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COMPARATIVE ANALYSIS OF CAR FOLLOWING MODELS BASED ON DRIVING STRATEGIES USING SIMULATION APPROACH

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RESEARCH ARTICLE

ABSTRACT: Transportation and traffic affect all the aspects of everyday life. To better understand traffic dynamics traffic models are developed. On microscopic level, car-following models are developed and improved during long period of time. They are used in traffic simulation tools or are the basis for operation in some advanced vehicle systems. Car-following models describe traffic dynamics through movement of individual vehicle-driver units. This paper compares Gipps model and Intelligent Driver Model (IDM) as car-following models based on driving strategies. These models are derived based on assumptions such as keeping safe distance from the leading vehicle, driving at a desired speed and producing accelerations within a comfortable range. The models are implemented and simulated in MATLAB environment and the results are discussed in terms of the ability to reproduce real driving behaviour in car following scenarios.

KEY WORDS: traffic dynamics, traffic simulation, car-following model, driving behaviour

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UPOREDNA ANALIZA MODELA PRAĆENJA VOZILA NA OSNOVU STRATEGIJE VOŽNJE PRIMENOM SIMULACIJA

REZIME: Transport i saobraćaj utiču na sve aspekte svakodnevnog života. Da bi se što bolje razumela saobraćajna dinamika, razvijaju se modeli saobraćaja. Na mikroskopskom nivou, razvijeni su i unapređivani modeli praćenja vozila tokom dugog perioda vremena. Oni su korišćeni u alatima za simulacije saobraćaja ili su bili osnova za rad nekih naprednih sistema vozila. Modeli praćenja vozila opisuju dinamiku saobraćaja preko kretanje pojedinačnih elemenata vozilo-vozač. U ovom radu su upoređeni Gipps-ov model i Inteligentnim modelom vozača (eng. Intelligent Driver Model (IDM)) kao modeli praćenja vozila zasnovani na strategijama vožnje. Ovi modeli su izvedeni na osnovu pretpostavki kao što su: održavanje bezbednog odstojanja od vodećeg vozila, vožnja željenom brzinom i ubrzavanje u granicama komfora. Modeli su razvijeni i testirani u MATLAB okruženju. Dobijeni rezultati su analizirani sa stanovišta mogućnosti ponavljanja stvarnog ponašanja vozača u scenarijima praćenja vozila.

KLJUČNE REČI: dinamika saobaraćaja, simulacija saobraćaja, modeli praćenja vozila, ponašanje vozača

COMPARATIVE ANALYSIS OF CAR FOLLOWING MODELS BASED ON DRIVING STRATEGIES USING SIMULATION APPROACH

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1. INTRODUCTION

One of the key elements for good functioning and progress of modern societies is to have an efficient transport system. Limited road capacity and hence frequent traffic jams is the problem many of them face. Expanding road infrastructure is expensive and it cannot be done in dense urban areas. The solution should be sought in more effective usage of existing road infrastructure through application of new technologies. It is how the research area of intelligent transportation system emerged.

To better understand traffic situations and states, mathematical models are developed. These models also enable analysis and definition of traffic and transport problems, and they give possibility of predicting future conditions, as well as development of proposals for solutions. There are a lot of available traffic related data such as acceleration of individual drivers and vehicles, macroscopic data obtained from static detectors complemented by data from GPS, wireless LAN and mobile phone applications which can be used for modelling as well [9]. Experimental measurements also serve as a basis for mathematical modelling.

Traffic dynamics which can be mathematically interpreted, describes the interaction between number of vehicles and drivers. The interaction of complex so-called “driver-vehicle” units, leads to new joint traffic effects which do not depend on the details of the single units. Example can be stop-and-go waves but also more complex spatial – time patterns of congested traffic.

2. TYPES OF TRAFFIC FLOW MODELS

The types of traffic flow models can be divided on different basis, by the level of aggregation (the way in which the reality is presented), by the mathematical structure or by the conceptual aspects. When it comes to traffic models classification it is usually thought of the level of aggregation. According to it there are three ways to mathematically model real traffic events: macroscopic, microscopic and mesoscopic [1, 6, 9]. By the mathematical structure traffic flow models can be represented as partial differential equations, coupled ordinary differential equations, coupled iterated maps, cellular automata, discrete state variables - continuous time or static models. Also, classification can be made by conception foundation, identical versus heterogeneous drivers and vehicles, constant versus variable driving behaviour or single-lane versus multi-lane models.

