Toward Reproducibility and Comparability of IVC Simulation Studies: A Literature Survey

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***Abstract*—Inter-Vehicle Communication (IVC) is currently transitioning from being an academic exercise to a commercially attractive and feasible technology. Yet, many aspects of IVC protocols, their parameters and configurations, as well as application-specific adaptations are still to be studied – one of the key tools used is simulation. Looking back at recent years in 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. We reviewed simulation studies published at major vehicular network conferences from 2009 to 2011 with a key focus on *reproducibility* and *comparability* of the published simulation studies. We are glad to present a clear trend towards 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. This limits both the reproducibility and the comparability of simulations conducted. We further present commonly used basic building blocks of simulations that can serve as a first step towards deriving an agreed-upon set on which IVC simulations can be based. We advocate providing all essential information as set out in this paper to help keep future research reproducible and comparable.**

I. Introduction

Looking at the progress in the field of Inter-Vehicle Communication (IVC) protocols and applications, it is to be expected to see first applications in the market very soon. This trend has been confirmed by the automotive industry which invested a lot in IVC projects and is eager to commercialize many of the ideas. Willke et al. [1] as well as Hartenstein and Laberteaux [2] reviewed typically considered applications and the resulting challenges on Intelligent Transportation Systems (ITS). They point out a wide variety of possible applications ranging from vehicular safety to traffic information systems and even to entertainment solutions, all requiring cooperative behavior [3]. Even though there is a trend towards designing applications based on rather simple beaconing protocols (e.g., using Cooperative Awareness Messages (CAMs) [4]) on top of IEEE 802.11p [5], there are still many open questions regarding the design of the protocol stack (advanced beaconing approaches, e.g., [6], [7], have been proposed but are not in the scope of this article). For all these developments in vehicular networks, simulation is still the primary tool for performance evaluation [8].

The credibility of simulations (we focus on telecommunication network simulations also including vehicular network simulation studies) is a constant source of discussions. Pawlikowski et al. [9] investigated numerous papers in the telecommunication network simulation area, in particular evaluating the use of appropriate Pseudo Random Number Generators (PRNGs) and the proper analysis of simulation output data. They were able to show 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. Yet, there is still a general lack of confidence interval analysis. We contribute to these findings by looking at another important aspect influencing the credibility of simulation studies: *repeatability* of simulation experiments. This is essential as each scientific activity should be based on controlled and independently repeatable experiments [9].

In the case of vehicular network simulation studies, it turns out that generating reproducible and validated simulation results is even more difficult. Fortunately, there are already a variety of simulation tools and models available (e.g., iTetris [10] or Veins [11]) 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 enhanced 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 leading IVC conferences. This amounts to a literature body of more than 1000 papers out of which we selected all 116 simulation studies focusing on IVC using short range communication.

Investigating the presented simulation studies in detail, 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. This, in combination with a consolidation of tools and models, 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 article, 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.

The main contributions of this article can be summarized as follows. Based on a large body of recent publications in the leading ACM and IEEE conferences focusing on IVC, 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 is taking place. Yet, looking at individual papers, we commonly find key information (such as the used model) missing. Our objective is to come up with a set of building blocks that need to be described for setting up simulation based performance studies of IVC supporting both the comparability and the reproducibility of obtained results.

II. Investigated Simulation Studies

The database used for our survey of simulation studies of IVC protocols and applications is based on a selection of the most focused events in the ITS domain. We surveyed all related papers published between 2009 and 2011 which were presented at the following conferences – this amounts to a literature body of more than 1000 papers out of which we selected all 116 simulation studies focusing on IVC using short range communication; we excluded all cellular networking approaches for this particular study:

- *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 – aligned by the seasons of the northern hemisphere) as a flagship conference of the IEEE Vehicular Technology Society and has a long history which dates back to 1950. Considering only the last decade of vehicular networking research, the conference focused on research topics regarding the physical layer and medium access.

Figure 1 shows, for each edition of the selected conferences, 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 any other criteria.

