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Mobility Models for Vehicular Ad Hoc Networks: A Survey and Taxonomy

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Abstract

Vehicular Ad-hoc Networks (VANETs) have been recently attracting an increasing attention from both research and industry communities. One of the challenges posed by the study of VANETs is the definition of a generic mobility model providing an accurate, realistic vehicular mobility description at both macroscopic and microscopic levels. Today, most mobility models for vehicular studies only consider a limited macro-mobility, involving restricted vehicles movements, while little or no attention is paid to micro-mobility and its interaction with the macro-mobility counterpart. On the other hand, the research community cannot have access to realistic traffic generator which have not been designed to collaborate with network simulators. In this paper, we first introduce a classification of existing methods for the generation of vehicular mobility models, then we describe the various approaches used by the community for realistic VANET simulations. Finally, we provide an overview and comparison of a large range of mobility models proposed for vehicular ad hoc networks.

Index Terms

Survey, Taxonomy, Classification, Mobility Models, Traffic generator, Vehicle Ad Hoc Networks.

Contents

List of Figures

1 Introduction

Vehicular Ad-hoc Networks (VANETs) represent a rapidly emerging, particularly challenging class of Mobile Ad Hoc Networks (MANETs). VANETs are distributed, self-organizing communication networks built up by moving vehicles, and are thus characterized by a very high node mobility and limited degrees of freedom in the mobility patterns. Such particular features often make standard networking protocols inefficient or unusable in VANETs, whence the growing effort in the development of communication protocols which are specific to vehicular networks.

While it is crucial to test and evaluate protocol implementations in a real testbed environment, simulation is widely considered as a first step in the development of protocols as well as in the validation and refinement of analytical models for VANETs.

One of the critical aspects when simulating VANETs is the employment of mobility models that reflect as closely as possible the real behavior of vehicular traffic. This notwithstanding, using simple random-pattern, graph-constrained mobility models is a common practice among researchers working on VANETs. There is no need to say that such models cannot describe vehicular mobility in a realistic way, since they ignore the peculiar aspects of vehicular traffic, such as cars acceleration and deceleration in presence of nearby vehicles, queuing at roads intersections, traffic bursts caused by traffic lights, and traffic congestion or traffic jams. All these situations greatly affect the network performance, since they act on network connectivity, and this makes the adoption of a realistic mobility model fundamental when studying VANETs.

In this paper, we describe how vehicular mobility models may be classified in four classes according to the methods used to generate them. Then, we illustrate the particular relationship between network simulators and traffic generators used for civil and transportation studies. Finally, we investigate the degree of realism of the different mobility models freely available to the research community on vehicular ad hoc networks. Realism is based on a framework related to realistic vehicular behavior and urban configurations. According to it, we give a broad view of the state-of-the-art mobility models adapted for VANETs. To the best of our knowledge, this is the fist work that provides a detailed survey and comparison of mobility models for vehicular ad hoc networks.

The rest of this paper is organized as follows. Section 2 describes the framework related to realistic vehicular motions, while Section 3 provides a description of the process of generating vehicular mobility models. Then, in Section 4, we cover the relationship between network and traffic simulators, and in Section 5, we propose a detailed survey and a taxonomy of mobility models available to the vehicular networking community. Finally, in Section 6, we conclude this survey, and provide some hints on future orientation of realistic vehicular mobility models.

2 A Framework for Realistic Vehicular Mobility Models

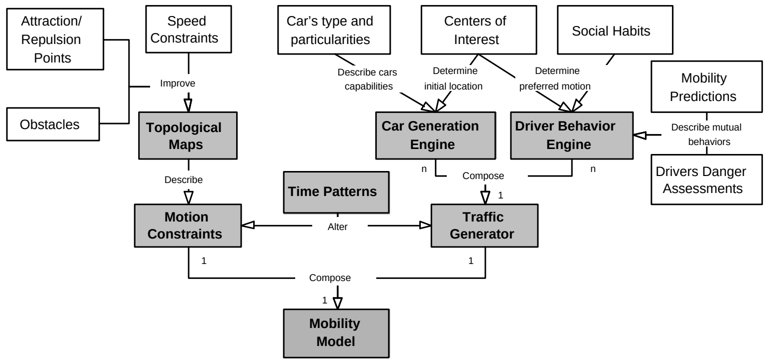


Figure 1: Proposed concept map of mobility model generation for inter-vehicle communications

In the literature, vehicular mobility models are usually classified as either **microscopic** or **macroscopic**. When focusing on a macroscopic point of view, motion constraints such as roads, streets, crossroads, and traffic lights are considered. Also, the generation of vehicular traffic such as traffic density, traffic flows, and initial vehicle distributions are defined. The microscopic approach, instead, focuses on the movement of *each* individual vehicle and on the vehicle behavior with respect to others.

Yet, this micro-macro approach is more a way to analyze a mobility model than a formal description. Another way to look at mobility models is to identify two functional blocks: **Motion Constraints** and **Traffic Generator**. **Motion Constraints** describe how each vehicle moves (its relative degree of freedom), and is usually obtained from a topological map. Macroscopically, motion constraints are streets or buildings, but microscopically, constraints are modeled by neighboring cars, pedestrians, or by limited roads diversities either due to the type of cars or to drivers' habits. The **Traffic Generator**, on the other hand, generates different kinds of cars, and deals with their interactions according to the environment under study. Macroscopically, it models traffic densities or traffic flows, while microscopically, it deals with properties like inter-distances between cars, acceleration or braking.

The framework states that a realistic mobility model should include:

- **Accurate and Realistic topological maps:** Such maps should manage different densities of roads, contains multiple lanes, different categories of streets and associated velocities.

- **Smooth deceleration and acceleration:** Since vehicles do not abruptly break and move, deceleration and acceleration models should be considered.

- **Obstacles:** We require obstacles in the large sense of the term, including both mobility and wireless communication obstacles.
- **Attraction points:** As any driver knows, initial and final destination are anything but random. And most of the time, drivers are all driving in similar final destinations, which creates bottlenecks. So macroscopically speaking, drivers move between a repulsion point towards an attraction point using a driver's preferred path.
- **Simulation time:** Traffic density is not uniformly spread around the day. An heterogeneous traffic density is always observed at some peak time of days, such as *Rush hours* or *Special Events*.
- **Non-random distribution of vehicles:** As it can be observed in real life, cars initial positions cannot be uniformly distributed in a simulation area, even between attraction points. Actually, depending of the *Time* configuration, the density of cars at particular *centers of interest*, such as homes, offices, shopping malls are preferred.
- **Intelligent Driving Patterns:** Drivers interact with their environments, not only with respect to static obstacles, but also to dynamic obstacles, such as neighboring cars and pedestrians. Accordingly, the mobility model should control vehicles mutual interactions such as overtaking, traffic jam, preferred paths, or preventive action when confronted to pedestrians.

The approach can be graphically illustrated by a concept map for vehicular mobility models, as depicted in Figure 1.

3 Generating Mobility Models for Vehicular Networks

Although being a promising approach, the proposed Framework in the previous section suffers from non negligeable drawbacks and limitations. Indeed, parameters defining the different major classes such as *Topological Maps*, *Car Generation Engine*, or *Driver Behavior Engine* cannot be randomly chosen, but must reflect realistic configurations. Therefore, due to the large complexity of such project, the research community took more simplistic directions and moved step by step.

