDS ON VEHICULAR NETWORK SIMULATIONS

The credibility of telecommunication network simulations (we focus on a subset, vehicular network simulations) is a constant source of discussions. In order for simulation results to be both accurate and reproducible, for each simulation three aspects have to be both correct and well-described: its models, its execution, and its evaluation.

Pawlikowski et al. [7] investigated numerous papers in the telecommunication network simulation area, addressing both the *execution* and *evaluation* aspect of simulation studies, in particular evaluating the use of appropriate Pseudo Random Number Generators (PRNGs) and the proper analysis of simulation output data. It has turned out that the majority of presented simulations were not able to satisfy these two requirements. This led to a substantial credibility crisis in the field of simulation and modeling in about 2002. However, these findings very positively influenced the way how simulations are being carried out. For example, well-tuned PRNGs such as the Mersenne Twister are now implemented in all major simulation toolkits.

For vehicular network simulation studies, it turns out that generating reproducible and validated simulation results is even more difficult. This is mainly because of the need to combine a substantial number of simulation models and tools. Furthermore, the ongoing trend of developing even better and more precise models for vehicular network simulation further complicates the task of picking the right ones. In the following, we therefore focus more on the *model* and *execution* aspects of IVC studies, describing typically needed models and tools as a minimum set of requirements.

2.1 Network Simulation

The availability and validity of the mentioned models is highly dependent on the employed *network simulator*. There are several network simulation toolkits available such as ns-2, ns-3, OMNeT++, OPNET, QualNet, and SWANS, which are all based on a discrete-event simulation core. As mentioned before, the usage of an appropriate PRNG is essential. The network simulators ns-2, ns-3 and OMNeT++ use the Mersenne Twister as a source of randomness which has been proven to be sufficient for current computing power. The two commercial simulators, QualNet and OPNET, do not reveal the used PRNG [1]. Finally, SWANS uses the standard random number generator provided by Java (java.util.Random), which is a linear congruential generator.

Many models have been developed for modeling physical channel conditions, network, transport, or application protocols in the different network simulators. However, the *accuracy* (level of abstraction) and *validity* of the available models differ quite a lot. In addition, the legitimate question *Which models are needed and applicable in vehicular network simulations?* needs to be answered very carefully. Hence, it is important that not only the network simulator is mentioned in a simulation study, but that the right models for vehicular networks are used and the choice is described, helping validity as well as repeatability.

Starting at the physical level, the first factor influencing performance evaluations of vehicular networks is the employed *radio propagation model*. The interest in obtaining better and more realistic results with a strong focus on the physical layer increased especially in the last few years. Most recent research results are given in [2, 4, 11] for modeling radio propagation accurately for different scenarios, which have been validated by means of measurements and field tests. This includes models for signal fading, attenuation by buildings and other obstacles, reflection effects, and the impact of the Fresnel zones. However, since many vehicular networking simulation studies are currently simplifying and even neglecting the radio channel effects [5], we decided not to evaluate the degree of realism of physical layer modeling in our literature review.

Considering the next higher layer, the *medium access*, standards often include as well the definition of physical layer technologies. The use of an adequate Medium Access Control (MAC) protocol has become a major concern when simulating vehicular networks. One of the major achievements in vehicular network research was the definition of a standard MAC protocol within the IEEE 802.11 family, namely the *IEEE 802.11p standard*.

As shown in [3], it is important to use a fully featured IEEE 802.11p MAC model, especially at high node densities or when high load is put on the wireless channel. We therefore decided to specifically check the employed MAC protocols, most importantly focusing on the newly published IEEE 802.11p standard. In short, the reviewed simulation studies used a wide palette of different MAC protocols until the new standard was released.

Protocol	Year	Frequency	Data rate
IEEE 802.11	1997	2.4 GHz ISM	2 Mbit s^{-1}
IEEE 802.11a	1999	5 GHz U-NII	54 Mbit s^{-1}
IEEE 802.11b	1999	2.4 GHz ISM	11 Mbit s^{-1}
IEEE 802.11p	2010	5.9 GHz reserved	27 Mbit s^{-1}

Table 1: Radio standards used in IVC simulations.

A brief overview of the most popular MAC protocols is given in Table 1. This table shows the publication year, the dedicated frequency band, and the desired maximum data rate of the individual standards.