III. Simulation of IVC Protocols and Applications

In the following, we briefly discuss the challenges and requirements faced by simulation studies in the field of IVC. Essentially, the listed tools and models can be seen as a minimum set of requirements.

A. Network Simulator

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. They are long established in the networking community and can be considered good candidates to start IVC protocol studies with.

We start our discussion by having a look on the distribution of employed network simulators (cf. Figure 2). 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, compared to 2009, OMNeT++ was able to increase its user base by 400 %, making it the second most used.

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

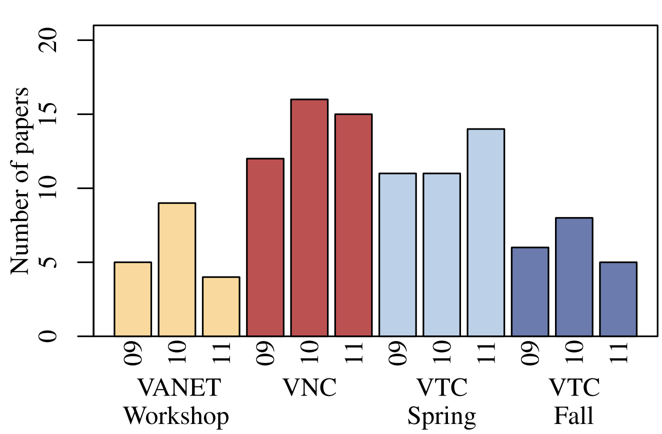

Figure 1. Number of reviewed papers per year and conference.

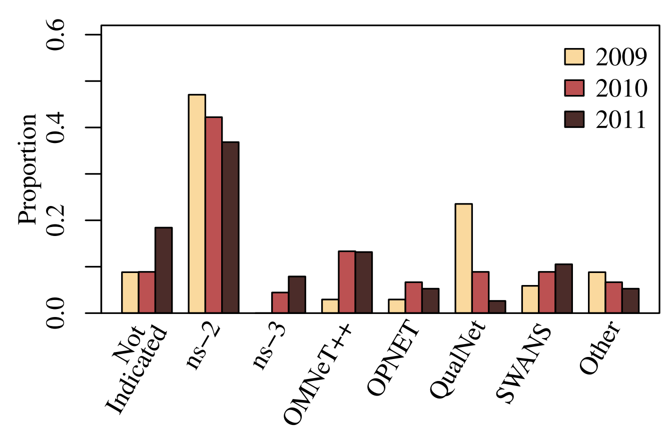

Figure 2. Distribution of network simulators.

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, now the third most used, shows a slight but steady positive trend over the last three years. Although SWANS itself has not been further developed 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 2 shows that in a small part of studies some *other* network simulators have been employed and their use has been decreasing over time.

While on the face of it, the choice of simulation core is of little to no consequence to the results of simulation studies, it commonly implies a certain set of models and default parameters. Recommendations for simulation toolkits suitable for IVC applications can be found for example in [10], [11]. This might substantially impact the validity, comparability, and reproducibility. Thus, it is particularly worrying that our study revealed a rather high proportion and increasing number of simulation studies which do not at all indicate the used network simulation tool: their proportion was nearly 10 % in 2009 and 2010, and is up to 18 % in 2011.

B. Physical Layer

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 [12]–[14] 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. All these models together build a very good basis for very precise simulation of the physical layer in IVC scenarios. However, since many vehicular networking simulation studies are currently simplifying and even neglecting the radio channel effects [15], we decided not to evaluate the degree of realism of physical layer modeling in our literature review. Nevertheless, we want to emphasize the importance of them for future IVC simulation studies.

C. Medium Access

Considering the next higher layer, the use of an adequate Medium Access Control (MAC) protocol, along with matching physical layer technology, 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 [16], 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 variety of MAC protocols until the new standard was released, followed by a phase of quickly increasing consolidation.

