Mobility Models in Inter-Vehicle Communications Literature

Marco Fiore
Politecnico di Torino
Email: marco.fiore@polito.it

I. Notation

With reference to the vehicular traffic scenario depicted in Figure 1, we define as i the vehicle whose behavior is currently under investigation. At a given time instant t, such vehicle is at a position $x_i(t)$, and travels with a speed $v_i(t)$, meaning that its instantaneous acceleration can be expressed as $\frac{dv_i(t)}{dt}$. Indexes $i-1$ and $i+1$ identify the back and front vehicles with respect to i, which are located at $x_{i-1}(t)$ and $x_{i+1}(t)$, and travel at velocity $v_{i-1}(t)$ and $v_{i+1}(t)$, respectively, at time t. The front bumper to back bumper distance between i and $i+1$ is identified as $\Delta x_i(t)$. Indexes $j-1$ and $j+1$ identify the back and front vehicles with respect to i, in a different lane, considered for lane change. These vehicles are at positions $x_{j-1}(t)$ and $x_{j+1}(t)$ and travel with speed $v_{j-1}(t)$ and $v_{j+1}(t)$, respectively. Also, we denote input parameters for the vehicular mobility descriptions with consistent notation in different models. The symbols used are listed in Table I.

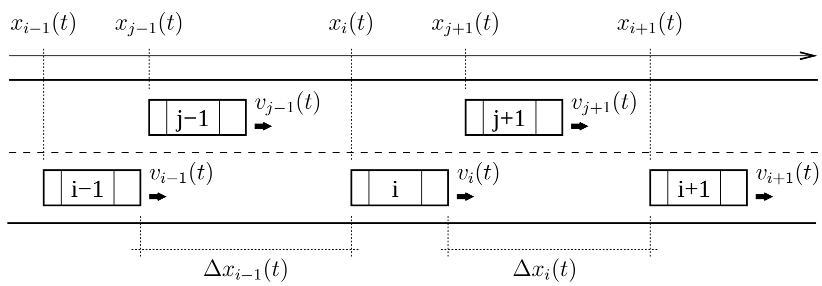


Fig. 1. Vehicular traffic notation.

Parameter	Symbol
acceleration	a
deceleration	b
driver's reaction time	τ
time step	Δt
maximum (desired) speed	v_{max}
minimum speed	v_{min}
safe time headway	T

TABLE I
LIST OF SYMBOLS

II. Stochastic models

We classify as stochastic models all those mobility descriptions which constrain random movements of nodes on a graph. The graph represents a road topology, and the movement is random in a sense that vehicles, individually or with group dynamics, follow casual paths over the graph, usually traveling at randomly chosen speed. Stochastic models are the simplest vehicular mobility descriptions used in VANETs research, as they do not consider any vehicular traffic theory result. Basic aspects such as car-to-car interaction and intersection modeling are neglect or tackled simplistically, with the result that fundamental phenomena of vehicular mobility cannot be reproduced. Stochastic models are often compared against fully random mobility models, i.e., models that do not constrain the random nodes movement over a graph, such as the Random Walk [1] or the Random Waypoint [2]. However, such

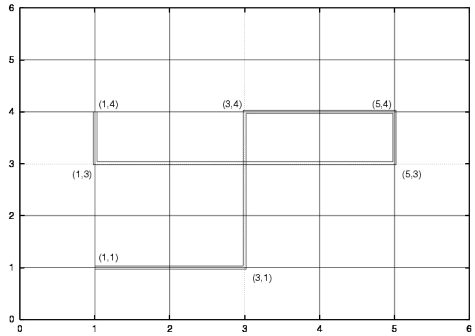


Fig. 2. Example of City Section mobility, with dotted lines representing high-speed roads. The simulated vehicle moves from $(1, 4)$ to $(4, 4)$ in multiple steps.

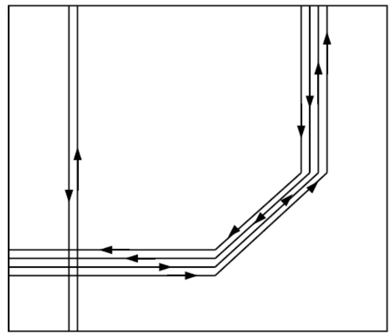


Fig. 3. Freeway model topology, each line representing a single highway lane. Vehicular movement occurs on the direction shown by the arrows.

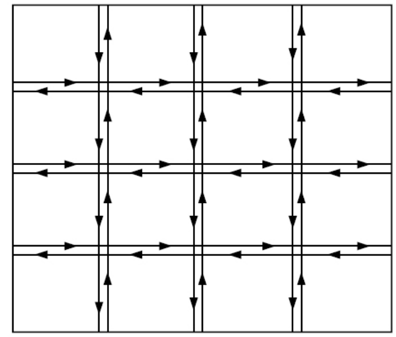


Fig. 4. Manhattan model topology, each line representing a single-lane road. Vehicular movement occurs on the direction shown by the arrows.

tests can hardly validate the realism of stochastic models.

The *City Section* mobility model introduced by Davies [3] constrains nodes movement on a grid road topology, where all edges are considered bi-directional, single-lane roads. Vehicles randomly select one of the intersections as their destination over the grid and move towards it with constant speed, with (at most) one horizontal and one vertical movement. The speed depends on the road the vehicle is traveling on: two road classes, high-speed and low-speed, are considered, and each node sets its speed to a high or low value accordingly. Car-to-car interactions are ignored, since all adjacent vehicles travel at the same speed, and vehicles are allowed to overlap at road junctions. No pauses at intersections, nor at the end of trips are specified. In Figure 2 an example of vehicle trip over with the City Section model is provided.

Within the IMPORTANT framework [4], Bai *et al.* adopt a Freeway mobility model and a Manhattan mobility model to verify the effect of different mobility descriptions on several metrics of networking interest. The *Freeway* model uses the map in Figure 3, representing several bi-directional multi-lane freeways. The movement of each node is restricted to the lane it is moving on, and the following speed rules apply to vehicle i:

$v_i(t + \Delta t) = v_i(t) + \eta\ a\ \Delta t;$
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 $\Delta x_i(t) \leq SD$ THEN $v_i(t) = v_{i+1}(t) - a/2;$

where SD is the minimum safety distance between two vehicles and η is a random variable uniformly distributed in $[-1, 1]$. The first rule adds some randomness to the update of vehicle's speed, which is first selected as uniformly distributed in an interval $[v_{min}, v_{max}]$. The second rule introduces a minimum safety distance requirement between vehicles. Each vehicle starts its movement at the beginning of a lane, and ends it once it reaches the end of the same lane. Then a new movement, on a randomly selected lane, is started over.

