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► **To cite this version:**

Prisca Laure Bogne Nyitchogna, Lydie Nouveliere, Olivier Orfila, Sébastien Glaser, Saïd Mammar. Impact of Full Speed Range ACC on the Traffic, the Safety and the Energy Consumption. 5th Transport Research Arena (TRA2014), Apr 2014, Paris, France. hal-01009739

**HAL Id: hal-01009739**

**<https://hal.science/hal-01009739>**

Submitted on 12 Jul 2021

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# Impact of Full Speed Range ACC on the Traffic, the Safety and the Energy Consumption

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## Abstract

In this paper, an assessment of the FSRACC impacts on a simultaneous combining of traffic, safety and environment is made on the basis of the simulation across a network while taking into account the penetration rate of FSRACC (from 0% to 100%). To carry out this study, it is necessary to have some indicators and models. Various variables can be used to evaluate the longitudinal ADAS impacts on these key characteristics referring to indicators of traffic, safety and environment that will therefore be used for this evaluation. Some models consider the behavior of individual drivers under the influence of vehicles in their proximity (microscopic models) or the collective flow of vehicles (macroscopic models) or the platoon of vehicles (mesoscopic models). Within the framework of this study, a simulator is developed with driver and FSRACC models. Both driver and FSRACC simulators are merged. The indicators matching each model are calculated, analyzed, interpreted and compared before and after merging according to the penetration rate of FSRACC equipped vehicles. It is shown that the proposed system can provide a natural following performance similar to a human driving. The proposed simulator can be used to evaluate other longitudinal ADAS based on accelerations models and to compare different kinds of such longitudinal ADAS.

*Keywords:* Driver model ; ADAS model ; HDM ; IDM ; traffic simulator.

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## Résumé

Dans cet article, une évaluation des impacts du système FSRACC sur une combinaison simultanée de trafic, sécurité et environnement se fait sur la base de la simulation à travers un réseau, tout en tenant compte du taux de pénétration du FSRACC (de 0% à 100%). Pour mener à bien cette étude, il est nécessaire d'avoir des indicateurs et des modèles. Différentes variables peuvent être utilisées pour évaluer les impacts des ADAS longitudinales sur ces caractéristiques clés faisant référence à des indicateurs de trafic, de sécurité et d'environnement qui seront donc utilisés pour cette évaluation. Certains modèles prennent en considération le comportement des conducteurs individuels sous l'influence de véhicules dans leur proximité (modèles microscopiques) ou un flux collectif de véhicules (modèles macroscopiques) ou un peloton de véhicules (modèles mésoscopiques). Dans le cadre de cette étude, un simulateur est développé avec des modèles pour le conducteur et le FSRACC. Le conducteur et le FSRACC sont fusionnés. Les indicateurs correspondant à chaque modèle sont calculés et analysés, interprétés et comparés avant et après la fusion en fonction du taux de pénétration des véhicules équipés. Il a été démontré que le système proposé peut fournir une performance de poursuite naturelle similaire à la conduite humaine. Le simulateur de trafic proposé peut être utilisé pour évaluer d'autres ADAS longitudinales basées sur des modèles d'accélération et pour comparer différents types de systèmes longitudinaux.

*Mots-clé:* Modèle de conducteur, Modèle d'ADAS, HDM, IDM, simulateur de trafic.



## Nomenclature

$v_0$	Desired speed (m/s)
$T$	Time headway for the FSRACC model (s)
$a$	Maximum FSRACC acceleration ( $m/s^2$ )
$b$	Desired FSRACC deceleration ( $m/s^2$ )
$s_0$	Jam distance (m)
$\beta, \alpha$	Vehicles in interaction in the driver model
$n_a$	Number of anticipated vehicles in the driver model
$T'$	Reaction time for the driver model (s)
$V_s$	Relative distance error (%)
$r_c$	Inverse Time To Collision error (1/s)
$\tau$	Error correlation time (s)

## 1. Introduction

Advanced driver-assistance systems (ADAS) support a driver in his driving tasks (van Arem et al., 2006). Road transport is related to many problems which are remaining difficult to be solved. Among others are the problems of traffic congestion, pollution, climate change, energy saving, risk of accidents. ADASs are being developed to enhance driving comfort, reduce driving errors, improve safety, increase traffic capacity and reduce energy consumption (Xiao & Gao (2010), e.g. Adaptive Cruise Control).