Table I
IEEE 802.11 STANDARDS USED IN IVC SIMULATION STUDIES.

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

A brief overview of the most popular MAC protocols is given in Table I. 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. 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 have now settled on building on this standard and are now focusing on the higher layer network and application protocols. A similar trend can be observed for simulation studies relying on an *Ideal 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 (cf. Figure 3) 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). A number of simulation studies also relies on using a small set of modified parameters to emulate the behavior of IEEE 802.11p. However, it has been shown that using IEEE 802.11b without or with simple adaptations to common WiFi models to mimic the behavior of IEEE 802.11p (we call these 802.11p') can only be used in low density

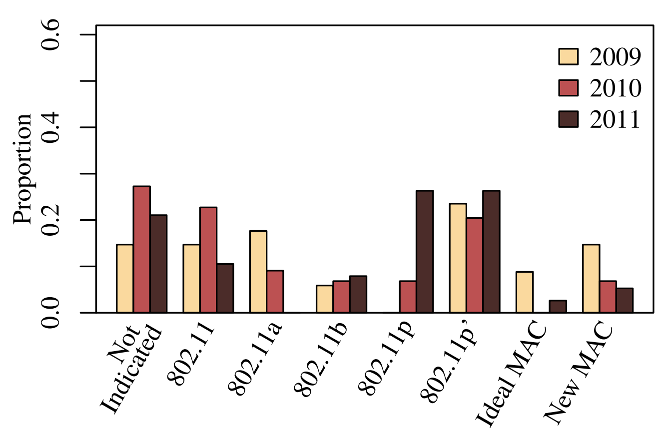

Figure 3. Distribution of MAC protocols.

scenarios [16]. Still, the number of simulations which use these adaptations stays quite constant over time.

As a very positive finding, the number of simulation studies using the new standard 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).

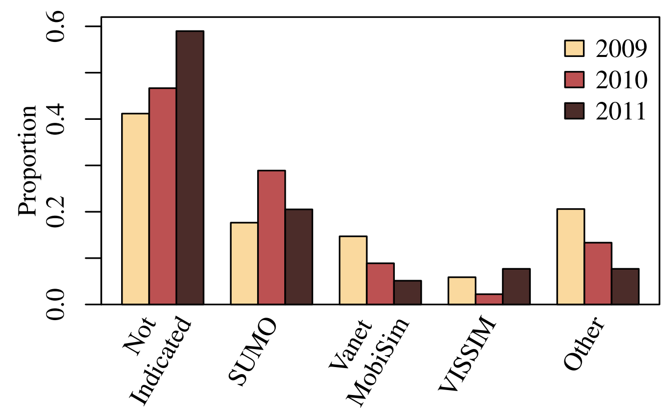

Figure 4. Distribution of road traffic simulators.

D. Road Traffic Mobility

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 [17] – this substantiates a clear trend towards using a specific *road traffic simulator* in addition to the network simulation toolkit [8]. 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' density or their average speed and treat traffic like fluids; whereas microscopic simulations analyze each car individually, thus lending themselves well to IVC simulation. 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 empty or completely occupied by one vehicle. 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 has been developed further to consider physical and 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) – implementations for both are available in the SUMO (Simulation of Urban Mobility) simulator. 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.

As shown in Figure 4, the most popular road traffic simulator, SUMO, 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.

Yet, again, we need to emphasize the current peculiar trend of road traffic simulation. Although the impact of accurate mobility modeling has been shown already in 2004 [17] and confirmed in full in 2008 [8], 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 has grown – from 40 % in 2009 to almost 60 % in 2011.

E. Scenario Description

Besides the right tools and models, a proper *scenario description* is needed for assessing the validity and furthering the reproducibility of IVC simulations 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 [1], [8].

The scenarios in vehicular network simulations can be divided into two main types, highway and city, which require further different scenario descriptions. Please note that, for exact modeling of the physical layer, city scenarios need to be further divided into suburban (characterized by spaces between sparsely distributed buildings) and urban ones (characterized by 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.