Similarly to the City Section model seen before, the *Manhattan* mobility model uses a grid road topology, as shown Figure 4. This model was first introduced in [5] and is also implemented in the BonnMotion framework [6]. With respect to the City Section, the Manhattan model employs a probabilistic approach in the selection of nodes movements, since, at each intersection, a vehicle chooses to keep moving in the same direction with probability $1/2$ and to turn left or right with probability $1/4$ in each case. In the IMPORTANT framework implementation, the speed management is the same observed in the Freeway model, which adds realism with respect to the City Section model, where all cars traveling on the same lane have instead an identical velocity.

Note that the randomness and safety conditions with respect to the ahead driver imposed to nodes speed by the IMPORTANT implementation of the Freeway and Manhattan descriptions make these model fall somehow in between random mobility and car following theory, discussed in Section IV. However, we classify the Freeway and

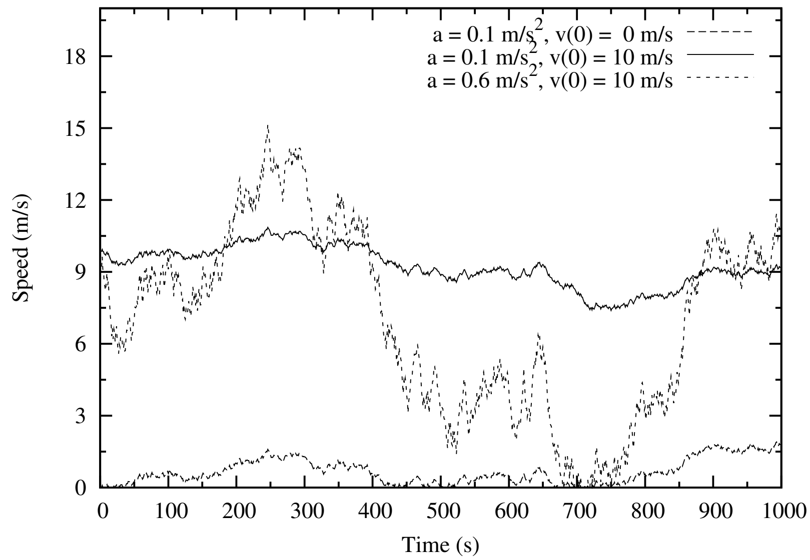


Fig. 5. Free flow speed versus simulation time obtained with the IMPORTANT speed rules, in the case $[v_{min}, v_{max}]$ equal to $[0, 30]$ m/s. It can be noticed that a comfortable real world value of the acceleration ($a = 0.6$ m/s^2) causes unrealistic substantial fluctuations of the speed. Reducing the acceleration value ($a = 0.1$ m/s^2) determines a more stable curve. In any case, modeling zero speed driven phenomena, such as queues and traffic shockwaves, is prevented by the absence of a desired speed target in the model: as a matter of fact, if the car stops for some reason, the speed tends to remain around the initial zero value ($v(0) = 0$ m/s).

Manhattan models as random mobility models because the car interaction rules they employ are too simple and do not reproduce a realistic drivers behavior. This is evident in Figure 5, where the time evolution of the speed of a single vehicle in free flow conditions (i.e., with no vehicle ahead) is depicted for the above $v_i(t)$ expression.

Saha and Johnson [7] modeled vehicular traffic with a random mobility of nodes over real road topologies extracted from the maps of the US Census Bureau TIGER database [8]. An example of road graph obtained this way is depicted in Figure 6. In Saha's work, nodes select one point over the graph as their destination and compute the shortest path to get there. The edges sequence is obtained weighting the cost of traveling on each road on its speed limit (which is recorded by the TIGER format) and on the number of vehicles already moving on it, in a way to reproduce the real world tendency of drivers to avoid congested paths. The speed of a node is set to a constant value in the range $[v_{max} - \epsilon, v_{max} + \epsilon]$, where v_{max} is the speed limit of the road the car is moving on. All roads are considered bi-directional and single lane, and no car-to-car interaction is modeled.

Zhou *et al.* [9] propose a Real Track mobility model, derived from the Virtual Track model [10]. The *Virtual Track* model binds nodes movement over a graph, whose vertices are referred to as switch stations, and whose edges are defined virtual tracks. The edges have a length, equal to the distance between the switch stations they connect, and a width, which is user-defined. Thus, they can be graphically represented as rectangles more than lines. Nodes moves in groups, according to the Reference Point Group Mobility (RPGM) model [11], which defines a common direction for the group, and then adds some bounded randomness to the movement of the single nodes within the group with respect to the common direction. Groups of nodes are allowed to move following a Random Waypoint model [2] from one switch station to another switch station only within the virtual tracks, and only in the direction of the next switch station (i.e. the Random Waypoint is biased so that the next destination must be nearer than the current position to the target switch station). At switch stations, nodes may leave their current group and join other groups. The *Real Track* model applies the Virtual Track model to real road topologies, extracted, as it was the case for Saha, from the TIGER database. Road intersections are mapped into switch stations and roads into virtual tracks, to which a fixed width is assigned. Figure 7 shows a simple example of a Virtual/Real Track topology. The idea at the base of the Real Track model is to reproduce the clustering of vehicles occurring at intersections and propagating over the roads. However, the strategy chosen is not based on any vehicular traffic theory result, nor it is validated against other models or real world data. Moreover, Since this model bases vehicles movements on the RPGM mobility model, the patterns are random and no car to car interaction is considered.

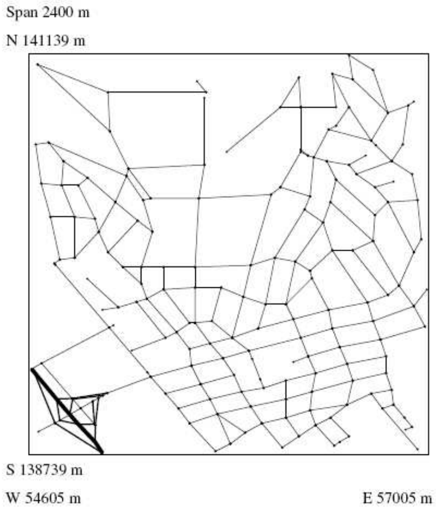


Fig. 6. Example of map extracted from a US Census Bureau TIGER database map, showing the Westwood area near UCLA in Los Angeles, CA.

