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Contextual and Applications-Aware Communications Protocol Design for Vehicle-to-Vehicle Communications

Miguel Sepulcre · Javier Gozalvez

Abstract Cooperative vehicular ad-hoc networks are currently under development for improving traffic safety and efficiency. The strict requirements of traffic safety applications demand robust communication protocols that are able to efficiently operate under diverse and challenging operating conditions. In this context, this work proposes the joint study and evaluation of cooperative applications with potential dependencies, and evaluates a context-aware communications mechanism that exploits traffic context information to maximize the applications' effectiveness. The benefits of the proposed approach are illustrated with the intersection collision warning and emergency electronic brake lights applications.

Keywords Vehicular ad-hoc networks · Intelligent transportation systems · Cooperative protocols · Context-awareness

1 Introduction

Cooperative vehicular systems are foreseen to significantly improve traffic safety and efficiency, while providing Internet access on the move. To this aim, V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) communication systems will allow the continuous and ubiquitous exchange of traffic safety and efficiency information among vehicles and with RSUs (Road Side Units) that will provide the drivers with information about potential dangerous and traffic congestion road conditions. To enable V2V and V2I communications, the IEEE is developing the WAVE (Wireless Access in Vehicular Environments) protocol stack, which adapts the IEEE 802.11 standard to the vehicular environment. The IEEE 802.11 p [1]

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standard defines the WAVE physical and MAC (medium access control) layers, and is being adapted to the European context by ETSI under the ITS-G5 standard. The operation of cooperative vehicular systems is mainly based on the exchange of two types of messages. On one hand, cooperative awareness messages (CAMs) are periodically transmitted by all vehicles and infrastructure units on the so called control channel to broadcast positioning data and other basic information to surrounding vehicles. The information included in CAMs helps each vehicle to maintain the connectivity with its neighbouring nodes, and supports high level applications, including cooperative road safety applications. On the other hand, decentralized environmental notification messages (DENMs) provide support to event-driven applications. These messages are generated when a potential dangerous situation is detected (e.g. a car's hard braking) in order to inform surrounding vehicles about the situation type, severity and location.

Cooperative vehicular systems will enable a wide variety of new applications and services, ranging from cooperative road safety applications to distributed traffic management services or in-vehicle infotainment services [2]. Although some interesting studies evaluating the performance of cooperative applications can be found in the literature, to date, the configuration and evaluation of multiple cooperative applications and services have been performed independently without considering their potential interrelations and/or dependencies. To illustrate the need of taking into account such interrelations, this work considers safety applications due to their strict QoS (quality of service) requirements, and the resulting difficulty to design reliable and efficient communication protocols.

Cooperative road safety applications can be classified as cooperative awareness applications, which base their operation in the exchange of periodic CAMs, and road hazard warning applications, which are event-driven applications using DENMs. ETSI [2] and VSC [3] have defined a set of preliminary application requirements in terms of communications distance, packet transmission frequency, latency, or positioning accuracy. Current ETSI and VSC definitions propose fixed reference requirements for each specific application to be used in the initial communications protocol design and testing. However, the critical nature of cooperative vehicular applications requires a more detailed definition of the application requirements, but to date limited work has been done on this topic with regards to traffic safety applications. The work in [4] shows an example of detailed definition of safety metrics for rear-end, lane change, and roadway departure crashes for different ITS systems. Some studies propose to extend these performance metrics to cooperative vehicular systems. For example, the work published in [5] derives analytical bounds for the maximum acceptable message delivery latency and minimum packet retransmission frequency required to satisfy the requirements of rear-end collision avoidance applications. The author demonstrates the strong impact of the traffic and operating conditions (speed, state of the road surface, radio channel variability conditions, etc.) on these two metrics. The work in [6] develops the detailed requirements of an overtaking assistance and a lane change assistance application, to illustrate the importance of considering the application requirements in the design and evaluation of cooperative communication protocols and policies. The results obtained demonstrate the impact of the application requirements on the communication settings of each vehicle, and on the overall channel load generated.

Intersection collision warning (ICW) is one of the cooperative awareness safety applications that is attracting more interest due to the high percentage of accidents at intersections [7]. The ICW application warns the driver when a potential collision at an intersection is detected following the exchange of cooperative messages. The application can use V2V or V2I communications. When based on V2V, vehicles periodically broadcast CAMs to detect each other before reaching an intersection. In case of V2I, an RSU installed at the intersection receives and processes all CAMs received from approaching vehicles, and transmits a series of periodic DENMs when it detects that a collision between two vehicles could occur at the intersection. Although the use of an RSU at an intersection significantly improves the communications between two vehicles, the wide scale deployment of RSUs faces significant economic difficulties, and critical safety applications should then also reliably work using V2V communications. Independently of the ICW communications scenario, vehicles need to receive the warning information with enough time for the driver to decelerate and avoid the collision at the intersection. As a result, a minimum warning distance required to inform a driver to stop before the intersection is normally defined as performance metric [8]; ICW applications require vehicles to efficiently and reliably exchange at least one message before the warning distance. Different studies have conducted dimensioning or sensitivity studies to analyse the ICW performance under different operating and communicating conditions. For example, the work in [9] shows that the use of high packet transmission frequencies and low data-rates can improve the performance of an intersection warning system due to the earlier detection of the risk of collision. However, the use of high packet transmission frequencies or transmission power levels at intersections with high traffic density could congest the radio channel, as shown in the study reported in [10]. To overcome this situation, advanced communication schemes that efficiently use the radio channel and satisfy the application requirements are needed. One example is the work in [11], which proposes a geo-opportunistic transmission mechanism that adapts each vehicle's transmission parameters to reliably and efficiently exchange a message before reaching a critical safety area, for example an intersection. Other studies such as [12] propose the use of RSUs to manage the communications among the potentially colliding vehicles at intersections to avoid using high transmission power levels when there are buildings blocking the radio signal. In this context, the work in [13] provides an overview of the recent developments, limitations, standards and protocols that can facilitate IEEE 802.11-based V2I communications.

The emergency electronic brake light (EEBL) application is one of the most representative examples of road hazard warning application. Whenever a vehicle breaks hard, the EEBL application automatically sends time limited periodic DENMs to other vehicles behind to avoid or mitigate rear-end collisions. This application will help following vehicles by providing an early notification of lead vehicle braking hard, even when the driver's visibility is limited. To date, several studies have analysed the efficient, reliable and fast propagation of cooperative emergency alerts through a vehicle chain to avoid rear-end collisions after a sudden emergency deceleration. To avoid the broadcast storm problem that could be created with conventional broadcast dissemination protocols, and reduce the contention at the MAC layer, the work in [14] proposes different probabilistic and timer-based broadcast suppression techniques to be used at the network layer. Similarly, in [15], the authors propose a direction-aware broadcast forwarding protocol to propagate the emergency message based on an implicit acknowledgement. In [16], a position-based message forwarding strategy is proposed. In particular, the paper presents a timer-based broadcast suppression technique in which the timer of each potentially forwarding vehicle is set proportional to the distance to the previous forwarder. In general, these studies showed that the use of multihop dissemination protocols can help reducing collisions among nearby vehicles through the rapid propagation of messages for EEBL applications.