Macroscopic models describe the traffic flow as the flow of fluids. Dynamic variables are locally aggregated quantities, such as the traffic density $\rho(x,t)$, flow $Q(x,t)$, mean velocity $V(x,t)$ or the change in velocity $\sigma V2(x,t)$. Macroscopic models describe collective phenomena such as the evolution of congested regions or the propagation velocity of traffic waves.

Microscopic models include car-following models and cellular automata. These models describe individual "driver-vehicle" units as particles α, which form the traffic flow. Microscopic models describe the reaction of each driver (acceleration, braking or lane change) depending on the surrounding traffic. Dynamic variables are position $x\alpha(t)$, velocity $v\alpha(t)$ and acceleration $\dot{v}\alpha(t)$ of the vehicle.

Mesoscopic models are hybrids of the microscopic and macroscopic approach. In local field models, parameters of the microscopic model may depend on macroscopic quantities such as traffic density or local velocity and velocity changes.

2.1 Microscopic models

Microscopic traffic flow modelling is based on description of the motion of each individual vehicle which is a part of the traffic stream. It implies modelling the actions i.e. accelerations, decelerations, and lane changes of each driver-vehicle unit in relation to the surrounding traffic.

In cellular automata models variables are discrete. The space is divided into fixed cells and the time is updated at fixed intervals. The status of each cell is 0 ("no vehicle") or 1 ("vehicle" or "part of a vehicle"). Cell occupancy is determined at each time step and depends on the occupation in the previous step.

In this paper the focus of interest are the car-following models which describe traffic dynamics from perspective of individual "driver-vehicle" units. Literally, car-following models describe the behaviour of the driver (vehicle) only in case of interaction with other vehicles, while the free flow is described by a separate model. However, a car-following model is considered complete if it can describe all situations, including acceleration and free flow, following other vehicles in stationary and non-stationary situations, approaching slow or stopped vehicles and a red traffic light. The first car-following models were proposed as early as the 1950's by Reuschel (1950) and Pipes (1953). These two models contained one of the basic elements of modern microscopic modelling which is the minimum distance, from bumper to bumper to the leading vehicle, known as "safe distance", which should be proportional to the speed. The elementary car-following models also include optimal velocity model, full velocity difference model and Newell's car-following model.

By the logic used car-following models can be classified in three categories [2]:

- Gazis-Herman-Rothery models (GHR) which state that the following vehicle's acceleration is proportional to the speed of the follower, the speed difference between follower and leader and the space headway.
- Safety distance models which are based on the assumption that the follower always keeps a safe distance to the leader vehicle. These are also known as car-following models based on driving strategies. Model examples that fall into this category are Gipps, IDM, MITSIM model.
- Psycho-physical models use thresholds for, e.g., the minimum speed difference between follower and leader perceived by the follower. These are also known action-point models. Representatives in this category are Wiedemann and Fritzsche models.

Car-following model is implemented in every available traffic simulation tool like VISSIM, Paramics, Aimsun, MITSIMLab, SUMO, etc. [1].

3. CAR FOLLOWING MODELS BASED ON DRIVING STRATEGIES

Car-following models based on driving strategies are derived on assumptions from real driving behaviour such as keeping a safe distance to the leader vehicle, driving with the desired velocity or accelerating in real and comfortable range [9]. The relation between the braking distance and the velocity is also considered.

Driver-vehicle unit α is described with state variables vehicle's position $x\alpha(t)$ and velocity $v\alpha(t)$ in function of time t and vehicle's length $l\alpha$ (figure 1). From the positions and lengths of vehicles, the distance between them is obtained.

$$s_\alpha = x_{\alpha-1} - l_{\alpha-1} - x_\alpha = x_l - l_l - x_\alpha \tag{1}$$