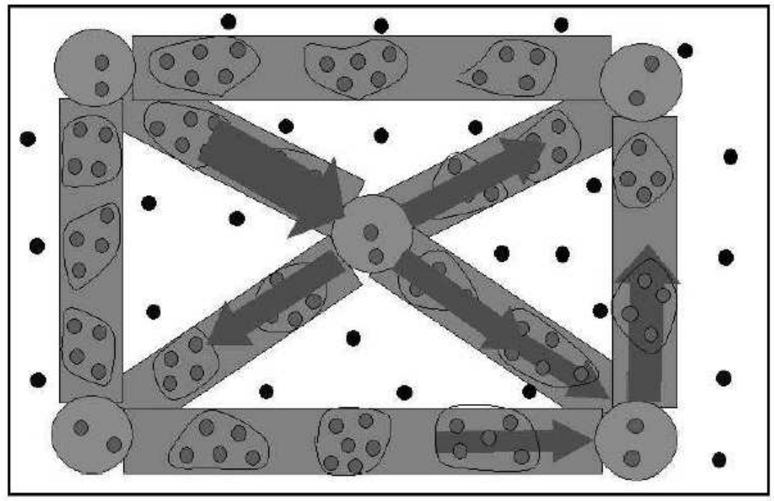


Fig. 7. Example of Virtual/Real Track mobility. Groups of nodes move within virtual tracks connecting five switch stations. Black dots represent mobile nodes which are unconstrained by the road topology, whose presence is allowed by the model.

III. TRAFFIC STREAM MODELS

Traffic stream models look at vehicular mobility as a hydrodynamic phenomenon, and try to relate the three fundamental variables of velocity $v(x,t)$ (measurable in km/h), density $\rho(x,t)$ (measurable in vehicles/km), and flow $q(x,t)$ (measurable in vehicles/h). All of them are functions of space x and time t, averaged over sufficiently large regions. Since they regard vehicular traffic as a flow, these models fall into the category of macroscopic descriptions. The basic equation comes from the idea that, given a road section, the number of vehicles can vary only due to cars entering or leaving the section. This leads to the following continuity equation

$$\frac{\partial \rho}{\partial t} = -\frac{\partial (\rho v)}{\partial x} \tag{1}$$

that is, the density over a small section dx varies, during a small interval dt, according to the corresponding flow. The simplest model of this kind was proposed by Lighthill and Whitham [12], assuming the velocity to be a function of the density

$$\frac{\partial \rho}{\partial t} + \frac{d}{d\rho}\left(\rho v(\rho)\right)\frac{\partial \rho}{\partial x} \tag{2}$$

which is capable of modeling kinematic waves. This model has been used along the last decades, but much more complex formulations, always based on the same assumptions, can be found in traffic flow literature.

Traffic stream models can handle large quantities of vehicles, at the cost of precision. This makes them interesting for high-level analytical studies of traffic behavior. However, they cannot model each vehicle independently, However, the study of VANETs is largely based on simulations which can rely on fast hardware, overcoming the problem of complexity. Moreover, in VANETs research the mobility of each vehicle is fundamental, as it dramatically impacts on key factors such as connectivity and links duration. As a consequence macroscopic level models are rarely found in communication networking literature.

A macroscopic approach is employed by Rudack *et al.* [40], again for a highway scenario. In fact, after presenting the fundamentals of traffic flow theory, the authors simply exploit common assumptions from the traffic flow literature, considering the distribution of vehicular speed as normal [41] and the distribution of vehicles interarrival times at the beginning of the considered road section as exponential [42]. Since the goal of the paper is to determine the duration of connections between traveling vehicles and fixed gateways along the highway, no higher detail than the shape of these distributions is needed by the authors.

IV. Car following models

In car following models the behavior of each driver is described in relation to the vehicle ahead, and, as they regard to each single car as an independent entity, they fall into the category of microscopic level descriptions. The first car following models date back 50's and, since then, they represent one of the most common ways to analytically represent vehicular traffic dynamics.

Most car following models compute the speed or acceleration of a car as a function of factors such as the distance to the front car and the current speed of both vehicles. A general delayed differential equation formulation, for a vehicle i, would thus be

$$\frac{dv_i(t)}{dt} = f(v_i(t), v_{i+1}(t), x_{i+1}(t) - x_i(t)) \tag{3}$$

where a common expression for f, named GHR after Gazis, Herman and Rothery, who first proposed it [13], is

$$\frac{dv_i(t)}{dt} = \alpha v_i^m(t) \frac{v_{i+1}(t) - v_i(t)}{(x_{i+1}(t) - x_i(t))^l}\bigg|_{t-\tau} \tag{4}$$

where α, m and l are free parameter which can adapted to the traffic scenario that must be modeled. Note that the computation of the derivative at time $t-\tau$ accounts for the finite reaction time τ of drivers. Many other factors, characterizing both cars technical constraints and drivers attitude, can be detailed in car following models, increasing their level of realism. Also, car following models often include lane changing rules to regulate movement of vehicles between lanes. Car following descriptions integrated by lane changing rules can model the behavior of vehicular traffic on individual multi-lane roads, and are thus typically employed in highway mobility analysis. In simulation, they can also be used to model vehicular dynamics on independent roads of an urban scenario. In that case however, a proper accounting for interactions between traffic flows at road junctions must be provided. That is, rules for intersections crossing, in presence of stop/priority signs and traffic lights, must be defined as well. The same is hard to accomplish within analytical frameworks, as the joint complexity of the different acceleration, lane changing and intersection management descriptions leads to intractable problems [14].

Compared to macroscopic descriptions, these models are usually more precise but computationally more expensive, as their execution cost increases with the number of simulated vehicles. For this reason, it is to be remarked that differential formulations of the car following problem, such as GHR, are rarely used when large scale simulations have to be run. Instead, discrete time models, as those listed in the remainder of this Section, are employed. For a survey and comparison of car following models, along with discussion on their implementation in traffic simulators, the reader can refer to in [15], [16], [17].

In her thesis, Breisermeister [18] uses a microscopic level description for vehicular movements on a single-lane, bi-directional straight road. The car-following model is taken from Krauß [19], [20]. The model takes four input variables (the maximum velocity v_{max}, the maximum acceleration a, the maximum deceleration b and the noise η that introduces stochastic behavior to the model), discretizes the time with step Δt, and is built up by the following set of equations

$$v_i^{safe}(t+\Delta t) = v_{i+1}(t) + \frac{\Delta x_i(t) - v_{i+1}(t)\tau}{(v_i(t) + v_{i+1}(t))/2b + \tau} \tag{5}$$

$$v_i^{desired}(t+\Delta t) = min\left[v_{max}, v_i(t) + a\Delta t, v_i^{safe}(t+\Delta t)\right] \tag{6}$$

$$v_i(t+\Delta t) = max\left[0, v_i^{desired}(t+\Delta t) - \epsilon\ a\ \Delta t\ \eta\right] \tag{7}$$