Despite providing very valuable results, most of the studies discussed analyse different applications independently of each other. Only a few studies (e.g [17–19]) consider the coexistence of multiple cooperative applications. In particular, the work in [17] proposes to combine the payload and headers information to be transmitted by different applications to reduce the channel load generated by each vehicle since various applications often require transmitting similar information (e.g. the position and speed of the vehicle). The work shows that the channel load can be considerably reduced by coordinating the data to be transmitted for different applications. The work in [18] proposes a new communications architecture that groups the different applications to solve the current TCP/IP inefficiencies when applied to VANETs. Unfortunately, the study does not include detailed information on the method to organize different applications and how to exploit their similarities. Other studies that analyse multi-application scenarios focus on the different needs or priorities required by each application. For example, the work in [19] proposes a prioritization and re-scheduling technique based on application-specific utility functions in order to control the amount of information sent to the wireless channel. These contributions represent initial and promising studies towards the design of cooperative vehicular systems capable to reliably and efficiently operate multiple and simultaneous applications. However, additional studies are necessary, in particular with regards to the design, configuration and optimisation of communications protocols capable to efficiently satisfy the requirements of different applications, in particular when such applications exhibit potential interrelations and/or dependencies that should be taken into account. The importance of these interrelationships can be illustrated for the case of the ICW and EEBL applications with the intersection scenario shown in Fig. 1. In this scenario, vehicles A_1 and B are approaching the intersection with a risk of collision. To detect each other's presence and avoid the accident at the intersection, vehicles A_1 and B periodically exchange positioning information by means of CAMs. The information exchanged allows the ICW application to alert the drivers of a potential intersection collision before reaching the intersection. However, although vehicle A_1 might avoid the accident at the intersection through a sudden deceleration, its action might result in a rear-end collision with its neighbouring vehicles (vehicles A_2 and A_3 in Fig. 1). This rear-end collision could be avoided if vehicle A_1 is alerted of the potential intersection collision with sufficient time to avoid a sudden deceleration. To this aim, the communications between vehicles A_1 and B should not be dimensioned considering just their potential intersection collision, but also the potential rear-end collision of vehicles A_x. In this context, this paper proposes and evaluates a novel cooperative vehicular communications scheme that bases its operation on the joint analysis of different application requirements. In addition, the proposed scheme exploits traffic context information to optimise both traffic safety and communications performance, while minimising the impact of individual vehicular decisions on nearby vehicles. Since each application has specific requirements and operation scenarios, the proposed scheme is illustrated considering the ICW and EEBL applications. However, it is important noting that the proposed approach could be easily extended to other traffic safety scenarios and applications, e.g. dangerous overtaking or entrance ramps.

2 Joint Applications and Traffic Context Characterization

In this section, the proposed approach is explained in detail through the joint analysis of ICW and EEBL applications, and the characterization of the traffic context. Based on the functional description of the applications and the traffic context information, the joint application requirements are derived, and the most significant traffic and operating parameters that could affect the design of context-aware communication techniques are identified.

2.1 Interaction of ICW and EEBL Applications

To illustrate the proposed context-aware approach and show its effectiveness, the study is based on the scenario presented in Fig. 1. In this scenario, vehicles A_1 and B might collide

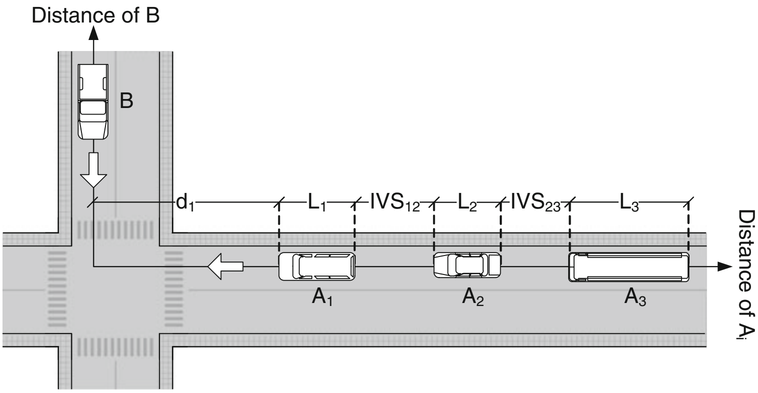


Fig. 1 Intersection scenario

at the intersection due to the driver's lack of attention, wrong/hidden traffic signals, or any other reason that could provoke the accident despite the driver's ability and perception capabilities. In this scenario, only V2V communications have been considered due to their more challenging radio propagation conditions compared to V2I under the presence of buildings, and the unfeasibility of ubiquitously deploying RSUs in every single intersection.

All vehicles periodically broadcast CAMs at 10 Hz to detect potential dangerous situations before reaching the intersection. In this case, vehicles A_1 and B must correctly exchange at least one of these messages with sufficient time to stop before reaching the intersection and avoid their collision. The critical distance *CD*, or minimum warning distance, can be defined as the minimum distance to the intersection at which, for example, vehicle A_1 needs to receive a CAM from vehicle B to avoid their collision at the intersection. Considering a uniform deceleration model, *CD* can be computed as:

$$CD = v \cdot RT + \frac{1}{2}\frac{v^2}{a_{\max}} \tag{1}$$

where v represents the vehicle's speed, *RT* the driver's reaction time, and $a_{\max}$ the vehicle's emergency deceleration. Following this approach, ICW applications could be dimensioned and configured to ensure that vehicles A_1 and B exchange at least one broadcast message before *CD* to avoid an intersection collision. However, this approach does not consider the possibility of rear-end collisions resulting from the sudden deceleration of A_1 caused by the late reception of the first broadcast message from vehicle B, or simply by a human reaction; the possibility of a rear-end collision could exist even if considering a rapid propagation of the safety alert through the vehicle chain using DENMs generated by the EEBL application. To avoid chain collisions and mitigate dangerous situations, this work proposes the dimensioning of ICW communications considering their impact on EEBL and potential rear-end collisions. In particular, the chain collision risk could be reduced if vehicle A_1 received earlier the broadcast alert from vehicle B. In this case, vehicle A_1 could avoid the intersection accident through a smoother deceleration that reduces the risk of rear-end collisions. To achieve this objective, this work proposes the dimensioning of ICW communication parameters allowing the first vehicles approaching the intersection to exchange messages at a distance to the intersection larger than the critical distance, i.e. at *CD* plus an extra distance (*ED*). As it will be shown in Sect. 2.2, the *ED* distance is defined based on the traffic context so that safety alerts are received with sufficient time to avoid sudden decelerations. The *ED*

