EVALUATING COMMUNICATIONS AND IDM IN A CONTEXT OF A CCA APPLICATION FOR VANETS

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ABSTRACT

Adaptive Cruise Control Systems (ACC) are becoming essential in developing advanced vehicular applications/services which help to reduce the risk of accidents and offer better conditions for comfort in the driving experience, Hartenstein and Leberteaux (2008). The IDM (*Intelligent Driver Model*) is a realistic car-following model whose main feature is the use of physical-oriented parameters to explain the different aspects related to mobility of vehicles. It has been evaluated as an ACC car-following scheme for future automatic car-driving, Kesting and Treiber (2010). However, IDM has been at first conceived to operate under general car-following conditions, Treiber (2000), where, for certain values of the model parameters, car traffic can be realistically recreated. Nevertheless, extreme but relevant situations, such as emergency braking, are not considered in detail. As we will show, the model parameters are not properly tuned to operate under these particular circumstances, mainly because related driving comfort (driving aggressiveness) is not actually taken into account. Therefore, in this paper we propose to benefit from the vehicle-to-vehicle communications (V2V) paradigm to enhance the functionality of ACC systems by performing a dynamic real-time tuning scheme of such model parameters. The application under test is a *Cooperative Chain Collision Avoidance* (CCA) application (Tomas-Gabarron, 2010) in which, in addition to achieve a significant lower number of vehicle accidents, the resulting deceleration policy provides a scheme that smoothens deceleration changes to further increase comfort even in these critical conditions.

Keywords: transportation, safety, CCA, ACC, VANET.

INTRODUCTION

For a long time, human consciousness about the number and severity of car traffic incidents have grown along with the advance of technology to mitigate them. Car accidents have become a major issue concerning road safety and nowadays large campaigns are promoted mainly by government agencies to alert drivers about the risk of driving misbehaviors. According to statistics from the DGT (*Dirección General de Tráfico*) in Spain, Spanish Traffic Agency (2009), thanks to these initiatives, the number of road victims has decreased by 50% in the last twenty years in Spanish roads (information of 2009). However, chain collision accidents still account for 24% of all car crashes in highways and conventional roads, and are currently the second major cause of fatal accidents in this country, after road exit (36% of all car traffic incidents). Furthermore, chain collision car accidents are a major cause of human fatalities, in which a minor variation on some physical or human-related parameters (i.e., state of the road or reaction time to stimuli) can heavily determine if a certain emergency-brake situation can be life threatening or not. As a result, the reliance on some type of technologies which can improve response of drivers (or at least avoid delayed human intervention) to the different states of vehicular traffic can be highly beneficial.

During the past decade, *Vehicle Ad-hoc Networks* (VANETs) have received major attention from the scientific community due to the multiple advantages their deployment will entail on public safety, Hartenstein (2008). Above all, relying on communication protocols to establish advanced functionality on vehicles will improve passengers' safety, provide new user services to them and eventually, reduce traffic congestion to an extent never seen before. However, their penetration in the market is not yet important due to the difficulties implied by the associated deployment transition and the questionable short-term economic profitability. At this concern, the release of the standard IEEE 1609/802.11p in November 2010 (see reference IEEE 1609/802.11p (2010)), has received special interest from the industry and the academic circles because VANETs needed urgently standardization in order to converge for the different manufacturers, developers and designers. Technically, these standard protocols will provide the different functional schemes which will serve to regulate communications in vehicular traffic environments. Multiple studies have been conducted to evaluate the performance of the standard under very different states of the communications channel. Anyway, academia and consortiums keep on developing and improving applications, protocols, strategies, marketing and campaigns which will be key in the near future to widespread these technologies.

Particularly, as regards road safety applications, multiple investigations have focused on developing new strategies to mitigate the impact of car accidents on passengers during the last twenty years. For example, the *National Highway Traffic Safety Administration* (NHTSA) and the *Crash Avoidance Metrics Partnership* (CAMP) have chosen eight applications as representatives of general safety user services for VANETs: Traffic Signal Violation, Curve Speed Warning, Emergency Brake-lights, Pre-crash Sensing, Forward Collision, Left Turn Assistance, Lane Change Warning, and Stop Sign Assistance. From these examples, Pre-crash Sensing and Forward Collision belong both to the type of applications named *Cooperative Collision Avoidance* (CCA) applications. These are devoted to reduce the impact on passengers due to sudden changes in vehicular traffic which can involve car collisions when driving mainly in highways.

Field research on road safety is, obviously, not easy. It inherently implies risking vehicles physical integrity and, more importantly, human lives. As a result, engineers rely on simulation to study the designs they carry out. For example, mobility models have played so far a major role in terms of simulating the conditions related to vehicular traffic, ranging from normal car-following traffic patterns to critical emergency-brake circumstances, among others. The use of such models allows developers to evaluate conditions of car traffic under very different situations, enabling the analysis under which conditions critical traffic events take place. These are mainly those related to car-congestion and car accidents.

The *Intelligent Driver Model* (IDM) has been proven to be a valuable mobility model which efficiently reproduces car traffic behavior in simulations. After a coherent calibration of parameters made by its authors, Kesting and Treiber (2008), the model exhibits its main advantages: it can show very realistically the evolution of mobility of vehicles as a function of time according to several values of the initial boundary conditions (speed, position, acceleration, etc.) by a fixed assignment of the model's physical parameters. In general, when the simulation model is tested against general *car-following* scenarios, the behavior of vehicles is very realistic, although their steady-state tendency always converges to stable velocities and equal intervehicular distances.

On the other hand, *car-following* models can also be used to model ACC systems. That is, using sensors to measure the input variables (distance to preceding vehicle, speed difference, etc.) their equations can be used to adapt the speed and acceleration to keep the desired safety gap to the leader car, see Kesting and Treiber (2010). In fact, IDM has also been used as an ACC automatic driving guider whose main features were tested in Kesting and Treiber (2010). In this evaluation, authors propose an extension to the IDM model as regards an acceleration smoothing heuristic (CAH, *Constant Acceleration Heuristic*) to avoid the unrealistic behavior of IDM in cases where the accelerations are really high (due to sudden lane changes, or sudden stops by vehicles located ahead). In spite of this fact, the performance of CAH could still be improved if a more specific real-time manipulation of model parameters was carried out (such as high variations in the deceleration in emergency brake situations).