In addition, ADASs can also have side effects on traffic-flow, safety and environment. Key characteristics, such as safety, traffic-flow efficiency and environmental protection are the focus of most transportation researches. Many researchers studied effects of ADAS on each of these key characteristics, or on a combination of two of them, even though there are few papers on the impacts on only both safety and environment. Furthermore, there are nearly no study on the impacts of ADAS on all these key characteristics. These researchers used some indicators symbolizing the key characteristics to assess these effects and in most cases, these indicators are linked. For example an indicator for the traffic can also be used to evaluate safety or environment. It follows that it becomes difficult to study impacts on traffic without those on safety or without those on environment. Consequently, it would be better and advantageous to study impacts of ADAS, at the same time, on all the key characteristics.

Several papers (Wang et al., 2004, Davis, 2007) assessing the impact of the proportion of ADAS equipped vehicles have appeared, but not all of them were found to have favorable effects (Davis, 2007). Problems such as cut-in, congestion at bottlenecks or near on-ramps on freeways are remaining difficult to assess with an ADAS equipped vehicle. New ADAS have been developed or are being developed; considering current difficulties, it is important to assess their impacts on the key characteristics above-quoted to meet the needs of researchers, automakers, governments and consumers. Control of the vehicle includes longitudinal control which is responsible for the axial dynamics evolution and lateral control which is responsible for maintaining the direction. This paper will focus on the longitudinal mode of the vehicle. Some examples of such longitudinal optimized-ADAS among others are:

- various forms of Adaptive Cruise Control systems (the international organization for standardization (ISO 15622, 2010) : ACC based on communication (e.g. Cooperative Adaptive Cruise Control, (van Arem et al., 2006), ACC based on traffic (e.g. Multi-vehicle target selection for ACC, (Moon et al., 2010));
- Stop and Go (S&G) or Low Speed Following (LSF) systems (ISO 22178, 2009);
- Full Speed Range Adaptive Cruise Control (FSRACC) systems (ISO 22179, 2009) ;
- Intelligent Speed Adaptation (ISA) systems (Young et al., 2010);
- Ecodriving (Saboochi et al., 2009).

Most of the recent ADAS researches concerns Adaptive Cruise Control (ACC) systems, which are now available on a wide range of passenger vehicles (Auckland et al., 2008) and are the focus of researchers, automakers, governments and consumers across the world (Xiao et al., 2010). Nowadays, they are available on standard vehicles (e.g. Cars). ACC systems are being developed by many researchers and the impacts on traffic-flow and/or safety and/or energy consumption of those optimized-ACC systems have also been investigated (e.g. Xiao



et al., 2010, Bose et al., 2001, Touran et al., 1999). By contrast, for alike effects, few researchers investigated S&G, FSRACC, ISA systems and Ecodriving (Moon et al., 2009, Servin et al., 2006, Barth et al., 2009). However, there are almost none paper on the impacts of only S&G systems.

Our review has showed that almost none paper has been published on the impact of the above-quoted optimized-ADASs on a simultaneous mix of traffic, safety and environment. Moon et al. (2009) described the design, tuning, and evaluation of a full-range ACC system with collision avoidance (CA). The goal of the control algorithm for the full-range ACC with CA is to achieve the behavior of the subject vehicle that would seem natural to a human driver in normal-driving situations and to achieve a safe behavior in severe-braking situations in which large decelerations are necessary. To integrate the ACC and CA systems, the proposed algorithm makes the subject vehicle operate in three modes: comfort (ACC), large deceleration (ACC+CA), and severe-braking (CA). By means of simulations with real data on driving, it has been shown that the proposed control strategy can provide a natural following performance that is similar to human manual-driving at both high-speed driving and low-speed S&G situations, and can prevent the vehicle-to-vehicle distance from dropping to an unsafe level in a variety of driving conditions (safe, warning and dangerous modes). Zhao et al. (2013) proposed a supervised adaptive dynamic programming (SADP) for a FSRACC system. The control action is based on the SADP and introduces the concept of inducing region to speed up the learning efficiency. The SADP control algorithm performs well in all simulations scenarios (normal ACC, S&G, emergency braking, cut-in and driver habits changing) and always better than more traditional controllers.

Our study is thus focused on the evaluation of the impacts of FSRACC system on the traffic, the safety and the energy consumption. After having described the system the methodology, models and crucial indicators will be presented. Then, for a given relevant scenario, we will present, analyze and understand the results of the simulations. Finally, we will conclude the evaluation of our system in the above-cited key characteristics and give a vision of future works.

