

Vehicular Mobility Simulation for VANETs*

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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. In this paper we first present and describe VanetMobiSim, a freely available generator of realistic vehicular movement traces for networks simulators. Then, VanetMobiSim is validated by illustrating how the interaction between featured macro- and micro-mobility is able to reproduce typical phenomena of vehicular traffic.

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, or the traffic signs description establishing the intersections crossing rules.

Micro-mobility instead refers to the drivers' individual behavior, when interacting with other drivers or with the road infrastructure: traveling speed in different traffic conditions; acceleration, deceleration and overtaking criteria, behavior in presence of road intersections and traffic signs, general driving attitude related to driver's age, sex or mood, etc.

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.

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In this paper, we introduce VanetMobiSim [3], a freely distributed, open source vehicular mobility generator based on the CanuMobiSim architecture [4] 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.

Due to the lack of room, we could not include a detailed related work on the current state-of-the-art of vehicular mobility modeling for VANETs simulations. We refer the interested reader to [1], which surveys and classifies major models available to the community. Moreover, an extended version of this work is also available [2].

The rest of the paper is organized as follows. A detailed description of the features of VanetMobiSim is given in Section 2. Section 3 presents some tests validating the movement traces produced by VanetMobiSim in specific scenarios. Finally, in Section 4, we draw some conclusions and discuss future work.

2. VanetMobiSim

VanetMobiSim is an extension to CanuMobiSim [4], a generic *user mobility* simulator. CanuMobiSim is a platform- and simulator-independent software, coded in Java and producing mobility traces for different network simulators, including *ns-2* [5], *QualNet* [6] and *GloMoSim* [7]. 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.

2.1. 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.

2.1.1. 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.
- *GDF map*: the road topology is imported from a Geographical Data File (GDF) [8]. Unfortunately, most GDF file libraries are not freely accessible.
- *TIGER map*: the road topology is extracted from a map obtained from the TIGER database [9]. 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.
- *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 [10], but we also consider the presence of areas with different road densities which we refer to as *clusters*.

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 1.

2.1.2. 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.
- definition of independent speed limits on each road of the topology

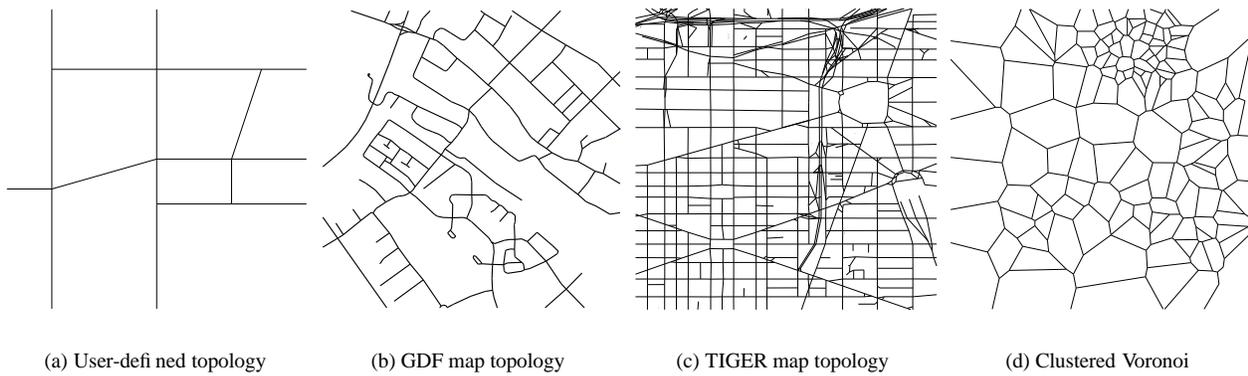


Figure 1. Road topologies examples

- 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.

2.1.3. 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.

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.

2.2. 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) [11], the *Constant Speed Motion* (CSM) [4] and the *Smooth Motion Model* (SMM) [12] 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) [13] and *Intelligent Driver Model* (IDM) [14] 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 traffic 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 traffic 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.

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

$$\frac{dv}{dt} = a \left[1 - \left(\frac{v}{v_0} \right)^4 - \left(\frac{s^*}{s} \right)^2 \right]$$

$$s^* = s_0 + \left(vT + \frac{v\Delta v}{2\sqrt{ab}} \right)$$

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 .

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. 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 for 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 similarly to 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 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. 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. A minimum breaking distance \bar{s} is evaluated by means of simple kinematic formulae as

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

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 the deceleration value, κb . The last parameter represents the maximum safe deceleration, i.e., the IDM comfortable braking value b scaled by a factor $\kappa \geq 1$. 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 dynamic semaphore are presented in Figure 2.