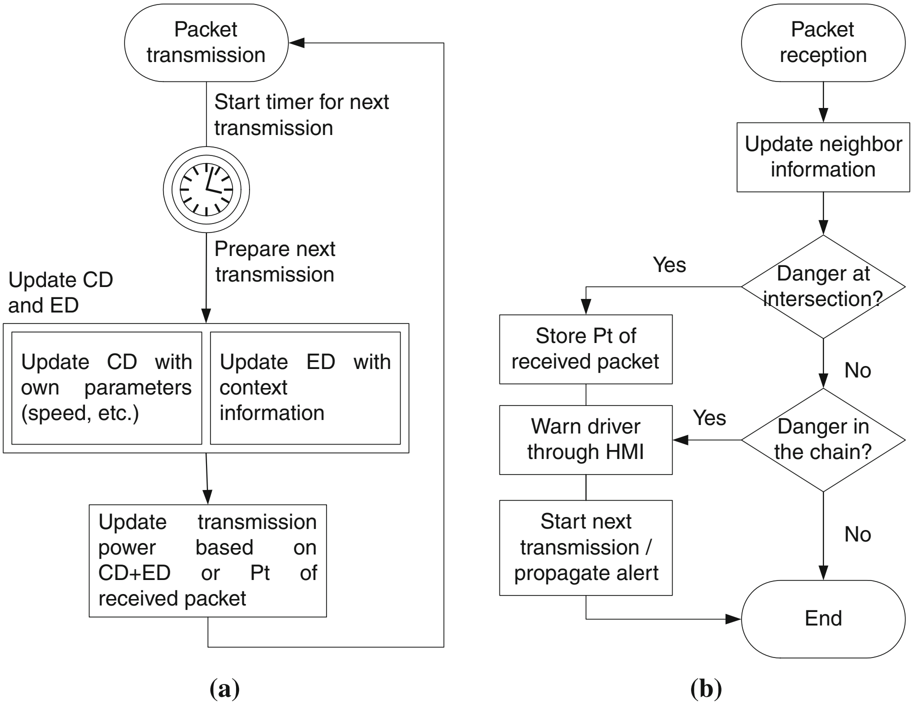


Fig. 2 Flow chart for the transmission and reception of CAM messages in the case of the proposed context-aware approach. **a** Transmission process. **b** Reception process

parameter is also dynamically computed by the first vehicle in the chain thanks to the periodic exchange of CAMs between vehicles A_x. The addition of *CD* and *ED* can then be defined as the minimum distance to the intersection at which vehicle A_1 needs to receive a message from vehicle *B* to avoid both the accident at the intersection and a possible rear-end collision.

To design the proposed context-aware mechanism and dynamically compute *ED*, this work considers the use of an internal spatial database or local dynamic map (LDM) on each vehicle, as it currently is determined in the ETSI standardization process. All relevant static, temporary and dynamic information of a vehicle's surroundings is constantly updated on the LDM. Before each data packet transmission, all vehicles approaching the intersection update their required *CD* distance based on their own parameters (speed, driver's reaction time and emergency deceleration), and their required *ED* following their traffic context (the *ED* computation is described in Sect. 2.2). As depicted in Fig. 2, after a packet is being received, the application updates the LDM database with the received neighbour information. Based on the positioning and speed information contained in the packet, the application is able to detect if a collision is likely to occur at the intersection if the current speed and acceleration of neighboring vehicles are maintained. In the proposed scenario, if a potential dangerous situation is detected at the intersection, the driver is first warned through the HMI (Human-Machine Interface). Then, a new packet is transmitted using the transmission power level (*Pt*) employed in the packet received from the potentially colliding vehicle. If multihop dissemination protocols are considered, the alert is propagated through the vehicle chain to avoid rear-end collisions.

The process to select the transmission power once the risk of collision at the intersection is detected is as follows. As shown in Fig. 1, vehicle B is not followed by any vehicle, and therefore does not require receiving the message with an extra distance *ED*. Vehicle B would then configure its transmission power to communicate with A_1 before *CD*. In this context, vehicle A_1 would receive the message from B before *CD*, but maybe not before $CD + ED$. On the other hand, vehicle A_1 detects the presence of following vehicles through the reception of their CAMs, and therefore requires an $ED > 0$. In this context, a higher transmission power and larger communications range is therefore needed to communicate with vehicle B. Vehicle B will then be the first vehicle receiving the alert of the potential collision at the intersection. After receiving the CAM from A_1, vehicle B will immediately increase its transmission power to at least the same level as that employed by A_1 so that vehicle A_1 is able to receive the alert from vehicle B before $CD + ED$. With the proposed two-way handshaking, both vehicles (A_1 and B) receive the message before their respective distance to the intersection at which they need to start decelerating to avoid any accident (intersection and rear-end collisions). With existing ICW application approaches, normally symmetric traffic situations are assumed, i.e. vehicles A_1 and B are characterized by the same traffic context. If this was the case, the two-way handshaking would not be required since vehicles A_1 and B would be characterized by the same *CD* and $ED = 0$. If transmission power levels are properly configured, this process will ensure the reception of at least one message with enough distance for the vehicles to smoothly decelerate and avoid the accident at the intersection and the rear-end collision. Without the proposed two-way handshaking, vehicle A_1 would not necessarily receive the message from B before $CD + ED$ (only before *CD*), which could provoke rear-end collisions due to the hard deceleration of A_1. Please note that vehicle B would be able to know the transmission power used by vehicle A_1 since international standards include information on the used transmission power in the packet headers [20,21].

2.2 Context-Aware Joint Application Requirements

To derive the joint traffic-aware ICW and EEBL application requirements, the scenario depicted in Fig. 1 is considered with $N - 1$ vehicles, $A_2, A_3, \ldots, A_N$, following vehicle A_1. In this work, all vehicles are approaching the intersection at the same speed, although the analysis could be extended to different speeds. The length of each vehicle A_n is L_n, and the inter-vehicle spacing that separates the rear bumper of vehicle A_n and the front bumper of vehicle A_{n+1} is $IVS_{[n,n+1]}$. We can then define for each vehicle the kinematic equations relating the time and distance to the intersection. Two movement phases can be differentiated: (a) constant speed phase before the reception of an alert and the driver's reaction, and (b) constant deceleration phase to avoid the accident. In terms of the timing definitions, $t = 0$ s corresponds to the time instant at which vehicle A_1 receives the first CAM from vehicle B. Consequently, vehicle A_1 starts the deceleration after the driver's reaction time *RT*, i.e. at $t = RT$, and it will completely stop at $t = RT + v/a_1$ (considering that A_1 decelerates with a_1) m/s^2. Following the same procedure, the timing for each vehicle can be established (Table 1), in which PT (propagation time) represents the time between the reception of an alert by vehicle A_n and its retransmission towards vehicle A_{n+1} that will be further discussed later.

