

Aspects and Trends in Realistic VANET Simulations

Agata Grzybek*, Marcin Sereczynski*, Grégoire Danoy† and Pascal Bouvry†

* Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg
Luxembourg, Luxembourg

Email: {agata.grzybek, marcin.sereczynski}@uni.lu

† CSC Research Unit, University of Luxembourg

Luxembourg, Luxembourg

Email: {gregoire.danoy, pascal.bouvry}@uni.lu

Abstract—Realistic simulations of Vehicular Ad hoc Networks (VANETs) are necessary to evaluate novel technologies based on such networks and to prove benefits obtained from their implementation. This survey gathers from several research domains aspects that increase the quality of VANET simulations. It explains a multi-fold nature of VANETs and presents main building blocks of their simulation—traffic and network simulators. The paper proposes a comprehensive architecture for VANET simulation platform that focuses on producing reliable results. The architecture contains traffic and network simulators that communicate with each other in a dynamic and bi-directional way. The concept of a realistic traffic generator is introduced. It uses real-world data (e.g. maps, traffic volume counts) to model an activity-based traffic varying in time. The traffic generator aims at reproducing accurate vehicular traces for urban scenario. A higher level of realism can be obtained by modelling of human behaviour with intelligent agents and by the implementation of related subsystems, like traffic management and control or weather factors.

Index Terms—VANETs; realistic simulation; traffic demand, mobility models; vehicular traces; user behaviour;

I. INTRODUCTION

The vision of whole cities covered with dynamic networks of “talking cars” is gradually becoming a reality because of the joint work of academia, industry and governments. Such networks are called *Vehicular Ad hoc Networks (VANETs)*. They consist of a large number of dynamically moving nodes over a broad area [1]. Advanced wireless technologies enable direct and instant communication among vehicles (*Vehicle-to-Vehicle V2V*) as well as between vehicles and the road infrastructure (*Vehicle-to-Infrastructure V2I*). VANETs have gained a lot of interest because their application can improve *road safety, efficiency* and *travel convenience*. For instance, they can be used to provide drivers with accurate and real-time traffic information [2]. VANET applications can range from enhanced traffic management and navigation to location-based and infotainment services. Communication standards and protocols have to consider specific conditions existing in vehicular networks, i.e. high velocity, long distances, constrained movement and various density determined by traffic demand that changes over time and space. Novel technologies as well as social, economic and environmental impact of VANET applications need to be thoroughly evaluated before the real-world deployment can be possible [3]. Testbeds are expensive and not scalable enough to produce sufficient report. Computer

simulations overcome these limitations without carrying a risk and interruptions in existing systems. Simulations can be run for large networks during a long time in arbitrarily different scenarios (e.g. urban, highway, rural) and repeated when needed [4]. To successfully aid researchers and accelerate the deployment of VANET applications a simulation platform must produce reliable results. This requires modelling of all elements included in VANETs such as electronics, networking, automotive and transportation. As far as the authors are concerned, this is the first survey that gathers aspects from many research domains, which are important for improving the quality of VANET simulations.

This paper is organised as follows. Section II introduces the fundamental concepts of VANET simulations. Sec. III focuses on the aspect of realism in the simulations. Sec. IV provides the information on traffic generators. It proposes a general architecture and presents examples of such generators. Sec. V addresses additional aspects influencing the realism in VANET simulations. It emphasises the need of modelling human behaviour in different areas of simulation and its impact on traffic. Sec. VI summarises the paper.

II. VANET SIMULATIONS

Simulation of VANETs includes two fundamental elements: *vehicular mobility* and *network communication*. These two characteristics are dependent, because as vehicles move, the network topology changes dynamically. In [1] Harri et al. describe different approaches taken by researchers for implementing VANET simulators. *Isolated architecture* exploits already existing traffic and network simulators. A traffic simulator generates vehicular movement in accordance to the surrounding environments and determines position of nodes in a network simulator. The one-way interaction enables to evaluate communications standards and protocols [5]. However, if the goal is to analyse the influence of a VANET-based application (e.g. traffic information system (TIS) [2]) on the road traffic, then bidirectional coupling between the two simulators is required. *Embedded simulators* contain well developed simulator (e.g. traffic simulator) with additional implementation of the complementary extension (e.g. network features). However, the added features are typically not so advanced as in already existing simulators. *Federated architecture* is the most popular

because it profits from two well-developed tools, that can communicate through interfaces (Fig. 1).