## 2. Full Speed Range Adaptive Cruise Control

### 2.1. Definition

FSRACC system is a combination of ACC and S&G systems. The purpose of FSRACC is a partial automation of the longitudinal control of the vehicle to reduce the load of the driver. FSRACC system is intended to provide longitudinal control of equipped vehicles while traveling on highways (roads where non-motorized vehicles and pedestrians are prohibited) under free-flowing and congested traffic conditions. FSRACC provides support, from the vehicle stop to the maximum speed of the system. The system will attempt to stop behind a vehicle already followed in his vehicle deceleration capabilities and will be able to restart after the driver had sent as command to the system to resume its journey from the stop. The system is not obliged to react to stationary or slow objects. FSRACC is essentially an improvement of the ACC (Automated Cruise Control or Adaptive Cruise Control) which allows the host vehicle to follow a target vehicle at an appropriate distance by controlling the engine and/or the transmission and the brake up to the stop.

### 2.2. FSRACC system constraints

In our study, we have applied the ISO limitations for FSRACC system. All the vehicles have their speeds between 0 and 130 km/h (French maximum authorized speed). The range of accelerations is dependent to the values of current speed. These limitations have been applied only to the FSRACC equipped vehicles. Then, the velocity-dependent acceleration limitations,  $a_{\max}$  and  $a_{\min}$  which are respectively the upper boundary and the lower boundary of accelerations, are determined as follows:

$$a_{\max} = 2m/s^2 \quad a_{\min} = -5m/s^2 \quad a_{\min} = -3.5m/s^2 \quad \text{Linear interpolation of } a_{\min} \text{ for } 5 < \text{speed} < 20m/s$$

Thus, the accelerations of the FSRACC vehicles is calculated based on the reference model and restricted by the acceleration limit.



### 3. Methodology for FSRACC impacts study

To estimate the impacts of our system on the traffic-flow, the safety and the energy consumption, the method used here is the modeling: driver, FSRACC and fuel consumption models are used and the effects are analyzed using a simulation scenario on highways. Simulations to be applied are either microscopic (individual vehicle) or mesoscopic (platoons of vehicles). The simulator has been developed on Matlab (Matrix Laboratory), we have supposed to have a road network, the simulator incorporates the driver and FSRACC vehicles according to their penetration rate (from 0% to 100% in the traffic). Many simulations can also be done, the simulator takes into account, the initial conditions, the data from Simulink of the leader of the platoon (first vehicle in the file), the generation of equipped and non-equipped vehicles, the choice of the type of model, the appeal of functions calculating driver and FSRACC accelerations, the mathematical equations of indicators. The simulator is designed such as to work only in a simulator incorporating the driver model, we can just turn the rate of percentage (0%), and to work on a simulator incorporating only the FSRACC vehicles, a penetration rate of 100% is chosen. The indicators matching each model can also be calculated, analyzed, interpreted and compared before and after merging according to the penetration rate of FSRACC equipped vehicles.

### 4. Models

In this section, the driver and FSRACC models used in the simulations on Matlab are presented.

#### 4.1. FSRACC model

The model used to represent FSRACC vehicles is the Intelligent Driver Model (IDM) presented by Kesting et al. (2008) at which we added the ISO accelerations limitations to have the desired FSRACC system. Kesting et al. (2008) proposed an ACC-based traffic assistance system with an active jam avoidance strategy. In such a system, the driving behavior automatically adapts to different traffic situations (moving in free traffic, approaching an upstream congestion front, moving in congested traffic, leaving the downstream congestion front, and passing infrastructural bottleneck sections) by means of local information. The detection of the local traffic state can be improved by non-local information provided by infrastructure to-car and inter-vehicle communication. Traffic simulations of a three-lane freeway with an on-ramp bottleneck and a mixed flow consisting of cars and trucks showed improvement in traffic stability and dynamic road capacity with 'intelligent' ACC vehicles. Only a small percentage of ACC vehicles can significantly improve the traffic performance. An ACC equipment level of 5% improves the traffic flow quality and reduces the travel times for the drivers in a relevant way, while an equipment level of 25% ACC vehicles eliminated completely traffic congestion.

The main function of ACC (enhancement of conventional cruise control) is to control vehicle speed adaptively to a forward vehicle by using information about: (1) ranging to forward vehicles, (2) the motion of the subject (ACC equipped) vehicle and (3) driver commands. It is fundamentally intended to provide longitudinal control of equipped vehicles while traveling on highways under free-flowing traffic conditions. Kesting et al. (2008) proved that the IDM model is appropriate for simulating ACC systems because this model meets a number of compulsory criteria (collision-free of the car-following dynamics, the dynamics should also correspond to a natural and smooth manner of driving, only a few parameters). Some car following models cannot be simulated as an ACC system (e.g. Optimal Velocity Model, Bando et al., November 1995).