Vehicular communications have a great potential to improve ACC systems since they remarkably extend the range of the available input and feedback and remove to some extent instabilities caused by parameters such as reaction times. For this reason, in this paper we propose to improve safety of passengers when using ACC (with IDM) on critical situations such as emergency braking by modifying dynamically model parameters which influence directly the braking procedure by the use of vehicle to vehicle (V2V) communications. To the best of the author's knowledge, there has not appeared any evaluation trying to study how communications can influence the behavior of the IDM model (when changing model parameters in real time after receiving warning notification messages), and particularly, for the aforementioned situation. Our intention here is to determine in which way it can impact on the best improvement of safety and driver's comfort. Thereby, we propose a braking algorithm which will effectively reduce the probability of accident, and increase the driving comfort (understood as the maximum reduction of the driving style aggressiveness) in such critical situations, thanks to the exploitation of communications. An extensive performance evaluation of the proposed solution will be provided, along with multiple illustrative results.

The rest of the paper is organized as follows. In the next section relevant related work is described. In the following section, our view of communications in IDM is explained; three implementations of the CCA application (in ACC) are compared together to remark the usefulness of vehicular networks to improve the performance of the IDM model. Then, they are evaluated against our proposed braking algorithm (LBA, *Linear Brake Algorithm*). Some results and graphs are represented and discussed to illustrate the main features of our proposal. Eventually, the last section finishes the paper with some concluding remarks, and presents our main future work lines.

RELATED WORK

When engineers produce and test new technologies, they must always try to construct gadgets and prototypes which behave exactly (or at least with a very good approximation) as they were conceived. For these reasons, designers must deal in parallel with the correct choice of technology, tuning employed devices to work so that performance can be optimized, and analyze how the new technology can introduce changes in the behavior of the driver which could affect overall driving performance. In the particular case of CCA applications for ACC systems, there are two requirements which the system must necessarily satisfy: reduce the probability of accident with severe consequences, and increase the driving comfort (namely, reducing the driving aggressiveness). To this aim, designers must deal first of all with what is referred as *Behavioral Adaptation* (BA).

BA involves how *Intelligent Transportation Systems* (ITS) systems induce behavioral adaptation in drivers, mainly due to changes in their driving style, risk detection and hazard treatment. This concept has not been treated in detail so far by the industry, since engineers, designers and developers have always assumed that any single technology which can improve mechanical response to a traffic event on vehicles would always mean better driving conditions for drivers. However, it is not always true. That is the case, for example, of Rudinbrown (2004), where authors show that at first glance ACC systems can reduce drivers workload (reliance by them on the technology is significantly increased), but the induced distractions can invalidate some optimistic engineering considerations which assure that car-collision frequency and severity are reduced. They propose to benefit from the so-called training programs to improve human response to avoid this safety issue. In Rudinbrown (2010), the same authors give some hints to face these already mentioned problems associated to BA. They suggest implementing adaptive interfaces which can, either explicitly or implicitly, learn from the driver about the conditions associated to his/her driving style. This will undoubtedly generate new information which will be used to better understand the reaction of the driver to a certain situation and simultaneously feedback her/him with instructions on how to improve her/his behavior at certain traffic events. In the case of ACC systems (Rudinbrown (2010)) some strategies are considered, like for example temporarily disabling the interface whenever the smart system notices larger reaction times to events on the road and longer periods of distraction by the driver. Pauwelusen *et al.* (2010) evaluates the causes by which drivers alternate between active and inactive ACC in vehicles. They characterize the system and human behavior by measuring some metrics like mean *Time Headway* (THW) and *Relative Differential Speed* (RDS) before and after a transition from one state to another state of the ACC system. Briefly, this study concluded that drivers tend to overrule the ACC when they need an extra acceleration (when with the ACC alone it is not possible to obtain), or when the intervehicular distance is too short in dense traffic and ACC alone is not capable of braking enough. Overall-in-time utilization of ACC (without human intervention) has been treated in Kesting and Treiber (2010), where authors of IDM propose an extension of the IDM model (the *Constant Acceleration Heuristic*, CAH), to avoid (or at least reduce) extreme changes in sudden acceleration/deceleration magnitudes which appear when vehicles change lanes or when there are critical emergency stops due to car accidents. A smoother driving style is obtained by their heuristic, which they apply for all the possible traffic states. However, using this smoothing scheme in all possible situations does not allow to improve specific patterns of the vehicle mobility which could induce a better driving experience. In our braking procedure for emergency scenarios, we study this in detail, taking into account that, on the one hand, at first it is possible that drivers will not rely the whole time during the journey on the ACC system, as can be shown in Pauwelussen (2010); and on the other hand, mobility patterns can be specifically modified (according to the particular state of traffic) to induce the best driving experience.

Apart from the concept of *Behavioral Adaptation* (BA), during the last years, and due to the remarkable increase in *Green Consciousness* among the population, new technologies aim at designing products which respect the environment, reducing gas emissions and contributing to a higher environmental wellness. In particular, *Green Driving* has evolved to be a key issue during the last decade, because of the predictable shortfalls in gas which are foreseen to take place in the near future, and over all, as a result of the widespread phenomena of the climate change. Applying policies to reduce gas emissions in any driving situation minimizes the impact of these problems. Multiple researches have focused on analyzing how the driving style can influence the fuel consumption mostly on normal traffic situations (city, highway), but critical situations like emergency stop have not been taken into account yet. We suppose that under such critical circumstances, the influence of the gas consumption per vehicle when designing policies which minimize the driving aggressiveness while minimizing the probability of accident may be negligible. Anyway, it is intuitive that reducing variations in acceleration even in critical situations like the one we consider here can be beneficial. This will be the main subject to study in a posterior work. The work in Tielert (2010) has evaluated for instance how Traffic-Light-to-Vehicle communications can significantly reduce gas emissions by anticipating drivers' information about the time remaining to turn to a different state. By using a detailed gas emissions model, they discover that it is possible to reach high percentages of savings in energy consumption and gas emissions to the atmosphere when such information is provided to drivers. The expenditure required to add this feature to vehicles and traffic lights is unfortunately expensive, and furthermore, BA has not been yet evaluated (as regards how this could affect pedestrians' safety). On the other hand, talking about initiatives already present in the market, we can find the *EcoGyzer,* EcoGyzer (2011)*,* which allows drivers to acquaint some driving skills to help reduce the gas emissions to atmosphere by minimizing driver aggressiveness. Thanks to an active adviser system, *EcoGyzer* technology benefits from smartphones to provide drivers with real time information about the features of their driving style; thus giving them the capability of consciously enhancing its conditions.