Basically, we focus our discussion on these protocols. However, many simulation studies used idealized or modified versions the IEEE 802.11 variants. A number of simulation studies rely on traditional WiFi models using a small set of modified parameters to try and emulate the behavior of IEEE 802.11p. In the following, we call such approximations *802.11p'*. Additionally, we identified those studies using an *ideal MAC* and added another category for simulation studies employing completely *new MAC* protocols or improvements to the current IEEE 802.11p standard.

NB: We excluded all layers above the MAC as these typically are already application specific and in most cases the protocol under study.

2.2 Road Traffic Simulation

Already in 2004, it has been shown that the *mobility model* used in VANET simulations has a substantial influence on metrics like the number of unreachable nodes, the average path length, and topology changes [8]. Furthermore, the evolution of mobility modeling in VANET simulations has been discussed, concluding the need for using a specific *road traffic simulator* in addition to the network simulation toolkit [10]. Both worlds, road traffic and network simulation, need to be coupled bidirectionally if the studied IVC protocol may influence the behavior of the vehicles on the streets.

Road traffic simulators have been designed for modeling different kinds of granularity. Macroscopic traffic simulations concentrate on traffic flow characteristics like vehicles' average density or speed; whereas microscopic simulations analyze each car individually. Traffic simulation can be established on top of either *car-following models* or *cellular automaton models*. The car-following models derive future acceleration/deceleration decisions based on the velocity and the distance of the vehicle and those ahead of it. Models inspired by cellular automatons divide the roads into sections of a certain length that can be either occupied by one vehicle or not. The velocity of a vehicle is modeled by occupying multiple segments in one discrete time step.

There are numerous approaches available for both classes of models which differ only in the level of detail. In the following, we concentrate on car-following models, because most of the microscopic road traffic simulators are based on this class of models. Historically, the Wiedemann model was the first car-following model (published in 1974) and also considers psychological aspects of drivers. It is currently employed in the VISSIM traffic simulator. Two other car-following models are the Gipps model and the Intelligent Driver Model (IDM). The IDM followed the Gipps model and tries to reproduce effects like such traffic instabilities which cannot be taken into account in the Gipps model.

Figure 1: Urban scenario with real-world map and buildings (top); Highway scenario with three lanes in each direction (bottom).

2.3 Scenario Description

Besides the right tools and models, a proper *scenario description* is needed for assessing the performance of IVC approaches in the diverse applications scenarios. The impact of all the aforementioned aspects – the network simulation models, the radio propagation models, and the mobility model – strongly depends on the chosen scenario [10, 14].

The scenarios in vehicular network simulations can be divided into two main types, highway and city, which require different further scenario descriptions. NB: For exact modeling of the physical layer, city scenarios need to be further divided into suburban (sparsely distributed buildings) and urban ones (very densely crowded buildings like in downtown Manhattan). Following the trends in the literature, in the following, we refer to all these city-like scenarios as urban.

In the following, we briefly outline both scenario types, *urban* and *highway*, and highlight the most important parameters needed in a proper scenario description:

Urban scenarios are dominated by buildings, intersecting roads, and complex movement patterns. Three different scenario cases can be distinguished.

First, *single/multiple intersection scenarios* focus on close-range interactions. Accordingly, these need a detailed description of how many intersections with how many lanes have been simulated. In addition, parameters like turning probabilities help increase the repeatability of such scenarios.

Secondly, *Manhattan grid scenarios* represent any grid-like scenario such as the downtown Manhattan area. Accordingly, the description needs to contain at least the space between vertical and horizontal roads and how many lanes are simulated for each road.

Finally, *real world scenarios* simulate the movement based on a real world map – either generated by a traffic simulator or replaying recorded traces. Accordingly, which city or area was selected, and what aspects were imported, has a strong influence on results of such simulation studies. An example real world scenario is presented in the top part of Figure 1 showing different kinds of intersections taken from the OpenStreetMap project.

Highway scenarios simulate a single trunk road, which might have a number of inflows or exits, but does not have any intersections with other roads. Aside from the high-

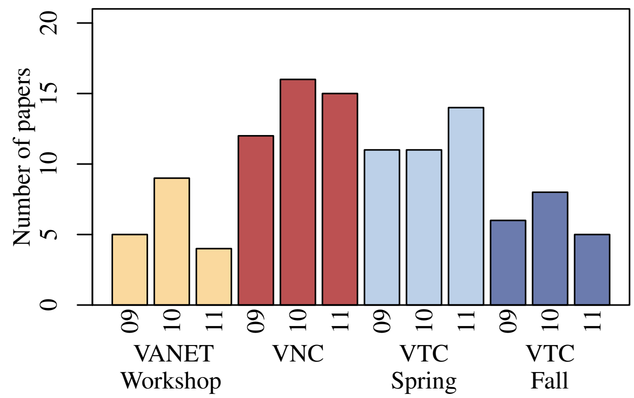

Figure 2: Number of reviewed papers per year and conference.