Globally, the development of modern vehicular mobility models may be classified in four different classes: *Synthetic Models* wrapping all models based on mathematical models, *Traffic Simulators-based Models*, where the vehicular mobility models are extracted from a detailed traffic simulator, *Survey-based Models* extracting mobility patterns from surveys, and finally *Trace-based Models*, which generate mobility patterns from real mobility traces. A proposed classification is illustrated in Fig. 2

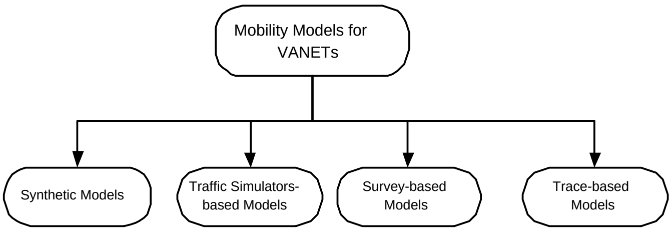


Figure 2: Classification of Vehicular Mobility Models

3.1 Synthetic Models

The first and most well known class includes the synthetic models. Indeed, major studies have been undertaken in order to develop mathematical models reflecting a realistic physical effect. Fiore wrote a complete survey of models falling into this category. We shortly summary the basic classification he developed. For a more complete version, we refer the reader to [1]. According to Fiore's classification, Synthetic models may be separated in five classes: *stochastic models* wrapping all models containing purely random motions, *traffic stream models* looking at vehicular mobility as hydrodynamic phenomenon, *Car Following Models*, where the behavior of each driver is modeled according to vehicles ahead, *Queue Models* which models roads as FIFO queues and cars as clients, and *Behavioral Models* where each movement is determined by a behavioral rules imposed by social influences for instance. Fig. 3 illustrate Fiore's classification.

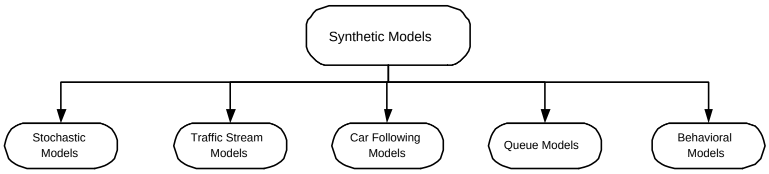


Figure 3: Classification of Synthetic Mobility Models

In order to validate a mathematical model, it should be compared to real mobility. Accordingly, one solution is to gather mobility traces by large measurement campaigns then compare the patterns with those developed by the synthetic model. In [2], authors proposed to validate some key characteristics of the RWP such as average speed and rest times using real life data. The Weighted Waypoint Model (WWM) [3] is a second attempt to validate a synthetic model which has been tuned by real traces. The WWM adds the notion of preference to the random waypoint. This calibration of this preference criterion has been performed based on mobility traces obtained inside the USC campus. The HWGui [4] generates realistic time dependant highway traffic patterns that have been validated against real traffic in German Highways.

A major critic from synthetic models is the lack of realism towards human behavior. Indeed, drivers are far from being machines and cannot be programmed for a specific behavior, but responds to stimuli and local perturbations which may have a global effect on traffic modeling. Accordingly, realistic mobility modeling must also consider behavioral theory, social networks for instance, which makes models far from being random. Musolesi and Mascolo illustrated this approach in [5] by developing a synthetic mobility model based on social network theory, then validating it using real traces. They showed that the model was a good approximation of human movement patterns.

3.2 Survey-based Models

However, although the behavioral theory is able to generate macro-motion models or deviation from micro-motion models, beside the comparison with real traces, another solution is calibration by means of comparison with realistic social behavior. The major large scale available surveys come from the US department of Labor, which established surveys and gathered extensive statistics of US workers' behaviors, going from the commuting time, lunch time, traveling distance, preferred lunch politics and so forth. By including such kind of statistics into a mobility model, one is able to develop a generic mobility model able to reproduce the non random behavior observed in real daily life urban traffic.

The UDel Mobility Model [6] falls into this category. Indeed, the mobility simulator is based on surveys from a number of research areas including time-use studies performed by the US Department of Labor and Statistics, time-use studies by the business research community, pedestrians and vehicle mobility studies by the urban planning and traffic engineering communities. Based on these works, the mobility simulator simulates arrival times at work, lunch time, breaks/errands, pedestrian and vehicular dynamics (e.g., realistic speed-distance relationship and passing dynamics), and workday time-use such as meeting size, frequency, and duration. Vehicle traffic is derived from vehicle traffic data collected by state and local governments and models vehicle dynamics and diurnal street usage. We can also cite the Agenda-based [7] mobility model, which combines both the social activities and the geographic movements. The movement of each node is based on individual agenda, which includes all kind of activities on a specific day. Data from the US National Household Travel Survey has been used to obtain activity distribution, occupation distribution and dwell time distribution.

3.3 Trace-based Models

Another major drawback of synthetic models is that only some very complex models are able to come close to a realistic modeling of vehicular motion patterns. A different approach has therefore been undertaken. Indeed, instead of developing complex models, and then validating them using mobility traces or surveys, a crucial time could be saved by directly extracting generic mobility patterns from movement traces. Such approach recently became increasingly popular as mobility traces started being gathered through various measurement campaigns launched by projects such as CrawDaD [8], ETH MMTS [9], UMASSDieselNet [10], MIT Reality Mining [11], or USC MobiLib [12]. The most difficult part in this approach is to extrapolate patterns not observed directly by the traces. By using complex mathematical models, it is possible to predict mobility patterns not reported in the traces to some extends. Yet, the limitation is often linked to the class of the measurement campaign. For instance, if motion traces have been gathered for bus systems, an extrapolated model cannot be applied to traffic of personal vehicles.

Another limitation from the creation of trace-based mobility models is the few freely available vehicular traces. The major research group are currently implementing testbeds, but the outcome might only be available in few months or years if they are even made available to the public. To corner this issue, some teams (ETH [9]), or the Los Alamos Research Labdeveloped very complex simulators, which are able to generate very realistic vehicular traces. However, due to the complexity of the simulator, the trace generation time has an order of magnitude of couples of hours or days. Then, this mobility data are usually considered as real traces for the generation or calibration of mobility models.

Tuduce and Gross in [13] present a mobility model based on real data from the campus wireless LAN at ETH in Zurich. They used a simulation area divided into squares and derive the probability of transitions between adjacent squares from the data of the access points. In [14], authors combines coarse-grained wireless traces, i.e., association data between WiFi users and access points, with an actual map of the space over which the traces were collected in order to generates a probabilistic mobility model representative of real movement. They derived a discrete time Markov Chain which not only considers the current location, but also the previous location, and also the origin and the destination of the path. However, this study does not consider correlation between nodes.

Kotz et al. [15] describe a measurement technique for extracting user mobility characteristics also from coarse-grained wireless traces. They derived the location of users over time and also emphasize popular regions. They major findings was unlike standard synthetic mobility models, the speed and the pause times follow a log-normal distribution. They also confirmed that the direction of movement closely reflect the direction of roads and walkways, and thus cannot be modeled by a uniform distribution. Similarly to [13], they ignore correlation between adjacent nodes.

