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A Realistic Mobility Simulator for Vehicular Ad Hoc Networks[2]

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A Realistic Mobility Simulator for Vehicular Ad Hoc Networks

Jérôme Härri, Marco Fiore, Fethi Filali, and Christian Bonnet.

Abstract

During the last few years, continuous progresses in wireless communications have opened new research fields in computer networking, aimed at extending data networks connectivity to environments where wired solutions are impracticable. Among these, vehicular traffic is attracting a growing attention from both academia and industry, due to the amount and importance of the related applications, ranging from road safety to traffic control, up to mobile entertainment. Vehicular Ad-hoc Networks (VANETs) are self-organized networks built up from moving vehicles, and are part of the broader class of Mobile Ad-hoc Networks (MANETs). Because of their peculiar characteristics, VANETs require the definition of specific networking techniques, whose feasibility and performance are usually tested by means of simulation. One of the main challenges posed by VANETs simulations is the faithful characterization of vehicular mobility at both macroscopic and microscopic levels, leading to realistic non-uniform distributions of cars and velocity, and unique connectivity dynamics. Yet, freely distributed tools which are commonly used for academic studies only consider limited vehicular macro-mobility issues, while they pay little or no attention to vehicular micro-mobility and its interaction with the macro-mobility counterpart. Such a simplistic approach can easily raise doubts on the confidence of derived VANETs simulation results. In this paper we first present and describe VanetMobiSim, a freely available generator of realistic vehicular movement traces for telecommunication networks simulators. VanetMobiSim is validated first by illustrating how the interaction between featured macro- and micro-mobility is able to reproduce typical phenomena of vehicular traffic. Then, the traces generated by VanetMobiSim are formally validated against those obtained from CORSIM, a benchmark traffic generator in transportation research.

Index Terms

Vehicular mobility modeling, validation, framework, macromobility, micromobility, vehicular ad hoc networks, VANET.

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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 from traveling vehicles, and are thus characterized by very high speed and limited degrees of freedom in nodes movement patterns. Such particular features often make standard networking protocols inefficient or unusable in VANETs, and this, combined with the huge impact that the deployment of VANET technologies could have on the automotive market, explains the growing effort in the development of communication protocols which are specific to vehicular networks.

Whereas it is crucial to test and evaluate protocol implementations in real testbed environments, logistic difficulties, economic issues and technology limitations make simulation the mean of choice in the validation of networking protocols for VANETs, and a widely adopted first step in development of real world technologies. A critical aspect in a simulation study of VANETs, is the need for a mobility model which reflects, as close as possible, the real behavior of vehicular traffic. When dealing with vehicular mobility modeling, we distinguish between macro-mobility and micro-mobility descriptions.

For *macro-mobility*, we intend all the macroscopic aspects which influence vehicular traffic: the road topology, constraining cars movement; the per-road characterization, defining speed limits, number of lanes, overtaking and safety rules over each street of the aforementioned topology; the traffic signs description, establishing the intersections crossing rules; the car class dependent constrains, providing differentiation in the above rulings for different types of vehicles; the traffic patterns delineation, outlining the popularity of different locations as traffic destinations during different hours of the day and for different classes of drivers, etc.

Micro-mobility instead refers to the individual behavior of drivers, when interacting with other drivers or with the road infrastructure: traveling speed in different traffic conditions; acceleration, deceleration and overtaking criteria; conduct in presence of road intersections and traffic signs; general driving attitude, related to driver's age, sex and mood, etc. The distinction between macro- and micro-mobility we propose is not to be confused with the difference between the macroscopic and microscopic scales commonly employed in traffic flow theory, and in physics in general. In that contest, macroscopic descriptions model gross quantities of interest, such as density or mean velocity of cars, treating vehicular traffic according to fluid dynamics, while microscopic descriptions consider each vehicle as a distinct entity, modeling its behavior in a more precise but computationally more expensive way.

It would be desirable for a trustworthy VANETs simulation that both macro-mobility and micro-mobility descriptions be jointly considered in modeling vehicular movements. Indeed, many non-specific mobility models employed in VANETs simulations ignore these guidelines, and thus fail to reproduce peculiar aspects of vehicular motion, such as car acceleration and deceleration in presence of nearby vehicles, queuing at road intersections, clustering caused by semaphores, vehicular congestion and traffic jams.

In this paper, we introduce VanetMobiSim [1], a freely distributed, open source vehicular mobility generator based on the CanuMobiSim architecture [2] and designed for integration with telecommunication network simulators. VanetMobiSim can produce detailed vehicular movement traces employing different macro- and micro-mobility models and taking into account the interaction of the two, and can simulate different traffic conditions through fully customizable scenarios. We validate the mobility patterns generated by VanetMobiSim by recreating distinctive vehicular mobility effects, such as speed decay with increasing car density, non-uniform distribution of vehicles in urban areas, and shock waves due to stop-and-go perturbations. We also formally validate VanetMobiSim by comparing this vehicular traces with those generated by a benchmark traffic generator in the transportation community.

The rest of the paper is organized as follows. Section 2 discusses related work in the field of vehicular mobility modeling for network simulation. In Section 3 we illustrate the need for realistic simulations in vehicular networks, and in Section 4, we describes a framework for realistic mobility model generation. A detailed description of the features of VanetMobiSim is given in Section 5. Section 6 presents validating tests on movement traces produced by VanetMobiSim in specific scenarios and by comparison with TSIS-CORSIM. Finally, in Section 7, we draw some conclusions and discuss future work.

2 Related Work

In this section, we review some research works focusing on modeling vehicular mobility for VANETs simulation.

First, we point out that many realistic traffic simulation tools, such as PARAMICS [3], CORSIM [4], VISSIM [5] or TRANSIMS [6] have been developed to analyze vehicular mobility at both microscopic and macroscopic level with a very high degree of detail. However, all the aforementioned software is distributed under commercial licenses, a major impediment to adoption by the academic research community. With the exception of few teams that developed parsers [7,8] or federated a realistic traffic simulation tool with a network simulator [9], these tools have been originally designed for traffic analysis, and do not generate 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 the one VanetMobiSim is intended for. For a complete review and comparison of commercial traffic simulation tools, the interested reader can refer to [10].

Purely random models, such as the Random Waypoint model, the Random Walk model, the Reference Point Group (or Platoon) model, the Node Following model or the Gauss-Markov model, just to cite the most known ones, are often used when simulating MANETs mobility. However, when VANETs are considered, employing these models severely risks to produce unreliable results, as they do not even pose fixed road constraints to nodes motion. The simple Freeway model and Manhattan model [11] represent an initial step in mimicking vehicular movements, while several pioneering works in this field involve the generation of mobility patterns based on real road maps [12] or monitoring of real vehicular movements in cities [13]. In most of these models, only the macro-mobility of nodes is considered, although car-to-car interaction is a fundamental factor to take into account when dealing with vehicular mobility [14]. Further details on many of these models can be found in [15–17].

Several open-source tools for the generation of vehicular mobility patterns became available in the last few years. In the rest of this section, we briefly review the most known ones, but an extended review and comparison of such tools can be found in [18]. Most of them are capable of producing traces for network simulators such as *ns-2* [19], *QualNet* [21] or *OPNET* [22]. The IMPORTANT tool [11], and the BonnMotion tool [23] implement several random mobility models, including the Manhattan model. They both focus on macro-mobility, as IMPORTANT only includes a basic car-to-car inter-distance control schema called *Car Following Model*, whereas BonnMotion does not consider any micro-mobility. Consequently, the output traces are definitely too simple to represent realistic motion. Within the MONARCH project, a tool to extract road topologies from real road maps obtained from the TIGER database [24] was realized [12], but, again, the lack of micro-mobility support makes it impossible to reproduce a real world vehicular mobility.

The *Simulation of Urban MObility (SUMO)* [26] is an open source, highly portable, microscopic road traffic simulation package designed to handle large road networks. SUMO contains parsers for various topologies, including TIGER files. 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 [28], a federated model including ns2. Using a 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 [29]. 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.

The Street Random Waypoint (STRAW) tool [30] is a mobility simulator based on the freely available Scalable Wireless Ad Hoc Network Simulator (SWANS). STRAW is able to parse TIGER files and also implements a complex intersection management using traffic lights and traffic signs, but its dependence on SWANS prevents research communities adopting different network simulators from using it. The GrooveSim tool [31] is a mobility and communication simulator, which again uses files from the TIGER database to simulate realistic road topologies. However, GrooveSim neither models vehicles micro-mobility, nor produces traces usable by network simulators. The City Model [32], although considering car-to-car interactions, falls short from producing a realistic mobility, mainly due to a poor grid-based macro-mobility description. The SSM/TSM model [33] includes a *Stop Sign Model* and a *Traffic Sign Model*, but it only considers intersection behavior, whereas no car-to-car mobility seems to be taken into account when vehicles are traveling on roads. MobiREAL [34], although appearing mainly focused on modeling pedestrian mobility, introduces a novel approach of cognitive modeling which could be promising in the direction of future extension to vehicular mobility.