Considering the previously defined time origin, and that vehicle A_1 needs to receive the first CAM from vehicle B at a distance to the intersection at least equal to $CD + ED$, we consider that vehicle A_1 is located at $d_1(0) = d_1 = CD + ED$ at $t = 0$ s. Following the vehicular scenario depicted in Fig. 1, it can then be derived that at $t = 0$ s, vehicle A_2 is at

Table 1 Time instants for alert reception, reaction and vehicle stopped

Vehicle	Alert reception	Start deceleration: $t_{decel(n)}$	Vehicle stopped: $t_{stop(n)}$
A_1	t = 0	t = RT	t = RT + v/a_1
A_2	t = PT	t = RT + PT	t = RT + PT + v/a_2
A_n	t = (n − 1) PT	t = RT + (n − 1) PT	t = RT + (n − 1) PT + v/a_n

a distance to the intersection equal to $d_2(0) = d_2 = CD + ED + L_1 + IVS_{[1,2]}$, and vehicle A_n at $d_n(0) = d_n = CD + ED + \sum_{i=1}^{n-1} (L_i + IVS_{[i,i+1]})$. Using the previously defined parameters, the kinematic equations $d_n(t)$ for each vehicle in the chain can finally be derived as follows:

$$d_n(t) = \begin{cases} -vt + d_n & 0 \le t < t_{\text{decel}(n)} \\ \frac{1}{2}a_n \left(t - t_{\text{decel}(n)}\right)^2 - vt + d_n & t_{\text{decel}(n)} \le t \le t_{\text{stop}(n)} \end{cases} \tag{2}$$

While the first term in Eq. (2) corresponds to the constant speed phase, the second term corresponds to the constant deceleration phase. Considering that the possibility of collision between two contiguous vehicles depends on their deceleration after receiving a traffic safety alert, if there were no other vehicles in the chain ($N = 1$), A_1 could decelerate with $a_1 = a_{\max}$ and define the extra distance *ED* as zero. If other vehicles follow A_1, the decelerations that avoid chain collisions need to be carefully identified to compute *ED*. In order to calculate the maximum deceleration that a vehicle can apply to avoid a chain collision, the function that defines the distance between two consecutive vehicles can be employed:

$$D_{[n+1,n]}(t) = d_{n+1}(t) - (d_n(t) + L_n) \tag{3}$$

Since the objective is that vehicles A_n and A_{n+1} do not collide during their deceleration, their minimum distance during their deceleration must always be above zero, i.e. $D_{[n+1,n]}(t) > 0$. To calculate this minimum distance, first the second term of Eq. (2) needs to be substituted in Eq. (3):

$$D_{[n+1,n]}(t) = \frac{1}{2}a_{n+1}(t - RT - nPT)^2 + IVS_{[n,n+1]} - \frac{1}{2}a_n(t - RT - (n-1)PT)^2 \tag{4}$$

Then, the Fermat's theorem can be applied to calculate the minimum distance: every minimum of the function is a stationary point (the function first derivative is zero in that point), and the function second derivative is positive at that point. Following the Fermat's theorem and the function first derivative equal to zero, the time at which the minimum distance between two consecutive vehicles is produced, $t_{\min}$, can be obtained from the following equation:

$$\left.\frac{\partial\left[D_{[n+1,n]}(t)\right]}{\partial t}\right|_{t_{\min}} = a_{n+1}(t - RT - nPT) - a_n(t - RT - (n-1)PT)\big|_{t_{\min}} = 0 \tag{5}$$

and is:

$$t_{\min} = RT + nPT + \frac{a_n PT}{a_{n+1} - a_n} \tag{6}$$

The second derivative of $D_{[n+1,n]}(t)$ is always positive at $t = t_{\min}$ in the proposed scenario:

$$\frac{\partial^2\left[D_{[n+1,n]}(t)\right]}{\partial t^2} = a_{n+1} - a_n > 0 \tag{7}$$

Then, the maximum deceleration value of vehicle A_n that could avoid a chain collision can be calculated by substituting the value of $t_{\min}$ obtained in Eq. (6) into Eq. (4) as:

$$D_{[n+1,n]}\left(t_{\min}\right) > 0 \Rightarrow a_n < \frac{2IVS_{[n,n+1]}a_{n+1}}{2IVS_{[n,n+1]} + PT^2 a_{n+1}} \tag{8}$$

Since the deceleration of the last vehicle in the chain does not depend on the traffic context, and assuming that this deceleration a_N is equal to $a_{\max}$, the deceleration value for vehicle A_{N-1} can be obtained from Eq. (8). This process can be applied to any vehicle A_n in the chain in order to obtain its deceleration based on that of vehicle A_{n+1}. Following this process, a_1 for vehicle A_1 can then be estimated. Given that vehicle A_1 needs to stop before reaching the intersection to avoid colliding with vehicle B, the minimum value of *ED* can be worked out from Eq. (2) at the time at which A_1 completely stops ($t = t_{\text{stop}(1)}$). Equation (9) shows the resulting equation for *ED*:

$$ED = \frac{v^2}{2}\left(\frac{1}{a_1} - \frac{1}{a_{\max}}\right) \tag{9}$$

The methodology to obtain *ED* using Eq. (8) is not always valid. In fact, it is possible that the time when the spacing between two vehicles is minimum is higher than the time at which any of the two vehicles stop. In particular, the result for a_n obtained in Eq. (8) will only be valid if the following two conditions are satisfied:

$$t_{\min} \leq t_{\text{stop}(n)} \;;\; t_{\min} \leq t_{\text{stop}(n+1)} \tag{10}$$

Using the value of $t_{\min}$ obtained in Eq. (6), the relationship between a_n and a_{n+1} shown in Eq. (8), and t_{stop} values in Table 1, it can be demonstrated that the conditions in Eq. (10) are equivalent to:

$$vPT \geq 2IVS_{[n,n+1]} \tag{11}$$

As a consequence, when the condition in (11) is not satisfied, the Fermat's theorem cannot be directly applied in the proposed context and the minimum distance between the vehicles is produced at the function's extreme values (i.e. the time at which the vehicles stop). In this case, the value for a_n can be obtained from the equation of the distance between the vehicles A_{n+1} and A_n when they stop ($t_{\text{stop}(n)}$ and $t_{\text{stop}(n+1)}$):

$$d_{n+1}(t_{\text{stop}(n+1)}) - \left(d_n(t_{\text{stop}(n)}) + L_n\right) > 0 \Rightarrow a_n < \frac{a_{n+1}v^2}{2a_{n+1}(vPT - IVS_{[n,n+1]}) + v^2} \tag{12}$$

The vehicle's deceleration to avoid chain collisions can then be expressed as follows:

$$a_n = \begin{cases} \frac{2IVS_{[n,n+1]}a_{n+1}}{2IVS_{[n,n+1]}+PT^2 a_{n+1}} & \text{if } vPT \geq 2IVS_{[n,n+1]} \\ \frac{a_{n+1}v^2}{2a_{n+1}(vPT-IVS_{[n,n+1]})+v^2} & \text{if } vPT < 2IVS_{[n,n+1]} \end{cases} \tag{13}$$