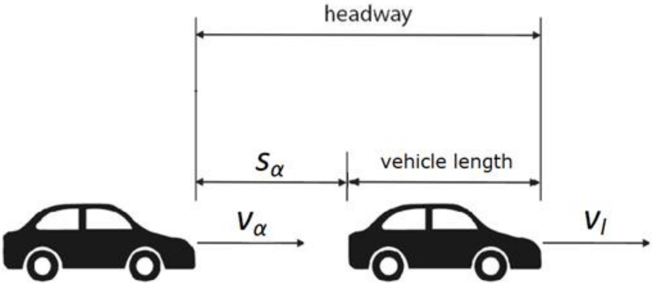

Figure 1. State variables in car-following models

This distance s_α along with vehicles' velocities represents the main input in microscopic models. Of course, depending on the model, additional variables are needed. In time-continuous models driver reaction is given in relation to the acceleration function $a_{mic}(s,v,v_l)$, or when instead of leader velocity v_l, velocity difference ($\Delta v_\alpha = v_\alpha - v_l$) is given, then it is $\tilde{a}_{mic}(s,v,\Delta v)$. In discrete-time models time is not modelled as a continuous variable but is discretized in finite and constant time steps. The driver reaction is given in relation to the velocity function $v_{mic}(s,v,v_l)$.

3.1 Gipps model

Gipps model is named after Peter G. Gipps who developed it in the late 1970's and published it in 1981. The model proposed by Gipps is one of the most extensively used. Studies show that it produces unrealistic acceleration profile because there is no difference between comfortable and maximum braking [3, 4, 9]. Still it is the simplest and complete model without accidents which is accomplished by introducing a safe velocity $v_{safe}(s,v_l)$.

The original formulation of Gipps model states:

$$v(t+\Delta t) = \min[v_{acc}(t+\Delta t), v_{dec}(t+\Delta t)] \tag{2}$$

where

$$\mathrm{v_{acc}}(\mathrm{t}+\Delta\mathrm{t}) = \mathrm{v}(\mathrm{t}) + 2.5\cdot\mathrm{a}\cdot\Delta\mathrm{t}\cdot\left(1-\frac{\mathrm{v}(\mathrm{t})}{\mathrm{v_0}}\right)\cdot\sqrt{0.025+\frac{\mathrm{v}(\mathrm{t})}{\mathrm{v_0}}} \tag{3}$$

presents the limitation of the acceleration process, and

$$\mathrm{v_{dec}}(\mathrm{t}+\Delta\mathrm{t}) = \mathrm{b}\cdot\Delta\mathrm{t} + \sqrt{\mathrm{b}^2\cdot\Delta\mathrm{t}^2 - 2\cdot\mathrm{b}\cdot(\mathrm{s}-\mathrm{s_0}) - \mathrm{v}(\mathrm{t})\cdot\Delta\mathrm{t} - \frac{\mathrm{v_l}^2}{\hat{\mathrm{b}}}} \tag{4}$$

presents the limitation of the braking process. This model is used in traffic simulation package Aimsun and a modified version is used in DRACULA [1]. In 1998 Krauss did a modification of the model which now is used in SUMO traffic simulator [2, 7].

The simplified Gipps model is defined as a discrete-time model with v_{safe} as the main component:

$$\mathrm{v}(\mathrm{t}+\Delta\mathrm{t}) = \min[\mathrm{v}+\mathrm{a}\cdot\Delta\mathrm{t}, \mathrm{v_0}, \mathrm{v_{safe}}(\mathrm{s},\mathrm{v_l})] \tag{5}$$

where v_0 is the desired velocity.

Braking manoeuvres are performed with constant deceleration *b*, which means there is no difference between comfortable and maximum deceleration. Braking distance, which the vehicle leader should pass to full stop, is given by $\Delta\mathrm{x_l} = \mathrm{v_l^2}/2\mathrm{b}$.

Constant reaction time Δt exists. So for complete stop of the current vehicle to occur it is not necessary for the vehicle just to pass the braking distance $v^2/2\cdot b$, but also the additional distance $v\cdot\Delta t$ that is passed during the reaction time: $\Delta\mathrm{x} = \mathrm{v}\cdot\Delta\mathrm{t} + \frac{\mathrm{v}^2}{2\mathrm{b}}$.