Equation 5 computes the speed of vehicle i required to maintain a safety distance from its leading vehicle. The reaction time of the driver is represented by the time τ. Equation 6 determines the desired new speed of vehicle i, which is equal to the current speed plus the increment determined by the uniform acceleration, with upper bounds represented by the maximum and safe speeds. Equation 7 finally determines the speed of the following vehicle, by adding some randomness, in the measure of a maximum percentage ϵ of the highest achievable speed increment $a\Delta t$ (η is a random variable uniformly distributed in $[0,1]$). Also, note that in [18], only single-lane roads are simulated, thus no overtaking model is considered. However, in [20] a set of lane changing rules extending the above car following equations is proposed. Such rules determine a driver's willingness to change lane, as well as the safety requirements that must be satisfied for the lane change to occur. In particular, the lane changing model distinguish between two possible situations, namely a movement to the left lane and a movement to the right lane. Different rules are proposed in order to mimic the use of left lanes for overtakings and right lanes for free flow travel. In the following, we use the notation $|\cdot|_L$ and $|\cdot|_R$ to indicate the value of the expression within bars, computed as if the vehicle was in the lane at its left and at its right, respectively. First, a traffic congestion ($\mathcal{C}$) condition is introduced as

$$\text{IF } \left(v_i^{safe}(t) < v_t^{safe}\right) \text{ AND } \left(\left|v_i^{safe}(t)\right|_L < v_t^{safe}\right) \text{ THEN } \mathcal{C};$$

where v_t^{safe} is a threshold safe velocity, under which a lane is considered congested. Also, conditions for safe lane changes to left ($\mathcal{S}_L$) and right ($\mathcal{S}_R$) lanes are formulated as follows

$$\text{IF, FOR EACH } i, \left(|v_i(t)|_X - b\Delta t \leq \left|v_i^{safe}(t)\right|_X\right) \text{ THEN } \mathcal{S}_X \text{ WITH } X \in [L, R];$$

where the inequality guarantees that, is the lane change is performed, each vehicle in the system is still able to brake with a finite deceleration b and avoid a collision with the vehicle ahead. Then, a lane change is considered favorable, with respect to a left ($\mathcal{F}_L$) and to a right ($\mathcal{F}_R$) movement, under the following conditions

$$\text{IF } v_i^{safe}(t) < v_{max} \text{ AND NOT } \mathcal{C} \text{ THEN } \mathcal{F}_L;$$
$$\text{IF } v_i^{safe}(t) \geq v_{max} \text{ AND } \left|v_i^{safe}(t)\right|_R \geq v_{max} \text{ THEN } \mathcal{F}_R;$$

meaning that a lane change to the left can be operated only if the current lane does not allow to reach the desired speed and if the traffic is not congested, as in that case changing lane would not increase the traveling speed. On the other hand, a movement to the right is allowed if the desired speed can be reached on both lanes, thus making occupancy of the left lane unnecessary. The lane change algorithm is then

$$\text{IF } (\mathcal{F}_X \text{ OR } \eta < p_{change}) \text{ AND } \mathcal{S}_X \text{ THEN MOVE TO } X, \text{ WITH } X \in [L, R];$$

which simply states that the movement can be performed if the change is favorable and the safety condition holds. Some randomness is added to the process, by allowing the vehicle to change its lane even if not favorable, with a small probability p_{change}, as η is a random variable uniformly distributed in $[0, 1]$. Finally, the model prevents overtakings on right lanes, with the exception of those occurring in congestion regime, by means of the following condition

$$\text{IF } v_i(t) > \left|v_i^{safe}(t)\right|_L \text{ AND NOT } \mathcal{C} \text{ THEN } v_i(t) = \left|v_i^{safe}(t)\right|_L;$$

so that a vehicle in non congested traffic situation lower bounds its speed not only on the safety speed evaluated with respect to the front vehicle on the lane it is currently traveling on, but also on that computed with respect to the front vehicle on its left lane.

The same model by Krauß is employed within the Simulation of Urban MObility (SUMO) project [21], which is developing an open source traffic simulation package. In that case, both acceleration and lane changing rules are adopted. The tool also uses a dynamic user equilibrium approach by Gawron [22] to model realistic traffic assignments, and an original intersection management scheme to handle vehicle movement through road junctions. This tool is of interest for the VANET research community mainly because Karnadi *et al.* [23] developed the Mobility Model Generator for Vehicular Networks (MOVE) tool, which stands over SUMO and includes GUIs to facilitate the process of road topology and vehicular mobility definition, as well as output traces converters for network simulators as ns-2 and QualNet.

Haerri *et.al* [24] propose a vehicular mobility simulator for VANETs, called VanetMobiSim, which employs a different car following model from Treiber *et al.* [25], defined Intelligent Driver Model (IDM). Such model characterizes drivers behavior through the instantaneous acceleration of vehicles, computed through the following equations

$$\frac{dv_i(t)}{dt} = a\left[1 - \left(\frac{v_i(t)}{v_{max}}\right)^4 - \left(\frac{\delta}{\Delta x_i(t)}\right)^2\right] \tag{8}$$

$$\delta = \Delta x_{min} + \left[v_i(t)T + \frac{v_i(t)\left(v_{i+1}(t) - v_i(t)\right)}{2\sqrt{ab}}\right] \tag{9}$$

In Equation 8, δ is the so called desired dynamical distance, computed, as shown in Equation 9, as a function of the minimum bumper-to-bumper distance Δx_{min}, the minimum safe time headway T, the speed difference with respect to front vehicle, and the maximum acceleration and deceleration a and b. When combined, these formulae give the instantaneous acceleration of the car, divided into a desired acceleration $[1-(v_i(t)/v_{max})^4]$ on a free road, and a braking deceleration induced by the preceding vehicle $(\delta/\Delta x_i(t))^2$. A lane changing model from the same authors [26] is used to model overtakings in VanetMobiSim. The model, called MOBIL, follows a game theoretical approach, and allows a vehicle to move to an adjacent lane if his/her advantage, in terms of acceleration, is greater than the disadvantage of the back car in the new lane. The model also consider a politeness factor and a right lane advantage bias, which reproduce the real world behavior of drivers to stay on rightmost lanes. Adopting again the convention that $|\cdot|_L$ and $|\cdot|_R$ indicate the value of the expression within bars, computed as if the vehicle was in the lane at its left and at its right, and the concept of safe and favorable movement to the left ($\mathcal{S}_L$, $\mathcal{F}_L$) and to a right ($\mathcal{S}_R$, $\mathcal{F}_R$), MOBIL allows a car to change its lane under the following safety condition

$$\text{IF } \left|\frac{dv_{j-1}(t)}{dt}\right|_X > -b_{safe} \text{ THEN } \mathcal{S}_X, \text{ WITH } X \in [L, R];$$

that is, is the back vehicle in the new lane does not have to brake more than a safe deceleration value b_{safe} after the completion of the maneuver. Lane change are considered favorable, as follows

$$\text{IF } \left|\frac{dv_i(t)}{dt}\right|_X - \frac{dv_i(t)}{dt} \pm a_{bias} \geq p\left(\frac{dv_{j-1}(t)}{dt} - \left|\frac{dv_{j-1}(t)}{dt}\right|_X\right) + a_t \text{ AND } \mathcal{S}_X \text{ THEN } \mathcal{F}_X, \text{ WITH } X \in [L, R];$$

where the left hand side of the inequality is the advantage that the lane change would bring to the car under study and the right hand side represents the disadvantage brought by the same movement to the back car in the new lane. Thus, the lane change is favorable only if the advantage of the current driver is higher than the disadvantage of the new back driver. The a_{bias} acceleration term is subtracted when the movement is to the left, and added when the movement is to the right, so that vehicles tend to stay on their right. The p value models the driver's politeness, by weighting the disadvantage of the other drivers, while the a_t acceleration threshold avoids that lane hopping phenomena occur in borderline conditions. VanetMobiSim also adds to the acceleration and lane changing models intersection management techniques in presence of stop signs and traffic lights, so to reproduce vehicular mobility in urban environments.