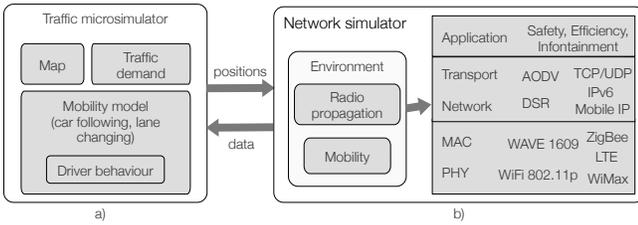


Fig. 1. VANET simulation. Traffic simulator (a). Network Simulator (b).

The two-way integration of state-of-the-art NS-3 [6] and SUMO [7] simulators are present in the iTetris project [8] and the OVNIS platform [9]. The significance of the bi-directional coupling is discussed in [10]. Description and comparison of the most popular VANET simulators can be found in [11].

A. Traffic simulators

Traffic simulators (Fig. 1a) reproduce realistic vehicular mobility. They were initially developed for transportation engineers to support road planning and assess transportation control systems [12]. Traffic modelling is a challenging task, because vehicular movement is non-arbitrary, i.e. it is strongly determined by the surrounding environment like road topology, traffic rules, other vehicles. Moreover, it is additionally influenced by individual driver behaviour. To obtain accurate results, a microscopic simulator needs to import real maps, determine realistic traffic demand and consider human behaviour in an advanced mobility, car-interaction model.

1) *Mobility models:* There exists various models reproducing mobility of nodes [13]. Stochastic mobility models, like Random Way-Point or models with constrained movement (Manhattan) are not able to reproduce the realistic traffic mobility [14]. To reflect better the vehicular movement, interactions among vehicles as well as between vehicles and the environment are described by *flow models* [1]. Flow models specify rules for car following, lane changing and overtaking behaviour and are categorised by the level of granularity as: *macroscopic*, *mesoscopic* and *microscopic*. Macroscopic models represent traffic as fluid streams by using aggregated values such as density or average velocity. Mesoscopic models describe some interactions among cars at an individual level, but they base the interactions on general characteristics. Microscopic models consider mobility of each individual vehicle. They implement realistic car following behaviour by adjusting each vehicle's velocity in respect to the vehicle in front (e.g. Intelligent Driver Model [15], Krauss Model [16]). For VANET simulations, where communication among individual vehicles needs to be available, microscopic models are the most suitable.

2) *SUMO:* Traffic simulators differ in many features, like compatible map types or implemented mobility models. In our opinion, the most advanced and comprehensive tool is SUMO (Simulation of Urban MOBility)—a purely microscopic traffic

simulator developed by the German Aerospace Center. It is characterised by: (a) the ability of importing real maps, (b) extensive traffic demand modelling, (c) advanced microscopic mobility model using Krauss' car-following model enabling overtaking and intersection management, (d) generation of different output measurements (vehicles positions, traffic counts, pollution and noise emission, edge-based network performance). Users can retrieve and change values of a simulation step (vehicle, road or traffic lights states) through *Traffic Control Interface (TraCI)* which allows bi-directional coupling with a network simulator.

B. Network simulators

VANETs are distributed and self-organising networks consisting of moving vehicles whose mobility result in forming dynamic network topologies [17]. To model and study communication capabilities in such networks, features presented in Fig. 1b should be considered.