Recent works adopt an embedded approach, joining scalable vehicular mobility description and network stack modeling in a single simulation tool. MoVes [35] is a complex mobility generator, built on top of ARTiS [36], a scalable distributed simulation middleware. MoVes features cars following models, drivers behavior characterization, intersection management and includes a parser module to include GPS maps using the GPS TrackMaker program [37]. At the current stage of development, MoVes does not support lane changing and realistic path generation. Also [38] presents an ongoing project on an integrated network and mobility simulator, featuring a TIGER map parser and a VISSIM-like micro-mobility model [5]. These combined approaches have the big advantage of allowing a direct interaction between the communication network system and the vehicular traffic dynamics, so that the first can influence the second. However, two major flaws are induced by this modus operandi. First, the level of detail of both modules is necessarily lower than that provided by ad-hoc simulation tools. This is especially true for network simulation modules, which are nowadays required to model a variety of protocols, mechanisms and physical phenomena with a high degree of confidence, and even successful, dedicated, open-source projects, which enjoy the contribution and support of thousands of users struggle to reach such a goal. Thus, building and validating new simulators from scratches may result in reduced modeling capabilities and/or low realism. This is also at the basis of the second disadvantage of a joint simulation of mobility and network: in order to benefit from the mobility description, the embedded network simulator must be used. This prevents the largest part of networking research, used to common and reliable ad-hoc network simulators, from adopting these tools, therefore limiting their diffusion.

UDel Models [39] is a suite of tools for the generation of urban mobility and the computation of radio propagation, intended for large-scale urban mesh networks. The vehicular and pedestrian mobility description is significantly different from that presented in all of the aforementioned work, as it is based on statistical data from real world measurements and surveys, mainly obtained from databases of the US Department of Labor. The urban propagation model includes an accurate map builder capable of parsing GIS data and compute from that realistic radio signal propagation, and represents a valuable addition to the mobility description.

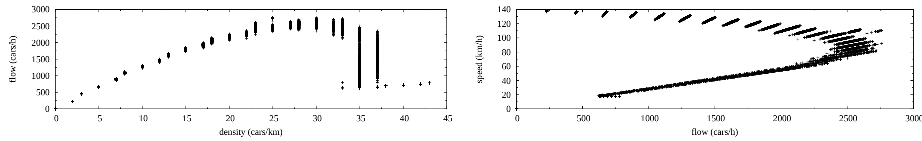


Figure 1: Flow versus density and speed versus flow under the Fluid Traffic Model.

However, as far as vehicular mobility is concerned, it is not clear which is the level of detail in the macro- and micro-mobility models.

Finally, the CanuMobiSim tool [2] is a generator of movement traces in a variety of conditions. It features extrapolation of real topologies from detailed Geographical Data Files (GDF) [25], concurrent employment of multiple micro-mobility models, GUI support, and generation of mobility traces for different simulators.

As a final remark, we would like to point out that, in most of the works mentioned in this Section, small or no attention is paid to the validation of the macro- and micro-mobility models used, and evaluations on the realism of the produced traces are often absent.

3 The Need for Realism in Vehicular Traffic Modeling

As it can be inferred from the related work presented in the previous section, only in recent times the networking community has started paying attention to the impact that realistic mobility modeling has on vehicular communications.

The use of simplistic mobility models that has characterized most of the literature on the topics of mobile and vehicular networks appears an evident flaw, when considering that vehicular traffic theory has undergone fifty years of increasingly accurate studies.

When comparing mobility models employed in recent works on vehicular networks and analytical descriptions following well known approaches of traffic theory, the difference in terms of results is dramatic, and it is clear that such a discrepance cannot have a null impact on the performance of networking protocols and techniques.

In traffic theory, since the 60's, models reproducing drivers behavior have been subject to standard tests in order to be considered realistic enough. As an example, a minimal requirement is the model capability of recreating the lambda-shaped relation between vehicular flow and density. Even low-complexity traffic stream models, which look at vehicular mobility as a hydrodynamic phenomenon, and thus do not model the behavior of each car individually, can reproduce it. An example is shown in Figure 1, depicting both the aforementioned lambda-shaped relation and that obtained for the speed and flow when using the Fluid Traffic Model implemented in VanetMobiSim and described in details later in the paper. The reason at the basis of the phenomena is that, given a straight road, as the in-flow

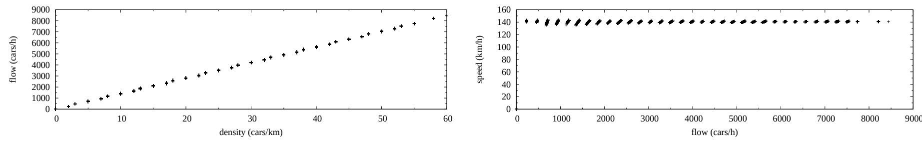


Figure 2: Flow versus density and speed versus flow under the Manhattan Model.

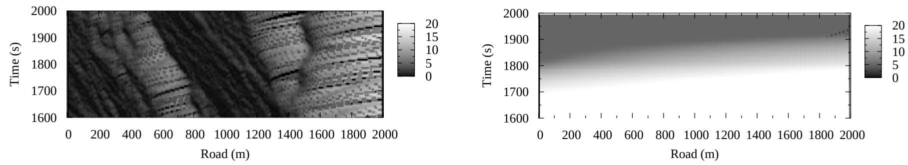


Figure 3: Speed versus time and space in a highway scenario, in presence of increasing car in-flow, when using the Intelligent Driver Model (left) and the Fluid Traffic Model (right).

rate, and consequently the car density, is increased, the out-flow of vehicles grows linearly at first. However, when the critical vehicular density is reached, the road capacity cannot sustain the arrival rate anymore, leading to queueing phenomena that slow down the system as the density increases.

When the same test is performed on the previously mentioned Manhattan model, described the the following set of rules:

$v_i(t + \Delta t) = v_i(t) + \eta \; a \; \Delta t;$
IF $v_i(t) < v_{min}$ THEN $v_i(t) = v_{min};$
IF $v_i(t) > v_{max}$ THEN $v_i(t) = v_{max};$
IF $\Delta x_i(t) \leq D$ THEN $v_i(t) = v_{i+1}(t) - a/2;$

where η is a random variable uniformly distributed in $[-1, 1]$, the results, in Figure 2, are not matching the expectations. Even if the Manhattan model implements some bounded randomness in the velocity update, and, from the fourth rule above, impose speed limitation to avoid overlapping of vehicles, the lack of a desired speed and of accurate car following rules make the description unrealistic, the inflow growth producing a linear increase on the car density.

Speed waves represent another condition of vehicular traffic commonly reproduced during the validation process of a mobility model in traffic theory works. These perturbations are known to be generated by heavy traffic conditions on highways or by periodic obstacles such as traffic lights or entering ramps, and are due to the finite response time of drivers to slowdowns determined by such events. A car following model, like the Intelligent Driver Model (IDM) implemented in VanetMobiSim and discussed later in the paper, can correctly recreate this phenomenon, as seen in Figure 3, where slow speed dark waves move against the direction of

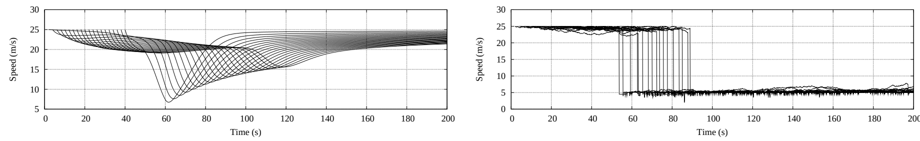


Figure 4: Evolution of speed for the first 20 vehicles belonging to a queue of cars meeting an obstacle which is then suddenly removed. The plots refer to the case in which the Intelligent Driver Model is employed (left) and that in which the Manhattan model is used (right).

traffic in time. The equivalent plot obtained using the Manhattan model appears as a white image, since all the vehicles maintain the maximum speed, and is thus not shown here. The Fluid Traffic Model fails to reproduce the desired behavior in this case, as shown in Figure 3. Since this model does not include a car-to-car interaction description, but only regards at the road as a single system, it tends to pass from a free-flow to a congested situation by slowing down at a time the entire traffic on the highway.

Another typical proof of the validity of a vehicular mobility model is determined by its response to dynamic situations, such as that occurring to a queue of cars in presence of an obstacle ahead suddenly removed. In that case, it is expected that the model forces the drivers to slow down while approaching the obstacle and then to accelerate again once the impediment is removed. This is actually what we can observe in Figure 4, when IDM is used. Each line represents the evolution of speed over time of one car, for the first twenty vehicles in the queue. It can be noticed that the first vehicle slows down as the obstacle becomes nearer, and that the cars behind follow the leader's speed dynamics, with some delay due to the reaction time of drivers. When the obstacle is removed, just before the leading car stops completely, the vehicles start accelerating again towards full speed. The cars back in the queue experience a different speed evolution, as they are far from the obstacle and are thus still moving at high speed when the impediment is removed. The same is not true when the Manhattan model is used, as the model prevents vehicle overlapping by abruptly reducing to zero the speed of the leading vehicle when it reaches the obstacle, but afterward is not able to induce a free-flow acceleration due to the lack of a desired speed description. The cars in the queue are forced to strictly follow the leading vehicle behavior, and thus describe similar curves. The resulting plot is shown in Figure 4.