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

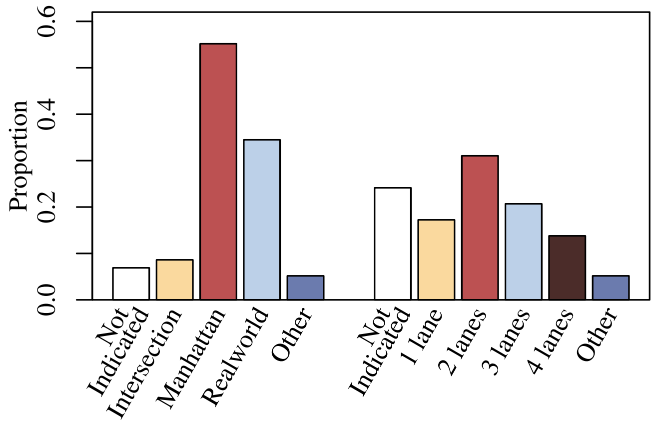

Figure 5. Distribution of scenarios simulated (left: urban, right: highway).

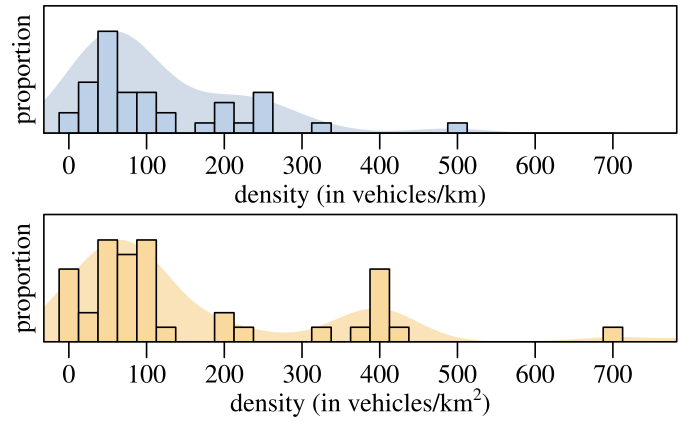

Figure 6. Distribution of used vehicle densities (top: highway, bottom: urban).

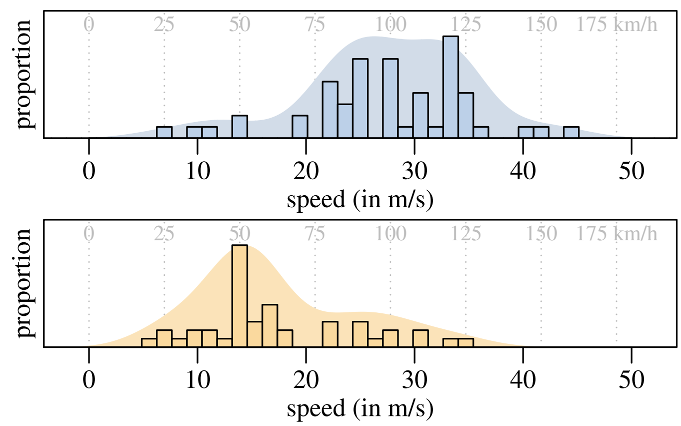

Figure 7. Distribution of used vehicle speeds (top: highway, bottom: urban).

turning probabilities help increase the repeatability of such simulation 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. Accordingly, which city or area was selected, and what aspects were imported, has a strong influence on results of such simulation studies.

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 highway having a realistic vehicle density and distribution, a description of a highway scenario needs to at least contain the number of lanes which are available in each direction. Moreover, it should be noted that for most protocols it is important to simulate both directions because the bimodality in relative speeds has a serious impact on vehicular network simulations.

In Figure 5, we first distinguish between urban and highway scenarios, then between their respective subclasses (please note that papers mentioning more than one subclass contribute to each). We found that the same number of papers investigated urban and highway scenarios, both 58, and only nine papers investigated neither. 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 one might expect that the highway scenario needs much less information for a comprehensive description (number of lanes in each direction vs. intersections, lanes, traffic lights, etc.).