In [16], user mobility are modeled by a semi-Markov process with a Markov Renewal Process associated with access point connection time instants. Unlike previous studies, this work is able to model how user mobility is correlated in time at different time scales. The authors also performed a transient analysis of the semi-markov process and extracted a timed location prediction algorithm which is able to accurately predict users future locations. This work is moreover the first attempt to characterize the correlation between movements of individual users.

Chaintreau et al. [17] studied the inter-contact time between wireless devices carried by humans using coarse-grained wireless traces but also experimental testbeds using iMotes. Their major outbreak was that unlike the widely accepted assumption that inter-contact time follows an exponential distribution, a more realistic assumption should be that the distribution exhibit a heavy tail similar to a power law distribution. Another study ([18]) analyzed the student contact patterns in an university campus using class time-tables and student class attendance data. A major restricted assumption has been taken, which force students to either be in classrooms or in some randomly chosen communication hubs. They showed that in this configuration, most students experienced inter-contact time of the order of magnitude of few hours. However, unlike other studies (such as [17]), the inter-contact time does not follow a power law distribution. This is where the limitation from trace-base mobility modeling appears. Indeed, this study is specific to class attendance, and results obtained remain also specific to the environment the study has been made.

By using traces, various research teams have therefore been able to extract mobility models that would reflect more realistically to motion we experience in real life. Moreover, a major result from trace-based mobility modeling, which is at odd with hypothesis used by synthetic models, is that the speed and pause time distributions followed a log-normal distribution, and that the inter-contact time may be modeled by a power law distribution,

3.4 Traffic Simulator-based Models

By refining the synthetic models and going through an intense validation process using real traces or behavior surveys, some companies or research teams gave birth to realistic traffic simulators. Developed for urban traffic engineering, fine grained simulators such as PARAMICS [19], CORSIM [20], VISSIM [21] or TRANSIMS [22], are able to model urban microscopic traffic, energy consumption or even pollution or noise level monitoring. However, those simulators cannot be used straightaway for network simulators, as no interface have been developed and traces are mutually incompatible. This, added to the commercial nature of those traffic simulator, became the raison d'être for the development of the novel off-the-self vehicular mobility models that we are going to describe in this paper.

By developing parser between traffic simulator traces and network simulator input files, the end-user gains access to validated traffic patterns and is able to obtain a level of detail never reached by any actual vehicular mobility model. The major drawback of this approach is the configuration complexity of those traffic simulators. Indeed, the calibration usually includes tweaking a large set of parameters. Moreover, the level of detail required for vehicular network simulator may not be as demanding as that for traffic analysis, as global vehicular mobility patterns and not the exact vehicular behavior are by far sufficient in most cases. We also want to emphasize that those commercial models require the purchase of a license that may exceed thousands of dollars, which is a major limitation for the VANET research community.

4 Mobility Models and Network Simulators: The Non-Speaking talking to the Deaf

In the previous section, we described various approaches that has been undergone by the research community in order to develop realistic mobility models adapted to vehicular traffic. Yet, in order to be used by the networking community, those models need to be made available to network simulators. And this is precisely where we fall into a kafkaien situation. The worlds of Mobility Models and Network Simulators may be compared to a non-speaking talking to deaf people. They have never been created to communicate, and even worse, they have been designed to be controlled separately, with no interaction whatsoever. When imagining the promising applications that could be obtained from vehicular networks, where networks could alter mobility, and where mobility would improve network capacity, this situation cannot be tolerated anymore if the vehicular networks community has the means of its ambitions.

Initially, mobility was seen by network simulators as random perturbations from optimum static configurations. Then, in order to give some control to the user on the mobility patterns, network simulators became able to load mobility scenarios. There is virtually no limitation to the complexity of the models handled by those simulators, loading scenarios extracted from traffic simulators, or complex synthetic models for instance. However, as illustrated in Fig. 4, the models must be generated prior to the simulation and must be parsed by the simulator according to a predefined trace format. Then, no modification of the mobility scenario is allowed.

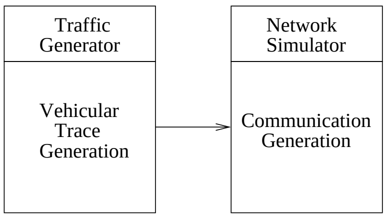


Figure 4: Interaction between Network and Traffic Simulators: The Isolated Case

For example, VanetMobiSim [23] is able to generate realistic vehicular mobility traces in urban area as well as highway scenarios. It models car-to-car interactions and car-to-infrastructure interactions, which allows it to integrate stop signs, traffic lights, safe inter-distance management and behavior based macro-mobility.

It is also able to generate mobility incidents such as accidents. Moreover, it is freely available and has been validated against realistic traces obtained from CORSIM, a validated traffic generator.

Beside the general waste of computational resources, no interaction are therefore possible between those two worlds. Unfortunately, all historical models and most of the recent realistic mobility models available to the research community fall into this category (see Section 5).

The research community then took a radically different step. If network simulators are unable to interact with mobility simulators, they should be replaced by simplistic off-the-shelf discrete even simulators which could do this task. Accordingly, new simplistic network simulator were created, where the lack of elaborated protocol stacks was compensated by a native collaboration between the networking and the mobility worlds, as depicted in Fig. 5.

MoVes [24] is an embedded system generating vehicular mobility traces and also containing a basic network simulator. The major asset of this project is its ability to partition the geographical area into clusters and parallelize and distribute the processing of the tasks from them, which improves the simulation performance. Although the mobility model reaches a sufficient level of detail, the project's drawback is the poor network simulation, which only includes a basic physical and MAC layer architecture and totally lacks routing protocols. In [25], authors also

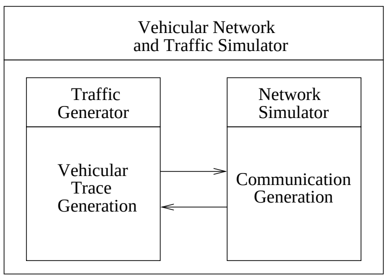


Figure 5: Interaction between Network and Traffic Simulators: The Integrated Case

proposed an integrated vehicular and network simulator. As all solutions proposed by this approach, the authors developed their own traffic and network simulator. The vehicular traffic simulator is a synthetic model integrating basic microscopic motions where drivers may be in one of the following four modes: *free driving, approaching, following, braking*. A basic macroscopic model handles multi-lane and intersection management. Although being basic, this traffic model brings sufficient level of detail. However, the network simulator part is by far the major limitation of this project, as it is only modeled by a simplistic discrete event simulator handling a basic radio propagation and CSMA/CA MAC layer protocol.

As mentioned, the major limitation of the embedded approach is actually the poor quality of the network simulator. Indeed, this approach has been so far only used to study basic network effects, but could not pass the test of recent mobile ad hoc routing protocols, including realistic and standardized physical and MAC layers. And this may also be seen as a non sense, as the actual direction in network simulations is a specific compliance with standard protocols and computational efficiency through parallel and distributed computing.