4 A Framework for Realistic Vehicular Mobility Models

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

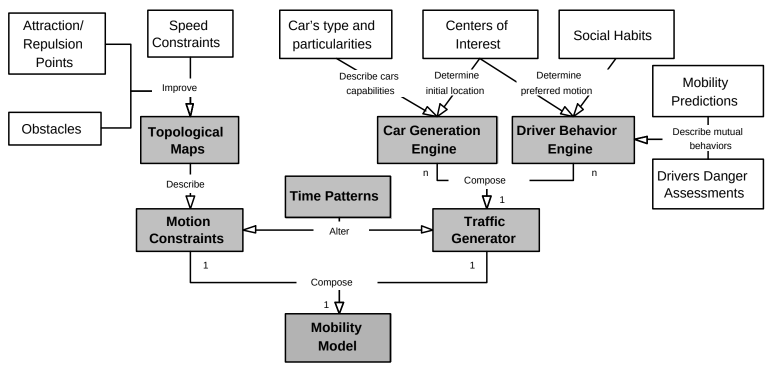


Figure 5: Proposed concept map of mobility model generation for inter-vehicle communications

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.

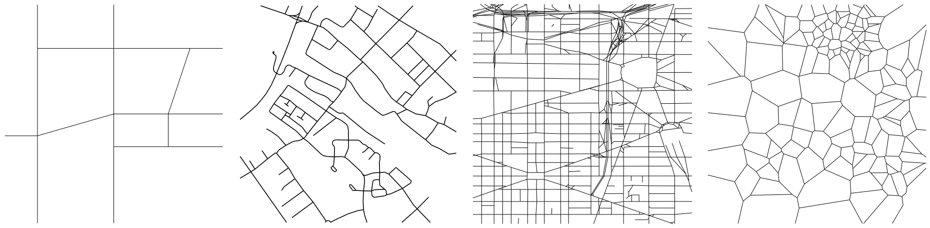
The approach can be graphically illustrated by a concept map for vehicular mobility models, as depicted in Figure 5.

5 VanetMobiSim

VanetMobiSim is an extension to CanuMobiSim [2], a generic *user mobility* simulator. CanuMobiSim is a platform- and simulator-independent software, being coded in Java and producing mobility traces for different network simulators, including *ns-2* [19], *OPNET* [22] and *GloMoSim* [20]. It provides an easily extensible mobility architecture, but, due to its general purpose nature, suffers from a reduced level of detail in specific scenarios. VanetMobiSim is therefore aimed at extending the vehicular mobility support of CanuMobiSim to a higher degree of realism. In this section, we outline the structure and characteristics of VanetMobiSim and detail the resulting vehicular mobility support.

5.1 Macro-mobility Features

When considering macro-mobility we not only take into account the road topology, but also the road structure (unidirectional or bidirectional, single- or multi-lane), the road characteristics (speed limits, vehicle-class based restrictions) and the presence of traffic signs (stop signs, traffic lights, etc.). Moreover, the concept of macro-mobility also includes the effects of the presence of points of interests, which influence movement patterns of vehicles on the road topology. All these different aspects of macro-mobility are discussed in details in the remainder of this section.



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

Figure 6: Road topologies examples

5.1.1 Road topology definition

The selection of the road topology is a key factor to obtain realistic results when simulating vehicular movements. Indeed, the length of the streets, the frequency of intersections, 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. VanetMobiSim allows to define the road topology in the following ways, the first two being already implemented in CanuMobiSim:

- *User-defined graph*: the road topology is specified by listing the vertices of the graph and their interconnecting edges. Although being an intuitive way of modeling a road topology, this approach may result in a very time-consuming task when large, complex or especially realistic topologies must be simulated.
- *GDF map*: the road topology is imported from a Geographical Data File (GDF) [25]. The multi-layered format defined by GDF allows to store information concerning the topology, the roads features and the location of points of interests. Unfortunately, most GDF file libraries are not freely accessible.
- *TIGER map*: the road topology is extracted from a map obtained form the TIGER database [24]. The level of detail of the maps in the TIGER database is not as high as that provided by the GDF standard, but this database is open and contains digital descriptions of wide urban and rural areas of all districts of the United States. In fact, topology descriptions from the TIGER database are becoming quite common in VANETs simulation.
- *Clustered Voronoi graph*: the road topology is randomly generated by creating a Voronoi tessellation on a set of non-uniformly distributed points. This approach is similar to that proposed in [40], but we also consider the presence of areas with different road densities which we refer to as *clusters*. The number of clusters and their density are customizable to represent diverse

geographical characterizations in the same map, such as city centers, suburban areas, or countryside. The clustered Voronoi graph can be especially useful to rapidly generate large road topologies.

In all these cases, the road topology is implemented as a graph over whose edges the movement of vehicles is constrained. Examples of different VanetMobiSim topologies are illustrated in Figure 6.

5.1.2 Road topology characterization

As stated before, the concept of vehicular macro-mobility is not limited to motion constraints obtained from graph-based mobility, but also includes all aspects related to the road structure characterization, such as directional traffic flows or multiple lanes, speed constraints or intersection crossing rules. None of these aspects is present in CanuMobiSim, thus the following enhancements are introduced by VanetMobiSim:

- introduction of roads with multiple lanes in each direction
- physical separation of opposite traffic flows on each road. This avoids that cars traveling in different direction overlap, confusing the resulting mobility and reducing the level of realism of the output traces
- definition of independent speed limits on each road of the topology
- implementation of traffic signs at each road intersection. By default, intersections are fully regulated by stop signs, forcing vehicles to stop and wait for free road before crossing. Alternatively, it is possible to regulate traffic at intersections by means of traffic lights, whose temporization is customizable. Based on predefined intersection patterns, traffic lights automatically adapt to the intersection structure.

Note that, for the road topology characterization to have an impact on vehicular mobility, a strong interaction between the macro-mobility description and the micro-mobility models that define drivers behavior is required. Thus, the micro-mobility model must be designed to keep roads characteristics in consideration. This issue is discussed in Section 5.2.

5.1.3 Vehicular movement patterns selection

Vehicular traffic schemes in urban scenarios are far from being random. Indeed, cars tend to move between points of interests, which are often common to many drivers and can change in time (e.g., offices may be strong attraction points, but mainly during the first part of the morning). Accordingly, VanetMobiSim exploits CanuMobiSim capability of building up movement patterns from the cooperation of a *trip generation module*, which defines the sets of points of interest, and a *path computation module*, whose task is to compute the best path between those points.

Two choices are given for the trip generation module. The first is a *random trip*, as the start and stop points of movement patterns are randomly selected among the vertices of the graph representing the road topology. The second is an *activity sequences* generation, in which 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.

Independently from the trip generation method employed, the path computation, i.e. the selection of the best sequence of edges to reach the selected destination, can be performed in three ways. The first method selects the shortest path to destination, running a Dijkstra's algorithm with edges cost inversely proportional to their length. The second method does not only considers the length of the path, but also the traffic congestion level, by weighting the cost of traversing an edge also on the number of cars traveling on it, thus modeling the real world tendency of drivers to avoid crowded paths. The last method, which is not present in the original CanuMobiSim, extends the other two, by also accounting for the road speed limit when calculating the cost of an edge, in a way that fastest routes are preferred.

The combination of trip generation and path computation methods offers a wide range of possibilities, when the definition of vehicular movement paths is a factor of interest in the mobility simulation.

5.2 Micro-Mobility Features

The concept of vehicular micro-mobility includes all aspects related to an individual car's speed and acceleration modeling. The micro-mobility description plays the main role in the generation of realistic vehicular movements, as it is responsible for effects such as smooth speed variation, cars queues, traffic jams and overtakings.

Three broad classes of micro-mobility models, featuring an increasing degree of detail, can be identified depending on whether the individual speed of vehicles is computed i) in a deterministic way, ii) as a function of nearby vehicles behavior in a single lane scenario, or iii) as a function of nearby vehicles behavior in a multi-flow interaction (i.e., urban) scenario.

CanuMobiSim provides implementations for models belonging to the first two classes. The *Graph-Based Mobility Model* (GBMM) [41], the *Constant Speed Motion* (CSM) [2] and the *Smooth Motion Model* (SMM) [42] fall into the first category, as the speed of each vehicle is determined on the basis of the local state of each car and any external effect is ignored. They all constrain a random movement of nodes on a graph, possibly including pauses at intersections (CSM) or smooth speed changes when reaching or leaving a destination (SSM). The movement is random in a sense that vehicles select one destination and move towards it along a shortest-length path, ignoring (and thus possibly overlapping) other vehicles during the motion. While these models may work for isolated cars, they fail to reproduce realistic movements of groups of vehicles.

The *Fluid Traffic Model* (FTM) [43] and *Intelligent Driver Model* (IDM) [44] are instead part of the second class, as they account for the presence of nearby vehicles when calculating the speed of a car. These models describe car mobility on single lanes, but do not consider the case in which multiple vehicular flows have to interact, as in presence of intersections.