COMMUNICATIONS IN IDM

IDM is a mobility model already tested to work under different traffic conditions, including support to lane change and smoothing of acceleration/deceleration magnitudes in general emergency brake situations, as it was shown by the simulated approach with ACC support in Kesting and Treiber (2010) (note that along the paper, the terms acceleration and deceleration will be used indifferently to denote the process of braking after a car accident occurs). As they showed, authors propose five traffic regimes in which the three IDM parameters (a, b and T) are used to set up the particular functionality of the model as regards the specific traffic regime in which vehicles operate (acceleration/deceleration policies, intervehicular spacing, etc.).

However, ACC support could provide a much better functionality to the general system if communications were applied, especially for those situations in which the system is affected by a critical event, such as an emergency brake. For example, assuming that the number of accidents is reduced to the minimum physically possible, deceleration values could be assigned to vehicles in such a way that the maximum comfort and extra safety are guaranteed to driver and passengers as an added value (Figure 1).

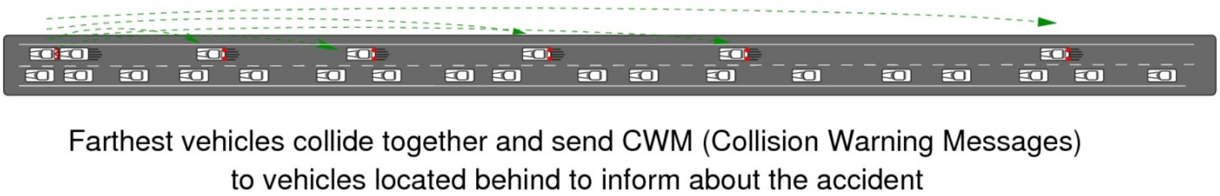

Figure 1 Critical emergency brake in which communications are used to provide information to anticipate the accident of a leading vehicle

In order to allow IDM to take advantage from communications, we must first interpret the physical/model implications of its most important parameters and the corresponding modifications should be carried out in order to give this support to the model. Let us have a look at the general expression for the calculation of the acceleration in IDM, Treiber (2006):

$$\dot{v}_\alpha = A\left[1 - \left(\frac{v_\alpha}{v_0}\right)^4 - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right] \quad (1)$$

$$s^*(v_\alpha, \Delta v_\alpha) = s_0 + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}} \quad (2)$$

where:

$\dot{v}_\alpha$: current acceleration of vehicle α
v_α: current velocity of vehicle α
A: acceleration factor
v_0: maximum velocity
$s^*(v_\alpha, \Delta v_\alpha)$: desired safe gap
s_α: current intervehicular spacing
s_0: minimum intervehicular distance
Δv_α: speed differential
a: desired acceleration factor

b: desired deceleration factor
T: desired time gap

According to (1), acceleration depends on the speed difference with the leading vehicle, the speed of the current vehicle and the intervehicular distance with the car in front. If we have a detailed glance at the equation, we can see that it can be decomposed into the sum of two expressions:

$$\dot{v}_\alpha = \dot{v}_{free} + \dot{v}_{brake} = \left(A\left[1 - \left(\frac{v_\alpha}{v_0}\right)^4\right]\right) + \left(-A\left[\left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right]\right) \quad (3)$$

where:
$\dot{v}_{free}$: free road acceleration procedure
$\dot{v}_{brake}$: deceleration strategy

The second addend ($\dot{v}_{brake}$) is the relevant one when we talk about hard-braking events in which a critical situation requires vehicles to stop as soon as possible due to a relatively small time gap to the leading car. Under this kind of critical conditions, it is possible to configure dynamically the IDM parameters which determine the behavior of the model in time. The *desired minimum gap* (T) and the comfortable acceleration/deceleration factors a and b can be thus modified during runtime when a critical situation takes place, especially considering that these three parameters are strongly related to the intervehicular distance a vehicle keeps against its ahead neighbor (T), and the way a vehicle accelerates (a) and decelerates (b) in critical emergency brake situations. Our purpose here is to restrict ourselves to the dynamic configuration of the *safety time gap* (T) to help vehicles react according to the braking algorithm we propose, and evaluate how it performs under different circumstances of sudden braking events when compared with other proposed smoothing deceleration algorithms, Kesting and Treiber (2010). Our particular focus on the T parameter can be explained assuming that the main intention is to simplify the dynamic scheme process. Taking into consideration a and b would mean many design variables which make the procedure development more intricate. A further study on the additional modification of parameters a and b will be carried out in a future work.

General Scenario Description

In this subsection we introduce the main scenario used to evaluate the performance of the IDM model with the different implementation variants which will be tested to optimize our proposal for the braking procedure. First, we show how communications can obviously improve the performance of a CCA application. Then, we present the new LBA algorithm to smooth the braking maneuver during an emergency event.

Our general scenario consists of 21 vehicles in a platoon, all of them behaving according to the IDM model's equation (1). The initial configuration for the scenario is set for vehicles to keep at the beginning of the simulation a intervehicular distance taken from an exponential distribution Wisitpongphan (2007), with an average gap ranging from 6 to 70 m in steps of 4 m. Initial speeds for all vehicles are equal and set to 30 m/s (at low distances, initial speeds of 30 m/s could seem unrealistic, mostly in highways, but this allows us to estimate a lower bound in order to evaluate such extreme event in detail). After a period of 20 s from the beginning of the simulation, vehicle 21 (the leading vehicle of the platoon, see Figure 1) brakes instantaneously and vehicle 20 crashes with it. Before this instant, vehicles drive in equilibrium (null accelerations and equal intervehicular distances). When the first car crash takes place, information in this regard is sent to further vehicles, entailing an automatic car brake procedure in them to avoid or at least reduce the impact of new hypothetical vehicle collisions. Reaction times are defined for each simulation case.