The acceleration of the IDM is a function of the headway spacing, the speed and the relative velocity. Its expression combines a free acceleration term and a braking term. The IDM has five crucial parameters (desired speed  $v_0$ , safe time gap  $T$ , maximum acceleration  $a$ , desired deceleration  $b$ , jam distance  $s_0$ ) (Kesting et al., 2008). This model is widely used by researchers.

#### 4.2. Driver model

The meta-model HDM (Human Driver Model) presented by Treiber et al. (2006) is used in our work to represent driver model. Treiber et al. (2006) generalizes a wide class of time-continuous microscopic traffic models to include essential aspects of driver behavior not captured by these models. Finite reaction time and errors in estimating the input variables are clearly essential factors of driver behavior affecting the performance and stability of vehicular traffic. More precisely, they have considered:

- estimations errors;



- finite reaction time (delay);
- temporal anticipation;
- spatial anticipation (looking several vehicles ahead).

They have showed that the destabilizing effects of reaction times and estimation errors can essentially be compensated for by the stabilizing effects of spatial and temporal anticipation. In order to put this balance of stabilizing and destabilizing effects into a more general context, they have formulated the human-driver model (HDM) as a meta-model that can be used to extend a wide class of car-following models, where the acceleration depends only on the positions, velocities and accelerations of the own and preceding vehicles.

Then the chosen driver model is the HDM applied to the IDM which has a built-in anticipative and smooth braking strategy, and which reaches good scores in a first independent attempt to benchmark micromodels based on real traffic data (Brockfeld et al., 2002). It is supposed that drivers are aware of their finite reaction time and anticipate the traffic situation accordingly. The future distance, the future velocity and the future relative velocity are anticipated. Predictive terms depending on the reaction time are added to the estimation errors for the anticipation of the gap, the speed and the relative speed. The new HDM acceleration (depending on the anticipative variables) is split up into a single vehicle acceleration on a nearly empty road depending on the considered vehicle only, and a braking deceleration taking into account the vehicle-vehicle interaction with the preceding vehicle. The reaction to several vehicles ahead is modeled by summing up the corresponding vehicle-vehicle pair interaction accelerations from a vehicle  $\beta$  to vehicle  $\alpha$  for the  $n_a$  nearest preceding vehicles  $\beta$ . The gap between the vehicles  $\beta$  and  $\alpha$  is the sum of all net gaps between them. The model has five parameters with two deterministic parameters, namely the reaction time  $T'$  and the number  $n_a$  of anticipated vehicles. The other parameters namely stochastic sources  $V_s$  and  $r_c$  characterize the degree of the estimation uncertainty of the drivers, while  $\tau$  denotes the correlation time of errors (Treiber et al., 2006).

#### 4.3. Fuel Consumption model

Fuel consumption models can be classified into three different approaches namely macroscopic (vehicles streams), mesoscopic and microscopic ones. Macroscopic and mesoscopic models are essentially based on the average speed of the traffic flow, they are suitable for the evaluation of the total fuel consumption on an urban traffic network. Microscopic models are based on estimating the instantaneous fuel consumption of the vehicle from the instantaneous values of different parameters related to the vehicle itself or to the conditions of operating (route type, road type, traffic conditions, road geometry). In the literature, the latter are divided into several approaches as follows :

- empirical models based entirely on data (Alçelik et al., 1989) ;
- physical models, by contrast to empirical ones, they are based on physical principles (Bosch, 2000);
- semi-empirical models based on physical principles like physical models and empirical data as empirical models (Wang et al., 2008).

The fuel consumption model used in our evaluation is the semi-empirical model developed in our laboratory. We proposed a fuel consumption model to estimate the effects of the penetration rate of Ecodriving on fuel consumption and traffic congestion: the model is based on the mechanical energy consumed with a performance ratio function of the vehicle speed (Orfila, 2011). To complete the work of Orfila, the model is used here for the evaluation of the FSRACC system on the fuel consumption with the same values of model parameters.

## 5. Indicators

Traffic-flow is a part of the traffic study focused on the analysis and characterization of the evolution of vehicles on selected routes (Buisson et al., 2010). Various variables can be used to assess the impacts of a longitudinal driver-assistance system on traffic-flow, they refer to indicators. An indicator of road traffic is one way to evaluate the performance of a ride or a network. It is calculated from macroscopic (e.g. throughput, compactness, occupancy rate, spatial mean speed, life span and length of traffic jam) or microscopic (e.g. time-gap, spacing, individual speed) variables from the sensors (Cohen et al., 2000) or computed from numerical models. The measures for traffic are instantaneous position, speed, acceleration of a vehicle in the platoon, indicators can be global mean speed, global mean distance. The impacts of road transportation on environment have to deal with concerns from the greenhouse effect, by the atmospheric pollution to the rarefaction of fossil fuel resources. Some indicators are used to assess impacts of ADAS on fuel consumption and gases emissions and they can be





classified in global and local indicators. Global indicators intervene in the level of a whole road network whereas local indicators intervene in the level of the ego-vehicle (the one equipped with the ADAS). For example, among them, there are consumption per vehicle (local) and total consumption (global).