The FTM describes the speed as a monotonically decreasing function of the vehicular density, forcing a lower bound on speed when the traffi c congestion reaches a critical state, by means of the following equation

$$s = max \left[s_{min}, s_{max} \left(1 - \frac{k}{k_{jam}} \right) \right]$$

where s is the output speed, s_{min} and s_{max} are the minimum and maximum speed respectively, k_{jam} is the vehicular density for which a traffi c jam is detected, and k is the current vehicular density of the road the node, whose speed is being computed, is moving on. This last parameter is given by $k = n/l$, where n is the number of cars on the road and l is the length of the road segment itself. According to this model, cars traveling on very crowded and/or very short streets are forced to slow down, possibly to the minimum speed, if the vehicular density is found to be higher than or equal to the traffi c jam density. On the other hand, as less congested and/or longer roads are encountered, the speed of cars is increased towards the maximum speed value. Thus, the Fluid Traffi c Model describes traffi c congestion scenarios, but still cannot recreate queuing situations, nor can it correctly manage cars behavior in presence of road intersections. Moreover, no acceleration is considered and it can happen that a very fast vehicle enters a short/congested edge, suddenly changing its speed to a very low value, which is defi nitely a very unrealistic situation. Finally, the implementation of the FTM in CanuMobiSim cannot model the zero speed case, as the condition $s = 0$ causes cars to stop and not move anymore, since a loop is entered, in which the vehicular density remains constant in time if all vehicles are still and in turns vehicles cannot increase their speed if the vehicular density does not decrease. It is thus necessary that $s_{min} > 0$.

On the other hand, the IDM characterizes drivers behavior depending on their front vehicle, thus falling into the so-called *car following* models category. The instantaneous acceleration of a vehicle is computed according to the following equations

$$\frac{dv}{dt} = a \left[1 - \left(\frac{v}{v_0} \right)^4 - \left(\frac{s^*}{s} \right)^2 \right] \qquad \text{and} \qquad s^* = s_0 + \left(vT + \frac{v \Delta v}{2\sqrt{ab}} \right)$$

In the left hand Equation, v is the current speed of the vehicle, v_0 is the desired velocity, s is the distance from preceding vehicle and s^* is the so called *desired dynamical distance*. This last parameter is computed as shown in the right hand equation, and is a function of the minimum bumper-to-bumper distance s_0, the minimum safe time headway T, the speed difference with respect to front vehicle velocity Δv, and the maximum acceleration and deceleration values a and b.

When combined, these formulae give the instantaneous acceleration of the car, divided into a "desired" acceleration $[1 - (v/v_0)^4]$ on a free road, and braking decelerations induced by the preceding vehicle $(s^*/s)^2$. By smoothly varying the instantaneous acceleration, the IDM can realistically mimic car-to-car interactions on a single-lane and straight road. Interesting real world situations, such as queuing of vehicles behind a slow car, or speed reduction in presence of congested traffic can be reproduced. However, as we will illustrate in Section 6, this model alone is not yet sufficient to obtain a realistic vehicular mobility in an urban environment.

VanetMobiSim adds two original microscopic mobility models, both of which account for the interaction of multiple converging flows, by acting consistently with the road infrastructure, and thus fall into the third category mentioned above. These models extend the IDM description, which is the most realistic among those present in CanuMobiSim, in order to include the management of intersections regulated by traffic signs and of roads with multiple lanes.

The first new micro-mobility model is referred to as *Intelligent Driver Model with Intersection Management* (IDM-IM). It adds intersection handling capabilities to the behavior of vehicles driven by the IDM. In particular, IDM-IM models two different intersection scenarios: a crossroad regulated by stop signs, or a road junction ruled by traffic lights. In both cases, IDM-IM only acts on the first vehicle on each road, as IDM automatically adapts the behavior of cars following the leading one. Every time a vehicle finds no intermediate car between itself and an intersection regulated by stop signs, the following parameters are used by IDM-IM

$$\begin{cases} s = \sigma - S \\ \Delta v = v \end{cases}$$

where σ is the current distance to the intersection and S is a safety margin, accounting for the gap between the center of the intersection and the point the car would actually stop at. Thus, compared to the IDM, the distance from preceding vehicle is substituted by the distance to the point the vehicle has to stop at. On the other hand, the speed difference is set to the current speed of the car v, so that the stop sign is seen as a still obstacle. This allows vehicles to freely accelerate when far from the next intersection, and then to smoothly decelerate as they approach a stop sign. Once a car is halted at a stop sign, it is informed by the macroscopic level description of the number of cars already waiting to cross the intersection from any of the incoming roads. If there are no other cars, the vehicle may pass. Otherwise, it has to wait until its turn in a first-arrived-first-passed and right hand rule policy.

When a vehicle is heading towards a traffic light intersection, it is informed by the macroscopic description about the state of the semaphore. 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, by using the modified IDM parameters as in the case for a stop sign.

It may also be stressed out that vehicles behavior can dynamically vary in presence of traffic lights, according to red-to-green and green-to-red switches. In the

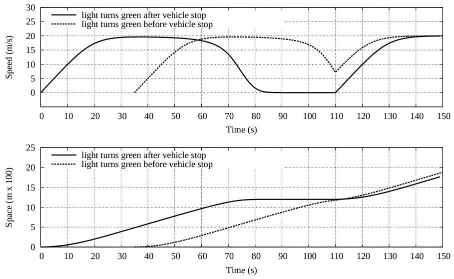


Figure 7: Traffic light *red-to-green* scenario. A vehicle, driven by the IDM-IM setup in Table 2, starts its movement from zero speed, and travels towards a red traffic light. The upper figure shows the evolution of speed in time, while the lower one depicts the car movement on the road versus time. In a first case, represented by solid-line curves, the vehicle starts to move at $t = 0\ s$, accelerates up to the desired speed, decelerates as the traffic light becomes closer, and comes to a full stop in front of the traffic light. The movement is started over only when the traffic light turns green, at $t = 110\ s$. This can be easily observed in both figures. In a second case, represented by dashed-line curves, the vehicle starts its movement at $t = 35\ s$ and thus arrives in proximity of the traffic light at $t = 110\ s$ circa, i.e. right on time to observe the traffic light switch to green. Since the vehicle is still in its deceleration phase and has not halted yet, it accelerates again as shown by the upper figure. In the lower image, we can observe that the traveled space has an almost straight trajectory, and that the advantage, in terms of acceleration experienced by the vehicle at the traffic light, leads to an increased traveled space.

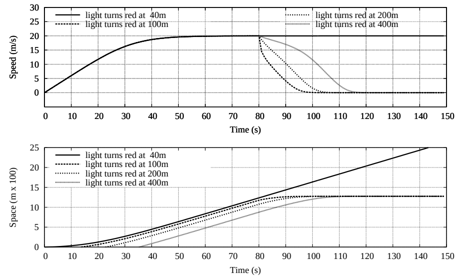


Figure 8: Traffic light *green-to-red* scenario. A vehicle, driven by the IDM-IM setup in Table 2, starts its movement from zero speed, and travels towards a green traffic light, which turns into red at time $t = 80\ s$. The upper figure shows the evolution of speed in time, while the lower one depicts the car movement on the road versus time. Different curves represent different positions of the vehicle under study (at distances of 40, 100, 200 and $400\ m$) with respect to the traffic light, when the latter switches from green to red. The $40\ m$ case, represented by solid-line curves, is an example of absence of safety conditions, since $45\ m = \bar{s} > \sigma - S = 40\ m$. The car is too close to the traffic light when the color changes, thus the vehicle keeps its speed through the intersection. In the other cases, the safety condition is satisfied, and the vehicle decelerates to a complete stop in front of the semaphore, as shown in the lower figure. However, the deceleration is started at various distances from the traffic light, leaving different reaction margins to the driver. As proved by the upper plot, this results is peculiar braking evolutions, with more comfortable decelerations as the distance from the semaphore at color switch time grows.

former case, a car currently decelerating to stop at a red light will accelerate again if the semaphore turns green before it has completely halted, as in the example described in Figure 7. In the latter case, a vehicle keeping its pace towards a green light will try to stop if the light becomes red before it has passed through the intersection. In this last case, a minimum breaking distance $\bar{s}$ is evaluated by means of simple kinematic formulae as

$$\bar{s} = v\,t - \frac{\kappa b}{2}\,t^2 = v\left(\frac{v}{\kappa b}\right) - \frac{\kappa b}{2}\left(\frac{v}{\kappa b}\right)^2 = \frac{v^2}{2\kappa b}$$

which describes the space needed to come to a full stop as a function of the current speed of the vehicle, v, the time t and the deceleration value, κb. The last parameter represents the maximum safe deceleration, i.e., the IDM comfortable braking value b scaled by a factor $\kappa \geq 1$. The final expression above is obtained by substitution of t with $(v/\kappa b)$, which is the time at which a zero velocity is reached by inducing a constant deceleration κb on current speed v. Upon computation of $\bar{s}$, if the vehicle finds that it is not possible to stop before the intersection, even braking as hard as possible, i.e., if $\bar{s} > \sigma - S$, then it crosses the intersection at its current speed. Otherwise, it stops by applying a strong enough deceleration. This reproduces a real world situation, since, when a traffic light switches to red, drivers only stop if safety braking conditions can be respected. Examples of driving behaviors in presence of a green-to-red semaphore are discussed in Figure 8.