Network simulators should allow a detailed specification of *network protocol layers* including implementation of new communication standards for PHY/MAC layer, like DSRC (Dedicated Short Range Communications) with IEEE 802.11p and IEEE WAVE (Wireless Access in Vehicular Environments) [18]. VANET transport layer has to support multi-hop multicast/broadcast communication and considers routing protocols, like AODV (Ad-hoc On-demand Distance Vector) or DSR (Dynamic Source Routing). They are usually implemented over the conventional TCP/UDP protocols, but recently new specially developed transport layer protocols are proposed, e.g. VANET TCP [19]. Mobile IP allows maintaining a single address when a vehicle is moving from one network to another [20]. Characteristics of a *radio signal propagation* in a dynamic environment should also be considered. There exist many radio propagation loss models, that present an attenuation of the signal (e.g. Nakagami-m model [21]). However, in urban scenarios, a radio signal is often impacted by obstacles. An example of a computationally efficient radio propagation model that considers an urban environment is proposed in [22]. Researchers need a network simulator to assess feasibility and impact of VANET applications. The network performance (e.g. channel throughput) can be evaluated under different conditions (e.g. transmission power). They can also test the efficiency of routing protocols by calculating the ratio of successfully delivered messages and the delay time as done in [17]. Furthermore, the simulator needs to be both *scalable* in order to work with large networks and *extensible* to easily modify implementation details.

1) *The Network Simulator 3 (NS-3):* is a more scalable and easier to use successor of a popular open-source network simulator NS-2. The biggest advantage is the continuous maintenance and rapid growth due to a large development community. It facilitates the creation of ad hoc wireless networks and simulation of radio propagation fading. The visible trend is to implement more features suitable for VANETs, like enhancements in device and channel models or an implementation of vehicular mobility models. We believe that NS-3 is

the most flexible and forward-looking tool to be incorporated in VANET simulation platform.

III. REALISTIC VANET SIMULATIONS

A proposed process for realistic VANET simulations consists of four steps as depicted in Fig. 2. The basic idea of VANET simulation explained in the previous section, is preceded with two additional steps that gather and prepare traffic related data. The first step (1) emphasises the need for gathering *realistic data* that have influence on traffic (maps, statistical data, traffic counters, real traces, GPS-based data). The information is then processed by a *traffic generator* (2) that models *traffic demand* and generates *synthetic traces* as an input to a traffic simulator. Synthetic traces are usually described with departure time, origin and destination points, an exact route and a transportation mode. A *microscopic traffic simulator* then moves vehicles (3) in accordance to requested routes and physical rules. A network simulator based on new vehicles position update its own nodes positions and communications links in every time step. Interactions between particular elements present reciprocal impact and further increase the realism of a simulation. Traffic simulator can change vehicle routes as a result of VANET applications (e.g. rerouting request). Moreover, a traffic generator can use a feedback from traffic microsimulator. Information about current traffic situation, e.g. individual travel times, can influence the traffic demand by changing traveller decisions and adjusting activity schedules. The separation of particular steps ensures modularity what makes easier the replacement of each module and testing of different scenarios. Although many microscopic simulators enable to specify traffic demand integrally, researchers tend to implement a separated module to gain the flexibility and modularity of the platform [8], [23].

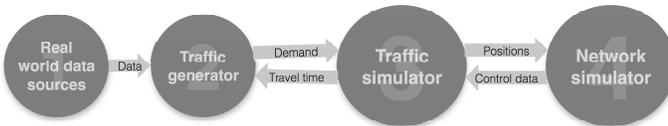


Fig. 2. VANET simulation process.

A. Real world data sources

1) *Maps*: Vehicular movement is strictly constrained by a road topology. To obtain a required level of details simple graphs reflecting length and shape of roads are not sufficient. Realistic street topology should consider such elements like number and type (e.g. only bus) of lanes, speed limits and intersection policies including priority of roads and traffic lights control. All these aspects are important for *microsimulation*, because they specify a final path between origin and destination and enable to estimate the travel time. Information obtained from maps can also help in the specification of *traffic demand*. Location of Points of Interest (POI), types of buildings (shopping centre, school, etc) or areas (residential, industrial, leisure, etc) can be used to determine travel stops.

Maps can be obtained through maps services, such as OpenStreetMap (OSM) [24] which provide a free and detailed map of the world that is constantly updated by a large community of contributors.

- 2) *Statistical data*: census forms, home interview surveys.
- 3) *Traffic counters*: induction loops, infrared sensors.
- 4) *Real traces*: the real world-traces of vehicles.
- 5) *GPS-based data*: collected by GPS tracking services.