Another approach recently carried on is to federate existing network simulators and mobility models through a set of interfaces (see Fig. 6). For instance, MOVE [27] contains a single graphical user interface for the configuration the mobility modeling and network simulation. However, MOVE does not itself include a network simulator, but simply parses realistic mobility traces extracted from a micro-motion model SUMO [26] into a network simulator-dependant input trace format, then generates the appropriate scripts to be loaded by the network simulator. No interaction is therefore possible between the network simulator and the mobility model.

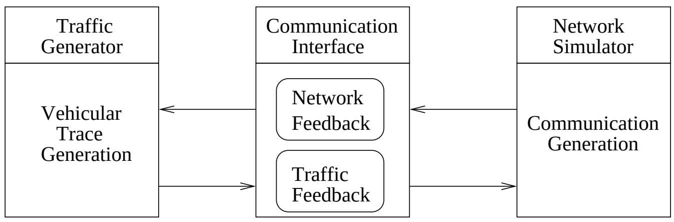


Figure 6: Interaction between Network and Traffic Simulators: The Federated Case

A different approach, taken by Prof. Fujimoto and his group in Georgia Tech [28] is to generate a simulation infrastructure composed of two independent commercial simulation packages running in a distributed fashion over multiple networked computers. They federated a validated traffic simulator, CORSIM, with a state-of-the-art network simulator, QualNet, using a distributed simulation software package called the Federated Simulations Development Kit (FDK) [29] that provides services to exchange data and synchronize computations. In order to allow direct interaction between the two simulators, a common message format has been defined between CORSIM and QualNet for vehicle status and position information. During initialization, the transportation road network topology is transmitted to QualNet. Once the distributed simulation begins, vehicle position updates are sent to QualNet and are mapped to mobile nodes in the wireless simulation. Accordingly, unlike MOVE, both simulators work in parallel and thus may dynamically interact on each other by altering for example mobility patterns based on network flows, and vice and versa. The only limitation comes from the complex calibration of CORSIM and its large number of configuration parameters which must be tweaked in order to fit with the modeled urban area.

A similar solution has been taken by a team from UC Davis [30]. They developed a simulation tool federating the network simulator Swans and a synthetic traffic model. The complex vehicular flows are based on the Nagel and Schreckenberg model, extended to include lane changing in highway scenarios. The network simulator and the traffic simulator interacts with each others by means of specific input and output messages.

Authors in [31] proposed *AutoMesh*, a realistic simulation framework for VANET. It is composed of a set of modules controlling all parts of a realistic simulation. It includes a *Driving Simulator Module*, a *Radio Propagation Module*, and *a Network Simulator Module*, all interlinked with feedback in order that any alteration made in one module influences the other modules. At the stage of the development of AutoMesh, the Driving Simulator Module only include random macro-movement and the IDM model for micro-movements. It is therefore unable to reproduce the non-uniform distribution of positions and speed usually experienced in urban area. However, the radio propagation module is very detailed, using 3D maps and digital elevation models in order to obtain a realistic radio propagation model in urban area.

Another promising approach is called *TraNS* [32] and also aims at federating a traffic simulator SUMO and a network simulator ns2. Using an interface called *Interpreter*, traces extracted from SUMO are transmitted to ns-2, and conversely, instructions from ns-2 are sent to SUMO for traffic tunning. TraNS will be extended to handle other network simulators such as Swans or Nab in the future. A similar project called MSIE [33] has been developped but using VISSIM instead of SUMO. This project is also more complete, as it proposes to interlink different simulators for traffic simulation, network simulation and application simulation. The major actual limitation is the communication latency between the different simulators, and the expensive price of VISSIM. Besides, the interlinking interface itself is also not freely available at this time. Authors in [34] chose to replace VISSIM by a complete tool developed by themselves, the *CARISMA* traffic simulator. Although not being as complete as VISSIM or SUMO, it allows to accurately evaluate the effects of car-to-car messaging systems in the presence of urban impediments by benefiting from the federated approach and a ”real-time” trip (re-)configuration.

By federating independent and validated simulators, the interlinking approach is able to benefit from the best of both worlds, as state-of-the-art mobility models may be adapted to work with modern network simulators. However, it is computationally demanding, as both simulators need to be run simultaneously, and the development of the interface may not be an easy task depending on the targeted network and traffic simulators. Nevertheless, this is probably in this direction that most of the future pioneer work will come in the field of vehicular mobility modeling and networking.

The networking and mobility modeling community have a mutual interest in interacting between each others. Indeed, at the time of the promising benefits obtained from the various cross-layer approaches in network research, the ability to proactively or reactively act on mobility patterns in order to improve network efficiency or radio propagation, or even more promising, the ability to alter mobility patterns based on dynamically events radio transmitted will probably be a central approach in future networking research projects.

5 A Taxonomy of existing Synthetic VANETs Mobility Models

In this Section, we provide a taxonomy of existing VANETs synthetic mobility models and simulators freely available to the research community. We first introduce a set of criteria that will be able to better differentiate and classify the different synthetic models. We then provide a short summary of each model, including its assets and drawbacks, and provide its taxonomy in Table 1 and Table 2 according to the classification criteria. We purposely chose not include commercial-based traffic simulators as they cannot be freely used by the researcher working in the VANET field. As a consequence, most of the federated models described in the previous section may not be included. Similarly, we can neither add *Trace-based models* not *Survey-based Models* to our taxonomy as they are extrapolated from real mobility and cannot be classified according to our criteria.

5.1 Taxonomy Criteria

Prior to providing a classification, one need to define the criteria based on which to generate the taxonomy. The proposed criteria fall in three categories: **Macro-mobility**, **Micro-mobility**, and **Simulator Related**.

5.1.1 Macro-mobility Criteria

When considering macro-mobility, we do not only take into account the road topology, but also include trip and path generation, or even the effects of points of interests, which all influence vehicles movement patterns on the road topology. We therefore define the following criteria:

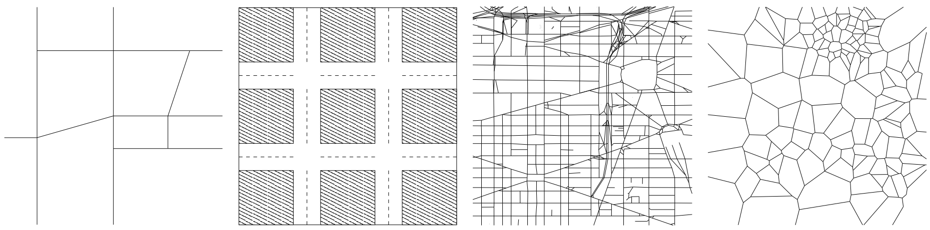
- *Graph* – The macro-motion is restricted to move on a graph.
- *Initial and Destination Position* – The positions may be either random, random restricted on a graph or based on a set of attraction or repulsion points.
- *Trip Generation* – A trip may be randomly generated between the initial and destination points, or set according to an activity sequence.
- *Path Computation* – Provides the algorithms used to generate the path between the points contained on the trip.
- *Velocity* – The simulated velocity may be uniform, smooth or road-dependant.