The second model we introduce is named *Intelligent Driver Model with Lane Changes* (IDM-LC), and extends the IDM-IM model with the possibility for vehicles to change lane and overtake each others, taking advantage of the multi-lane capability of the macro-mobility description detailed in Section 5.1.2. Two issues are raised by the introduction of multiple lanes: the first is the separation of traffic flows on different lanes of the same road, while the second is the overtakings model itself.

As far as the first problem is concerned, vehicular flows on parallel lanes of the same road are separated by forcing the car following model to only consider vehicles traveling on the same lane. However, as the number of lanes can vary from one road to another, a vehicle approaching a crossroad will receive from the macro-mobility description the information about the structure of the road it is going to move to. It can then adopt one of the following behaviors:

- if the lane the vehicle is currently moving on is also present in the next road on its path, then it moves through the intersection and keeps traveling on the same lane in the next street;

- if the lane currently used by the vehicle does not exist in the next road, then it tries to merge to its right as it approaches the junction. If it cannot do it, e.g. because the lane to its right is very crowded, it stops at the intersection and waits until a spot becomes available.

On the overtaking model itself, the MOBIL model [45] is employed, mainly due to its implicit compatibility with the IDM. This model adopts a game theoretical approach to address the lane changing problem, allowing a vehicle to move to a different lane if the lane change minimizes the overall braking of vehicles. Such requirement is fulfilled when the two conditions

$$a^l - a \pm a_{bias} > p\left(a_{cur} + a_{new} - a^l_{cur} - a^l_{new}\right) + a_{thr} \qquad \text{and} \qquad a^l_{new} > -a_{safe}$$

are verified. In the left hand inequality, a is the current acceleration of the vehicle, i.e., $\frac{dx}{dt}$ in the IDM formulae, while a^l is the equivalent acceleration, computed in the case the vehicle moved to an adjacent lane l. Similarly, a_{curr} and a^l_{curr} describe the acceleration of the car which currently follows the vehicle we are considering in the case the vehicle under study stays on its lane, or in the case it moves on another lane l. Finally, a_{new} and a^l_{new} represent the acceleration of the car which would become the new back vehicle if the car under study changed its lane to l, before and after a possible lane change of the latter. The model allows a vehicle to move to lane l if the left hand inequality is verified, that is, if, in terms of acceleration, the advantage of the driver who changes its lane $a^l - a$, is greater than the disadvantages of the following cars $a_{cur} - a^l_{cur}$ and $a_{new} - a^l_{new}$. The MOBIL model also consider a politeness factor p, which scales the right hand term, in a way that, for values of p towards (or above) one, a polite behavior towards other drivers is maintained, while, as p moves to (or below) zero, the driver can become selfish or even malicious. The threshold acceleration a_{thr} introduces a minimum acceleration advantage to allow a lane change, in order to avoid lane hopping in border cases. The bias term a_{bias} is instead added to favor movements to one side: in our case, this bias value is added to the advantage computed for movements to the right and subtracted for movements to the left, thus reproducing the real world tendency of drivers to stay on their right on a multi-lane road. Finally, in any case, the safety condition expressed by the right hand side equation above must be verified for the lane change to occur, meaning that the new back vehicle does not have to brake too hard (its deceleration must be over the safe value a_{safe}) as a consequence of the lane change.

6 VanetMobiSim Validation

Several tests were run on the vehicular movement traces produced by CanuMobiSim and VanetMobiSim, in order to verify that the overall mobility description provided by these tools is able to model vehicular traffic with a sufficient level of realism. This also gives us the possibility to comment on the different outputs obtained with various microscopic mobility models implemented by CanuMobiSim and by VanetMobiSim.

First, different micro-mobility models are tested on a user-defined graph representing a square city section of 1500 m side. The urban topology employed in those tests is shown in Figure 9, where, unless specified differently, all roads have a

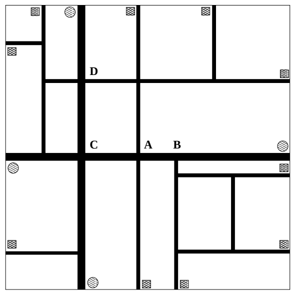


Figure 9: City section topology

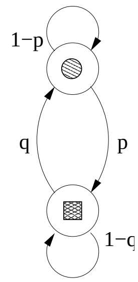


Figure 10: Activity chain

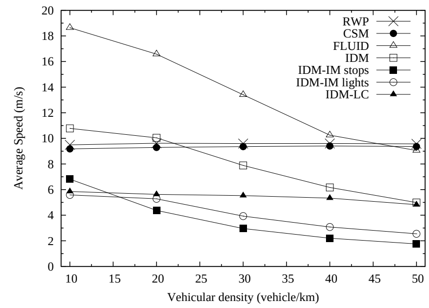


Figure 11: Average speed versus vehicular density

single lane, and a speed limit of 15 m/s (54 km/h), except for the roads represented with thicker lines, which allow a maximum speed of 20 m/s (72 km/h). Vehicles travel between entry/exit points at borders, identified with circles and squares, crossing the city section according to the fastest path to their destination. The trips generation scheme is activity-based (see Section 5.1.3), and the relative transition probability matrix describes a simple activity chain, depicted in Figure 10. There, the states denote the class of the selected destination: a round for the entry/exit points of high-speed roads, a square for the entry/exit points of normal-speed roads, as also shown in Figure 10. The chain is trivially ergodic, with steady state $\left(\frac{p}{p+q}, \frac{q}{p+q}\right)$. In our simulation, the probabilities are set so that $p = q = 1/2$, resulting in a stationary distribution $\left(\frac{1}{2}, \frac{1}{2}\right)$. This, along with the proportion between the number of entry/exit points of the two classes, determines a popularity of high-speed roads entry/exit points which is more than double with respect to that of normal-speed entry/exit points. This mimic the tendency of traffic flows to concentrate on the main, high-speed roads. The number of cars traveling at the same time within the city section ranges from 100 to 500, reproducing light (10 vehicles/km) to heavy (50 vehicles/km) traffic conditions. For each test, a single simulation was run, with statistics recorded for 3600 s, after a transient of 900 s. When computing 95% confidence intervals for mean values collected averaging in time and on the whole road topology, the error margin was found to be within 0.5% from the mean. However, we point out that vehicular traffic in presence of driver finite reaction times and continuous perturbations caused by flows interaction at intersections represents, by its nature, an unstable system. Thus, the vehicular density and speed distributions showed next are not representative of a steady state behavior, but rather give a view on which is the general car mobility under the different models. The mobility models parameters used in these experiments are listed in Table 1 and in Table 2.

In the rest of this section, we will first compare vehicular mobility patterns generated by VanetMobiSim with those of other popular vehicular models, then we

Model	RWP		CSM		FTM		
Parameter	speed	pause	speed	pause	s_{min}	s_{max}	κ_{jam}
Value	$unif[10,20]m/s$	$unif[0,60]s$	$unif[10,20]m/s$	$unif[0,45]s$	$3m/s$	$20m/s$	$0.125car/m$

Table 1: Parameters value for RWP, CSM and FTM micro-mobility models

Model	IDM					IDM-IM	IDM-LC		
Parameter	v_0	s_0	T	a	b	κ	a_{bias}	p	a_{thr}
Value	$unif[10,20]m/s$	$1m$	$0.5s$	$0.6m/s^2$	$0.9m/s^2$	5	$0.2m/s^2$	0.5	$0.2m/s^2$

Table 2: Parameters value for IDM, IDM-IM and IDM-LC micro-mobility models

will formally validate VanetMobiSim against TSIS-CORSIM, a benchmark traffic simulator. Finally, we will illustrate a real case of traffic modeling obtained by VanetMobiSim.

6.1 Validation against Popular Vehicular Models

In this section, we validate VanetMobiSim by showing how it is able to produce mobility patterns more realistic than those produced by other popular vehicular mobility models. In the following, we also report results obtained with the Random Waypoint Model (RWP), in order to provide a benchmark of this popular model, which causes nodes to move with random constant speed over a straight trajectory towards a destination casually selected in the square area, and then to pause for a random amount of time. Due to its nature, this model is not bound by road constraints.

In Figure 11, the trend of the average speed versus the number of vehicles is shown. RWP and CSM, ignoring car-to-car interactions, are not affected by the number of vehicles present on the topology , leading to an unrealistically constant mean speed. The mean velocity recorded with CSM is slightly lower than that measured with RWP, even if the mean pause time is shorter in CSM than in RWP. The reason is that CSM limits nodes movement to the road topology, with pauses at every intersection encountered on the path. Thus, the average distance between subsequent pauses is reduced in CSM, with the consequence of a lower average speed.