B. Traffic demand model

Traffic generators aim to reproduce an accurate traffic demand. Vehicular traffic is not distributed evenly, but exposes dominant flows between specific areas. Traffic can be described by following aspects: (a) the number of travels, (b) their origins and destinations, (c) exact path for each travel and (d) type of a transport mode [25].

A *traditional four-step model* generates origin-destination (O-D) table of trips in following stages: (1) trip generation and (2) trip distribution, where O-D zones and number of trips are selected; (3) choice of transportation mode; (4) assignment of routes i.e. exact paths from origin to destination points. The model, although intuitive and simple, does not consider a time-variance of trips.

In [25] the authors outline the importance of underlying reasons for trips (activities taken by the travellers). These considerations led to the evolution of more behaviourally realistic *activity-based models*. In this model travels are derived from *daily activities* undertaken by habitants. Individual travel is modelled as a *tour*—a sequence of trips often starting and ending at a home place. Davidson et al. in [26] underline the advantages of a new generation model over a traditional one. The microscopic approach ensures that all decisions regarding travel choices are made at individual level which preserves the consistency in time, space and a transportation mode. Realism is further increased by modelling intra-household interactions and joint travels. Decisions of people travelling together within one household affects the factual number of used vehicles and adjust the time of activities. The activity-based method requires large and up-to-date data sets, that include detailed schedules of daily activities and household interactions, e.g. census long forms, home interview surveys.

IV. REALISTIC TRAFFIC GENERATORS

A. Motivation

The importance of realistic traffic generators for improving the quality of VANET simulation is discussed in [23], [17]. The authors agree that different mobility models change simulation results. They show that networks built on realistic traces tend to be less connected and less stable. It means that the use of simplistic mobility models can lead to overoptimistic evaluation of communications protocols. In order to obtain reliable VANET simulations it is then necessary to reproduce the most accurate traffic mobility.

The real world-traces of individual vehicles would be the most accurate representation of traffic behaviour. Unfortunately today no data sets exist that are freely available or of

sufficient detail and scope. Recently, traffic traces are being more often collected by GPS tracking services. However, such databases are not publicly accessible, because of privacy and business issues. For example GPS-based navigation system providers, (e.g. TomTom [27]) use traces to evaluate traffic conditions in a real-time navigation service.

More traffic data is gathered at *macroscopic* level of detail by e.g. traffic volume counters built in a road infrastructure. Collected data describes the cumulated volume of the traffic flow over a particular spot and can be distinguished regarding time, direction or type of a vehicle. The main disadvantage of such measurements is that mobility paths cannot be easily reconstructed, because no relations can be concluded between different points. Moreover, traffic counters are primarily mounted on highways and main roads, leaving urban areas not sufficiently covered.

Taking into account aforementioned reasons, the need for generation of *synthetic traces* is evident. Advantages of synthetic traces over the real ones are pointed out in [28]. Real traces are just able to reflect one particular situation observed during measurements. On the contrary, synthetic traces can be parameterised, so may present different traffic scenarios and cause an emergence of traffic phenomena that are not easily captured through measurements.

B. Architecture

A general idea for *traffic generator architecture* is presented in Fig. 3. Traffic generator fuses all real-world data that can be useful to determine the traffic demand. Examples of real world data sources are given in the previous section.

Traffic distribution module specifies the volume and spacial distribution of traffic demand and supply. To improve reality, the distribution origins and destinations should be dependent on time (see subsec. “Traffic demand model”).

Route assignment module assigns the exact route (subsequent road segments) for each traveler. The shortest route can be computed by a simple *weighted Dijkstra algorithm* based on e.g. the maximum speed. However, it can lead to traffic congestion on the most popular road segments. In reality, drivers do not take the same shortest way. In order to obtain more realistic traffic distribution *Gawron’s algorithm* [29] is widely used. First, it computes the fastest routes and calculates travel costs under existing conditions for each road segment. Then, iteratively, the part of traffic is moved to less congested roads and cost is recomputed until no significant improvements are observed. In this way the dynamic user equilibrium is achieved that considers different traffic conditions changing over time.