Besides traffic and environmental concerns, safety issues are incontrovertible in the development of ADAS which are believed to reduce risk of accidents, improve safety and enhance performance of drivers. To assess the impacts of longitudinal ADAS on safety, it will be necessary to use some safety indicators like time to collision (TTC), time headway (TIV). Why these indicators and these measures than others? The positions of the vehicles can show if there are collisions or not, they can also show that the vehicles run with constant gap during the simulations. The positions can also show if the presence of FSRACC system affects the total travel time during traffic disturbances (Ioannou et al., 2007). Jerk analyses make it possible to identify safety critical driving behavior or "accident prone" drivers. They also facilitate the development of safety measures such as active safety systems or advanced driver assistance systems, ADAS, which could be adapted for specific groups of drivers or specific risky driving behavior (Bagdadi et al., 2011). Accelerations (Ioannou et al., 1993) are ideal to see the FSRACC system in terms of limitations, they can be compared to jerks. Speeds are ideal to see if the other vehicles mimic the leader speed profile or to evaluate the efficiency of the system (Kesting et al., 2008). In the one hand, it would be better to see the gaps (Wang et al., 2004), time headway (Fancher et al., 2001), relative velocity of each vehicle for each penetration rate and each simulation to optimize our system well. In the other hand, it will be better and fast to see the results for all penetration rates in the same figure to have a good understanding of the results, so the best idea would be to calculate global and deterministic indicators.

Within the framework of this study, the relevant measures for the assessment of the impacts of FSRACC system on our key characteristics are the instantaneous jerk, acceleration, speed and position. The relevant indicators are respectively:

- global mean speed, global mean distance ;
- consumption in liters per 100 kilometers of vehicles (Greenwood, 2003);
- headway time, spacing, percentage of time where the time headway is under 2 seconds (Legal headway time limit in France).

## 6. Simulations Results

### 6.1.Scenario for the FSRACC simulation

The main function of Low Speed Following (LSF) systems is to control vehicle speed adaptively to a forward vehicle. In contrast with ACC systems, it provides automatic car-following at lower speed ranges, it doesn't provide speed regulator control and allows stopping and starting vehicle on highways under congested traffic (ISO 22178 ,2009) .

The objective is to elaborate a scenario which represents ideally the FSRACC system which is a combination of LSF and ACC systems. The figure 1 illustrates the speed profile used for the leader (first vehicle in the file), it combines well the driving at lower and higher speeds on highways under free-flowing and congested traffic conditions.

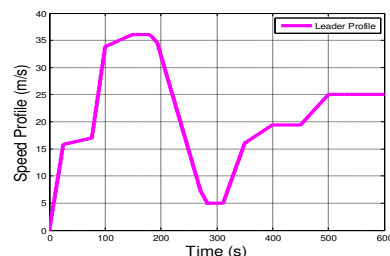


Fig. 1. Speed profile of the first vehicle.

### 6.2.Initial conditions and models parameters

Simulations was made on a single-lane road section with 20 vehicles where the leader has the profile defined as in figure 1. The maximum length of vehicles is assumed to be 5 m and the minimum length is assumed to be 3 m, the step rate is 25% and the percentage varies from 0% to 100%. For each percentage, five simulations were performed for more data, this will allow a better understanding of the results. Each simulation lasted 10 minutes and the update time interval was 0.1 s. The maximum and minimum jerks for the FSRACC vehicles are assumed to be  $1.5 \text{ m/s}^3$  and  $-3 \text{ m/s}^3$  respectively to keep the concept of comfort in acceleration while permitting severe braking. The initial gaps, speeds, accelerations, jerks are 10 m, 0 m/s,  $0 \text{ m/s}^2$  and  $0 \text{ m/s}^3$  respectively. The initial



position of the leader is 190 m. The parameters used for the FSRACC and HDM-IDM combination (application of the meta-model HDM to the car-following model IDM) models are given by the table 1.

Table 1. Values of the IDM and HDM parameters as used in the simulations.