Using Eq. (13), we can recursively estimate the deceleration values a_n until being able to calculate the deceleration for the vehicle in front of the chain, a_1. With this value, we can then derive the extra distance *ED* using Eq. (9). Once *ED* is obtained, it can be estimated the distance at which the first vehicle of a vehicle chain (in our case vehicle A_1) needs to receive the first CAM from the potentially colliding vehicle (in our case vehicle B). As it has been shown, this distance is equal to $CD + ED$ and is dependent on traffic context information:

- *Traffic information*: speed, type and acceleration of surrounding vehicles, together with their inter-vehicle spacing. This information is obtained through the periodic exchange of CAMs.
- *Road topology/state information*: information retrieved from digital maps (e.g. presence of an intersection) and information obtained from onboard sensors (e.g. state of the road surface to estimate the maximum applicable deceleration with a hard brake).
- *Propagation conditions*: estimation of the time needed to propagate a safety alert among nearby vehicles (*PT*, Propagation Time). *PT* represents the time between the reception of an alert by vehicle A_n and its retransmission towards vehicle A_{n+1}. In terms of alert propagation conditions, two scenarios have been differentiated: visual alert propagation through brake lights, and radio alert propagation through an EEBL application using multihop dissemination protocols. In the case of visual alert propagation, *PT* is equal to *RT* since the safety alert is transmitted to the following vehicle after the driver reacts and presses the brake. In the case of radio alert propagation, *PT* is composed by the processing time (the time needed to acquire data and construct the packet), and the transmission latency (the time needed to access the channel and transmit the packet, which depends on the medium access control protocol, the channel load, message priority level, etc.) [22].

As an example, Fig. 3 illustrates the achieved results using the proposed analytical methodology considering $N = 5$ vehicles in the chain and constant *IVS* values. In particular, Fig. 3a depicts the computed distance to the intersection $d_n(t)$, where the time instants separating the different movement phases have been highlighted with marks for the different vehicles in the chain. As shown in Fig. 3a, the final distance to the intersection for vehicle A_1 is zero, i.e. it stops at the intersection and avoids the collision with vehicle B. Using the results in Fig. 3a, b shows that the distances between any pair of consecutive vehicles in the chain $D_{[n+1,n]}(t)$ is always above zero before they stop for the proposed *ED* solution, i.e. no rear-end collisions take place.

Figure 4 shows the impact of the vehicle's speed and the inter-vehicle spacing on the *ED* distance considering a visual alert propagation in the vehicular chain ($PT = RT$), for two typical reaction time values: $PT = RT = 0.75$ s and 1.5 s [15]. The obtained results show that the distance at which a broadcast message needs to be received from the potentially colliding vehicle can be defined as *CD* (i.e. $ED = 0$) under high *IVS* distances and low speeds.

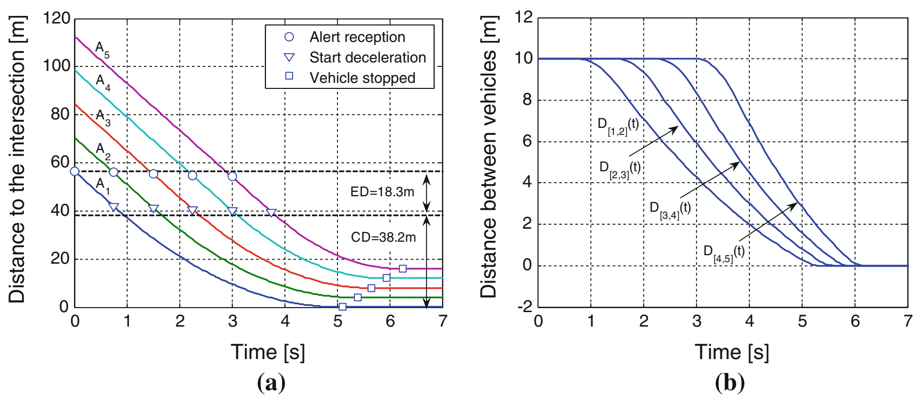


Fig. 3 Illustration of the distance to the intersection and distance between vehicles considering the proposed methodology. Case: RT = PT = 0.75 s, v = 70 km/h, IVS = 10 m, L_n = 4 m, N = 5 vehicles. **a** Distance to the intersection. **b** Distance between vehicles

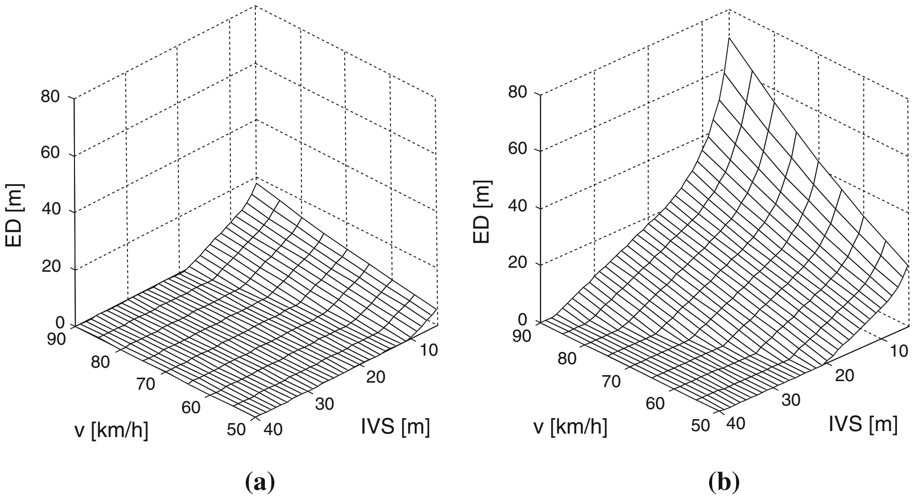
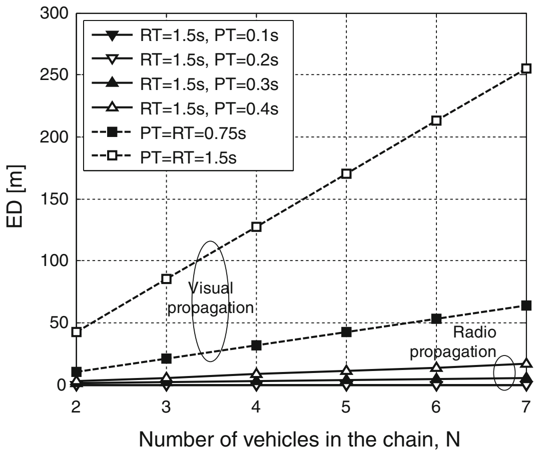


Fig. 4 Extra distance as a function of the vehicular speed and the IVS distance for N = 2 vehicles. **a** RT = PT = 0.75 s. **b** RT = PT = 1.5 s

Fig. 5 ED as a function of the number of vehicles in the chain for v = 70 km/h and IVS = 5 m



On the other hand, the *ED* distance required to avoid chain collisions can be quite significant at high speeds and at short *IVS* distances, especially for high driver's reaction times.