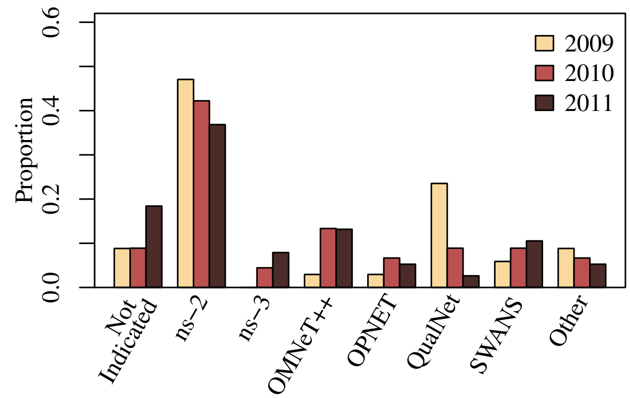

Figure 3: Distribution of network simulators.

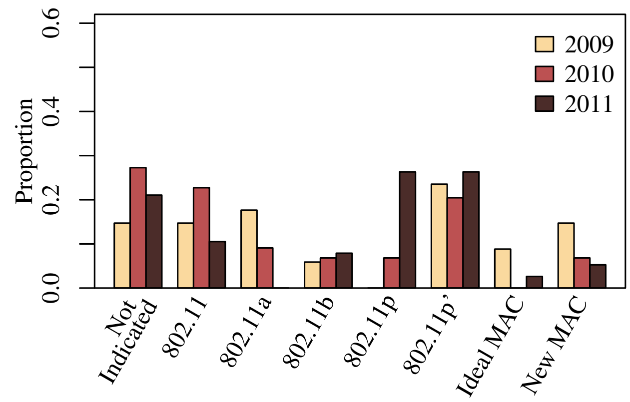

Figure 4: Distribution of MAC protocols.

way having a realistic vehicle density and distribution, a description of a highway scenario needs to contain at least the number of lanes which are available in each direction. Moreover, it should be noted that it is important to simulate both directions because the bimodality in relative speeds has a serious impact on vehicular network simulations. An example of such a highway scenario is depicted in the bottom part of Figure 1 which shows a highway with three lanes in each direction and cars, vans, and trucks driving on it.

3. EVALUATION

Figure 2 shows, for each edition of the selected conference, the number of papers that we reviewed. It can be seen that the number of IVC related simulation studies has been rather constant over the last three years. Please note that we have not filtered the papers according to other criteria.

3.1 Network Simulator

In Section 2.1, we have already seen differences of current network simulators and the resulting implications. Therefore, we start our discussion by having a look on the distribution of employed network simulators (cf. Figure 3). First of all, it can be seen that ns-2 – most probably the best known network simulator – has been used in more than 45 % of all simulation studies in 2009, but its successor ns-3 is taking over and is gaining more acceptance in 2010 and 2011. Moreover, OMNeT++ was able to attract an increasing user basis.

The commercial simulator OPNET has been used by a small proportion which has not changed a lot over the last three years. A more drastic effect can be observed for QualNet. Its usage is shrinking to nearly zero after being widely used (about 25 % of all simulation studies) in 2009. This negative trend might be explained by the fact that QualNet is a commercial version of the former GloMoSim tool and concentrates currently more on battle field applications.

The JiST/SWANS simulator shows a slight positive trend over the last three years. Although SWANS itself has not been developed further since 2005, this positive trend in the VANET research field can be explained because several research institutions took SWANS as a basis for their own extensions to build fully-featured VANET simulators.

Figure 3 shows that in a small part of studies some *other* network simulators have been employed and their use has been decreasing over time.

As an interesting fact our study revealed the fact that the proportion of simulation studies which do not indicate the used network simulation tool at all is rather high: their proportion was nearly 10 % in 2009 and 2010, and is up to 18 % in 2011.

In a next step we evaluate the used MAC protocols – one of the most critical aspects when studying IVC protocols and applications. Figure 4 shows the obtained results. Back in 2009, there have been a number of proposals for new MAC protocols or for enhanced versions of existing ones. We find that this number has decreased substantially after the IEEE 802.11p standard was published in 2010. Most of the research activities are now focusing on the higher layer network and application protocols. A similar trend can be observed for simulation studies relying on an idealistic MAC.