The same model from Treiber is used by Jaap *et al.* [27], but without considering lane changes and with a simplified intersection management with respect to the previous work by Haerri.

Recent works by Gorgorin *et al.* [28] and Bononi *et al.* [29] employ implementations of a particular category of car following models, which is referred to as psycho-physical models [30], [31], [32]. These models divide the bi-dimensional space of distance Δx and speed difference Δv with respect to front vehicle into several areas corresponding to different driver behaviors. In Figure 8, we show an example of space division and vehicle interaction from [30], detecting the following four driving modes:

- no reaction. No influence is exerted from the ahead vehicle, which is too distant or traveling at higher speed than the considered vehicle. The car under study is thus free to reach and keep the desired speed;
- reaction. The vehicle is approaching the car ahead, and thus has to reduce its speed to keep at safety distance;
- unconscious reaction. The vehicle is in short distance with respect to the car in front, the speed difference is small and the two vehicle build up a cluster;
- deceleration. The distance is too small if compared to the current speed difference, and the vehicle under consideration is forced to brake.

These behavioral areas are separated by thresholds, which trigger consistent acceleration changes. In the example of Figure 8, AX and BX are the minimum and desired safety distances, SDV and $CLDV$ are the distances at which

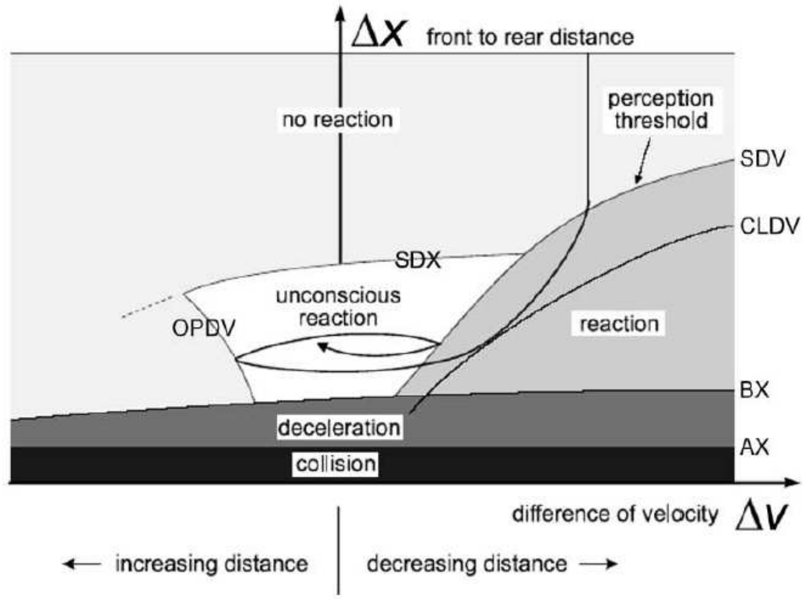


Fig. 8. Example of psycho-physical vehicular interaction. The Δx axis divides positive (vehicle approaching front car) and negative (front vehicle increasing its distance) speed difference Δv. A possible trajectory is shown by the arrow: a vehicle, initially in free flow condition (i.e., in the no reaction zone), starts approaching a vehicle in front. As long as the distance is high enough, the driver ignores the obstacle ahead, keeping his/her pace. However, when the distance becomes too small with respect to the current speed (i.e., the reaction zone is entered) the driver starts slowing down. The braking process brings the driver to match the front car speed ($\Delta v = 0$). Any increase in the speed of the ahead vehicle is then matched by the back vehicle with some delay, due to the finite reaction time of drivers ($\Delta v < 0$). For the same reason, any reduction in front car's speed is matched by the back vehicle with delay as well (the last segment of the movement curve, in the $\Delta v > 0$, unconscious reaction area).

the driver perceives he is approaching a slower vehicles and ends the approaching procedure, $OPDV$ and SDX model the distances beyond which the driver understands he is free to accelerate. All these distances are obviously functions of the speed difference. The main challenge of this kind of mobility models lies in the characterization of such thresholds.

In an undergoing work to simulate a complete urban mobility, Kim *et al.* [33] use a desired-spacing model. Desired-spacing models perform car following between simulated vehicles by maintaining among them a given space headway [16]. In [33], a simple desired-spacing model is employed, which computes the headway of a vehicle i as a linear function of the current speed:

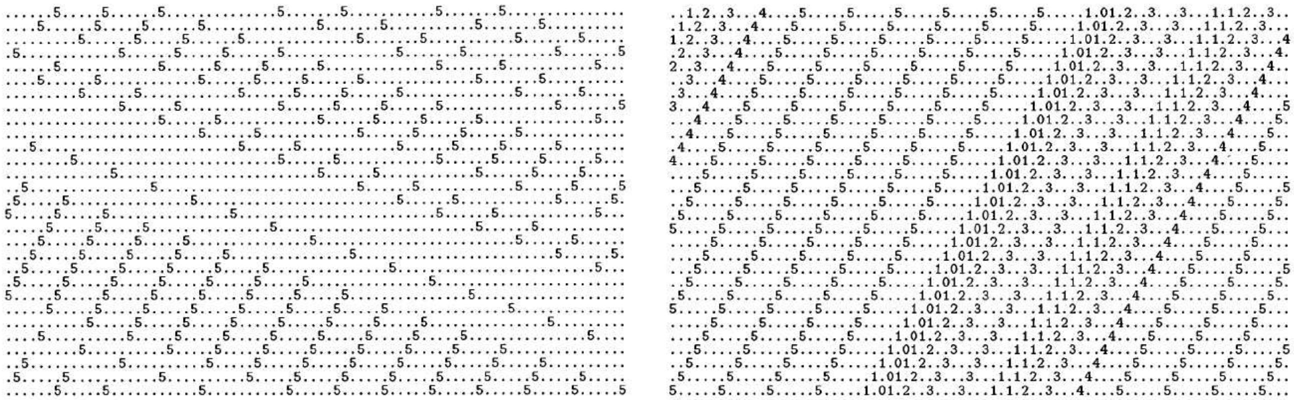
$$\Delta x_i(t) = \alpha + \beta v_i(t) \tag{10}$$

where α and β are two constants whose value is determined from real world observations [35]. The same framework implements a lane changing model, from [36], according to which the desire of a driver to change lane is modeled as a probability p_{change}:

$$p_{change} = \frac{1}{1 + e^{\alpha_M + \beta_M(\bar{v} - |\bar{v}|_X)}} \tag{11}$$

where α_M and β_M are merging constants from real world measurements, while $\bar{v}$ and $|\bar{v}|_X$ are the average speeds of vehicles between the current node and the next intersection, on the current lane and on the lane considered for change ($X \in [L, R]$, according to the notation adopted for the lane change models already presented), respectively.