For those cases in which communications apply, the *Nakagami* channel propagation fading model is used for the transmission of information, see Torrent-Moreno (2004). Transmission-reception delay of messages can be ignored (since we assume that the communications channel is not shared with other applications). The study of the communications channel access will be a subject of detailed evaluation in an upcoming work.

Constant simulation parameters for all simulation cases can be seen in Table 1. For each case, only variable parameters are shown to reduce paper space. To compare the performance of our proposal against real traffic circumstances, we choose the values for the parameters set up in Kesting and Treiber (2008). Initial speeds are set to 30 m/s since this is an average value found in highways.

Table 1 Constant parameters for all simulations

Emergency Brake Scenario	
Model parameters	Values
A	1
B	1.5
s_0	2 m
A	1 m/s^2
v_{ini}	30 m/s
v_0	33 m/s
Simulation parameters	Values
N (Number of vehicles)	21
a_{stop} (Max. deceleration value)	-8 m/s^2
d (Inter-vehicle distance range) exp.distribution (Wisitpongphan, 2007)	[6-70] m

The evolution of the percentage of collided vehicles in the platoon is shown for the range of intervehicular distances mentioned before. We also represent the average variance of the braking decelerations that vehicles use to decrease speed to a complete stop versus every intervehicular distance. The purpose of representing this evolution is to provide further information regarding the associated driving aggressiveness related to the corresponding deceleration algorithm employed (when it applies), in order to give a general qualitative view of the comfort offered to passengers by the respective braking procedure. According to Berry (2010), maximum comfort is obtained when changes in braking decelerations to reach the final traffic state (all cars stopped) are reduced to the minimum physically affordable.

In some illustrative cases we represent the average final speed to stop for all vehicles (20 samples), when the intervehicular distance is 6 m, along with the minimum theoretical obtainable values of speeds to stop, see Fig. 3. Theoretical minimum speeds are defined as the speed the vehicles will reach when they stop completely (either by crashing or stopping successfully) if they react to the first accident by braking at the maximum deceleration physically obtainable (8 m/s^2) with null reaction time (vehicles begin to decelerate at the same time instant the first accident takes place). The use of a maximum theoretical deceleration value of 8 m/s^2 can be justified assuming that it acts as an upper reference (in reality, vehicles achieve such value under very favorable road, driver and environmental conditions). In red we show the averaged simulation speeds when stopping versus the minimum theoretical speeds (in blue). Simulations are performed and shown with a 99% confidence interval for all the statistics we measure.

Need for communications

Now, we discuss the advantage of using a system which supports vehicular communications to reduce the number of car accidents (as a prologue to the definition of our braking procedure). When communications are not in use, microscopic mobility patterns are calculated according to the general expression in (1). In this equation, vehicles react to the changes of the vehicle located ahead. This entails a chain induced reaction, in which there is an obvious incremental delay from the instant in which the first vehicle collides until the last car in the chain begins to decelerate due to the platoon's leading vehicle which crashed first. To show this, we conduct a simulation supporting IDM with null reaction time, along with general values for the model's parameters in Table 1. The platoon is composed of 21 vehicles (as in the general scenario description), the maximum deceleration value is -8 m/s^2 (as a physical upper value for the maximum deceleration), and the reaction time is set to 0 s because we are using IDM (however, since the sampling period of the network simulator is established to 100 ms, the delay to react to phenomena is intrinsically 0.1 s, which accounts for the turn-around time to transmit, receive and process messages by vehicles).

If we observe Figure 2, we can notice that even though reaction time is very small (approximately the time taken by the ACC system to account for the change of the speed of ahead vehicles), when the average intervehicular distance is 6 m, more than 75% of the vehicles of the platoon still collide (this metric decreases obviously as the average intervehicular gap increases). In Figure 3 we show the average speeds of the vehicles in the platoon when stopping, averaged with 20 samples and for a mean intervehicular distance of 6 m. The red bars in Figure 3 show that there is a large amount of vehicles (mainly located at the middle of the platoon) which could have stopped previously, thus reducing the average speed to stop (or even avoiding collision, which happens when the speed is null), mainly if some kind of communications system were used to inform them earlier about the incidence. We have chosen the short distance of 6 m for the intervehicular distance because it is a worst-case scenario (differential speed between theoretical and simulated speed is smaller as the intervehicular distance is increased).