C. Implementations

1) *Cologne, Germany* [23]: The model produces a large dataset of vehicular traces over the city Cologne. The authors indicate and combine several aspects that improve realism of generated traces. First, a real map is obtained from OSM servers. Second, a large set of travels is produced by a microscopic activity-based traffic demand model, that uses a statistic

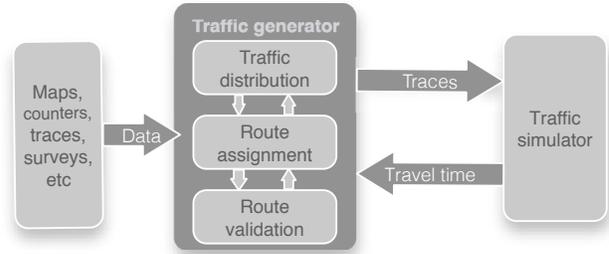


Fig. 3. Traffic generator architecture.

surveys. Third, routes are assigned by Gawron’s algorithm. The results of SUMO simulation show that generated traces capture demand evolution over a day in the most exact manner, as compared with results obtained from less sophisticated traffic generators.

2) *VehLux, Luxembourg* [30]: The generator does not require statistical surveys, but instead utilises freely available data sources to generate and validate the traffic for city of Luxembourg. Authentic macroscopic data from traffic counters installed over the road network and provided by transportation administration [31] indicates the volume of traffic in strategic points. A proposed *destination distribution model* uses also information about areas extracted from OSM and considers the underlying reason of travels: *an activity type* (commercial, industrial or residential). Results of SUMO simulation were compared with counting data, specially left for a validation purpose and confirmed to reproduce commuting flows close to the real-world traffic. In [32] the authors demonstrate how the values of the parameters of VehLux can be discovered using genetic algorithms.

V. MORE ASPECTS OF REALISM

A. Human behaviour

Vehicles are controlled by human beings what brings to simulation *randomness* and *heterogeneity*. In microscopic modelling of *vehicular dynamics*, drivers differ in aspects of experience, age and gender. These factors have impact on reaction times, and driving preferences like aggressiveness described by acceleration and deceleration capabilities or overtaking probability. These parameters should be included in car interaction models (car-following, lane-changing etc) used by traffic simulators. Implementation of human imperfection allows the emergence of unpredictable situations, like collisions or traffic jams.

Human aspects also impact on *traffic demand*, when routes are determined by personal activities. Drivers can decide and change each aspect of a travel: origin and destination points, departure times, transportation mode and the exact path. Travels can be extracted from real traces and surveys or artificially simulate with social network behaviour. For example, Working Day Movement Model [33] considers *inter-contact* and *contact duration times* to reproduce traffic in Helsinki. Another example defines communities that users

visit more often and periodically revisit to determine travel choices [34]. The authors derive analytical model, propose connectivity metrics: hitting and meeting time and evaluate performance of routing protocols.

B. TIS and driver reaction to information

Many of VANET applications provide information to drivers. With information about the current road condition and eventual traffic problems applications can assist in navigation, suggest re-routing or warn about an imminent danger. Feedback from application requires changes in vehicle's movement, but drivers act differently to the received information. The reaction can be influenced by following aspects:

1) *Type of information*: User is more likely to respond to critical information like safety warning than to an entertainment-based such as an advertising of a new facility.

2) *Psychological profile*: Driver is not always willing to comply on the received information. The authors in [35] model four behavioural classes of drivers and examine their willingness of the route change on quality of TIS.

3) *Travel experience*: Drivers can gather experience that later influences their decisions. In [36] drivers choose the route and departure time dependent on perceptions of both previously experienced and currently provided travel times.

C. Agent-based Urban Traffic Systems Simulations (UTS)

Simulations of a particular city scenario are necessary when benefits of VANET systems need to be delivered. UTS presents the traffic in a city scenario including traffic network, vehicles, pedestrians as well as traffic control and management systems [37]. Simulations of UTS allow to observe realistic traffic behaviour under different demand volumes, indicate traffic-related problems and support planning decisions.

UTS is well suited for an *agent-based modelling*, because it consists of many distributed autonomous, re-active and intelligent entities. Schleiffer in [38] marked that individual agents determined by simple rules, when interacting with each other, can well reflect *dynamic and cooperative behaviour* of the *complex traffic system*. An extensive review of agent-based applications in transportation systems is described in [39]. The authors present several management and control systems and explain the role of intelligent agents for the simulation purpose. In such models each vehicle is presented as a mobile agent that is able to make decisions depending on its preferences and knowledge.