Similarly, the usage of IEEE 802.11a has dropped to zero – initially, this protocol has been used as it operates in almost the same frequency range as IEEE 802.11p. After the latter one became a standard, most simulation studies moved to the new standard instead.

The fact that the number of simulation studies using IEEE 802.11b is quite constant over time may be explained by having a closer look at the objectives of the specific simulation studies. Nearly all of those using IEEE 802.11b have studied vehicular networks that incorporate Roadside Units (RSUs). However, it has been shown that using IEEE 802.11b without or with simple adaptations to common WiFi models to mimic

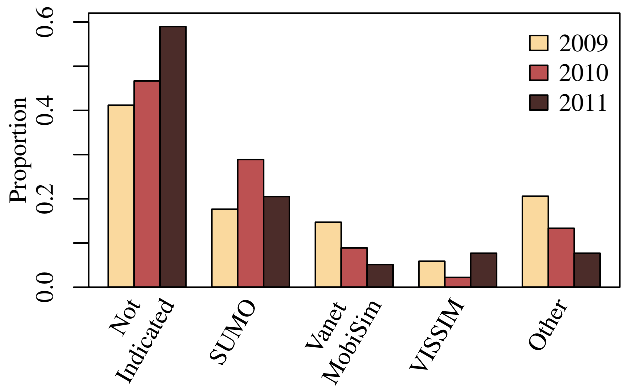

Figure 5: Distribution of road traffic simulators.

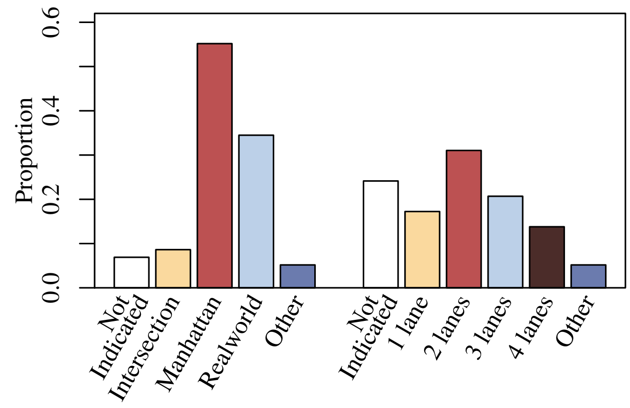

Figure 6: Distribution of subclasses of the major scenario types urban (left) and highway (right).

the behavior of IEEE 802.11p (we call these 802.11p') can only be used in low density scenarios [3]. Still, the number of simulations which use these adaptations stays quite constant over time.

The number of simulation studies using the new standard, however, has increased sharply and already reached about 30 % in 2011. The figure therefore supports the expectation that proportions will further shift towards using real IEEE 802.11p models, so in the near future the majority of IVC simulations might be using models of wireless communication specifically geared towards vehicular networking.

It should be noted that we found a relatively large number of simulation studies that did indicate the use of 802.11 models, but did not state which one out of the current IEEE 802.11 family of standards was used (or whether they relied on just the IEEE 802.11 base standard published in 1997).

3.2 Road Traffic Simulator

The fact that microscopic traffic simulators are best suited for mobility simulation in vehicular networks has already been discussed in Section 2.2. This can be confirmed by looking at the used road traffic simulators in the reviewed publications. Figure 5 shows the results of our evaluation.

The most popular road traffic simulator, SUMO (Simulation of Urban Mobility), has constantly been used in more than 20 % of all papers with a peak in 2010 at 30 %. In contrast, the dedicated vehicular network movement simulator VanetMobiSim has been used in nearly 20 % of the studies in 2009, but has experienced a decreasing trend with only a marginal proportion for 2011. VISSIM, which is a commercial tool, maintained an average proportion of about 6 % during last three years.

The category *other* contains implementations of mobility models with functionality close to one of the validated road traffic simulators. This category also experienced a negative trend in the last three years.

Finally, we need to emphasize the current peculiar situation of road traffic simulation. Although the impact of accurate mobility modeling has been shown already in 2004 [8] and confirmed in full in 2008 [10], there is no positive trend observable towards applying realistic mobility models. On the contrary, the proportion of simulation studies which did not indicate that a road traffic simulator was employed did even grow – from 40 % in 2009 to almost 60 % in 2011.