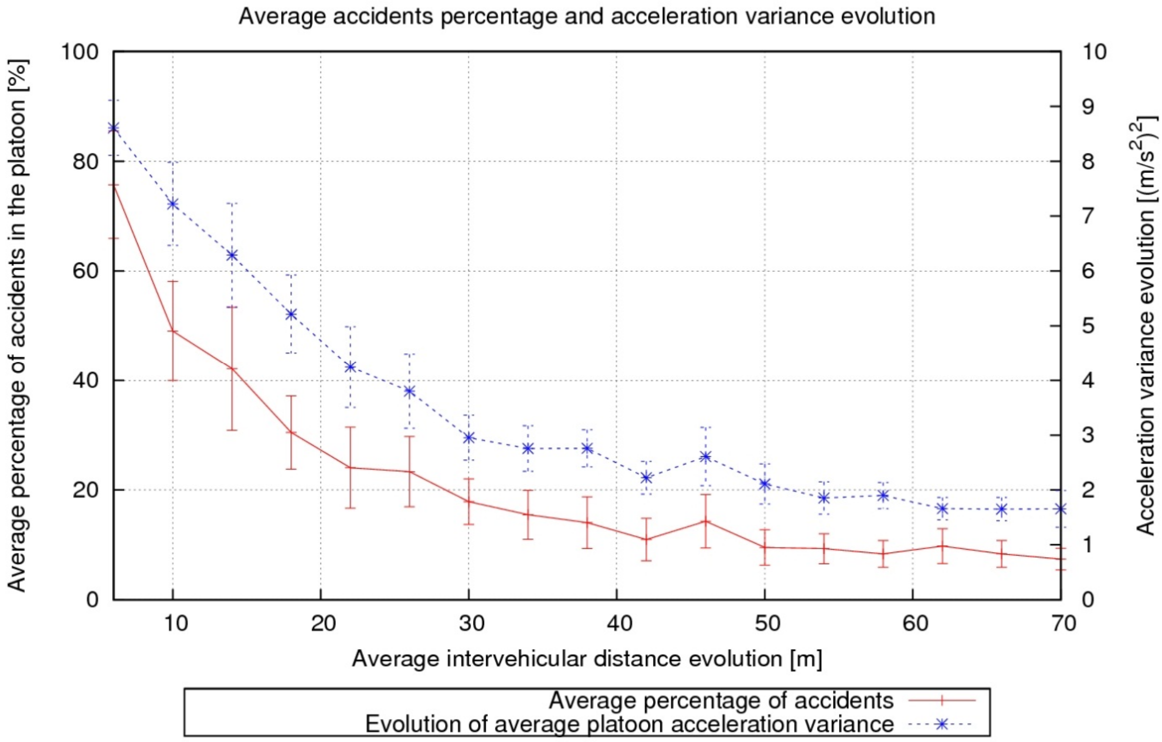

Figure 2 Average percentage of accidents in the platoon (left axis) and evolution of average acceleration variance of vehicles in the platoon (right axis)

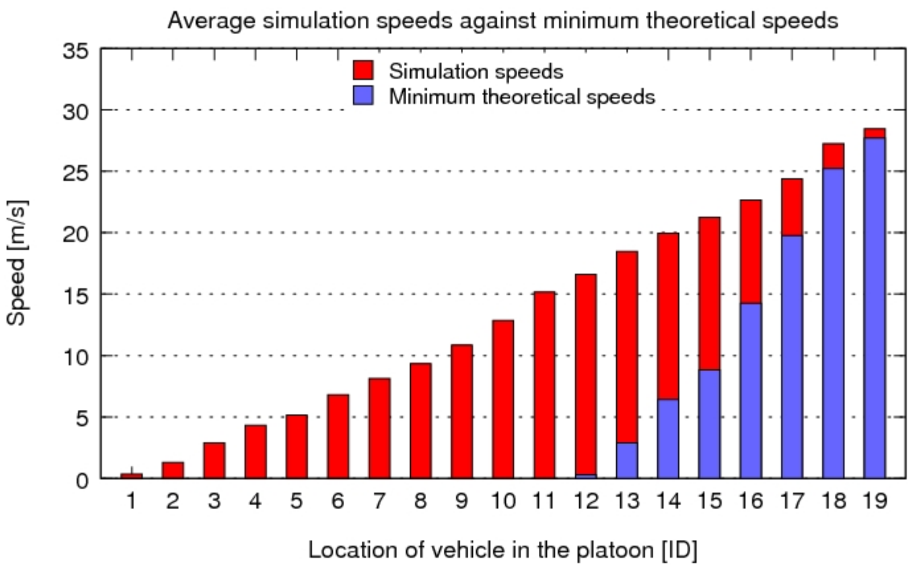

Figure 3 Minimum obtainable speeds to stop (blue) versus simulation speeds (red) to stop for an average intervehicular distance of 6 meters

Communications in IDM: *T* conservative approach

As it was observed in the previous subsection, some kind of system to anticipate information to vehicles facing a critical event like an emergency brake is beneficial to mitigate the impact of chain collisions on a context of *cooperative chain collision avoidance* (CCA). The communication system's main purpose consists of beaconing status information periodically to inform about the mobility data of every vehicle. Whenever an unpredictable event takes place (i.e. an accident) beacons are replaced by *collision warning messages* (CWM), with higher priority, which will be sent to the remaining vehicles in the chain (only by collided cars, periodically after the emergency incident). The way in which these messages are treated (how they affect to the model parameters *a*, *b* and *T*) will influence the braking procedure of every vehicle until a complete stop. The contents of beacons and CWM are detailed in Table 2:

Table 2 Data fields of messages

	Beacons	CWM
Purpose	Transmission of general mobility information	Transmission of accident related information
Type	Periodical	Event-driven
Position [m]	✓	✓
Speed [m/s]	✓	×
Acceleration [m/s^2]	✓	×
Timestamp [s]	✓	✓
Priority flag	×	✓

Position, *speed* and *acceleration* fields inform about the mobility patterns associated to the sender, while the *Timestamp* registers the time in which this information was recorded. The *priority flag* denotes the importance of the message (1 maximum, 0 normal). With these data, vehicles will have enough information to react earlier in order to perform a complete stop, thus reducing the probability of crashing. To define the main features of our particular braking algorithm we first find out how is the behavior of the system with the support for communications without a dynamic configuration of the IDM parameter *T*, that is to say, this parameter will take for all vehicles a more conservative value at the time a CWM is received (which will make all vehicles increase the distance respect to their frontal one). The main reason for this test is to evaluate the performance of a general approach in which vehicles tend to keep a conservative distance to neighbors ahead when they receive a CWM, without taking into account the associated driving aggressiveness in the protocol design. Configuration values for the present simulation are summarized in Table 3:

Table 3 Specific simulation parameters for simulation 2

Emergency Brake Scenario (configuration of parameters when a CWM is received)	
Model and simulation parameters	Values
T	1.5 s (constant)
T_r (Reaction Time)	0 s

As can be seen from Figures 4 and 5 (and comparing them with Figures 2 and 3), the system obviously behaves much better when communications are used, because vehicles can react to the incident earlier, adopting a remarkable conservative approach respect to ahead vehicles. This helps to reduce the probability of getting involved in an accident: around 50% less accidents with communications (when compared to Simulation Case 1, without communications support). On the other hand, if we observe the evolution of the acceleration variance when braking proceeds, values tend to be notably high (very similar to those of Simulation Case 1). This implies that although car collisions are reduced, accelerations employed to brake to a complete stop are still inadequate, since extreme variations in the braking acceleration show that the braking procedure could be effectively improved (reaching the same average acceleration to a complete stop, but minimizing the variations in acceleration). This would enhance the driving experience even under these critical situations, since driver and passengers would not be exposed to so high acceleration variations, meaning a better and more comfortable braking process (of course, in those cases in which it is physically possible).