In [43], a mobility model based on cellular automata [44], [45] is used. Cellular automata vehicular mobility models discretize the road in cells, each containing at most one vehicle. Then, some rules are applied to determine the speed of each car, according to nearby cells status, which depends on whether a vehicle is present in the cell and, if so, on its current speed. Since the level of details of this category of models reaches the behavior of the single vehicle, cellular automata descriptions belong to the microscopic class. Also, it is the front vehicle that constrains the speed of a driver, thus these models are also part of the car following descriptions.



(a) Subcritical density (b) Supercritical density

Fig. 9. Space-time plots of a cellular automata model. Each character represents one cell. Dots are empty cells, while cells occupied by cars show the speed of the car, from 0 (stopped) to 5 (max speed). The left plot shows a non congested scenario, where vehicles are free to travel at high speed. The right plot shows a congested scenario, in which typical traffic shockwaves moving against traffic direction can be distinguished.

In [43], one bidirectional highway is considered, with two lanes in each directions. In the following, we define as $\langle i \rangle$ the cell occupied by vehicle i. Nagel's model determines the speed of i, according to the following algorithm:

IF $v_i(t) < v_{max}$ THEN $v_i(t+\Delta t) = v_i(t) + 1$;
IF $v_i(t+\Delta t) \geq \langle i+1 \rangle - \langle i \rangle$ THEN $v_i(t+\Delta t) = \langle i+1 \rangle - \langle i \rangle - 1$;
IF $v_i(t+\Delta t) \geq 1$ THEN WITH PROBABILITY p DO $v_i(t+\Delta t) = v_i(t+\Delta t) - 1$;

where the first line accounts for acceleration, the second for braking induced by slower cars ahead, the third introduces randomness in the process. Once the speed has been updated, the vehicle movement is performed, by changing its cell to $\langle i \rangle + v_i(t+\Delta t)$. Examples of vehicular behaviors obtained with this model are shown in Figure 9. This model also includes lane changing rules, which allow a vehicle to move to its left lane under the condition

$$v_{i+1}(t) \leq v_i(t) \text{ OR } v_{j+1}(t) \leq v_i(t)$$

that is, the lane change is granted if there is a slower front vehicle on the current lane, or on the left lane ($j+1$ refers to the front vehicle on the left lane in this case). The second condition prevents that overtakings on the right occur, by forcing the car to move left and to try an overtaking using a lane further on the left. A movement from the left to the right is permitted under the condition

$$v_{i+1}(t) > v_i(t) + \Delta \text{ AND } v_{j+1}(t) > v_i(t) + \Delta$$

where $j+1$ refers to the front vehicle on the right lane. Thus, a car moves to its right if the ahead vehicles on the current lane and on the right lane are faster than it is. Δ is a so-called slack parameter, modeling the drivers tendency to stay on the left lane after overtaking another car. In both cases, the following safety conditions must hold

$$\langle j+1 \rangle - \langle i \rangle \geq v_i(t)$$
$$\langle i \rangle - \langle j-1 \rangle \geq v_{max}$$

meaning that there must be enough space on the new lane between the back car $j-1$ and the front car $j+1$ for the movement to take place. In particular, the front gap must be at least the velocity of i, while the back gap must match the maximum allowed speed.

Other related works in VANETs literature employing generic car following models are those from Choffnes *et* *al.* [38] and Mahajan *et al.* [39]. In both cases, basic car following techniques are employed jointly with intersection management mechanisms, which reproduce stop sign and traffic light behaviors at intersections.

V. Queue models

Recent work from Baumann *et al.* [46], [47] present very large scale (i.e. on a whole county) VANETs performance evaluations, using a vehicular traffic simulator from ETH [48]. In such tool, queue models are employed.

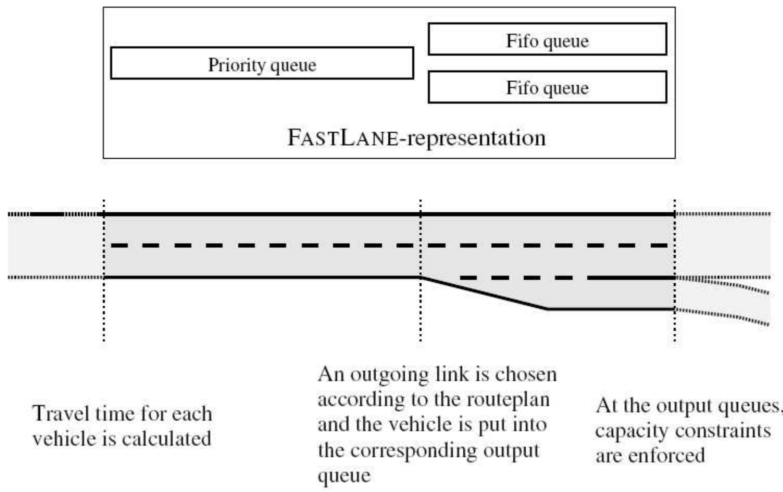


Fig. 10. Queue model of a two-lane road section with one exit ramp.

Queue models for were first introduced in the vehicular traffic field by Gawron [49]. According to the queue paradigm, each road is modeled as a FIFO queue, and each vehicle as a queue client. Each road queue k is characterized by its length l^k and a maximum flow q^k_{max}, determined by the number of lanes. Every time a vehicle enters a road, a travel time is computed, depending on the desired free flow speed of the driver v_{max}, on the number of vehicles on the road n^k and the road length. It has been shown in [49] that even a simple expression of travel time l^k/v_{max}, which neglects the effect of vehicular density on the speed, leads to very good approximations of results obtained with much more complex microscopic mobility models. The car is then enqueued in the priority queue of the road, according to the travel time calculated before. At every time step, vehicles whose travel time has expired can be removed from the head of the queue and inserted into the queue representing the next road in their trip. However, when multiple choices are available to exit a road, an intermediate step in necessary, and first-in-first-out queues are added for each outgoing flow, ad shown in Figure V. In that case, vehicles at the head of the priority queue are moved to one of the FIFO queues, depending on their destination. The FIFO queues have a finite capacity, meaning that only a certain number of vehicles per second can access them. Since the movement from one road to another is constrained by the capacity of such next road, which can be, a vehicle at the head of an output queue can join the following queue only if there is space on the following road. The capacity of a road is easily modeled as $c^k = \frac{n^k q^k_{max}}{x_{min}}$, where x_{min} is the distance between the front of two adjacent vehicles in jam conditions. Thus, if the new road has c^k cars already queued, it will not accept further vehicles, and drivers willing to enter the road will have to wait until a spot is freed. Note that more complex expressions for the travel time and capacity can be easily implemented, and realistic intersection management can be modeled [48], e.g. giving different priorities to multiple queues accessing the same road.