IDM parameter	IDM parameter value	HDM parameter	HDM parameter value
$v_0$	120 km/h	$T$	{1.1 s; 0 s}
$T$	1.5 s	$n_a$	{5;1}
$a$	0.73 m/s <sup>2</sup>	$V_s$	{5%;0%}
$b$	1.67 m/s <sup>2</sup>	$r_c$	{0.01/s;0/s}
$s_0$	2 m	$\tau$	20 s

### 6.3. Results analysis

#### 6.3.1 Boxplots

Some figures are represented by boxplots which is nowadays most used by researchers to represent schematically the distribution of a variable. The boxplot of a sample has these values:

- the first quartile value (Q1);
- the median value (M);
- the third quartile value (Q3);
- the 2 boxplots, lower and upper, represented on either side of the box. These two whiskers delimit adjacent values which are determined from the interquartile range (Q3-Q1);
- the extreme or aberrant values located beyond adjacent values are individualized. They are represented by markers (square, or star, etc.).

The interests of the box plot are various: this is a quick way to include the profile of a quantitative statistical series; it allows to identify aberrant observations; it allows to highlight the symmetry or not of a distribution by identifying the position of the median in the box, and the asymmetry of mustaches; it facilitates the comparison between different distributions; it graphically represents both the parameters of central tendency (median) and the parameters of dispersion (quartile).

#### 6.3.2. Results for the combination of IDM and HDM-IDM for the values of HDM parameters $T^i=1.1$ s, $n_a=5$ , $V_s=0.05$ and $r_c=0.01/s$

The reaction time and the number of anticipated vehicles are the most pertinent HDM parameters, the IDM parameters are fixed. The figure 2 shows the boxplots for some indicators, there are no aberrant values for each indicator (due to the choice of the step rate and the number of simulations). They can be understood as follows: the percentage of time where the time headway is under 2 s is represented for all the vehicles at different penetration rates (figure 2.a). We can see that the HDM-IDM vehicles drive most safely without FSRACC system. The higher the percentage, the greater the vehicles drive too close. For a 100%-FSRACC vehicles, the boxplot is only a line representing the median, it means that data are not enough, it is normal because we are in the case of the basic model IDM where there almost are no random values, so each of the five simulations have nearly the same data.

Table 2. Values of the boxplots for the percentage of time where the time headway is under 2 s.

Penetration rate vs. box plot values	Min	Q1	M	Q3	Max
0%	2.635	3.334	15.89	17.67	18.71
25%	18.82	23.8	28.28	28.7	28.89
50%	30.77	34.91	37.87	38.58	39.41
75%	45.48	45.73	48.87	50.15	52.11
100%	None	None	57.69	None	None

The same analysis is made for the fuel consumption in liters per 100 km (figure 2.b), it appears that the fuel consumption is asymmetric regarding the percentages, for each percentage the values are increasing and the





highest value of the consumption is reached for only 25%. Moreover, the values of boxplots are close. So with FSRACC the vehicles consumed not so higher than without it. The test seems to keep the fuel consumption constant when the percentage of FSRACC increases, this is due to the results obtained for the speeds in figure 2.d. The fuel consumption heavily depends on the speeds which vary slightly with the increase of the penetration rate of the FSRACC vehicles. The fuel consumption also depends on the vehicle parameters, the factors related to the condition of operational use of the vehicle (stop, kind of trip, road type, traffic conditions, road geometry) and the driver.

Table 3. Values of the boxplots for the Fuel consumption in liters per 100 km.

Penetration rate vs. box plot values	Min	Q1	M	Q3	Max
0%	11.05	11.11	11.3	11.47	11.51
25%	10.88	11.28	11.77	11.9	12.23
50%	11.01	11.1	11.17	11.68	11.86
75%	11.42	11.44	11.6	11.65	11.72
100%	11.89	11.9	11.95	12.04	12.06

From the figure 2.c, it appears that the increase in the percentage rate has no influence on the covered distance. Figure 2.d makes appearing that the speeds are slightly different, so the system has slightly influence on the speeds of the vehicles. For a 100%-FSRACC,  $Q1=M=Q3=20.43$  m/s (no maximum, no minimum). For a 0%-FSRACC, the height of the boxplot for other percentage is due to the presence of drivers (many random values). Figures 3 to 6 show the accelerations, jerks, speeds and locations of all vehicles for a simulation with a 0%, 25% and 100%-FSRACC vehicles: the vehicles jerks were all initialized at zero, throughout the simulation until the end, the jerks of vehicles equipped with FSRACC decrease while those of drivers are delayed and train oscillations, due to the Wiener process which takes into account the persistence of estimation errors. The higher the percentage, the lower the values of jerks and the smaller the oscillations. We have large values of jerks for almost the first 200 seconds while from the almost 200<sup>th</sup> s to the end, the jerks are trying to stabilize at zero. The jerks of FSRACC vehicles are limited by the minimum and maximum values of the jerks.