Even in situations where the vehicle leader suddenly slows down and brakes to a full stop, the distance from the vehicle to the vehicle leader should not be less than the minimum defined s_0:

$$\mathrm{s} \geq \mathrm{s_0} + \mathrm{v}\cdot\Delta\mathrm{t} + \frac{\mathrm{v}^2}{2\mathrm{b}} - \frac{\mathrm{v_l}^2}{2\mathrm{b}} \tag{6}$$

The safe velocity is:

$$\mathrm{v_{safe}}(\mathrm{s},\mathrm{v_l}) = -\mathrm{b}\cdot\Delta\mathrm{t} + \sqrt{\mathrm{b}^2\cdot\Delta\mathrm{t}^2 + \mathrm{v_l}^2 + 2\cdot\mathrm{b}\cdot(\mathrm{s}-\mathrm{s_0})} \tag{7}$$

3.2 Intelligent Driver Model (IDM)

The intelligent driver model (IDM) is also simple and complete, accident-free model but produces more realistic acceleration profiles. The model is developed by Treiber, Hennecke and Helbing who published it in 2000 [8].

IDM is time-continuous model which has the following characteristics [5, 6]:

The equilibrium distance to vehicle leader cannot be less than the safe distance $s_0+v\cdot T$, where s_0 is minimum distance and T is time gap to the leading vehicle.

It has braking strategy i.e. intelligent control for approaching slower vehicles. Under normal conditions the braking is smooth; the deceleration gradually increases to value *b* and gradually decreases to *0* before reaching the situation of a steady-state car-following or complete stop. In critical situations deceleration exceeds the comfort value until the danger is avoided.

Transition between driving modes is smooth which means that the time derivative of the acceleration function which is the jerk (m/s^3) is finite at any time. Equivalently, the acceleration function $a_{mic}(s,v,v_l)$ or $\tilde{a}_{mic}(s,v,\Delta v)$ is differentiable by all three variables.

IDM acceleration function has the form $\tilde{a}_{mic}(s, v, \Delta v)$, which is a continuous function of the velocity v, the gap s, and the velocity difference Δv to the leading vehicle:

$$\dot{\mathrm{v}} = \mathrm{a}\left[1 - \left(\frac{\mathrm{v}}{\mathrm{v}_0}\right)^2 - \left(\frac{\mathrm{s}^*(\mathrm{v}, \Delta \mathrm{v})}{\mathrm{s}}\right)^2\right] - \mathrm{IDM} \tag{8}$$

and it is consisted of two parts. The first part is comparing the current velocity v with the desired v_0 and the second is comparing the current distance s with the desired s^*.

$$\mathrm{s}^*(\mathrm{v}, \Delta \mathrm{v}) = \mathrm{s}_0 + \max\left(0, \mathrm{v} \cdot \mathrm{T} + \frac{\mathrm{v} \cdot \Delta \mathrm{v}}{2 \cdot \sqrt{\mathrm{a} \cdot \mathrm{b}}}\right) \tag{9}$$

When there is a situation of an approaching to a stopped vehicle or red traffic light $\Delta v=v$, the equilibrium part $s_0+v \cdot T$ of the dynamical desired distance $s*$ (Eq. 9) can be neglected and deceleration function gets the form:

$$\dot{\mathrm{v}} = -\mathrm{a}\left(\frac{\mathrm{s}^*}{\mathrm{s}}\right)^2 = -\frac{\mathrm{a} \cdot \mathrm{v}^2 \cdot (\Delta \mathrm{v})^2}{4 \cdot \mathrm{a} \cdot \mathrm{b} \cdot \mathrm{s}^2} = -\left(\frac{\mathrm{v}^2}{2 \cdot \mathrm{s}}\right)^2 \cdot \frac{1}{\mathrm{b}} = -\frac{\mathrm{b_{kin}}^2}{\mathrm{b}} \tag{10}$$

which defines kinematic deceleration $\mathrm{b_{kin}} = \frac{\mathrm{v}^2}{2 \cdot \mathrm{s}}$. Kinematic deceleration is the minimum deceleration to avoid collision. A critical situation is considered if b_{kin} is being greater than the comfortable deceleration b ($b_{kin}>b$). In regular situation the actual deceleration is less than the kinematic deceleration ($b_{kin}< b$), which means b_{kin} increases over time and approaches the comfortable deceleration.

Intelligent driver model development was mainly been in direction of using it in ACC (Adaptive Cruise Control) systems in vehicles [5, 6, 9].

4. SIMULATION

In order to compare the properties of Gipps and IDM model, both models were implemented in MATLAB script and simulations were performed within the same scenario. The scenario consists of 1km of road in urban conditions that come to intersection from where vehicles can go left or right (T-shaped intersection, figure 2). So, every vehicle which comes to the intersection point needs to stop before it makes the turn maneuver. Five vehicles are included in simulations which last for 120 seconds.