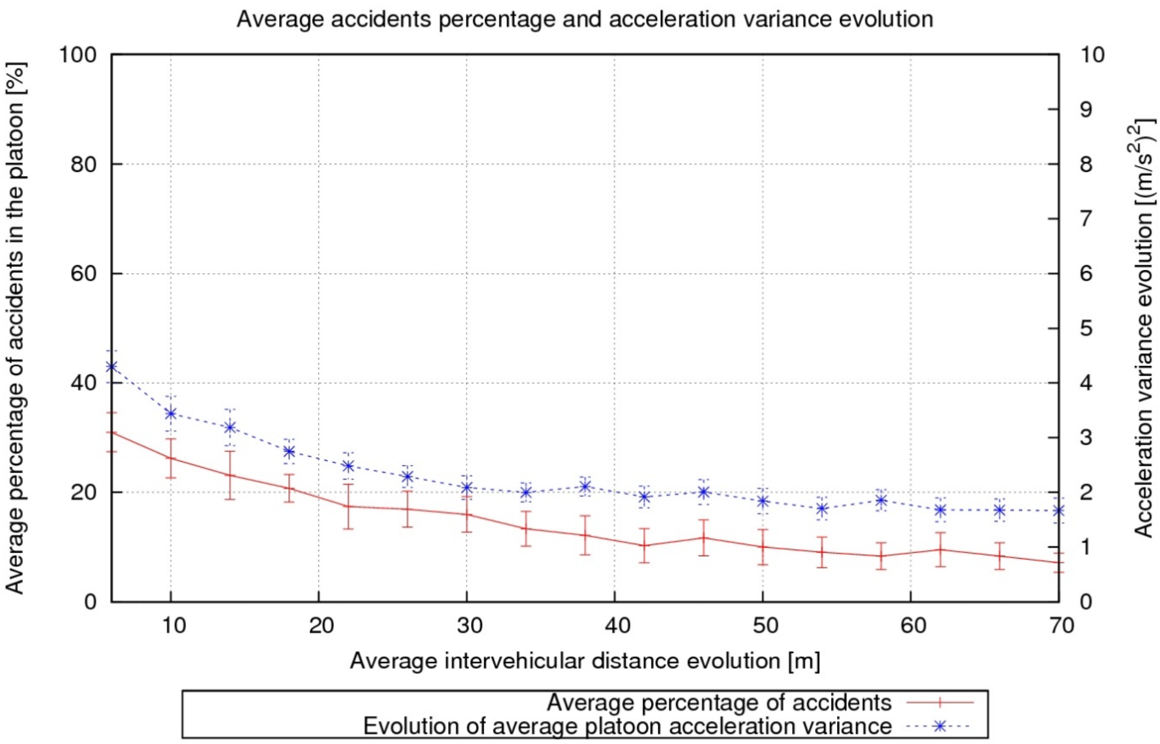

Figure 4 Average percentage of accidents within the platoon (left axis) and evolution of average acceleration variance of vehicles in the platoon (right axis)

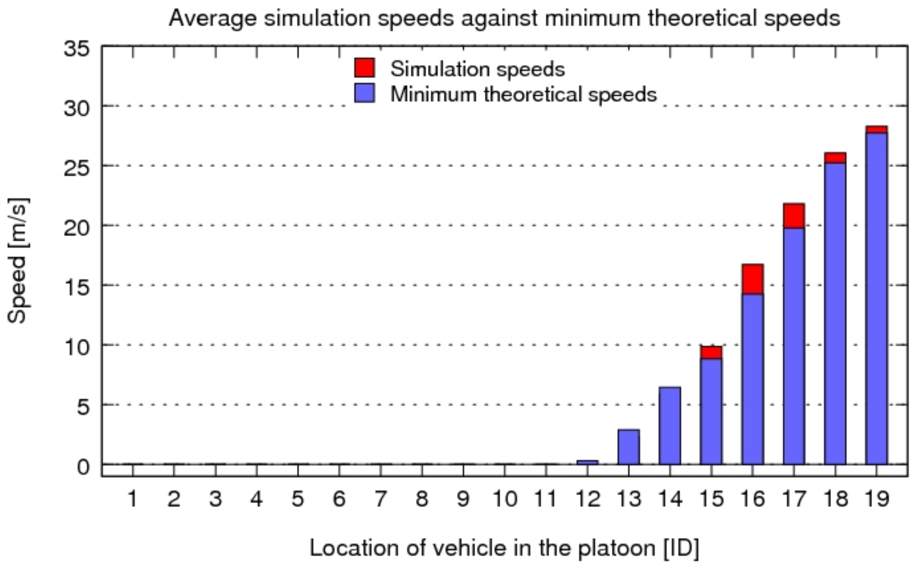

Figure 5 Minimum obtainable speeds to stop versus simulation speeds to stop for an average intervehicular distance of 6 meters

Linear Braking Algorithm (LBA)

After introducing the main technical aspects related to the brake procedure, as well as the communications protocol associated, we will perform a simulation of the proposed braking scheme and represent its results. Another simulation regarding the CAH (*constant acceleration heuristic*), will be carried out to compare the performance of our proposal with this smoothing acceleration/deceleration procedure already presented in other work by the authors of the IDM, Kesting and Treiber (2010). For a fair comparison, the CAH will rely on communications as well, working only when a CWM is received (accelerations according to this heuristic will be calculated only when CCA is triggered). The main functionality of CAH is described in Table 4. Two graphs, as regards the *Average acceleration variance evolution* and the *Average percentage of accidents in the platoon* will be represented, to compare the four cases illustrated in this paper together.