The results shown in Fig. 5 highlight the strong dependence of the *ED* distance with *PT* and the number of neighbouring vehicles *N*, for both the visual and radio alert propagations. In the case of radio alert propagation, different values of *PT* have been analysed taking into account the limits proposed in current ETSI draft standards [22]: processing time $\leq$0.05 s, and transmission latency $\leq$0.3 s. High *PT* values could correspond to situations with a high channel load (high channel access time) and slow packet forwarding protocols, while low values of *PT* could correspond to low channel load, and efficient and fast packet forwarding protocols. The results shown in Fig. 5 emphasize that the use of low latency multihop VANETs can significantly reduce the *ED* necessary to avoid chain collisions, and thereby benefit the operation of cooperative vehicular systems. In particular, it is important to note that for high *PTs* and challenging propagation conditions at urban intersections (presence of obstructing buildings), it might be difficult to guarantee that two vehicles can establish a reliable V2V communications at $CD + ED$ as N increases. On the other hand, such difficulty is significantly reduced through the use of low latency multihop communications independently of N.

3 V2V Communications Contextual Design and Operation

The previous section described a methodology to determine the communication requirements in the case of simultaneous applications exhibiting certain dependencies or interrelations. The presented methodology exploits the traffic context information. Based on the presented methodology, this section analyses the resulting communications dimensioning and the impact of traffic context information on V2V-based context-aware communications.

3.1 Simulation Environment

The study has been conducted using the ns-2 simulation platform modelling the urban intersection scenario depicted in Fig. 1. In this scenario, all vehicles periodically broadcast 10 CAMs per second in the control channel with a 100 Bytes payload each. The transmission is based on the IEEE 802.11p standard, and follows the process summarized in Fig. 2. All CAMs are transmitted at 6Mbps using the 1/2 QPSK transmission mode. The emergency deceleration or the vehicle length have been fixed to $a_{max} = 8\,m/s^2$ and L = 4 m, respectively. In the case of the vehicular speed or the IVS values, fixed values are initially selected although the use of realistic traffic mobility is studied in Sect. 3.4. Table 2 summarizes the main traffic and communication parameters considered in this study.

As demonstrated in [23,24], an adequate modelling of radio propagation is very important for a correct study of the operation and performance of vehicular communications. Considerable efforts have been lately done towards the characterization and development of V2V radio channel models. However, to the authors' knowledge, there is no complete system level model for urban environments properly reflecting pathloss, shadowing and multipath fading effects differentiating LOS (Line of Sight) and NLOS (Non-LOS)

Table 2 Traffic and communications simulation parameters

Traffic parameters	
Speed	50–90 (km/h)
IVS	5–15 (m)
RT	0.75 and 1.5 (s)
a_{max}	$8\,m/s^2$
Communication parameters	
Carrier frequency	5.9 (GHz)
Bandwidth	10 (MHz)
Antenna gain	0 (dB)
Noise floor	−90 (dBm)
Data rate (transmission mode)	6 (Mbps) (1/2 QPSK)
Payload	100 (Bytes)
Packet transmission frequency	10 (Hz)

propagation conditions. Interesting studies that propose radio channel models for highway and suburban scenarios were published for example in [25]. For urban environments, [26] highlights the need to differentiate between LOS and NLOS propagation conditions, and to distinguish between dense and sparse scenarios in terms of pathloss. To account for the relevant identified effects, the urban micro-cell propagation model developed in the European project WINNER [27] has been used. Although this model does not perfectly match the V2V communication scenario,[1] to the authors' knowledge, this is one of the models that currently best fit the proposed scenario for system level simulations (relatively low antenna heights, valid for the 5GHz band, specifically designed for urban scenarios, LOS and NLOS propagation conditions, etc.). This model considers the pathloss, shadowing and multipath fading effects, and differentiates between LOS and NLOS propagation conditions. While the shadowing has been modelled through a log-normal random distribution, the multipath fading has been implemented through Ricean and Rayleigh distributions for LOS and NLOS conditions respectively [27]. To reduce the complexity of system level simulations, the effects of the physical layer have also been included by means of Look-Up Tables (LUTs) [28]. These LUTs map the Packet Error Rate (PER) to the experienced channel quality conditions expressed in terms of the effective Signal to Interference and Noise Ratio (SINR).

3.2 Context-Based Vehicular Communications Dimensioning

To illustrate the need and benefits of the proposed multi-applications context-based vehicular communications dimensioning, the potential consequences of not considering such dimensioning are first illustrated. If this was the case, V2V communications would be configured in the case of the scenario depicted in Fig. 1 so that vehicles A_1 and B exchange CAM messages before CD to avoid their collision at the intersection. Under certain conditions, this configuration could result in a sudden deceleration of A_1 and rear-end collisions if the first message exchanged between vehicles A_1 and B is not exchanged before $CD+ED$. The probability of having a rear-end collision is illustrated in Fig. 6 in the case that the transmission power of vehicles A_1 and B is configured so that the probability that A_1 (or B) does not receive a CAM from B (or A_1) before CD is equal to $p_n = 0.01$ (i.e. the probability of correctly exchanging at least one CAM before CD is equal to $p = 1 - p_n^2 = 0.9999$ considering independent packet receptions). The rear-end collision probability[2] has been obtained as the probability that a vehicle does not receive a CAM before $CD+ED$. As shown in Fig. 6, dimensioning the V2V communications protocol based solely on the avoidance of intersection collisions (i.e. receiving the alert just before CD) can be a viable solution for low PT and high IVS values given that these operating conditions do not result in rear-end collisions despite the sudden deceleration of the first vehicle in the vehicular chain. However, such dimensioning is not a viable option for high reaction and PTs given that the probability of not receiving a CAM before $CD + ED$ can significantly increase, and hence create a risk of rear-end collision.

To prevent both the accident at the intersection and the rear-end collisions in the vehicle chain, a reconfiguration of communication protocols and transmission policies would be required as proposed in Sect. 2; in particular, a transmission power adaptation is proposed, since different studies such as [29] demonstrated that the transmission power is one of the most significant parameters affecting the communications performance in VANETs.

1 The minimum validated transmitting antenna height is 5 m.

2 The authors would like to stress that cooperative systems represent a driver assistance technology and not an automated driving one. Consequently, not receiving a broadcast message before CD or $CD + ED$ does not necessarily imply a collision since it depends on whether the drivers respect the traffic rules and signalling.