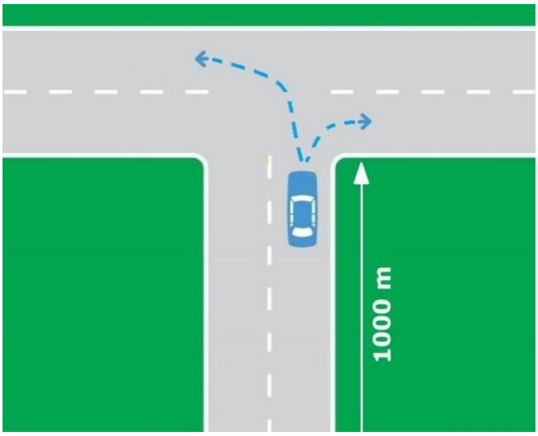

Figure 2. T-shaped intersection

In both car-following models the desired velocity is 54km/h and the minimum distance gap is 2m. The time and the velocity of appearance of a new vehicle in traffic are same in both simulations. The comparative results are given in figure 3. The figure includes results about the gap between vehicles (top graphs), velocities (middle graphs) and accelerations of the vehicles (bottom graphs). Simulation parameters regarding desired velocity, maximum acceleration / deceleration, comfortable deceleration and minimum gap are according to the recommendation of [9].

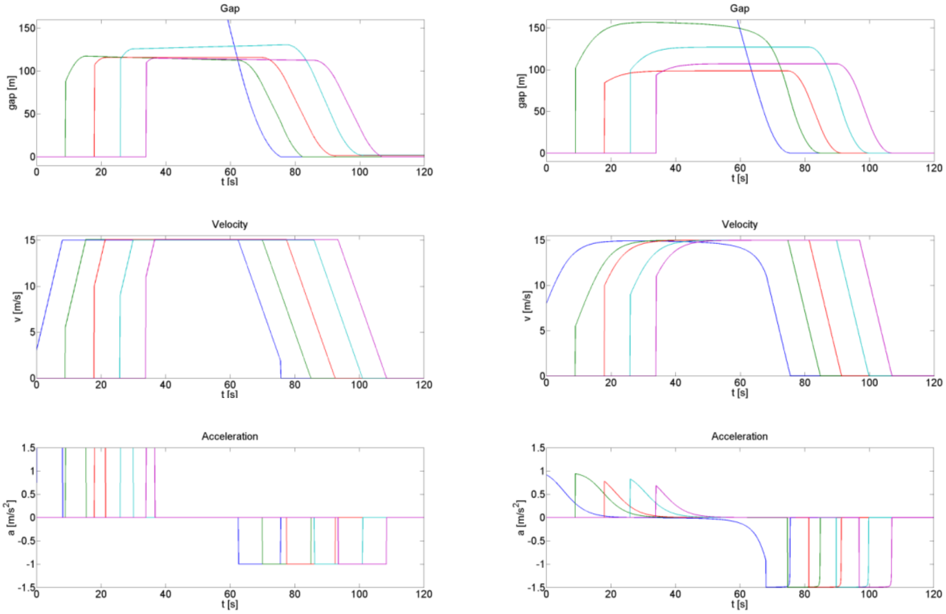

Figure 3. Gipps (left column) and IMD (right column) models' simulation results

In both models, acceleration, car-following and deceleration regimes are clearly visible. In view of simplicity Gipps model produces good results, but the acceleration profile is unrealistic. There are just three acceleration values: a, b and 0. Figure 3 graphs presenting the velocity and the acceleration show resemblance of a robotic driving. Gipps model does not have comfortable and critical deceleration. So if b value is set for critical deceleration, every braking will be done with full braking intensity which is uncomfortable in real driving behaviour. Also, transitions between acceleration / deceleration or no acceleration regimes are hasty and unrealistic.

Intelligent driver model produces more realistic acceleration / deceleration profile but also during the process of acceleration / deceleration the value does not increase gradually. It starts with a maximum (a or b) or near maximum value and then the transition continues smoothly.

As it can be seen from the figure 3 it is a situation with loose traffic. The time interval of appearance of a new vehicle is quite long, up to 8 seconds and the vehicles' gap is large too. If the time of appearance of a new vehicle is reduced the unrealistic acceleration profile of Gipps model is more noticeable (figure 4).