Since queue models describe the movement of each vehicle in an independent way, but also with a minimal level of detail, they fall into an intermediate category with respect to macroscopic and microscopic descriptions, which can be referred to as mesoscopic. Queues models have very low computational cost, because they update the status of a vehicle only when a vehicle enters a new priority or FIFO queue. This allows to model very large road topologies, up to hundreds of thousands of vehicles. The drawback is the reduced realism of the outcome, which is less precise than that obtained with other models (e.g., queue models do not reproduce shockwaves caused by periodic perturbations, a common phenomenon in vehicular traffic).

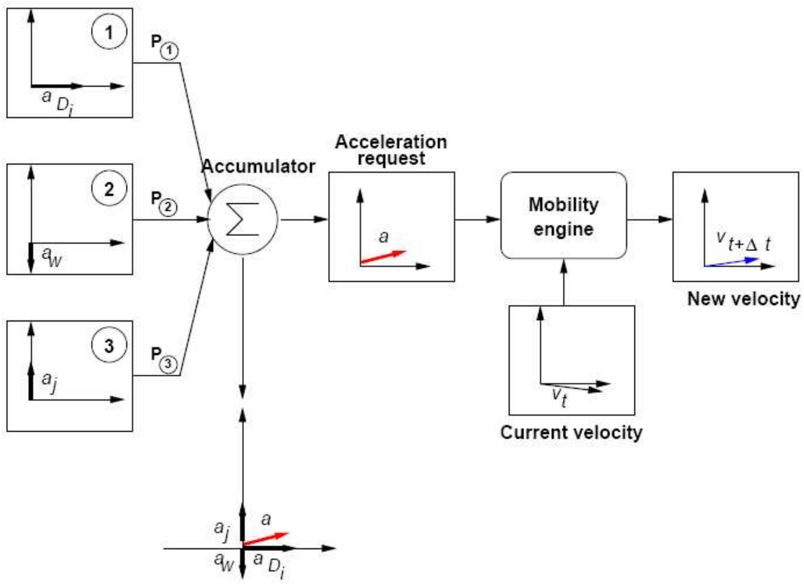


Fig. 11. Mobility engine for vehicle i: independent acceleration vectors, modeling different behavioral rules, are combined and result in an acceleration request. The request is converted into a new movement vector, through a mobility engine $\vec{v}_{t+\Delta t} = \vec{v}_t + \vec{a}\Delta t$

VI. Behavioral models

In [50], [51] Legendre *et al.* introduced a novel approach to the problem of modeling human mobility, which can be applied to vehicular traffic as well. The approach is called behavioral modeling and is borrowed from the fields of biological physics and artificial intelligence. The key idea is that every movement is determined by behavioral rules, which are imposed by social influences, rational decisions or actions following a stimulus-reaction process. These rules can be modeled as attractive or repulsive forces. In the case of vehicular mobility, the next intersection towards the trip destination wields an attractive force on the vehicle, whereas other vehicles or obstacles in general exert a repulsive force on it. The result from the composition of these forces determines the acceleration vector which drives the car movement. An example of force-composing model is illustrated in Figure V. However, this model is especially expensive under the computational point of view, as every movement require the elaboration and composition of multiple inter-object forces.

References

[1] A. Einstein, “Investigations on the Theory of the Brownian Motion”, ed. R. Frth, translated by A.D. Cowper (1926, reprinted 1956); Einstein, Collected Papers, vol. 2, 170-82, 206-22.

[2] D. B. Johnson, D. A. Maltz, J. Broch, “DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks”, Ad Hoc Networking, pp. 139-172, Addison-Wesley, 2001.

[3] V. Davies, “Evaluating Mobility Models within an Ad Hoc Network”, MS thesis, Colorado School of Mines, 2000.

[4] F. Bai, N. Sadagopan, A. Helmy, “The IMPORTANT framework for analyzing the Impact of Mobility on Performance Of RouTing protocols for Adhoc NeTworks”, Elsevier Ad Hoc Networks vol. 1 (2003), pp. 383-403, 2003.

[5] ETSI, Universal Mobile Telecommunication System (UMTS), “Selection procedures for the choice of radio transmission technologies of the UMTS”, UMTS 30.03 Version 3.2.0, 1998-04. Available at *http://www.3gpp.org/ftp/Specs/html-info/3003U.htm*.

[6] BonnMotion, a mobility scenario generation and analysis tool, *http://web.informatik.uni-bonn.de/IV/Mitarbeiter/dewaal/BonnMotion/*.

[7] A. K. Saha, D. B. Johnson, “Modeling Mobility for Vehicular Ad Hoc Networks”, ACM Workshop on Vehicular Ad Hoc Networks (VANET), 2004.

[8] U.S. Census Bureau - Topologically Integrated Geographic Encoding and Referencing (TIGER) system, *http://www.census.gov/geo/www/tiger*.

[9] B. Zhou, K. Xu, M. Gerla, “Group and swarm mobility models for ad hoc network scenarios using virtual tracks”, IEEE Military Communications Conference (MILCOM), 2004.

[10] A. Nandan, S. Tewari, S. Das, M. Gerla, L. Kleinrock, “AdTorrent: Delivering Location Cognizant Advertisements to Car Networks”, IEEE/IFIP Annual Conference on Wireless On- demand Network Systems and Services (WONS), 2006.

[11] X. Hong, M. Gerla, G. Pei, C.-C. Chiang, “A Group Mobility Model for Ad Hoc Wireless Networks”, ACM International Workshop on Modeling, Analysis, and Simulation of Wireless and Mobile System (MSWiM), 1999.

[12] M.J. Lighthill, G.B. Whitham, “On Kinematic Waves II: A Theory of Traffic Flow on Long Crowded Roads”, Royal Society A, 229, pp.317-345, 1955.