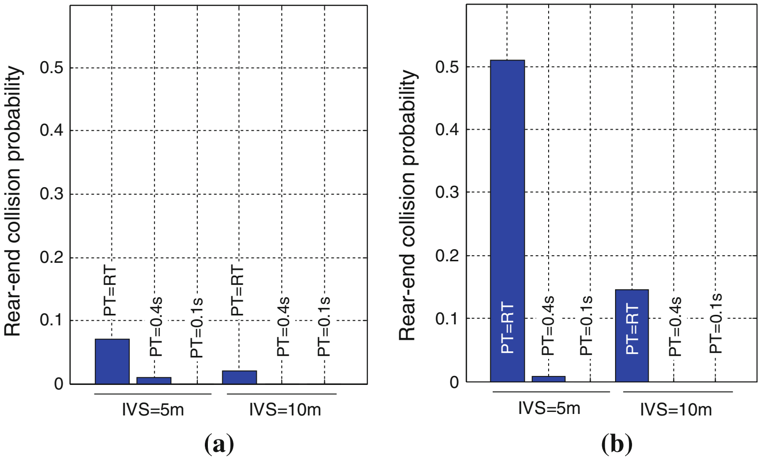


Fig. 6 Rear-end collision probability when dimensioning V2V communications protocols based solely on the avoidance of intersection collisions, i.e. with a transmission power so that the probability of not receiving a CAM before CD is equal to 0.01 for v = 70 km/h, N = 2 and 100 Bytes payload. **a** RT = 0.75 s. **b** RT = 1.5 s

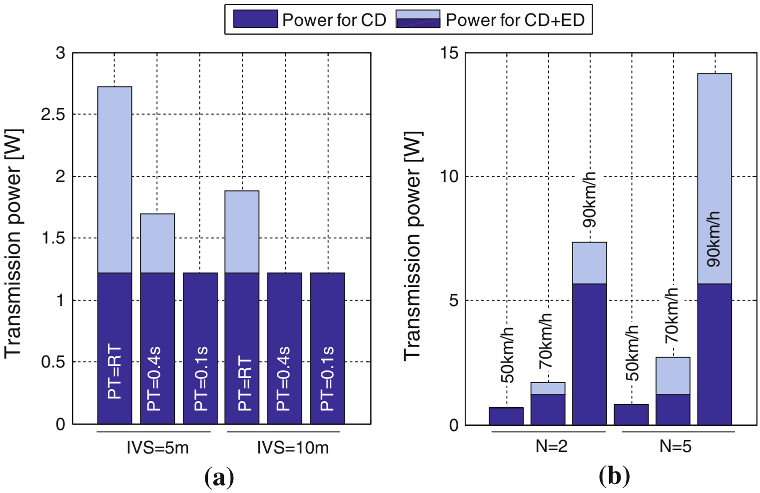


Fig. 7 Required transmission power to exchange at least one CAM before CD and before CD + ED with probability $p = 0.9999$ considering 100 Bytes payload. **a** v = 70 km/h, N = 2 vehicles and RT = 0.75 s. **b** IVS = 5 m, RT = 0.75 s and PT = 0.4 s

Figure 7 depicts the transmission power that two vehicles approaching the intersection would need to employ to guarantee that they correctly exchange at least one broadcast message at *CD* and *CD* + *ED* with $p = 0.9999$, i.e. with and without considering the proposed context-based multi-applications dimensioning approach. As depicted in Fig. 7a, low distances between vehicles and large *PTs* require to significantly increase the transmission power to avoid an intersection collision and prevent possible chain collisions. Such increase highlights the importance of multihop VANETs to enable the effective deployment of V2V-based traffic safety applications. Figure 7b highlights the significant impact of the number of vehicles in the chain and the vehicular speed on the communications parameters to prevent chain collisions. In fact, the control channel transmission power limits identified by the standards can be reached for high vehicular speeds; in this case, alternative solutions should be considered, like the deployment of RSUs at specific intersections where higher vehicular speeds are expected. The results illustrated in Fig. 7b also indicate that the number of vehicles in the chain should be considered to dimension V2V communications protocols.

3.3 Positioning Accuracy

The results previously shown assume error-free positioning to focus on the contextual communications dimensioning, although the proposed approach can operate under realistic positioning scenarios. The typical horizontal positioning accuracy of stand-alone GPS and Galileo systems can vary between $H_{ac} = 4$ m and $H_{ac} = 14$ m for open standard services [30], although it can be improved with sensors or V2V wireless data exchange to obtain positioning accuracies of around 1m [31]. The deployment of V2V-based road safety applications would only be feasible when such positioning accuracy and solutions are available. In fact, positioning accuracies in the order of 1–2 m are currently being required by ETSI [2] for road safety applications such as lane change assistance, co-operative forward collision warning, and co-operative merging assistance applications. However, it is necessary to analyse the impact of positioning errors on the dimensioning and configuration of V2V communications, and the resulting capability to satisfy the identified application requirements.

Positioning errors influence the estimated position of the vehicles in the chain, and therefore the *IVS* values that the first vehicle in the chain uses to compute *ED*. As a consequence, positioning errors influences the computation of *ED*, and its impact should be taken to properly dimension V2V communications. In particular, vehicle A_1 should consider the positioning accuracy of surrounding vehicles, based on the estimated accuracy or confidence intervals for latitude and longitude that are included in CAMs, to compute the accuracy of measured *IVS* values. Given the measured *IVS* values (IVS_m) and their accuracy ($IVSH_{acc}$), the computation of *ED* should consider the worst case scenario to prevent that positioning errors influence the application's performance. In this context, the worst case scenario corresponds to the case in which the actual *IVS* values are lower than the measured ones, since this would increase the risk of chain collision and the required *ED*. As a consequence, the *IVS* values used to compute *ED* should be equal to the measured ones but reduced with the *IVS* accuracy in meters: $IVS = IVS_m - IVSH_{ac}$. This would ensure that the computed *ED* considering positioning errors is equal or higher than the actual one. In this context, Fig. 8 shows the required transmission power levels to satisfy the traffic safety requirements when the measured *IVS* value with a realistic positioning device is $IVS_m = 10$ m. In this figure, $IVSH_{ac} = 0$ m corresponds to the error-free positioning scenario ($IVS = IVS_m$), and the resulting transmission powers match those presented in previous figures. As shown in Fig. 8, low positioning accuracy can considerably increase the required communication parameters to compensate the uncertainty about the inter-vehicle spacing. It is interesting to observe that the effect of the positioning error on the V2V communications dimensioning (in this case, configuration of transmission power levels) is significantly reduced for low *PT* values corresponding to the use of multihop dissemination protocols. These results confirm the need of higher precision positioning technologies for the efficient deployment of traffic safety cooperative applications.