By designing a *Linear Braking Algorithm* (LBA) we mean to configure dynamically the braking scheme of vehicles which must deal with a critical situation such as an emergency stop. The main purpose has been already mentioned: to decrease or smooth the changes in acceleration and, as a result, obtain a reduction in the driving aggressiveness as well. Communications receive a major attention here, since they allow vehicles to own and use relevant and updated information about their neighbors. When treated correctly, in a system like CCA (under the consideration of the IDM model), it can be really useful, as we have seen, not only for the reduction of the probability of accident, but also for the best improvement of the driving comfort even for extreme conditions of the vehicular traffic. In LBA, vehicles interchange beacons periodically, informing neighbors about their associated mobility patterns: acceleration, speed and position, and the related timestamp of these values. This way, vehicles will know in real time the mobility patterns of their surrounding neighbors. Assuming that driving is human-assisted before the critical event takes place, when this happens, CWMs are sent to inform about the incidence occurred. Thanks to the information provided by beacons and CWMs, it is possible to design a dynamic braking scheme which can help vehicles stop under a quasi-constant deceleration value (without human intervention). The main algorithm for the CCA support of IDM in this work is explained next (see also table 4):

Table 4 LBA and CAH pseudo-codes

Linear Brake Algorithm (LBA)

```
while Vehicles driving do
    while not carCrash then
        sendBeacons periodically
        if beacon received then
            update Neighbors info
        else if CWM received then
            calculateLinearDec
            while braking do
                decelerate
                if different CWM received (or
                neighbor info changes) do
                    recalculateLinearDec
                end while
            end while
        end if
    end while
    if carCrash
        stop sendBeacons
        send CWM periodically
    end if
end while
```

Constant Acceleration Heuristic (CAH)

```
while Vehicles driving do
    while not carCrash then
        if CWM received then
            applyCAH
        end if
    end while
    if carCrash
        send CWM periodically
    end if
end while
```

A vehicle will circulate on the road sending periodically state information regarding its main mobility parameters. If a beacon is received, the receiver will update its status table with new neighbors' information (position, speed and acceleration) according to the data contained in the message. If a vehicle receives a CWM, it calculates the LBA deceleration value to stop without colliding with neighbors ahead and to reduce the driving aggressiveness. Knowing the information related to vehicles in front and between the vehicle under consideration and the first collided car, the receiver computes an estimation of what is the position in which it should stop completely, obtaining thus the deceleration value necessary to brake to a complete stop without changing the deceleration while braking, that is, with constant deceleration. If the mobility patterns of vehicles located ahead (namely deceleration) change during the braking procedure, a vehicle will recalculate its deceleration value, to deal with unforeseen changes which could naturally occur in the emergency scenario. Afterwards, the T parameter is calculated according to the general equation which solves the safety time gap value T according to the general mobility parameters. This parameter will be calculated at every time step to keep the deceleration value constant and equal to the one calculated previously (Equation 4):

$$T = \frac{\sqrt{(-1)\left[a_i(t) - A + A\left(\frac{v_\alpha}{v_0}\right)^\delta\right]\frac{{s_\alpha}^2}{A} - s_0 - (v_\alpha \Delta v_\alpha)}}{v_\alpha 2\sqrt{ab}} \qquad (4)$$

where:

v_α:	current velocity of vehicle α
A:	acceleration factor
v_0:	maximum velocity
s_α:	current intervehicular spacing
s_0:	minimum intervehicular distance
$a_i(t)$:	current acceleration
Δv_α:	speed differential
a:	desired acceleration factor
b:	desired deceleration factor
T:	desired time gap

To test the behavior of our scheme, we compare the two previous cases with it and the acceleration-smoothing algorithm CAH proposed by Kesting and Treiber (2010). If we observe the evolution of the number of car accidents in the platoon for the different intervehicular distances (Figure 6), we can notice the great difference in performance between using and not using communications in the IDM model. When there is no communications support, at low intervehicular distances (6 m) the percentage of accidents reaches almost the 80% of the platoon. On the other hand, regardless of the braking procedure used, the probability of accident is reduced to the half (mainly at lower distances) when communications are used, which implies a remarkably higher guarantee of safety for drivers and passengers. At higher distances, results for all schemes are the same (Figure 6). This behavior can be explained assuming that vehicles keep large enough distances to neighbors ahead, so that it is possible to brake timely in order to avoid crashing. The percentage of accidents appearing at these high distances responds to those vehicles sufficiently close to the first accident, which do not have the chance of stopping without colliding.

However, when we evaluate the driving aggressiveness implied by all the braking procedures, it is clearly shown that there are some differences between each single approach (Figure 7). The plain IDM behaves noticeably much worse than the rest of the cases. It is caused by the fact that without communications support, vehicles tend to react later to the sudden brake of neighbors ahead. When communications are operating, in the case in which a constant (conservative) value of $T = 1.5$ s is employed when a CWM is received, the acceleration variance is reduced by half for low distances (6, 10 and 14 m of intervehicular distance). CAH also succeeds in smoothing deceleration changes by getting (little) lower values for the acceleration variance. Nevertheless, if we look carefully at the evolution achieved by the LBA proposal we can notice that configuring mobility parameters in such a way that braking deceleration is kept quasi-constant during the whole emergency procedure, means obtaining a very low acceleration variance which obviously implies higher driving comfort. Thereby it is possible to reduce the number of car accidents in the platoon (Figure 6), and simultaneously decrease the driving aggressiveness, which is actually a very important design concern for the vehicle industry, Fatma Nasoz (2010).