The agent architecture varies in details depending on the application but in general it implements blocks responsible for receiving information, taking decision and performing action as presented in Fig. 4. The example of implementation an intelligent agent in a route assistance application is shown. It contains *data acquisition module* responsible for gathering information that can be local (read from vehicle's sensors) or external (collected from other vehicles) and valued in terms of relevance (e.g. by time-stamps). Next, the *decision module* uses the information and rules to determine further actions performed by the *action module*. In the decision

module drivers mental behaviour introduce randomness and imperfection of human to the mobility model.

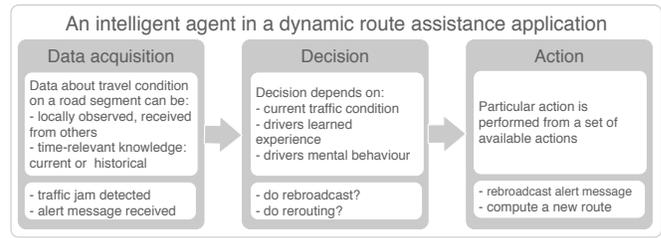


Fig. 4. An intelligent agent in a dynamic route assistance application.

D. Artificial Traffic Systems (ATS)

Rossetti et al. in [40] indicate recent directions in improving the mobility and productivity of traffic systems. The existing infrastructure can be used more efficiently by means of smarter, greener and safer technologies where users, their preferences and comfort are of central concern. He presents a concept of ATS initially introduced by Wang et al. in [41] as an extension to traditional traffic simulation systems. ATS is modelled as a multi-agent system which is able to generate complex *traffic phenomena* from simple objects and interactions. Microscopic approach and artificial intelligence (AI) methods allow not only to reproduce realistic traffic but also to grow live traffic processes which greatly improves realism of system evaluation and planning decisions. ATS models factors influencing drivers behaviour coming from many other urban subsystems integrally connected to traffic system such as weather, social, economic or traffic law. Main ideas of ATS can be summarise with an *ACP approach (Artificial, Computational, Parallel)*, which involves modelling with *artificial systems*, analysis with repetitive and customisable *computational experiments* and execution through *parallel interaction* between an actual transportation system and its corresponding artificial counterpart (what enable to emulate real-time road information for evaluation of traffic systems) [42].

VI. TRENDS AND CONCLUSION

This paper showed that realistic simulation is one of the biggest challenges in a VANET research domain, because it requires knowledge and experience from many fields. We underlined the necessity of simulations to evaluate new technologies and to provide benefits from their applications. Furthermore, we acknowledged the need of realism in every aspect of simulation in order to obtain reliable results.

We presented that recent trends lead to develop comprehensive simulation platforms consisting of many modules: real-world data sources, traffic generator, traffic and network simulators. We explained the aim and importance of interactions between particular modules for increasing the quality of simulations. Bi-directional coupling of the existing state-of-the-art network and traffic generator creates a solid foundation that enable testing VANET applications in arbitrary traffic

scenarios. Separation of a traffic generator enables to test many applications for various scenarios.

The paper indicated that the future direction in evolution of VANET simulations can be inspired by the modelling drivers behaviour and their needs. A combination of human behaviour modelling with AI methodologies like deduction, planning and learning enables to reflect more realism of traffic systems like heterogeneity, randomness and dynamism. An implementation of driver reactions to the received information allows better validation of the impact of VANET applications on traffic systems. A simulation platform could be used as a growing and alive counterpart to the real traffic system that enable to analyse, predict and solve traffic-related problems. Moreover, an integration of other connected subsystems, like economic or weather, would allow to test more applications and assesses their impact on a traffic system.

The major concern of VANET simulation is the lack of standardisation in evaluation of protocols and traffic systems. A common set of parameters for tested scenarios and the evaluation metrics to compare simulation results would be highly desirable. A validated, high-quality and flexible VANET simulation platform is necessary to spur the real implementation of working VANET systems.