Graphs

The selection of the road topology is a key factor for obtaining realistic results when simulating vehicular movements. Indeed, the length of the streets, the frequency of intersections, or the density of buildings can greatly affect important mobility metrics such as the minimum, maximum and average speed of cars, or their density over the simulated map. We categorize the graphs by the following criteria:

- *User-defined* – The road topology is specified by listing the vertices of the graph and their interconnecting edges.
- *Random* – A random graph is generated, which are often *Manhattan-grid*, *Spider*, or *Voronoi* graphs.
- *Maps* – The road topology is extracted from real maps obtained from different topological standards, such as *GDF*, *TIGER*, or *Arcview*.
- *Multi-lane* – The topology includes multi-lanes, potentially allowing lane changes, or not.

We show examples of the possible topologies in Fig. 7.



(a) User-defined topology (b) Manhattan-grid map topology (c) TIGER map topology (d) Clustered Voronoi

Figure 7: Road topologies examples

Attraction Points

Attraction or Repulsion points are particular source or destination points that have a potentially attractive or repulsive feature. For instance, for a weekly morning, residential areas are repulsion points and office builds are attraction points, as a large majority of vehicles are moving from the former and to the latter. We depict the use of attraction points on a user-defined graph in Fig. 8, where a round is for the entry/exit points of high-speed roads (thick lines), and a square for the entry/exit points of normal-speed roads (thin lines).

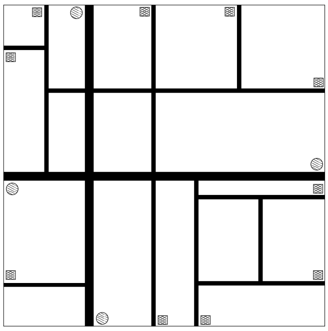


Figure 8: Example of Attraction Points on a User-defined graph

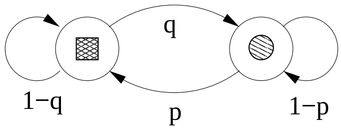


Figure 9: Activity-based Sequence between the attraction points in Fig. 8

Activity-based Trips

Activity sequences generation is a further restriction in vehicles spatial and temporal distributions. A set of start and stop points are explicitly provided in the road topology description, and cars are forced to move among them. In particular, multiple sets of points of interest can be specified, along with the probability matrix of a vehicle switching from one set to another. Fig. 9 illustrates an activity sequence generated from a first order Markov chain between two categories of attractions points.

5.1.2 Micro-mobility Criteria

In the proposed taxonomy, the micro-mobility aspect uses the following criteria:

- *Human Mobility Patterns* – The car's internal motion and its interactions with other cars may be inspired from human motions described by mathematical models such as *Car Following*, or not.
- *Lane Changing* – Describes the kind of overtaking model implemented by the model, if any.
- *Intersections* – Describes the kind of intersection management implemented by the model, if any.

In this section, we shortly describe the most widely used vehicular specific micro-mobility models. We refer to [1] for a larger coverage of the different microscopic mobility models.

Car Following Models

The car following models are a class of microscopic models that adapts a following car's mobility according to a set of rules in order to avoid contact with the lead vehicle. A general schema is illustrated in Fig. 10. Brackstone in [35] classi-

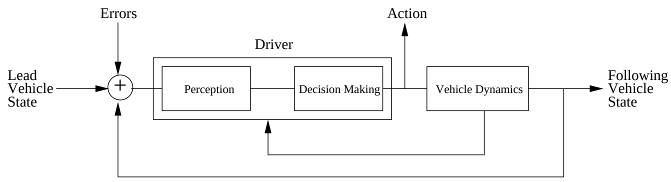


Figure 10: General Schema for Car Following Models

fi ed Car Following Models in fi ve classes: *GHR Models*, *Psycho-Physical Models*, *Linear Models*, *Cellular Automata*, *Fuzzy Logic Models*. A description of the differences between those models is out of scope of this paper. We refer the interested reader to [36]. We only list here the widely used models in traffi c simulations.

- Krauss Model (KM) [37]
- Nagel and Schreckenberg Model (N-SHR) [38]
- Wiedeman Psycho-Physical Model (Psycho) [39]
- General Motors Model (GM) [40]
- Gipps Model (GP) [41]
- Intelligent Driver Model (IDM) [42]

Lane Changing Models

Despite the large attention given to the driving tasks in general (such as Car Following Models), much less attention has been directed to lane changing.Modeling lane changing behavior is a more complex task. Indeed, it actually includes three parts: the need of lane changing, the possibility of lane changing, and the trajectory for lane changing. Each part is important to generate realistic lane changing models. And unlike car following models, it also needs to consider nearby cars and traffi c flow information. Most of the models are based on a *Gap Acceptance* threshold [43] or a set of rules [44]. But recent approaches ([45, 46]) also considered forced merging, behavior aspects or game theory. Lane changing is not widely considered in open vehicular mobility models. In this survey, we mostly fi nd

- Gibbs Model for Lane Changing (GP-LC) [43] and its variations
- Wiedeman Psycho-Physical Model for Lange Changing (Psycho-LC) [47]

- MOBIL [46]

Intersection Management

Intersection management adds handling capabilities to the behavior of vehicles approaching a crossing. In most cases, two different intersection scenarios are considered: a crossroad regulated by stop signs, or a road junction ruled by traffic lights. Nevertheless, all intersection management technics only act on the first vehicle on each road, as the car following model automatically adapts the behavior of cars following the leading one. The most basic ones consider intersections as obstacles and abruptly stop, yet more complex ones, such as the IDM_IM and IDM_LC [48], smoothly stop at stop-based crossing, or acquire the state of the semaphore in a traffic light controlled intersection. If the color is green, passage is granted and the car maintains its current speed through the intersection. If the color is red, crossing is denied and the car is forced to decelerate and stop at the road junction. Fig. 11 illustrates the IDM_IM behavior when approaching an intersection with respect to the deceleration and the multi-lane management.

(a) Acceleration management

(b) Multi-lane management

Figure 11: Intersection management in IDM_IM and IDM_LC

5.1.3 Simulator Related Criteria

Finally, we provide these additional criteria, which are more specific to the mobility simulator or to the interaction with a network simulator:

- *Obstacles* – The model considers radio obstacles, either in the form of an obstacle topology for network simulator and a propagation computation interface for network simulators, or directly a radio propagation trace file.
- *Visualization* – The model includes a visualization tool.
- *Output* – Describes the kind of output generated by the mobility model, such as NS-2 or QualNet compliant traces.

- *Language* – Provides the programming language on which the simulator has been developed.

5.2 Taxonomy of Synthetic Vehicular Models

In this section, we simultaneously provide a brief description of the major synthetic mobility models available to the vehicular networking community, and classify them in Table 1 and Table 2 according to the previously defined criteria. As previously mentioned, we cannot include the *Trace-based* nor the *Survey-based* models as they have been obtained from real mobility and do not fall in the taxonomy. We include some *Traffic Simulator-based* models if they are based on freely available traffic simulators.

First, we point out that many realistic traffic simulation tools, such as PARAMICS [19], CORSIM [20], VISSIM [21] or TRANSIMS [22] have been developed to analyze vehicular mobility at both microscopic and macroscopic level with a very high degree of detail. However, all the aforementioned softwares are distributed under commercial licenses, a major impediment to adoption by the academic research community. With the exception of few teams that developed parsers (e.g. [49, 50]), or federated a realistic traffic simulation tool with a network simulator (such as FDK [29]), these tools have been originally designed for traffic analysis and not for generation of movement traces usable by networking simulators. Furthermore, the presence of copyrights impedes the modification/extension of the sources when particular conditions, not planned by the original software, have to be simulated. For such reasons, we will not consider these tools in the following, their scope being very different from VANET mobility simulators are intended for. For a complete review and comparison of such traffic simulation tools, the interested reader can refer to [51].