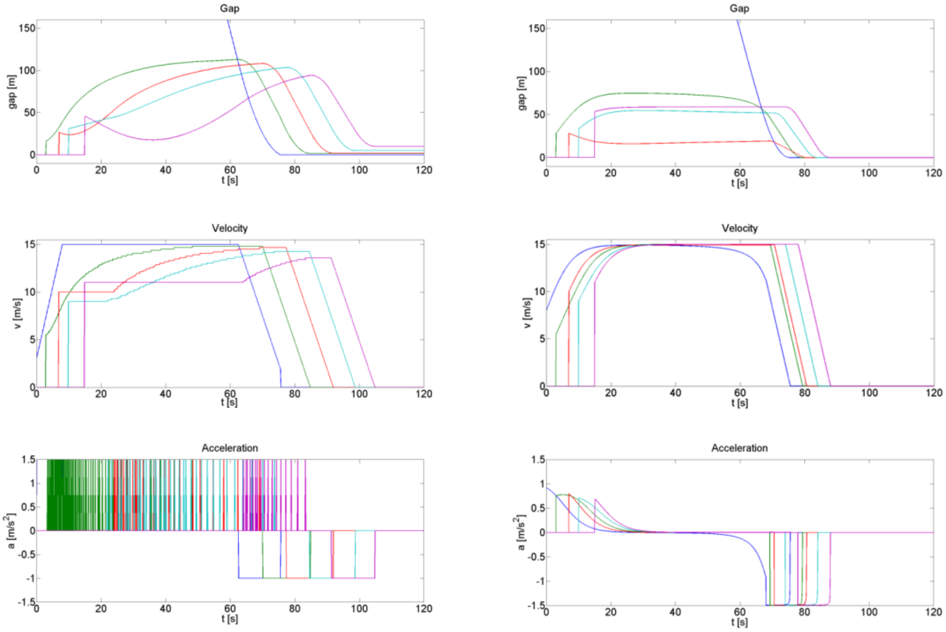

Figure 4. Gipps (left column) and IMD (right column) models' simulation results with a shorter time of appearance

A lot of fluctuations in vehicles' accelerations can be noticed in Gipps model which is not the case in real driving behavior. It is due to the model's formulation which does not include velocity difference between vehicles. The gap between vehicles in Gipps model changes all the time and in IMD it is clearly seen when a vehicle gets into a car-following regime and the desired gap is kept.

5. CONCLUSIONS

Car-following models should reproduce the general behavior of drivers and vehicles in the most realistic way possible. Gipps and IDM are simple and produce accident free results but their disadvantages need to be improved. Because of the unrealistic acceleration Gipps model produces, AIMSUN adopted a modified version which has different strategies for the selection of $\hat{b}$ (the most severe braking that the leading vehicle wishes to undertake), it allows more realistic distances to be kept among vehicles and introduced parameter that can be calibrated [4, 7]. The model used within SUMO is the Gipps model modified by Krauss in 1998, which defines new way of computing the safe velocity. Results of the simulation of Gipps model in MATLAB (given in figure 3 and 4) clearly show that the model gives an unrealistic acceleration profile, which is more apparent when the traffic is dense. When the number of vehicles is higher and the time gap lower, the unrealistic character of the acceleration is more prominent. Regime changes from acceleration mode to car-following mode and vice versa, are harsh. That is not the case in reality, or in the design of autonomous driving. The gap between vehicles in more frequent traffic is constantly changing, and that does not correspond to the objective which is car-following regime in a case of dense traffic.

IDM model gives much better results in terms of acceleration profile, but still improved acceleration function is done in the Improved Intelligent Driver Model (IIDM). The modification is in direction to improve the behavior near the desired speed. Further modifications of the model are done in terms of adapting for ACC systems [5, 6]. Simulation results show that the disadvantage of the intelligent driver model is the initial large acceleration, which would be more realistic if it gradually increases. The same happens in the braking process, with the exception of the first vehicle that moves in free flow regime. In the car-following regime the model produces good results and that can be seen from the gap graph (first row of figure 3 and 4). Comparing the simulation results of both models, it can be concluded that the IDM model produces better results and is more stable than the Gipps model.

In summary, due to its simplicity Gipps model is one of the most used car-following models in traffic modeling and simulations. IDM is a relatively new model, but it is also simple and gives realistic results in terms of the longitudinal parameters of vehicles' dynamics.

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