REFERENCES

- [1] H. Hartenstein and K. Laberteaux, *VANET: vehicular applications and inter-networking technologies*. Wiley, 2010.
- [2] M. Seredynski and P. Bouvry, "A survey of vehicular-based cooperative traffic information systems," in *Proc. 14th International IEEE Conference on Intelligent Transportation Systems*, 2011, pp. 163–168.
- [3] U. D. of Transportation, "ITS Strategic Research Plan 2010-2014," <http://www.rita.dot.gov/>, Tech. Rep., 2010.
- [4] C. Sommer and F. Dressler, "Progressing toward realistic mobility models in VANET simulations," *Communications Magazine, IEEE*, vol. 46, no. 11, pp. 132–137, 2008.
- [5] L. Passos, R. Rossetti, and Z. Kokkinogonis, "Towards the next-generation traffic simulation tools: a first appraisal," in *Proc. Information Systems and Technologies (CISTI)*, 2011, pp. 1–6.
- [6] The network simulator 3. [Online]. Available: <http://www.nsnam.org/>
- [7] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "SUMO - Simulation of Urban MObility: An Overview," in *Proc. 3rd International Conference on Advances in System Simulation, SIMUL*, 2011.
- [8] V. Kumar, L. Lin, D. Krajzewicz, F. Hrzi, O. Martinez, G. Sempere, J. Manuel, and R. Bauza, "iTETRIS: adaptation of ITS technologies for large scale integrated simulation," in *Proc. 3rd IEEE International Symposium on Wireless Vehicular Communications*, China, 2010.
- [9] Y. Pigné, G. Danoy, and P. Bouvry, "A platform for realistic online vehicular network management," in *Proc. IEEE GLOBECOM Internat. Workshop on Management of Emerging Networks and Services*, 2010.
- [10] F. Dressler, C. Sommer, D. Eckhoff, and O. K. Tonguz, "Towards Realistic Simulation of Inter-Vehicle Communication: Models, Techniques and Pitfalls," *IEEE Vehicular Technology Magazine*, vol. 6, no. 3, pp. 43–51, 2011.
- [11] F. J. Martinez, C. K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A survey and comparative study of simulators for vehicular ad hoc networks (VANETs)," *Wirel. Commun. Mob. Comput.*, vol. 11, 2011.
- [12] N. R. C. U. T. R. Board, *Highway capacity manual*, ser. Special report. Transportation Research Board, National Research Council, 1985.
- [13] J. Härrri, F. Filali, and C. Bonnet, "Mobility models for vehicular ad hoc networks: A survey and taxonomy," 2006.
- [14] R. Baumann, F. Legendre, and P. Sommer, "Generic mobility simulation framework (gmsf)," in *Proc. 1st ACM SIGMOBILE workshop on Mobility models*, ser. MobilityModels '08, 2008, pp. 49–56.
- [15] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *PHYSICAL REVIEW E*, vol. 62, p. 1805, 2000.
- [16] S. Krauss, P. Wagner, and C. Gawron, "Metastable states in a microscopic model of traffic flow," *Physical Review E*, vol. 55, no. 5, pp. 5597–5602, 1997.
- [17] M. Fiore and J. Härrri, "The networking shape of vehicular mobility," in *Proc. 9th ACM international symposium on Mobile ad hoc networking and computing, MobiHoc*, 2008, pp. 261–272.
- [18] Y. L. Morgan, "Managing DSRC and WAVE Standards Operations in a V2V Scenario," *International Journal of Vehicular Technology*, 2010.
- [19] W. Viriyasitavat, F. Bai, and O. Tonguz, "Toward end-to-end control in vanets," in *Proc. Vehicular Networking Conference*, 2011, pp. 78–85.
- [20] A. E. Coronado Mondragon, E. S. Coronado Mondragon, C. E. Coronado Mondragon, and F. Mung'au, "Estimating the performance of intelligent transport systems wireless services for multimodal logistics applications," *Expert Syst. Appl.*, vol. 39, pp. 3939–3949, 2012.
- [21] N. Beaulieu and C. Cheng, "Efficient nakagami-m fading channel simulation," *Vehicular Technology, IEEE Transactions on*, vol. 54, no. 2, pp. 413–424, 2005.