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 2.1.2. Two issues are raised by the introduction of multiple lanes: the first is the separation of traffic flows on different

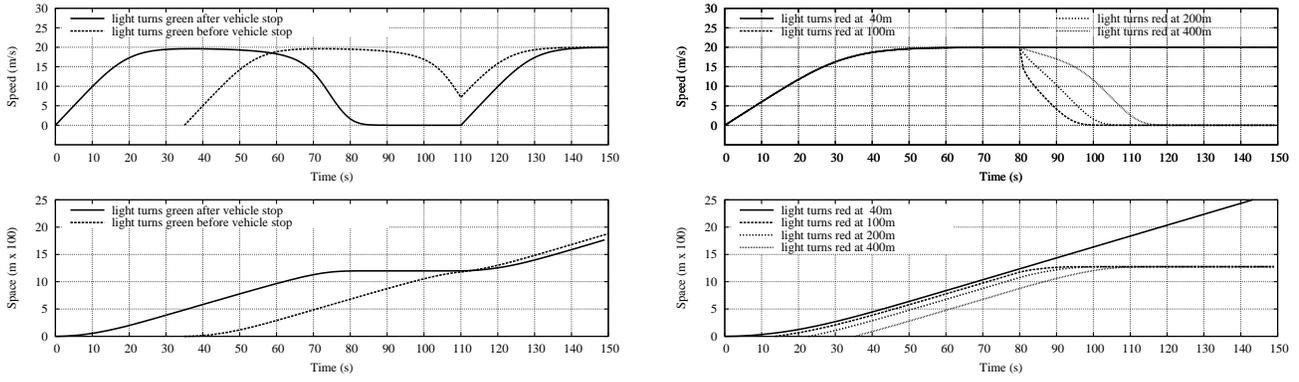


Figure 2. Traffic light *red-to-green* (left) and *green-to-red* (right) scenarios. A vehicle, driven by the IDM-IM setup in Table 1, starts its movement from zero speed, and travels towards a red (green) traffic light, which then turns green (red) before the car reaches it. The upper figure shows the evolution of speed in time, while the lower one depicts the car movement on the road versus time. Different curves represent different driver behaviors, depending on his/her distance from the traffic light when the color switch happens.

lanes of the same road, while the second is the overtaking 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 [15] 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

$$a^l - a \pm a_{bias} > p (a_{cur} + a_{new} - a_{cur}^l - a_{new}^l) + a_{thr}$$

$$a_{new}^l > -a_{safe}$$

are verified. The model allows a vehicle to move to lane l if the first 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 in the current ($a_{cur} - a_{cur}^l$) and in the candidate ($a_{new} - a_{new}^l$) lanes. 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.

3. 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-

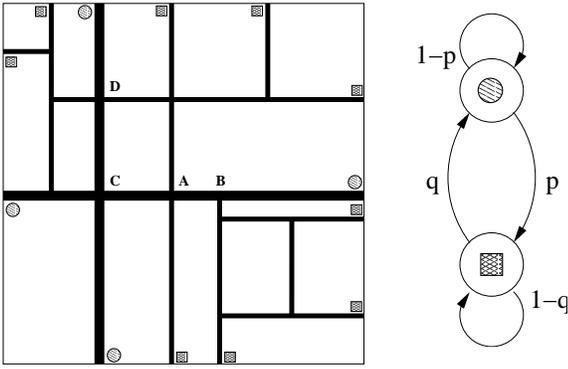


Figure 3. City section map and activity chain

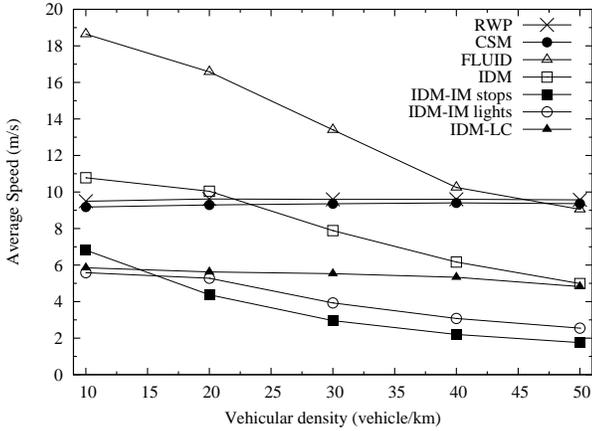


Figure 4. Average speed versus car density

defined graph representing a square city section of 1500 m side. The urban topology employed in those tests is shown in Figure 3, where, unless specified differently, all roads have a 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 2.1.3), and the relative transition probability matrix describes a simple activity chain, depicted in Figure 3. 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 3.

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

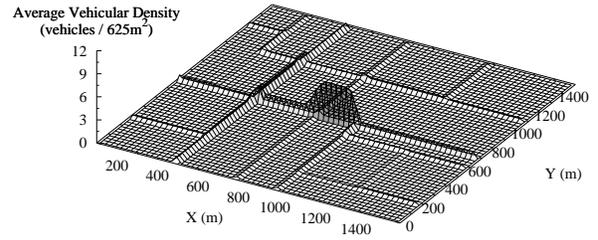


Figure 5. Vehicular density: FTM

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. We stress that different values of IDM-IM k and IDM-LC p did not lead to significant differences in the results, and that the IDM parameters were set to suitable real world values.

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 4, 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.