The higher the percentage of FSRACC increases and the vehicle accelerates and decelerates more modestly. The acceleration values of the FSRACC vehicles stay within the limitations imposed by the system depending on the values of the corresponding speeds as found by Nouvelière et al. (2013). The higher the penetration rates, the lower the oscillations of the accelerations. The drivers tend to follow the leader's trajectory. All the vehicles speeds are between 0 km/h and 130 km/h. Vehicles tend to reach their desired speed, the equipped vehicles are struggling to follow the trajectories of drivers. The more we increase the percentage, the more oscillations decrease. The increasing of penetration rate of FSRACC has no influence on the locations and the total travel time as also found by Ioannou et al. (2007). It appears from figure 7 that the higher the penetration rate increases, the more the gap between the trajectories of the vehicles regulates and then the vehicles increase the safety in their driving. Figure 8 shows that the time headway of the vehicles is high at the beginning and becomes lower during the simulation until the end. They are lower than the safe time headway (2 s) with the equipment. This result is due to the speed profile. It should be noted that if  $T=0$ ,  $n_d=1$ ,  $V_s=r_c=0$ , the human-driver extension HDM-IDM is switched off and the original basic model IDM is recovered.

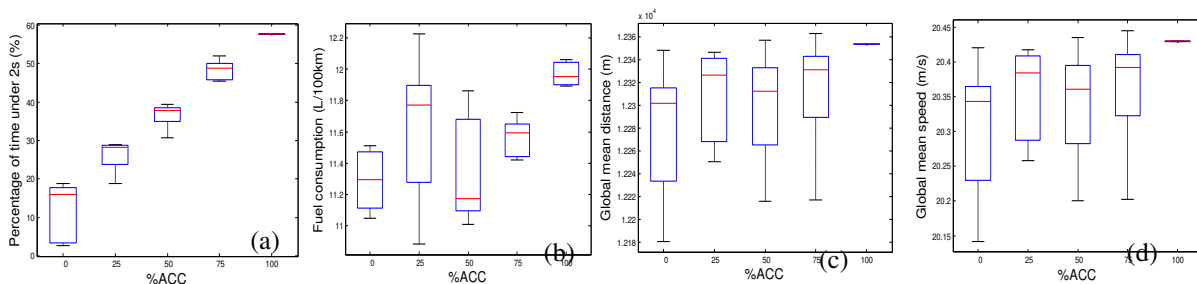


Fig. 2. Boxplots for relevant indicators. From left to right : (a) percentage of time where the time headway is under 2s at the top left; (b) fuel consumption in liters per 100 kilometers; (c) Global mean distance; (d) Global mean speed.



From figure 3 to figure 8, the following legend is used: (a) 0% FSRACC all in blue at the left; (b) 25% FSRACC in the middle, the drivers are the blue ones and the FSRACC the red dash-dot ones; (c) 100% FSRACC all in red at the right.

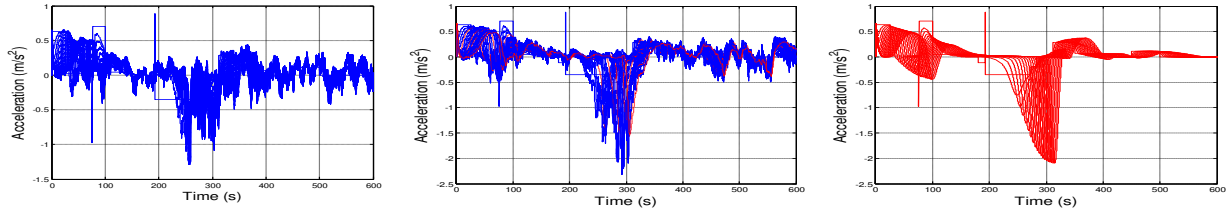


Fig. 3. Accelerations of all vehicles.

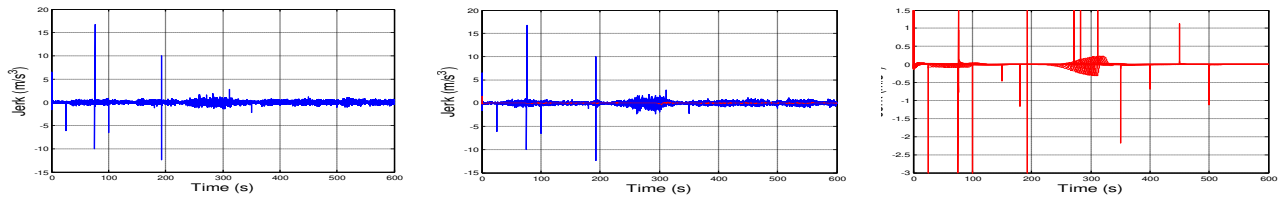


Fig. 4. Jerks of all vehicles.