The low level of realism of these models is further evidenced in Figure 12 and Figure 13, depicting the time-averaged vehicular density distributions over the road

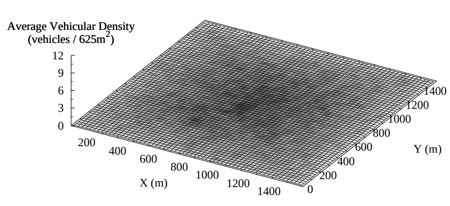


Figure 12: Vehicular density: RWP

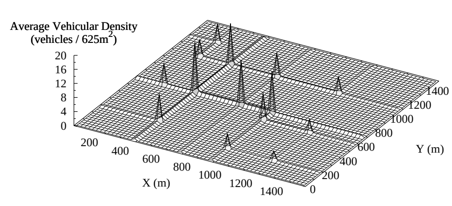


Figure 13: Vehicular density: CSM

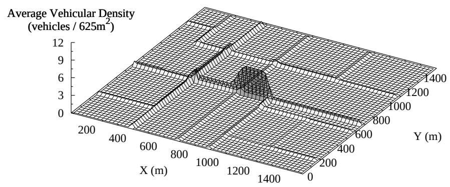


Figure 14: Vehicular density: FTM

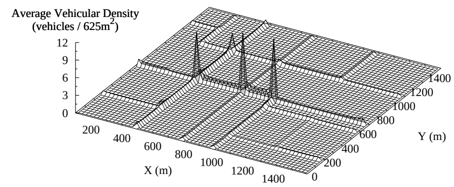


Figure 15: Vehicular density: IDM

topology obtained with RWP and CSM, respectively. These distribution plots, as well as the equivalent ones for the other mobility models in the remainder of this Section, refer to the 30 vehicle/km case.

As expected, RWP spreads nodes all over the square area, with a higher density of nodes in the center of the map, which is part of RWP normal behavior [17].

On the other hand, cars driven by CSM follow the road topology, and we can observe a non-zero density only where roads are present. Also, in Figure 13 the effect of the activity-based mobility can be observed: the two faster and more frequented roads experience a higher vehicular density with respect to the other streets in the topology. The same can be observed also in the vehicular density plots obtained with the other micro-mobility models. However, CSM produces what we call an *on-off* behavior, with a constant vehicular density on roads and sudden high peaks (note the different speed scale with respect to the equivalent plots of the other micro-mobility models) at intersections, where vehicles overlap and stop for a random amount of time. The absence of car-to-car interaction leads thus to an unrealistic complete absence of queuing or acceleration/deceleration phenomena in proximity of intersections.

Looking back at Figure 11, modeling the vehicular mobility with FTM produces a very high average speed, due to the fact that vehicles never stop with this model, as the zero speed condition would cause a deadlock as discussed in Section 5.2. Probably, a smaller value of the κ_{jam} parameter would have reduced this effect, producing a lower and more realistic figure of the average velocity. However, the settings we chose force vehicles to move at a minimum speed of 10 km/h when they are at a distance of 3 m or less from each other, which represents a suitable real world condition. As expected, FTM reproduces the average speed reduction caused by the vehicular density growth, since the increase of the number of cars traveling concurrently on the same road reduces the fluid speed. However, the vehicular density distribution depicted in Figure 14 demonstrates the non sufficient realism of this model. In the considered scenario, a high density is experienced by the central segment marked as AB in Figure 9, which is shared by many of the possible paths drivers can choose from. The high quantity of cars driving through determines a reduction of the speed according to the model and creates an even higher vehicular density, which is consistent with what would happen in a real world situation. However, FTM reasons on a per-edge basis and produces a con-

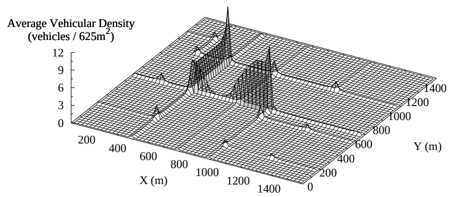


Figure 16: Vehicular density: IDM-IM stops

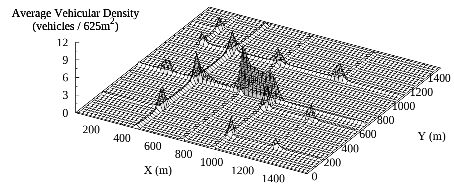


Figure 17: Vehicular density: IDM-IM lights

stant car density over each street, which results in the absence of traffic correlation over connected roads. In our case, it can be noticed that the high car density in AB suddenly disappear in roads after intersections A and B (see Figure 9 for the mapping of letters to intersections). Moreover, as FTM ignores intersections, the average number of vehicles at crossroads does not differ from that of vehicles on roads nearby, which, again, is far from reality.

As far as IDM is concerned, the average speed curve in Figure 11 shows lower values when compared with that obtained with FTM, and, quite surprisingly, appears to be affected by the number of cars present on the topology. The speed reduction with respect to FTM is imputable to a more realistic car-to-car interaction, which leads to queuing of fast vehicles behind slow cars. The dependence from vehicular density has instead a two-fold nature: first, the higher density increases the probability of encountering slow vehicles, which generate queues and force a reduction on other drivers' speed. Second, there exists a side effect of the CanuMobiSim implementation, that occurs when vehicles coming from different directions and overlapping at intersections suddenly notice that the safety distance condition is violated. According to the current implementation, they stop and wait for a distance s_0 to be restored before leaving the junction. Such a circumstance causes the average speed to decrease, and occurs more and more frequently as the vehicular density grows. In Figure 15, the vehicular density proves that the realism of an accurate car-to-car interaction model in urban scenarios is low, if intersection management is not taken into account. Spikes at highly frequented intersections A, B and C are to impute to the implementation issue explained above, while in general we can state that IDM does not perform more realistically than FTM in an urban context.

Two different tests were run for IDM-IM, the first with intersections regulated by stop signs, and the second with traffic lights at road junctions. As observed in Figure 11, in the first case the model produces a very low average speed, since cars spend most of their time queued at intersections. The problem is exacerbated as the density of vehicles increases and causes longer queues. This can also be noticed by looking at the vehicular density in Figure 16, where high vehicular densities, accounting for long queues, are recorded in the neighborhoods of the main intersections A, B, C and D. The higher concentration of vehicles around

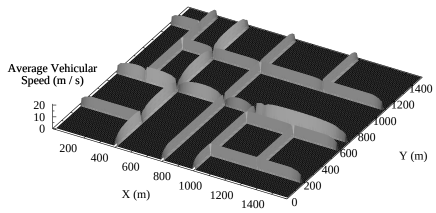


Figure 18: Speed distribution: IDM

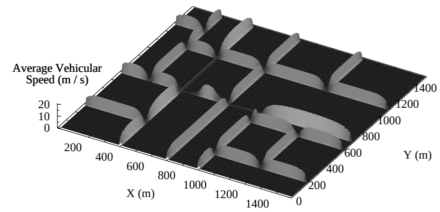


Figure 19: Speed distribution: IDM-IM stops

these intersections also has the side-effect of reducing the number of vehicles on the other roads of the topology, which, as a matter of fact, record lower vehicular densities. A realistic effect of smooth vehicular density, increasing towards the congested crossroads, is obtained with this model. It can be noticed that such effect in not limited to single segments as it happened with FTM, but also impacts adjacent roads.

When traffic lights with a period of 90 s are used to regulate traffic at intersections, vehicular mobility is improved with respect to the stop sign case, especially in dense scenarios, as proved by Figure 11. This could be expected, as traffic lights replace the slow “taking-turns” crossroads management induced by stop signs with a faster “burst” mechanism, in which groups of cars are allowed to cross the junction one after the other, thus saving on acceleration delay. However, the mean speed is still reduced when more cars are introduced in the road topology, for the same reason observed in the stop sign case. An interesting effect can be observed when the vehicular density is low, as the stop sign case outperforms the traffic light one. This occurs because, when the number of cars is small, the probability that a crossroad is free is high, thus passage is often granted immediately with a stop handling of intersections, at the cost of slowing and accelerating again. On the other hand, when a traffic light management is considered, vehicles still have to stop in presence of red traffic lights, even if there are no other cars waiting to cross the intersection, and wait for the light to turn green. The vehicular density, presented in Figure 17, appears consistent with the speed figure, as queuing at highly visited intersections is still present, but noticeably reduced with respect to the previous IDM-IM scenario. Thanks to the improved distribution of traffic over the whole topology, the queuing phenomenon can now be observed at minor intersections, where vehicles have to wait for green traffic lights.

In Figure 18 and Figure 19, the mean vehicular speed recorded on the road topology is presented, when IDM and IDM-IM in conjunction with stop signs at intersections are respectively used. The darker the color, the lower the average speed of vehicles traveling on it, down to zero speed for black areas (such as those outside the road topology). By looking at these figures it is clear that the presence of a model accounting for the car-to-infrastructure interaction can noticeably affect

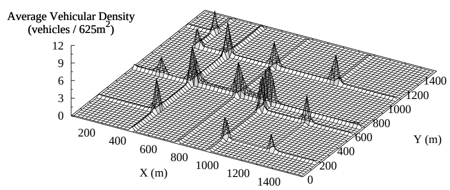


Figure 20: Vehicular density: IDM-LC lights

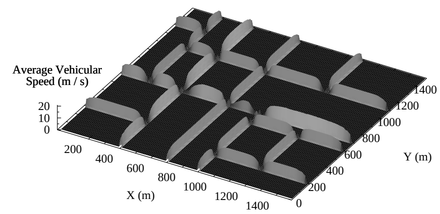


Figure 21: Speed distribution: IDM-LC lights

the outcome of the simulation. Indeed, if such aspect is ignored, even in presence of accurate car-to-car analysis, as is the case in Figure 18, the speed distribution is almost constant all over the road topology, with the exception of main intersection points where the speed is slightly lower due to the IDM safety distance management issue discussed before. A constant speed behavior can be observed at minor intersections, where cars never stop. On the other hand, when the vehicles behavior at road junctions is correctly modeled, as in Figure 19, the speed figure over the road topology appears far more realistic, with decelerations and queuing when approaching the junctions, and accelerations when leaving them. These figures also depict the higher average speed of vehicles moving on the high-speed central roads, represented by brighter surfaces.