3.3 Scenario Description

After investigating network simulation and road traffic simulation, we now turn to the scenarios. In the results, plotted in Figure 6, we first distinguish between urban and highway scenarios, then between their respective subclasses as outlined in Section 2.3. Please note that, for both scenarios, each bar indicates the percentage of papers mentioning this subclass. We found that the same number of papers (58) investigated urban and highway scenarios, respectively, only nine papers investigated neither, and that this ratio was maintained over the investigated years, so we do not present the results grouped by year.

Looking at the subclasses of urban scenarios, we found that the majority of papers either investigated Manhattan grid or real world scenarios with other subclasses only playing a minor role. Only a very small number of papers gave no further information on the used scenario.

Looking at highway scenarios we found most papers evaluating between one and four lane (per direction) scenarios, the majority of those using two lanes. Surprisingly, compared to urban scenarios the proportion of highway papers giving no detailed information on the scenario subclass was substantial: roughly one in four papers merely stated that some highway was simulated, although we would expect that the highway scenario is much simpler and needs less information for a comprehensive description (number of lanes in each direction vs. intersections, lanes, traffic lights, etc.).

3.4 Current Trends in IVC Simulation

For better understanding the current trends in IVC simulation studies, we give an aggregate overview of how well each of the presented aspects was covered in our dataset and plot these results in Figure 7. We observe that both network simulation tools and related models (again, with a focus on the MAC) are very well described with only 10 % to 20 % of papers lacking a proper description. Moreover, we notice that road traffic simulators have been used (and described) by nearly 60 % in 2009 with a negative trend to 40 % in 2011. The used scenario has been described in most of the papers even though details such as the number of lanes or the vehicle density might be missing.

Although the descriptions for individual factors (tools, models, and scenarios) are getting better, the overall quality of the described simulation settings still requires improve-

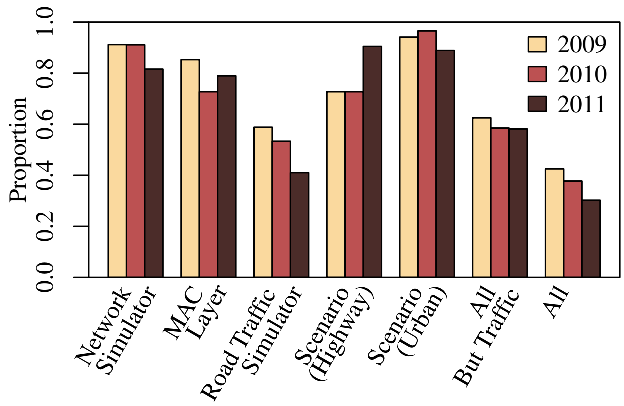

Figure 7: Trends in current IVC simulation studies.

ments. Looking at the whole set of aspects, we found that only about one third of the publications has specified *All* these aspects correctly. The results indicated as *All But Traffic* help to understand that this fact not only results from missing information about the road traffic simulator. In total, only about 50 % of the reviewed simulation studies properly mention the used network simulator, the employed MAC protocol, and the studied scenario.

Unfortunately, for each of the metrics plotted in Figure 7 a slightly negative trend can be observed over time, i.e., even less information in provided in 2011 papers compared to those published in 2009. One explanation for this current trend is that a vast amount of information (i.e., room in a paper) is needed to fully specify a vehicular network simulation. However, we need to be clear that by not mentioning all details (as is currently done by more than the half of the surveyed simulation studies) we harm both the reproducibility and the comparability of papers and might end up *comparing apples and oranges*.

From our findings, we can derive the following guidelines: There are well established network simulators available that, if used, can just briefly be mentioned including the set of used models together with version information. Similarly, the vehicles' mobility can be easily be modeled by using publicly available traces or validated road traffic simulators.

Regarding the used scenario, we recommend the community working on a set of well defined basic settings as building blocks for standard scenarios. This enables simplified descriptions and reproducibility of simulation studies.

4. CONCLUSION

In conclusion, it can be said that substantial improvements have been made over the last years concerning the credibility of simulation studies in the field of Inter-Vehicle Communication (IVC) protocols and applications. The used simulation tools and models are getting more precise and realistic. Still, our review of 116 simulation studies published between 2009 and 2011 clearly outlines the need to better indicate selected aspects that need to be addressed in each and every simulation study for improved reproducibility and comparability of the algorithms under investigation.

We also see the strong need to motivate the vehicular networking community to work on a set of standard scenarios that can and should be used for simulation based performance evaluation of IVC protocols.

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