From Figure 4, 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 in the FTM formula. 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 re-

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

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 1. Parameters value for the micro-mobility models

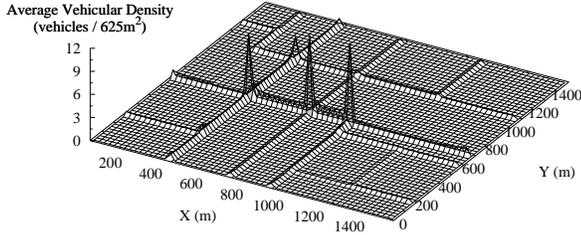


Figure 6. Vehicular density: IDM

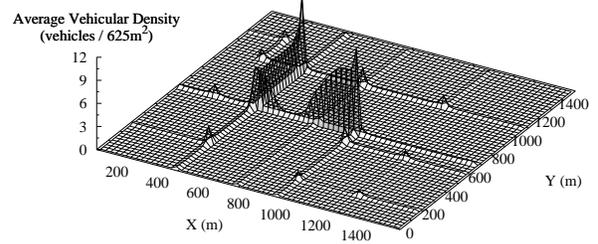


Figure 7. Vehicular density: IDM-IM stops

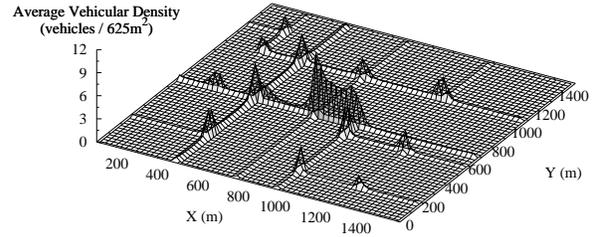


Figure 8. Vehicular density: IDM-IM lights

alistic 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 5 demonstrates the non sufficient realism of this model. This distribution plot, as well as the equivalent ones for the other mobility models in the remainder of this Section, refers to the 30 vehicle/km case. In the considered scenario, a high density is experienced by the central segment marked as AB in Figure 3, 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 constant 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 3 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 4 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 generates queues and forces a reduction on other drivers' speed. Second, there exists a side effect of the CanuMobiSim implementation, which 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 6, 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 4, in the first

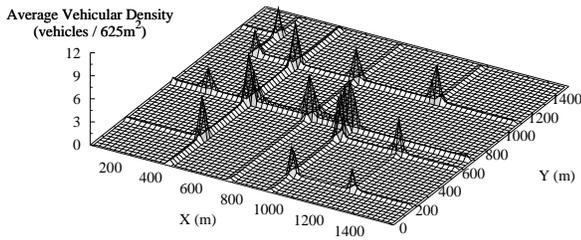


Figure 9. Vehicular density: IDM-LC lights

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 7, where high vehicular densities, accounting for long queues, are recorded in the neighborhoods of the main intersections *A*, *B*, *C* and *D*. A realistic effect of smooth vehicular density, increasing towards the congested crossroads, is obtained with this model. It can be noticed that such effect is 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 4. 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 8, 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.

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 4, modeling vehicular micro-mobility with IDM-

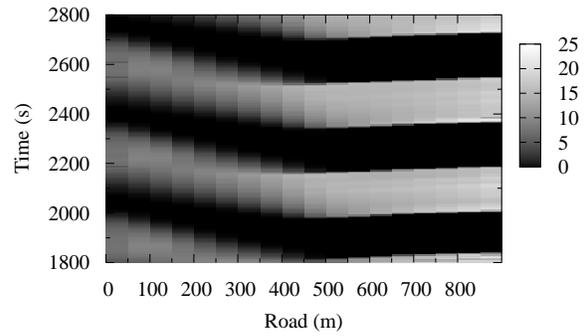


Figure 10. Vehicular speed shock waves

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 9 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.

In a different test, we exploited the vehicular mobility description provided by VanetMobiSim to recreate a typical effect of vehicular traffic. In Figure 10, the shock waves produced on vehicular speed 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 decreasing vehicular speed, 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 low speed shock wave propagates in the opposite direction with respect to movement of cars as time goes on. Shock waves are a common phenom-

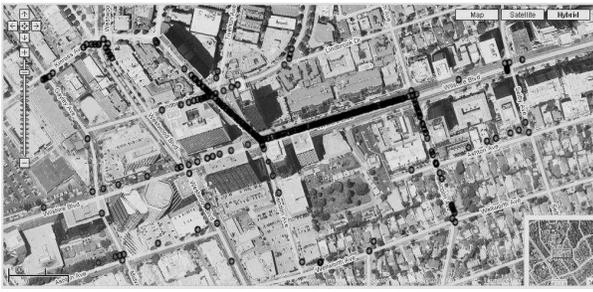


Figure 11. Simulated vehicular mobility in the Westwood area

ena of real world traffic. When long queues form in proximity of perturbation sources (crowded intersections, toll stations, inflow 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.

As a further addition to the validation of the mobility generated by VanetMobiSim, Figure 11 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 snapshot refers to a simulation involving IDM-IM, traffic lights at intersections, a random speed-based path selection. 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 Figure 11, 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 traffic lights management capability, 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.

4. 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.

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 de-

tail 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.

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