Finally, we report the results obtained when IDM-LC is employed as micro-mobility model. We considered two per-direction lanes on each road, and traffic lights at intersections. From Figure 11, modeling vehicular micro-mobility with IDM-LC seems to avoid most of the speed decay effect discussed before. This is an interesting result, motivated by the fact that i) vehicles actually employ overtakings to avoid slow cars and congested lanes, thus increasing the average velocity, and ii) the presence of multiple lanes helps vehicular mobility in presence of densely populated intersections, as multiple cars can pass through the intersection at the same time and reduce the bottleneck effect of road junctions. In other words, the availability of two parallel unidirectional lanes on each road not only physically doubles the capacity of the urban infrastructure, leading to a halved perceived vehicular density, but also brings important correlated effects. In our case, the maximum simulated density of 50 vehicles/km would appear, for the reasons explained before, as a density of less than 25 vehicles/km, a condition which does not seem to generate severe traffic congestion. The vehicular density measured with IDM-LC is depicted in Figure 20 and shows that queuing phenomena at intersections are almost equally distributed over the whole topology. Minor intersections experience a higher density with respect to the IDM-IM case as, in absence of critical congestion situations at main junctions, vehicles are more uniformly spread and their presence at smaller crossroads is more noteworthy. By showing the speed distribution in the same IMD-LC scenario, Figure 21 confirms the aforementioned

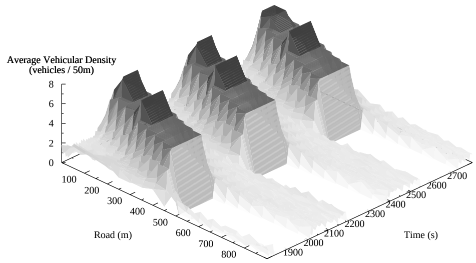


Figure 22: Vehicular density shock waves

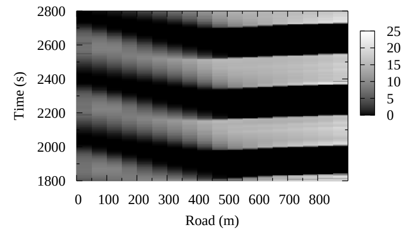


Figure 23: Vehicular speed shock waves

traffic flow improvements. Yet, this figure demonstrates that, even in smooth traffic conditions, speed degradation and pauses at intersections are fundamental aspects of a realistic simulation of vehicular mobility and thus must be correctly modeled.

In a different test, we exploited the vehicular mobility description provided by VanetMobiSim to recreate a typical effect of vehicular traffic. In Figure 22, the shock waves produced on vehicular density by a periodic perturbation are shown. This result has been obtained with IDM-LC on a 1 km long, unidirectional, double lane, straight road. Cars move towards positive abscissae and a traffic light, located halfway and with a period of 360 s, is used as the perturbation source. We can notice that the red traffic light inhibits the movement of vehicles, causing them to stop at 500 m. As more vehicles approach the traffic light, a queue is formed, as shown by the increasing vehicular density, but, when the traffic light turns green, queued vehicles start flowing towards and through the second half of the road. It is possible to see that the high density shock wave propagates in the opposite direction with respect to movement of cars as time goes on. The speed dynamics recorded during the same experiment are depicted in Figure 23, where we can observe even better the queuing perturbation, represented by the dark, zero-speed areas, propagating against the traffic flow direction in time. Shock waves are a common phenomena of real world traffic. When long queues form in proximity of perturbation sources (crowded intersections, toll stations, in-flow ramps, etc.) the finite reaction time of drivers determines a delay in the propagation of movement. Thus, vehicles queued far from the perturbation origin experience changes in velocity or local traffic density only a long time after the original mobility change occurs at the perturbation.

6.2 Validation against a Benchmark: TSIS-CORSIM

In the previous section, we illustrated how VanetMobiSim was able to reproduce more realistic mobility patterns than other widely spread models used by the community. However, we may raise the question of what *realistic* means. In the following section, we use a benchmark within the traffic generation TSIS-CORSIM in order to validate the traces generated by VanetMobiSim.

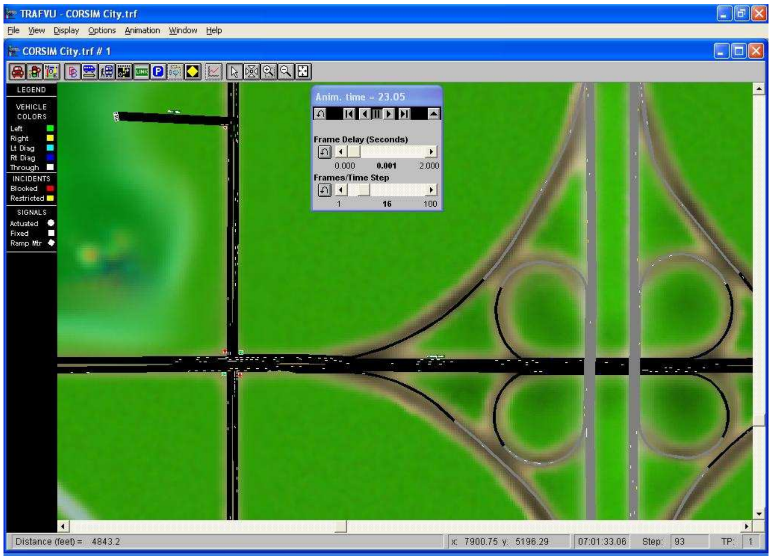
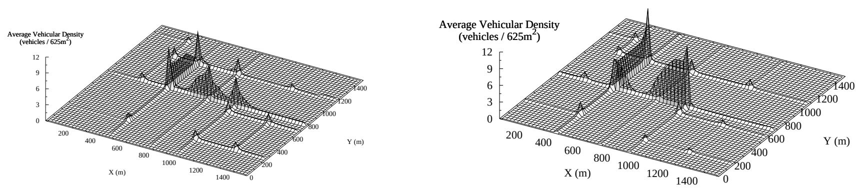


Figure 24: CORSIM Vizualizer

TSIS-CORSIM [4] is a comprehensive traffic simulator, applicable to surface streets, freeways, and integrated networks with a complete selection of control devices (i.e., stop/yield sign, traffic signals, and ramp metering). It simulates traffic and traffic control systems using commonly accepted vehicle and driver behavior models. CORSIM has been validated by showing its ability to model identical mobility patterns than real traces gathered in predefined testing areas. CORSIM has been applied by thousands of practitioners and researchers worldwide over the past 30 years and embodies a wealth of experience and maturity. Funded by the US Federal Highway Administration (FHWA) throughout the last three decades, TSIS-CORSIM has evolved into a benchmark within the transportation profession. We validated VanetMobSim against CORSIM in the version 5.1.

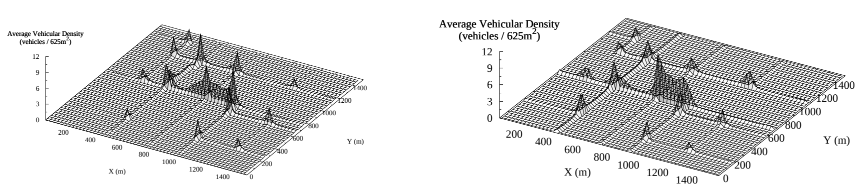
CORSIM has been created for transportation, traffic, and civil engineers. As no interaction has been created in CORSIM for network analysis or simulations, we had to create a specific parser to extract vehicular mobility information. Formally, CORSIM does not output any other data than statistics. However, it communicates with the visualization tool TRAFVU using a set of files from where we extracted the mobility traces. We configured CORSIM according to the same urban topology and activity chain as for VanetMobiSim (see Figure 9 and Figure 10). As CORSIM has been designed to model urban traffic in a high level of precision, it also contains a large set of configuration parameters. For parameters common to VanetMobiSim and CORSIM, we used the same values as in Table 1 and Table 2. For the other parameters, we kept the values defined by default in CORSIM. The exact number of cars simulated by CORSIM cannot be easily configured. Accordingly, we cannot guarantee that we have the same number of cars in both cases. That will be visually seen in the next figures as the local density will slightly differ. However, we are more interested in the geographical distribution of the cars than in local intensity.