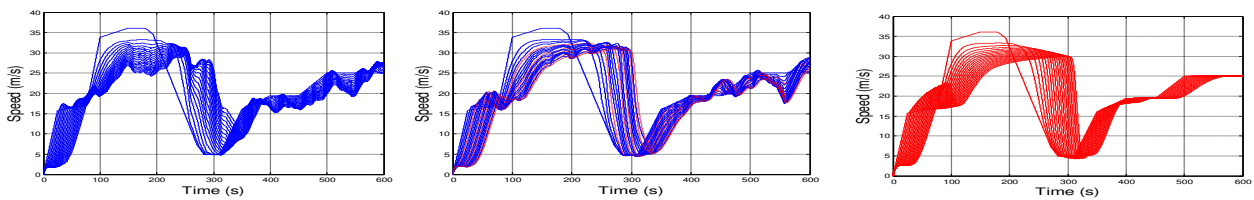


Fig. 5. Speeds of all vehicles.

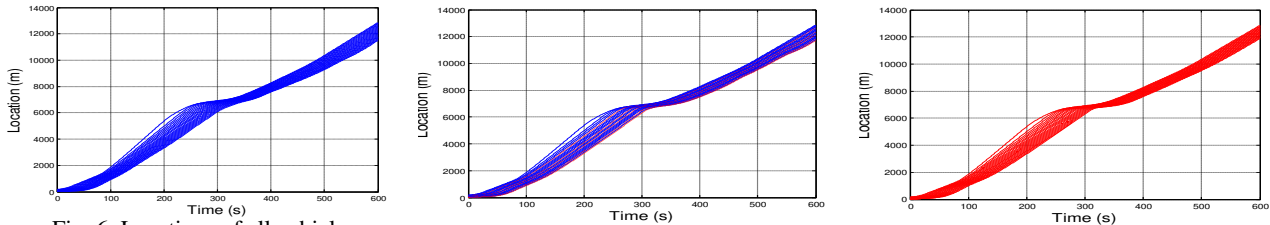


Fig. 6. Locations of all vehicles.

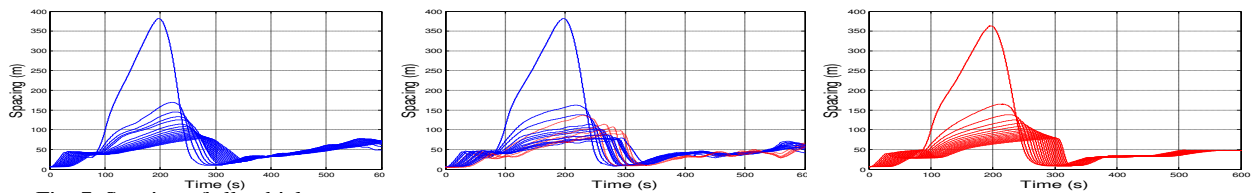


Fig. 7. Spacing of all vehicles.

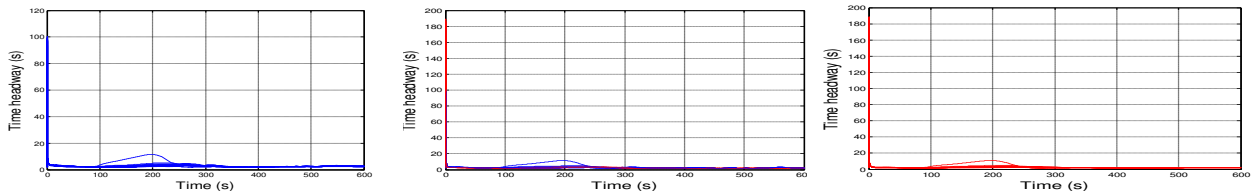


Fig. 8. Time headway of all vehicles.

## 7. Conclusions and future work

A traffic simulator was presented with the fusion of a driver simulator using HDM model applied to IDM model and an ADAS model for the Full Speed Range Advanced Cruise Control (FSRACC) using the IDM model. An evaluation under a given scenario on highways was made among several indicators symbolizing safety,



environment and traffic. The results are presented with box plots for a statistical view and with matlab simulations out of the FSRACC penetration rate in the traffic. It has been shown that the proposed FSRACC system can provide a natural following performance similar to human driving. Future work will consider other longitudinal ADAS to be evaluated in the same way, namely IDM with ISO accelerations limitations for the ACC system, IDM with ISO accelerations limitations concerning LSF system, and possibly the ISA and Ecodriving systems. These systems will be subsequently compared to one another.

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