- [22] E. Giordano, R. Frank, G. Pau, and M. Gerla, "Corner: A radio propagation model for vanets in urban scenarios," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1280–1294, 2011.
- [23] S. Uppoor and M. Fiore, "Large-scale Urban Vehicular Mobility for Networking Research," in *Vehicular Networking Conference*, 2011.
- [24] OpenStreetMap. [Online]. Available: <http://www.openstreetmap.org/>
- [25] D. A. Hensher and K. J. Button, *Handbook of transport modelling*. Pergamon, 2008.
- [26] W. Davidson, R. Donnelly, P. Vovsha, J. Freedman, S. Ruegg, J. Hicks, J. Castiglione, and R. Picado, "Synthesis of first practices and operational research approaches in activity-based travel demand modeling," *Transportation Research Part A: Policy and Practice*, vol. 41, no. 5, pp. 464–488, 2007.
- [27] TomTom LiveTraffic. [Online]. Available: <http://tomtom.com/livetraffic/>
- [28] M. Musolesi and C. Mascolo, "Mobility models for systems evaluation," *Middleware for Network Eccentric and Mobile Applications*, 2009.
- [29] C. Gawron, "An iterative algorithm to determine the dynamic user equilibrium in a traffic simulation model," *International Journal of Modern Physics C*, vol. 9, no. 3, pp. 393–407, 1998.
- [30] Y. Pigné, G. Danoy, and P. Bouvry, "A vehicular mobility model based on real traffic counting data," in *Proc. 3rd International Conference on Communication Technologies for Vehicles*, 2011, pp. 131–142.
- [31] Administration des ponts et chaussées, luxembourg. [Online]. Available: <http://www.pch.public.lu/trafic/comptage>
- [32] M. Seredynski, G. Danoy, M. Tabatabaei, B. Bouvry, and Y. Pigné, "Generation of realistic mobility for vanets using genetic algorithms," in *Proc. of the IEEE Congress on Evolutionary Computation*, 2012.
- [33] F. Ekman, A. Keränen, J. Karvo, and J. Ott, "Working day movement model," in *Proc. 1st ACM SIGMOBILE workshop on Mobility models*, 2008, pp. 33–40.
- [34] W. Hsu, T. Spyropoulos, K. Psounis, and A. Helmy, "Modeling time-variant user mobility in wireless mobile networks," in *Proc. IEEE INFOCOM*, 2007, pp. 758–766.
- [35] F. Dressler and C. Sommer, "On the impact of human driver behavior on intelligent transportation systems," in *Proc. 71st Vehicular Technology Conference*, 2010, pp. 1–5.
- [36] S. An, J. Cui, and L. Li, "Agent-based approach to model commuter behaviours day-to-day dynamics under pre-trip information," *IET Intelligent Transport Systems*, vol. 5, no. 1, 2011.
- [37] E. López-Neri, A. Ramírez-Treviño, and E. López-Mellado, "A modeling framework for urban traffic systems microscopic simulation," *Simulation Modelling Practice and Theory*, vol. 18, no. 8, pp. 1145–1161, 2010.
- [38] R. Schleiffer, "Traffic itself is simple-just analyzing it is not," in *Proc. 33rd Annual Hawaii International Conference on System Sciences*, vol. 2, 2000, p. 10.
- [39] B. Chen and H. H. Cheng, "A review of the applications of agent technology in traffic and transportation systems," *Trans. Intell. Transport. Sys.*, vol. 11, pp. 485–497, 2010.
- [40] R. J. F. Rossetti, R. Liu, and S. Tang, "Guest editorial special issue," *Artificial Transportation Systems and Simulation*, vol. 12, no. 2, 2011.
- [41] F.-Y. Wang and S. Tang, "A framework for artificial transportation systems: from computer simulations to computational experiments," in *Proc. Intelligent Transportation Systems*, 2005, pp. 1130–1134.
- [42] J. Li, S. Tang, and F.-Y. Wang, "An Investigation on ATS from the Perspective of Complex Systems," in *Proc. 11th International IEEE Conference on Intelligent Transportation Systems*, 2008, pp. 20–24.