When mobility was first taken into account in simulation of wireless networks, several models to generate nodes mobility patterns were proposed. The Random Waypoint model, the Random Walk model, the Reference Point Group (or Platoon) model, the Node Following model, the Gauss-Markov model, just to cite the most known ones, all involved generation of random linear speed-constant movements within the topology boundaries. Further works added pause times, reflection on boundaries, acceleration and deceleration of nodes. Simplicity of use conferred success to the Random Waypoint model in particular, however, the intrinsic nature of such mobility models may produce unrealistic movement patterns when compared to some real world behavior. Despites, random models are still widely used in the study of Mobile Ad-hoc Networks (MANETs).

As far as Vehicular Ad-hoc Networks (VANETs) are concerned, it soon became clear that using any of the aforementioned models would produce completely useless results. Consequently, the research community started seeking more realistic models. The simple Freeway model and Manhattan (or Grid) model were the initial steps, then more complex projects were started involving the generation of mobility patterns based on real road maps or monitoring of real vehicular movements in

	Macro-Mobility							
	Graph				Init/Dest Position	Trip	Path	Velocity
	User Defined	Random	Map	Multi-lane				
Virtual Track [81]	yes		TIGER [65]	no	random	random S-D	RWP	uniform
IMPORTANT [61]		Grid		no	random	random S-D	RWM, RWalk	smooth
Bonn-Motion [62]		Grid		no	random	random S-D	RWM	uniform
RiceM [64]			TIGER	no	random	random S-D	Dijkstra	uniform
SUMO [26] MOVE [27] TraNS [32]	yes	grid, spider	TIGER	yes	random, AP	random S-D activity	RWalk, Dijkstra	smooth, road-dep
CARISMA [34]			ESRI [67]	yes	random	random S-D	Dijkstra, Speed, Density	smooth, road-dep
SHIFT [69]	yes			yes	AP	activity		smooth, road-dep
STRAW [70]			TIGER	no	random	random S-D	RWalk, Dijkstra	smooth
GrooveSim [71]			TIGER	no	random	random S-D	RWalk, Dijkstra	uniform, road-dep
Obstacle [68]		Voronoi		no	random	random S-D	Dijkstra	uniform
Voronoi [76]		Voronoi		no	random	random S-D	RWalk	uniform
GEMM [63]		Grid		no	AP	random S-D	RWP	uniform
Canu-MobiSim [72]	yes		GDF [66]	no	random, AP	random S-D activity	RWP, Density, Dijkstra	uniform
City [74]		Grid		no	random	random S-D	RWM	smooth
Mobi-REAL [77]	yes			no	random	random S-D	RWalk	uniform
SSM/ TSM [75]		Grid	TIGER	no	random	random S-D	Dijkstra	uniform, road-dep
MoVES [24]			GPSTrack [79]	no	random		RWalk	uniform, road-dep
Gorgorin [25]			TIGER	yes	random		RWalk	smooth
AutoMesh [30]			TIGER	yes	random	random S-D	Dijkstra, Density, Speed	uniform, road-dep
VanetMobiSim [23]	yes	Voronoi	TIGER, GDF	yes	random, AP	random S-D activity	RWP, Density, Dijkstra, Speed	smooth, road-dep
S-D: Source-Destination; *AP*: Attraction Point; *road-dep*: Road dependent;								

Table 1: Macro-Mobility Features of the Major Vehicular Mobility Models

	Micro-Mobility				Simulator Related			
	Human Patterns	Intersection	Lane Changing	Radio Obstacles	Visualization Tool	Output	Platform	Remarques
Virtual Track [81]	no	no	no	no	no	ns-2, gloMoSim, QualNet	C++	
IMPORTANT [61]	CFM	no	no	no	no	ns-2	C++	unrealistic CFM
BonnMotion [62]	no	no	no	no	yes	ns-2, gloMoSim, QualNet	Java	
RiceM [64]	no	no	no	no	no	ns-2, gloMoSim, QualNet	C++	
SUMO [26] MOVE [27] TraNS [32]	CFM (Krauss)	stoch turns	no	no	yes	ns-2, gloMoSim, QualNet	C++	*federated* traf/net simulator, *validated* micro-model
CARISMA [34]	CFM (Krauss)	stop signs	no	yes	yes	ns-2, gloMoSim, QualNet	C++	*federated* traf/net simulator
SHIFT [69]	CFM	no	LC	no	yes	none	C++/SHIFT	configurable CFM/LC
STRAW [70]	CFM (Nagel Schreck)	traffic lights, signs	no	no	no	Swans	JiST-Swans	
GrooveSim [71]	no	no	no		yes	none	C++	
Obstacle [68]	no	no	no	yes	yes	ns-2, gloMoSim, QualNet	C++	
VoronoiM [76]	no	no	no	no	no	ns-2	C++	
GEMM [63]	no	no	no	no	no	ns-2	Java	
CanuMobiSim [72]	IDM	no	no	yes	yes	ns-2, gloMoSim, QualNet,	Java	
City [74]	IDM	stoch turns	no	no	yes	ns-2	C++	
MobiREAL [77]	CPE	no	no	yes	yes	GTNetS	C++	pedestrian mobility
SSM/TSM [75]	no	traffic lights, traffic signs	no	no	no	ns-2	C++	
MoVES [24]	CFM (Psycho)	random traffic lights, traffic signs	no	no	yes	none	C++	*integrated* traf/net simulator
Gorgorin [25]	CFM (Psycho)	traffic lights, traffic signs	CFM (Psycho-LC)	no	yes	none	C++	*integrated* traf/net simulator, *validated* micro-model
AutoMesh [30]	IDM	stop signs	no	yes	yes	ns-2, gloMoSim, QualNet	C++	*federated* traf/net simulator
VanetMobiSim [23]	IDM, IDM_IM, IDM_LC	traffic signs, traffic lights	MOBIL	yes	yes	ns-2, qualNet, glomoSim	Java	*validated* macro/micro model

CFM: Car Following Model; *IDM*: Intelligent Driver Model *CPE*: Condition-Probability-Event;
IDM_IM: IDM with Intersection Management; *IDM_LC*: IDM with Lange Changes;

Table 2: Micro-Mobility Features of the Major Vehicular Mobility Models

cities. However, in most of these models, only the macro-mobility of nodes was considered. Although car-to-car interactions are a fundamental factor to take into account when dealing with vehicular mobility [52], little or no attention was paid to micro-mobility. More complete and detailed surveys of mobility models can be found in literature [53–56].

Recently, new open-source tools became available for the generation of vehicular mobility patterns. Most of them are capable of producing traces for network simulators such as *ns-2* [57], *GloMoSim* [58], *QualNet* [59], or *OpNet* [60]. In the rest of this section, we review some of these tools, in order to understand their strengths and weaknesses.