[13] D. C. Gazis, R. Herman, R. W. Rothery, "Nonlinear Follow-the-Leader Models of Traffic Flow", Op. Res. 9, pp. 545567, 1961.
[14] "Revised Monograph on Traffic Flow Theory", Turner-Fairbank Highway Research Center, 2001.
[15] S. Panwai, H. Dia, "Comparative evaluation of microscopic car-following behavior", IEEE Transactions on Intelligent Transportation Systems, vol. 6 (2005), Issue 3 pp. 314–325, 2005.
[16] M. Aycin, R. Benekohal, "Comparison of car-following models for simulation", Transportation Research Record No. 1678, TRB, National Research Council, pp. 116127, 1999.
[17] Y. Zhang, "Scalability of Car-Following and Lane-Changing Models in Microscopic Traffic Simulation Systems", MS thesis, Louisiana State University, 2002.
[18] L. Breisemeister, "Group Membership and communication in highly mobile ad hoc networks", PhD thesis, School of Electrical and Computing Science, Tecnhical University of Berlin, 2001.
[19] S. Krauß, P. Wagner, C. Gawron, "Metastable States in a Microscopic Model of Traffic Flow", Physical Review E, vol. 55, no. 304, pp. 55-97, 1997.
[20] S. Krauß, "Microscopic Modeling of Traffic Flow: Investi- gation of Collision Free Vehicle Dynamics", PhD thesis, Mathematisches Institut, Universitat zu Koln, 1998.
[21] D. Krajzewicz, G. Hertkorn, C. Rossel, P. Wagner, "SUMO (Simulation of Urban MObility): An open-source traffic simulation", SCS Middle East Symposium on Simulation and Modelling (MESM), 2002.
[22] C. Gawron, "Simulation-Based Traffic Assignment", Inaugural Dissertation, 1998.
[23] F. Karnadi, Z. Mo, K.-C. Lan, "Rapid Generation of Realistic Mobility Models for VANET", International Conference on Mobile Computing and Networking (MobiCom), 2005, *http://www.cse.unsw.edu.au/ klan/move*.
[24] J. Haerri, M. Fiore, F. Filali, C. Bonnet, "VanetMobiSim: generating realistic mobility patterns for VANETs", ACM International Workshop on Vehicular Ad Hoc Networks (VANET), 2006.
[25] M. Trieber, A. Hennecke, D. Helbing, "Congested traffic states in empirical observations and microscopic simulations", Phys. Rev. E 62, Issue 2, August 2000.
[26] M. Treiber, D. Helbing, "Realistische Mikrosimulation von Strassenverkehr mit einem einfachen Modell", Symposium Simulationstechnik (ASIM), 2002.
[27] S. Jaap, M. Bechler, L. Wolf, "Evaluation of Routing Protocols for Vehicular Ad Hoc Networks in City Traffic Scenarios", International Conference on Intelligent Transportation Systems (ITS), 2005.
[28] C. Gorgorin, V. Gradinescu, R. Diaconescu, V. Cristea, L. Ifode, "An Integrated Vehicular and Network Simulator for Vehicular Ad-Hoc Networks", European Simulation and Modelling Conference (ESM), 2006.
[29] L. Bononi, M. Di Felice, M. Bertini, E. Croci, "Parallel and Distributed Simulation of Wireless Vehicular Ad Hoc Networks", ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2006.
[30] R. Wiedemann, "Simulation des Straßenverkehrsflusses", Schriftenreihe des Instituts fur Verkehrswesen der Universitat Karlsruhe, Heft 8.
[31] R. Wiedemann, "Modelling of RTI-Elements on multi-lane roads", Advanced Telematics in Road Transport, Comission of the European Community, DG XIII, Brussels, 1991.
[32] T. Schulze, T. Fliess, "Urban Traffic Simulation with Psycho-Physical Vehicle-Following Models", Winter Simulation Conference (WSC), 1997.
[33] J. Kim, V. Sridhara, S. Bohacek, "Realistic Simulation of Urban Mesh Networks - Part I: Urban Mobility", Technical Report, Univeristy of Delaware, 2006.
[34] M. Aycin, R. Benekohal, "Linear car-following model development and validation", Transportation Research Record No. 1644, TRB, National Research Council, pp. 10-19, 1998.
[35] P. Hidas, "A car-following model for urban traffic simulation", Traffic Engineering and Control, vol. 39 no 5, pp. 300-305, 1998.
[36] K. I. Ahmed, "Modeling drivers' acceleration and lane changing behaviors", PhD thesis, Massachusetts Institute of Technology, 1999.
[37] K. Nagel, "Particle Hopping Models and Traffic Flow Theory", Physical Review E, Volume 53, pp. 4655-4672.
[38] D. R. Choffnes, F. E. Bustamante, "An Integrated Mobility and Traffic Model for Vehicular Wireless Networks", ACM International Workshop on Vehicular Ad Hoc Networks (VANET), 2005.
[39] A. Mahajan, N. Potnis, K. Gopalan, A. Wang., "Evaluation of Mobility Models For Vehicular Ad-Hoc Network Simulations", IEEE International Workshop on Next Generation Wireless Networks (WoNGeN), 2006.
[40] M. Rudack, M. Meincke, M. Lott, "On the Dynamics of Ad Hoc Networks for inter-vehicle communications (IVC)", International Conference on Wireless Networks (ICWN), 2002.
[41] W. Schnabel, D. Lohse, "Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung", Bd. 1, 2, Aufl., Verlag fur Bauwesen, Berlin, 1997.
[42] W. Leutzbach, "Introduction to the Theory of Traffic Flow", Springer, Berlin, 1988.
[43] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "SOTIS a self-organizing traffic information system", IEEE Semiannual Vehicular Technology Conference (VTC), 2003.
[44] K. Nagel, M. Schreckenberg, "A cellular automaton model for freeway traffic", Journal de Physique I, vol. 1992, no. 2, pp. 22212229, 1992.
[45] K. Nagel, D. E. Wolf, P. Wagner, P. Simon, "Two-lane traffic rules for cellular automata: A systematic approach", Los Alamos National Laboratory, Tech. Rep. LA-UR 97-4706, 1997.
[46] R. Baumann, "Vehicular ad hoc networks (VANET)", MS thesis, ETH, Swiss Federal Institute of Technology Zurich, 2004.
[47] V. Naumov, R. Baumann, T. Gross, "An Evaluation of Inter-Vehicle Ad Hoc Networks Based on Realistic Vehicular Traces", ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2006.
[48] N. Cetin, A. Burri, K. Nagel, "A large-scale multi-agent traffic microsimulation based on queue model", Swiss Transport Research Conference (STRC), 2003.
[49] C. Gawron, "An iterative algorithm to determine the dynamic user equilibrium in a traffic simulation model", International Journal of Modern Physics C, 9(3), pp. 393407, 1998.

[50] F. Legendre, V. Borrel, M. Dias de Amorim, S. Fdida, “Reconsidering Microscopic Mobility Modeling for Self-Organizing Networks”, IEEE Network Magazine, December 2006.

[51] F. Legendre, V. Borrel, M. Dias de Amorim, S. Fdida, “Modeling Mobility with Behavioral Rules: the Case of Incident and Emergency Situations”, Asian Internet Engineering Conference (AINTEC), 2006.