(a) CORSIM (b) VanetMobiSim

Figure 25: Comparison of the spatial distribution with Stop signs

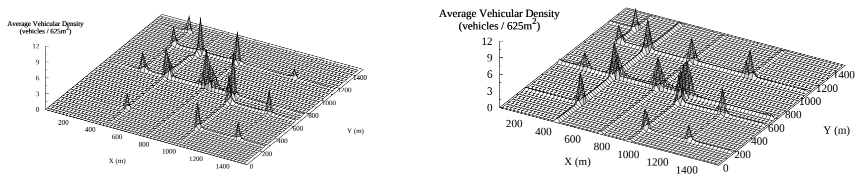
In Figure 25, we compare the spatial distribution of vehicles in the topology generated by CORSIM and by VanetMobiSim. Even though the local density are not similar, we can clearly see that the aggregation occurs at similar places. Similarly to VanetMobiSim, vehicles are likely to follow streets with a higher velocity. Accordingly, we see that in both figures, a bottleneck is generated on the *CD* and *AB* edges. Indeed, the intersection at *C* is a major crossroad between two high speed streets, and the intersection at *B* contains a side street which potentially attracts a lot of traffic due to the number of *attraction points*. As all intersections are modeled by stop signs where cars pass one at a time according to the right hand rule, the slow traffic flow at those intersections are generating similar mobility patterns.



(a) CORSIM (b) VanetMobiSim

Figure 26: Comparison of the spatial distribution with Traffic lights

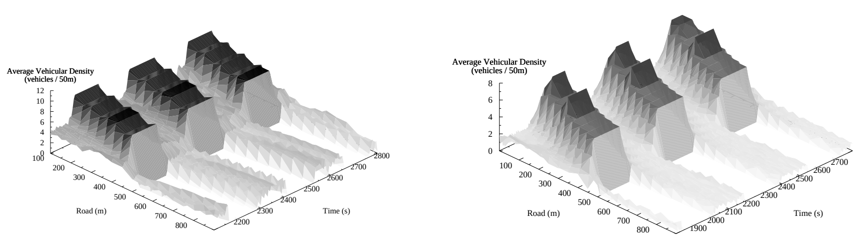
Figure 26 compares the spatial distributions between CORSIM and VanetMobiSim when intersections are controlled by traffic lights. Similarly to the previous graph, we can clearly see that the spatial distribution is very similar, cars aggregating in the same intersections or road-segments. We can also see the same effect of the traffic light located at the intersection *C*, which helps dissolving the vehicle aggregation on the edge *CD* both in CORSIM and VanetMobiSim.



(a) CORSIM (b) VanetMobiSim

Figure 27: Comparison of the spatial distribution with Traffic lights and lane changing

Finally, in Fig 27, we see that the added lane changing capability has a similar effect on traffic aggregation. In both cases, the large aggregations are reduced to local peak densities at similar intersections, which are more uniformly distributed per intersection. By allowing cars to overtake slow and potentially blocking cars, but also to overtake a car blocking an intersection where it needs to wait to turn, manages to reduce the clustering effect at the intersection, both in CORSIM and in VanetMobiSim. Accordingly, even though the two simulators use different macro- and micro-mobility models, potentially having different configuration parameters, we see that CORSIM and VanetMobiSim produces similar traffic distribution.

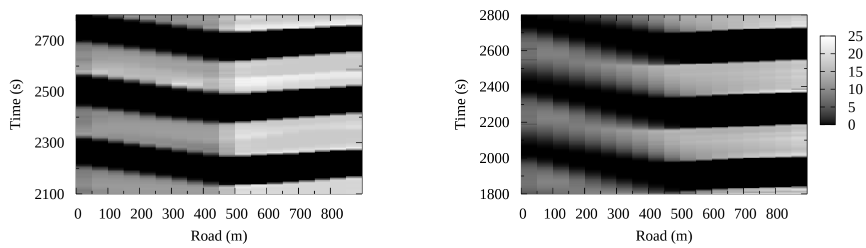


(a) CORSIM (b) VanetMobiSim

Figure 28: Comparison of the density shockwaves

In the next set of figures, we will compare the shock wave effects created by a periodic perturbation modelled by a traffic light. The topology is identical to the one used for the Figure 22 and Figure 23. We first can see by comparing the two plots in Figure 28 that CORSIM and VanetMobiSim generate similar density shock waves. In both cases, the local perturbation is backward propagated.

In Fig 29 the similarity is even more exacerbated as we see the periodic speed perturbation created by a red traffi c light. In both plots, the speed shock waves are also backward propagated according to the delayed stop and move patterns observable in waiting queues. Similarly to the traffi c distribution previously displayed, CORSIM and VanetMobiSim produces very similar mobility patterns generated by periodic perturbations.



(a) CORSIM (b) VanetMobiSim

Figure 29: Comparison of the speed shockwaves

To conclude this section, we would like to emphasize that although CORSIM and VanetMobiSim neither use similar micro-mobility patterns, nor are controlled by same confi guration parameters, we managed to show that the traffi c distribution and well as the shock waves generated by a periodic perturbation were similar and conformed to real life situation. Accordingly, this let us claim that the mobility patterns generated by VanetMobiSim are validated and realistically reflect real motion patterns.

6.3 Illustration in Real Urban Case

As a further addition to the validation of the mobility generated by VanetMobiSim, Figure 30 shows a snapshot of the vehicular mobility obtained with VanetMobiSim on the urban area of Westwood in Los Angeles is overlap to a real map of the same city section. The simulated vehicular mobility is extracted from the *nam* network animator of *ns-2*. The snapshot refers to a simulation involving IDM-IM, traffi c lights at intersections, a random speed-based path selection. Although TIGER maps do not include speed limits information, we deduced them from the street class, according to the local speed limitation policy. Drivers thus take into account the path length and the allowed speed along the path, making detours if a path appears globally faster. The consequence can be seen in in Figure 30, where Wilshire Boulevard attracts the majority of drivers, hoping to save time by using a large East-West commuting corridor instead of parallel streets. When the local vehicular density exceeds the traffi c lights management capability, like at inter-

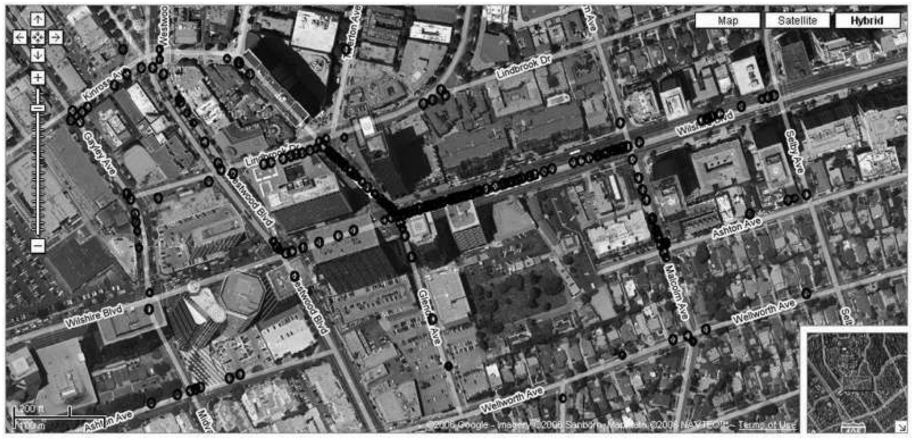


Figure 30: Simulated vehicular mobility in the Westwood area

sections between Wilshire and Glendon, and Glendon and Lindbrook, the traffic cluster pours out and cars start stacking up on the surrounding streets and not only at the road junctions. These congestion phenomena can be easily observed in real-life situations.

7 Conclusions and Future Work

In this paper we presented VanetMobiSim, an extension to the CanuMobiSim user mobility framework capable of producing realistic vehicular mobility traces for several network simulators. We reviewed the macroscopic and microscopic mobility descriptions of CanuMobiSim, and detailed the additions to both scopes brought by VanetMobiSim. Simulation results were presented and discussed, trying to understand the differences between various micro-mobility models, in terms of vehicular density and speed distribution.

Moreover, we compared the vehicular mobility traces obtained by VanetMobiSim with TSIS-CORIM, a benchmark traffic generator able to reproduce realistic and validated traffic traces. Through the illustration of the similarity between both traces, it allowed us to claim that VanetMobiSim was able to produce realistic vehicular mobility traces. That makes VanetMobiSim one of the few synthetic vehicular-oriented mobility simulator fully validated and freely available to the research community.

By taking a comprehensive look at the results obtained, it appears clear that the detail level of the micro-mobility models implemented by CanuMobiSim is not sufficient to reproduce realistic vehicular traffic traces. The increased degree of detail introduced by the micro-mobility models of the VanetMobiSim extension, and the possibility of their interaction with the new macro-mobility description appear necessary to reproduce real world phenomena. In particular, the progressive introduction of stops signs, traffic lights, multiple lanes and overtakings demonstrates how the modeling of each of these features brings noticeable changes to the system performance.

From a networking point of view, the differences observed between different micro-mobility models, in terms of vehicles and speed distribution, queuing dynamics and presence and size of clusters may heavily affect the connectivity of VANETs, and, consequently, the performance of ad-hoc network protocols. It is part of future work to investigate the actual impact of these different traffic phenomena on a vehicular network, so to understand which factors must be considered and which can be neglected for a confident VANETs simulation study.

Also, a very important factor when simulating highly mobile networks is the radio propagation model. Results obtained without accounting for the impact of large obstacles, such as buildings, on the radio signal propagation can hardly be realistic. We are thus interested in studying this aspect, taking benefit from the availability of a detailed topology description to introduce a new component in VanetMobiSim, capable of generating radio propagation information for network simulators.

8 Acknowledgments

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