The IMPORTANT tool [61], and the BonnMotion tool [62] implement most of the random mobility models presented in [53], including the Manhattan model. This model restrict nodes macro-mobility on a grid, while the micro-mobility contains a *Car Following Model*. The BonnMotion does not consider any micro-mobility. When related to our proposed framework, we can easily see that the structure of both tools is definitely too simple to represent realistic motions, as they only model basic motion constraints and hardly no micro-mobility.

The GEMM tool [63] is an extension to BonnMotion's and improves its traffic generator by introducing the concepts of human mobility dynamics, such as *Attraction Points (AP)*, *Activity*, or *Roles*. Attraction points reflect a destination interest to multiple people, such as grocery stores or restaurants. Activities are the process of moving to an attraction point and staying there, while roles characterize the mobility tendencies intrinsic to different classes of people. While the basic concept is interesting, its implementation in the tool is limited to a simple enhanced RWM between APs. It however represents an initial attempt to improve the realism of mobility models by considering human mobility dynamics.

The MONARCH project [64] proposed a tool to extract road topologies from real road maps obtained from the TIGER [65] database. The possibility of generating topologies from real maps is considered in the framework, however the complete lack of micro-mobility support makes it difficult to represent a complete mobility generator. Indeed, this mobility model is simply a Random Waypoint Model restricted on a graph extracted from real topological cities. Although it brings some spatial correlations, it absolutely lacks time, car-to-car and car-to-infrastructures correlations. Besides, the authors showed that their model was having similar patterns than the RWM.

The Obstacle Mobility Model [68] takes a different approach in the objective of obtaining a realistic urban network in presence of building constellations. Instead of extracting data from TIGER files, the simulator uses random building corners and voronoi tessellations in order to define movement paths between buildings. It also includes a radio propagation model based on the constellation of obstacles. According to this model, movements are restricted to paths defined by the Voronoi graph.

The *Simulation of Urban MObility (SUMO)* [26] is an open source, highly portable, microscopic road traffic simulation package designed to handle large road networks. The car microscopic movement model in SUMO is a car following model and includes a stochastic traffic assignment modeled by a probabilistic route choice according to driver models. SUMO contains parsers for various topologies, ranging from TIGER, Arcview, or even to VISSIM. Routes assignment may also be imported from various sources. However, at that time, SUMO is not able to output traces straightforwardly usable by network simulators.

The Mobility Model Generator for Vehicular Networks (MOVE) was recently presented [27]. It is a simple parser for the SUMO and enhances SUMO's complex configuration with a nice and efficient GUI. MOVE also contains a parser to generate traces usable by network simulators such as ns-2 or QualNet.

SUMO is also the root functionality of TraNS [32], a federated model including ns2. Using an interface called *Interpreter*, traces extracted from SUMO are transmitted to ns-2, and conversely, instructions from ns-2 are sent to SUMO for traffic tunning. Accordingly, interactions between the vehicular traffic and network may be implemented.

Another important microscopic mobility simulator is the SHIFT Traffic Simulator [69]. It has been developed by the PATH Project at the UC Berkley, and is now a well established micro-mobility simulator that generates the trajectories of vehicles driving according to validated models on realistic road networks. More specifically, SHIFT is a new programming language with simulation semantics and was used in *SmartAHS* as means of specification, simulation and evaluation framework for modeling, control and evaluation of Automated Highway Systems (AHS). The major limitation of this simulator is its limitation to the modeling of segments of highways and its lack of complete topology modeling.

The CARISMA traffic simulator [34] is a realistic simulator containing microscopic and macroscopic features. It implements the Krauss's car following model, adds a stop sign intersection management, imports real topological maps in ESRI standard [67]. It furthermore provides a real-time trip management, which is a very interesting feature for the evaluation of car-to-car messaging. This model has also been interlinked with ns-2 for realistic evaluations of vehicle-to-vehicle messaging systems. One major limitation comes from the ESRI shape files, which are not publicly available unless you buy some ESRI products. Moreover, lane changing models and complex intersection managements are not considered at that time.

The Street Random Waypoint (STRAW) tool [70] is a mobility simulator based on the freely available Scalable Wireless Ad Hoc Network Simulator (SWANS). Under the point of view of vehicular mobility, it provides urban topologies extractions from the TIGER database, as well as micro-mobility support. STRAW is also one of the few mobility tools to implement a complex intersection management using traffic lights and traffic signs. Thanks to this, vehicles are showing a more realistic behavior when reaching intersection. The concept behind STRAW is very similar to the framework described in section 2, as it contains accurate mobility constraints as well as a realistic traffic generator engine. STRAW also includes several implementations of transport, routing and media access protocols, since they are not present in the original SWANS software. The main drawback of the tool is the very limited diffusion of the SWANS platform.

The GrooveSim tool [71] is a mobility and communication simulator, which again uses files from the TIGER database to generate realistic topologies. Being a self-contained software, GrooveSim neither models vehicles micro-mobility, nor produces traces usable by network simulators. The interesting feature of this model is the non uniform distribution of vehicles speeds. Indeed, motion constraints such as speed limitations, often force vehicles to give up in their effort to reach the velocity initially set by the model. Although that is might look as a straightforward pattern, this type of motion constraints is, at this time, considered only by few simulators. GrooveSim includes four types of velocity models, where the most interesting is the road-based velocity when used in conjunction with a shortest trip path generation. The authors illustrated how vehicles were naturally choosing the roads with the highest speed limitations while on their journey. The main drawback of this tool is however its lack of a micro-mobility model as well as the lack of mobility traces for network simulators.

The CanuMobiSim tool [72] is a tool for the generation of movement traces in a variety of conditions. Extrapolation of real topologies from detailed Geographical Data Files (GDF) are possible, many different mobility models are implemented, a GUI is provided, and the tool can generate mobility traces for *ns-2* and *GloMoSim*. Unlike many other tools, the CanuMobiSim tool keeps micro-mobility in consideration, implementing several car-to-car interaction models such as the *Fluid Traffic Model*, which adjusts the speed given vehicles local density, or the *Intelligent Driver Model (IDM)*, which adapts the velocity depending on movements between neighboring vehicles. Also unlike other tools, CanuMobiSim includes a complex traffic generator that can either implements basic source-destination paths using Dijkstra-like shortest path algorithms, or similarly to the GEMM, it can model trips between *Attraction Points* depending on the class of users' specific motion patterns. This solution is actually the only fully implemented and available solution considering heterogeneous classes of user and destinations. In order to improve its modeling capability, CanuMobiSim has even been recently extended (see [73]) by the same authors and now includes radio propagation information for ns-2 and GloMoSim/QualNet.

In recent months, a couple of research teams proposed a new set of simulators that comes closer to the objective to accurately model vehicles' specific motions. The first one is the City Model [74]. It has been basically designed for routing protocols testing and no network simulator traces are provided. This model includes a basic micro-mobility model composed of the IDM and a simplistic crossing management. Crossings are modeled like obstacles, where a car needs to reduce its speed and stop before the crossing. Then, the vehicle changes its direction according to a particular probability. This simulator mostly lacks modularity mostly due to its unique grid-based macro-mobility constraints, to the restriction to stochastic turns, and to the lack macro-mobility patterns based on human mobility dynamics.