We also studied the used vehicle densities as well as the assumed vehicles' speed (Figures 6 and 7). An interesting artifact is visible in the density distribution. In urban scenarios, low and high density scenarios have been investigated, whereas the majority of investigations for highway scenarios studied low densities. This is not in line with realistic observations, where extremely high densities can be observed especially in severe jam situation on highways. The observed speed distribution behaves as expected. Some simulation studies used rather high speeds ($75\,\mathrm{km\,h^{-1}}$ to $125\,\mathrm{km\,h^{-1}}$) for in town maneuvers.

IV. Current Trends in IVC Simulation

Until now, we described isolated aspects of single models and simulation tools that need to be considered for reproducibility and comparability of simulation studies of IVC protocols and applications. We believe this is of course required but not sufficient. In fact, all parts of the used models and tools need to be described in detail. This need becomes clear when looking at an aggregated view of the individual aspects covered in our dataset.

As shown in Figure 8, 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 down to 40 % in

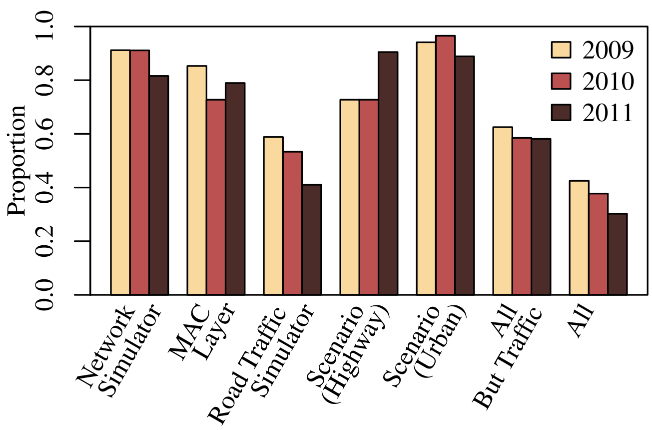

Figure 8. Trends in current IVC simulation studies. Prevalence of model descriptions by aspect and year.

2011. The used scenario has been described in most of the papers even though details such as on 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 improvements. Looking at the whole set of aspects, we found that only about one third of the publications has specified *All* of them correctly. The results indicated as *All But Traffic* summarize those publications taking into account all the listed categories but the road traffic simulator. As can be seen, only about 50 % of the reviewed simulation studies properly mention the used network simulator, the employed MAC protocol, and the studied scenario. This result underlines that even though all these individual aspects have been mentioned in a rather large subset of the publications, only 50 % indicate all these parameters together.

Unfortunately, for each of the metrics plotted in Figure 8, a slightly negative trend can be observed over time, i.e., even less information is 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* [18].

V. 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 IVC protocols and applications. The used simulation tools and models are getting ever more precise and more 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 compatibility of the algorithms under investigation.

From our findings, we can derive the following five core aspects that define IVC simulations and are key to ensuring their validity, comparability, and reproducibility. In any case, all individual parameters need to be well documented.

1) *Network Simulator*. There are well established network simulators available; relying on any of the established ones will imply a certain set of models and default parameters, thus supplementing the model description.
2) *Physical Layer*. The radio propagation models employed at the physical layer need to be chosen carefully depending on the simulated scenario.
3) *Medium Access*. The importance of using an appropriate MAC protocol has been well documented. The IEEE 802.11p standard is gaining acceptance in the community and should (if nothing else) serve as a benchmark for IVC studies.
4) *Road Traffic Mobility*. The vehicles' mobility can easily be modeled using publicly available traces or validated road traffic simulators.
5) *Scenario Description*. We 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 performance evaluation of IVC protocols.

By also providing a comprehensive overview of commonly used models, scenarios, and parameters, we hope that this work can serve as a first step towards deriving an agreed-upon set on which IVC simulations can be based.

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