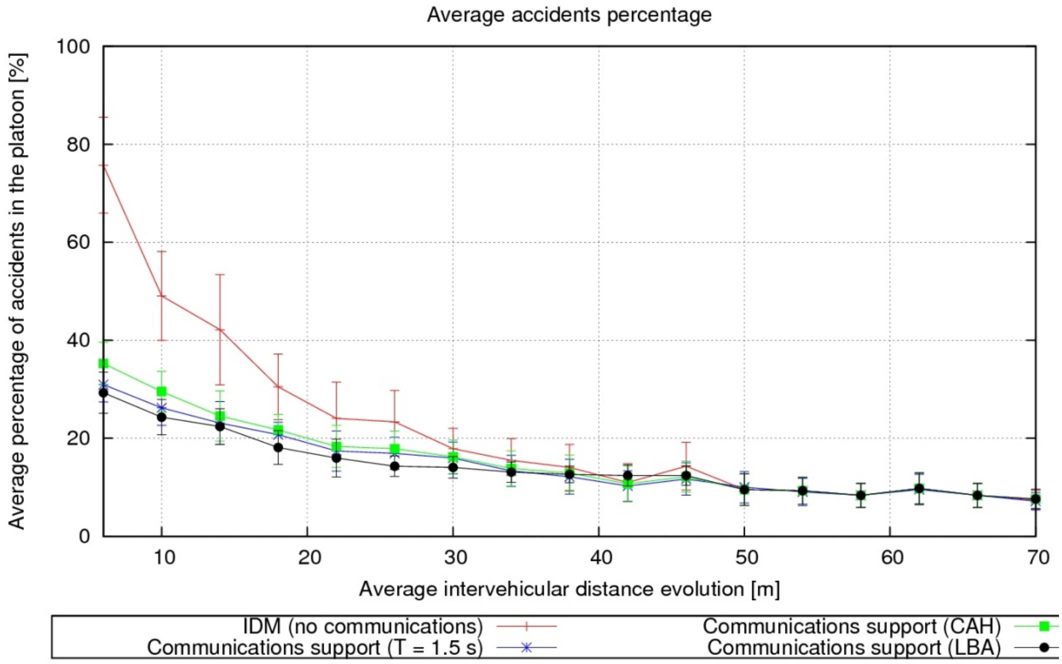

Figure 6 Evolution of average accidents percentage for the four implementation variants studied in this work

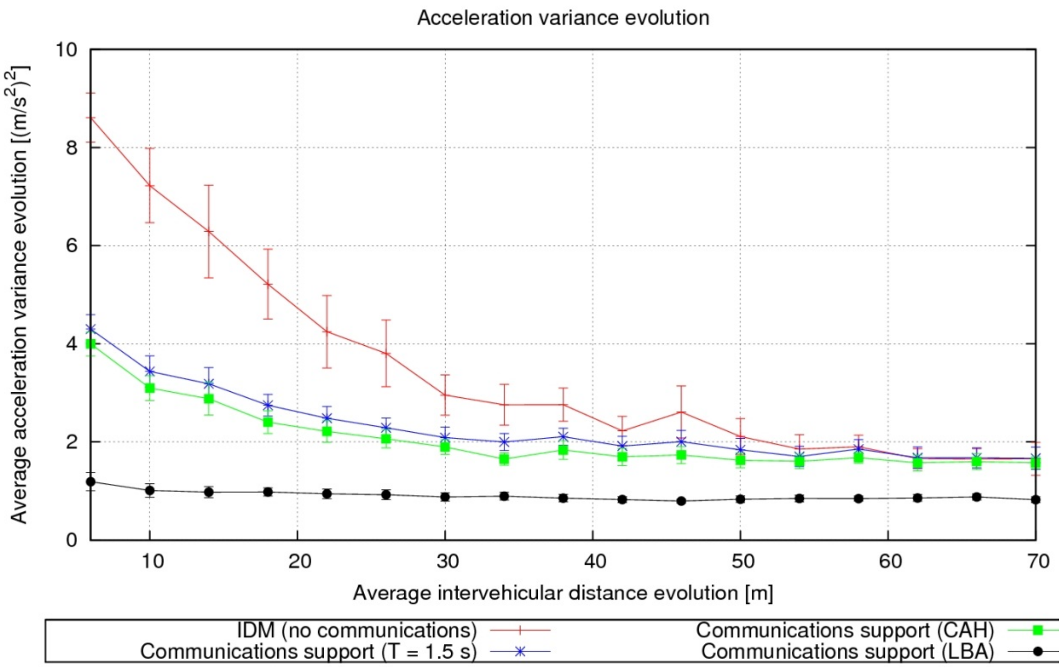

Figure 7 Evolution of acceleration variance for the four implementation variants studied in this work

CONCLUSIONS AND FUTURE WORK

As the previous sections reveal, the design of advanced braking policies is essential to cover all possible car traffic situations in order to assure the best performance and safety guarantees while driving. IDM, as regards the particular traffic configurations provided in the evaluations in Kesting and Treiber (2010), can achieve a very realistic performance in terms of safety, driving aggressiveness and general car traffic throughput. However, the coverage is very general, and at certain specific circumstances the model can miss a better performance which could be obtained if a more detailed manipulation of the model parameters was taken (see Figure 7). In this paper, we have shown that during emergency brake situations, it is possible to reduce the number of accidents in a platoon, while simultaneously decreasing the driving aggressiveness of drivers. Our *Linear Brake Algorithm* (LBA) enables the possibility to benefit from communications under emergency brake conditions to reduce the impact on the number of car accidents and the driving aggressiveness of the vehicle. This enhancement in the driving comfort will have positive health implications in passengers (since they will be exposed to lower braking decelerations as well as less changes in their magnitudes), along with minor gas consumptions and brake deterioration. Taking into account the previous results, acceptable scalability can be obtained in simulations when general configuration parameters (a, b and T) are assigned to the different traffic regimes in IDM. However, it is necessary to work on specific schemes to deal with those punctual circumstances where a better behavior of the system could be achieved if a particular configuration of such parameters was made.

Unfortunately, integrating communications into IDM and modifying dynamically the T parameter unavoidably has two important drawbacks: sensitivity of parameters to the changes, and the problem associated to the T parameter when the speed of a vehicle tends to zero (T value tends to infinite, see Equation 4). In order to get rid of these two inconsistencies, authors propose to analyze in future works how these issues could be solved. Furthermore, the model parameters a and b might be also useful to better improve the braking algorithm and reduce the effect of the two aforementioned inconsistencies related to parameters sensitivity and the T-infinite trend when approaching zero speed. On the other hand, the communications channel access should also be carefully evaluated to assess how the proposed CCA application can cohabit with other similar or general user services which also occupy the communications channel resources.

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