The second is the SSM/TSM model [75]. It represents actually two different mobility models, a *Stop Sign Model* and a *Traffic Sign Model*. The motion constraints part is dealt using a TIGER parser, while the traffic generator includes the *Car Following Model*. As GrooveSim, both SSM and TSM include a road-dependent velocity distribution. However, this model goes farer than GrooveSim, since it contains a basic traffic generator which makes its mobility traces more realistic than GrooveSim's. And similarly to STRAW, SSM/TSM has been specifically designed to model vehicles' motions at intersections. The authors managed to show how a basic intersection management such as a simple stop sign was able to produce a clustering effect at those intersection. In urban environment, this effect is better known under the name *Traffic Jam*, and is hardly represented in most of the actual simulators. But similarly to the City Model, the SSM/TSM also lacks macro-mobility patterns based on human mobility dynamics.

The Voronoi Model [76] is an illustration of how voronoi graphs proposed by some simulators could be refined and improved to generate smoother roads. Unlike other mobility models including voronoi tessellations, this *Voronoi Model* does not model roads as graph edges, but as voronoi channels. A voronoi channel is a spatial area obtained after multiple application of a Voronoi Tessellation algorithm. It provides a global moving direction, while keeping some degree of liberty in the local direction patterns. Most of this model contributions are on the improvement of the motion constraints component as a promising random topology generator, while the traffic generator engine is a simple implementation of a Random Walk within each voronoi channel. However, this model's absolute lack of micro-mobility considerations and macro-mobility patterns based on human mobility dynamics, makes it unrealistic for vehicular mobility modeling.

All models presented in this section so far claims to be able to model realistic vehicular motion patterns. However, with the exception of SHIFT, none of them formally validated their patterns agaist real vehicular traces, or validated traffic simulators. *VanetMobiSim* [23], on the other hand, is the only synthetic model so far, which motion patterns for urban and highways environments have been validated. Indeed, the authors compared the traces obtained from VanetMobiSim and from CORSIM on similar urban configurations. They managed to show that the spatial distributions, the speed distributions, and the traffic shock waves generated by both models were similar. As CORSIM has been formally validated against real urban traces, so are VanetMobiSim's.

VanetMobiSim models car-to-car and car-to-infrastructure interactions, allowing it to integrate stop signs, traffic lights, safe inter-distance management and behavior based macro-mobility including human mobility dynamics. It also includes various road topology definition, ranging from realistic GDF [66] or TIGER [65], to user-defined or random topologies. It lets the user define the trip generation between random source-destination, to activity-based trips. Moreover, the path used on the defined trip is also configurable between a Dijkstra shortest-path, a road-speed shortest path and a density-based shortest path. It finally generates traces for various network simulators, as well as a special *Universal Trace Format*, which is simply composed of

$$\text{Universal Trace Format}: \mathit{time}\ \mathit{node\_id}\ \mathit{pos\_X}\ \mathit{pos\_Y}\ \mathit{velocity}\ \mathit{acceleration}$$

which may be used by any tool capable of parsing that kind of trace file. VanetMobiSim is at that time one of the most realistic and configurable synthetic model for the generation of vehicular motion patterns.

A special attention should also be brough to a novel solution named *MobiREAL* [77]. Although that it focuses on the modeling of pedestrian mobility, its strict compliance with the proposed framework and its novel approach of cognitive modeling makes it very promising for a future extension to vehicular mobility. The most interesting features is that MobiREAL enables to change a node or a class of nodes' mobility behavior depending on a given application context. At this time, only CanuMobiSim, VanetMobisim and MobiREAL are able to include this feature. This particular application context is modeled by a *Condition Probability Event (CPE)*, a probabilistic rule-based mobility model describing the behavior of mobile nodes, which is often used in cognitive modeling of human behavior. As most of recent mobility models, MobiREAL is able to include geographical informations. Moreover, it is also able to use this information to generate obstacles and more specifically it is able to model radio's interference and attenuations on the simulation field. With CanuMobiSim's extension and the Obstacle model, they are the only models that are able to both generate motion traces and signal attenuation information. MobiREAL's major drawback at this time is the limited diffusion of Georgia Tech Network Simulator (GTNets) and the manual configuration of all necessary parameters, which requires a full recompilation of the simulator at each reconfiguration.

Recently, new approaches appears in realistic scalable simulations of vehicular mobility. In [24], the authors created MoVes, a complex mobility generator on top of Artis [78], a scalable distributed simulation middleware. MoVes features cars following models, drivers' characterization, intersection management and includes a parser module to include GPS maps using the GPS TrackMaker program [79]. However, unlike our project, MoVes does not include any lane changing model, and no realistic path generation is supported.

Gorgorin [25] also integrated a network and a mobility simulator. Although the idea looks promising, the major flow at this time is the relative simplicity of both simulators. Indeed, although the mobility model is able to import TIGER maps and includes a similar micro mobility model to VISSIM, it does not consider any macro-mobility aspect. Moreover, similarly to MoVes, the network simulator also suffers from its simplistic architecture and from its poor diffusion compared to QualNet, OpNet or Ns-2.

The UDel Models [6] are a set of mobility and radio propagation models generated for detailed large-scale urban mesh networks. The urban mobility part is significantly different from all the previous approaches, as detailed urban vehicular and pedestrian mobility is based on surveys. Indeed, urban planning and the

US Department of Labor generated a large database of statistics on time use or human mobility preferences. The generated simulator also considers a detailed urban propagation model and includes an accurate map builder capable of parsing GIS dataset and adding realistic radio obstacles.

6 Conclusion

As a prospective technology, Vehicular Ad Hoc Networks (VANETs) have recently been attracting an increasing attention from both research and industry communities. One of the fastest growing field of interest in VANETs is safety, where communications are exchanged in order to improve the driver's responsiveness and safety in case of road incidents. VANETs characteristics are a higher mobility and a limited degree of freedom in the mobility patterns. Such particular features make standard networking protocols inefficient or unusable in VANETs. Accordingly, one of the critical aspect when testing VANETs protocols is the use of mobility models that reflect as closely as possible the real behavior of vehicular traffic. In this paper, we first presented a framework which should be followed for the generation of realistic vehicular mobility patterns, then we disserted on the different approaches in vehicular mobility modeling and proposed a classification of vehicular mobility models according to the technics used for their generation. We finally described the most popular models available to the research community at this time, and provided their detailed taxonomy according to criteria based on natural building blocks required for realistic vehicular mobility modeling.

Unlike MANETs, the major objective of VANET protocols is a direct alteration of the traffic patterns for safety or trip optimization. Accordingly, we also described the new trend to interlink traffic and network simulators in order to create a cross-layer collaboration between routing and mobility schemes. As far as the authors are concerned, this is the first article which clearly addresses this issue in perspective to other approaches, and provides an insight of the future research directions in joint traffic and network simulations.

The aim of this survey is to facilitate the comprehensive understanding of the emerging development of realistic vehicular traffic generators, the different methods, their justifications, and the interlinking with network simulators. This could be a good guideline for people interested in understanding the unique relationship between traffic models and network protocols in vehicular networks. This article also provided a large coverage of the most popular mobility models for vehicular networks, and could thus be a good starting point for people starting in this field or desiring to increase their knowledge in Vehicular Ad Hoc Mobility Modeling.

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