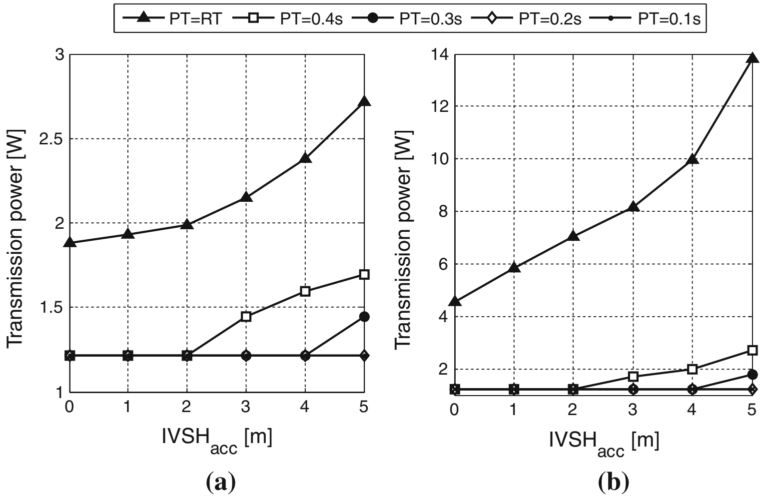


Fig. 8 Required transmission power to exchange at least one CAM before CD and before CD + ED with probability $p = 0.9999$ considering realistic positioning for $IVS_m = 10$ m, RT = 0.75 s, v = 70 km/h and 100 Bytes payload. **a** N = 2. **b** N = 5

3.4 Realistic Mobility Conditions

The previous sections were done considering simplified mobility conditions. On the other hand, this section analyses the proposed V2V context-based and multi-applications communications policy under realistic mobility conditions. To this aim, the microscopic road traffic simulator SUMO (Simulation of Urban Mobility) has been used to simulate mobility conditions in a Manhattan-like urban scenario consisting of a uniform grid of 15 × 15 blocks. The simulated scenario considers maximum speeds between 50 and 90 km/h. In addition, two traffic densities ($D1 = 7$ and $D2 = 12$ vehicles/km) have been simulated. All vehicles dynamically calculate their *CD* and *ED* distances based on their own speed, and the messages received from surrounding vehicles.

Figure 9 shows the impact of realistic mobility models on the number of vehicles behind the lead vehicle A_1 in the chain when it reaches the *CD* distance to the intersection, the inter-vehicle spacing and the vehicular speed. As it can be observed in Fig. 9a, although a non negligible amount of times at least 2 vehicles in a chain are approaching the intersection, the distance between them can be high (Fig. 9b). As a result, Fig. 10 shows the CDF of the required *ED* when considering $RT = 0.75$ s, visual alert propagation and different traffic conditions. The reported results emphasize the need to consider the traffic contextual V2V communications dimensioning proposed in this work. As it can be observed in Fig. 10, the lower the vehicular speed, the higher the percentage of vehicles that require ED > 0, and therefore would benefit from the proposed approach. This is the case because the *IVS* distances are reduced at low vehicular speeds with realistic mobility models. However, ED is reduced at low vehicular speeds since the speed directly influences the distance needed to decelerate, and then the probability of rear-end collisions.

The CDF of the transmission power levels required to satisfy that 99.99 % of the vehicles received a CAM before $CD + ED$ from the potentially colliding vehicle at an intersection is shown in Fig. 11. The vertical lines correspond to the transmission power level required to exchange a CAM message before *CD* at the proposed vehicular speeds with 99.99 %

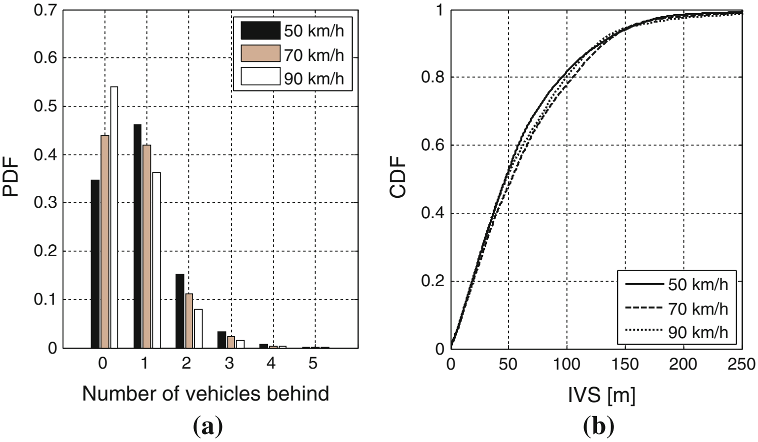


Fig. 9 Impact of realistic SUMO mobility scenarios on the number of vehicles and inter-vehicle distances with traffic density D2. **a** PDF of number of vehicles behind the lead vehicle in the chain. **b** CDF of inter-vehicle distances

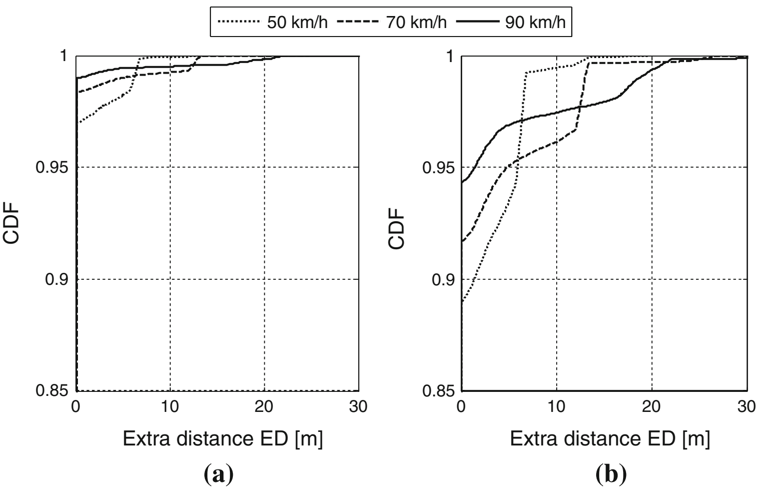


Fig. 10 Cumulative Distribution Function of ED estimated in realistic urban SUMO scenarios. PT = RT = 0.75 s. **a** Vehicular density D1. **b** Vehicular density D2

probability. The obtained results show that, under realistic mobility conditions, a non-negligible percentage of vehicles could be involved in intersection and rear-end collision situations such as the one analysed in this paper. In this case, these vehicles would benefit from the proposed context-based multi-applications communications dimensioning in order to prevent both types of accidents.

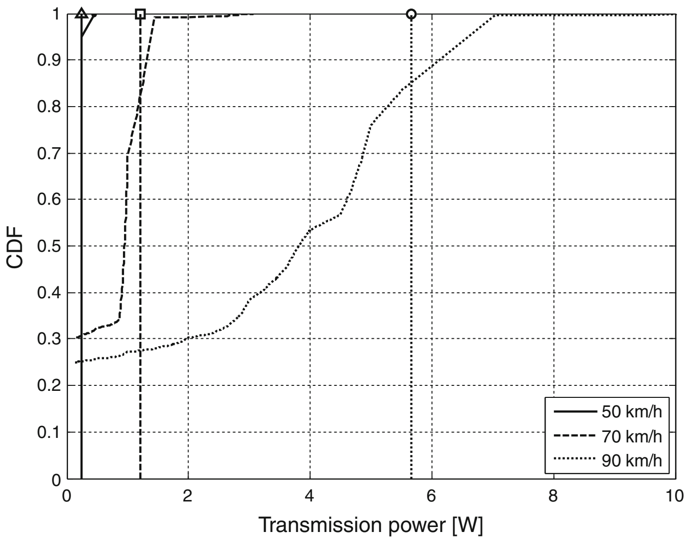


Fig. 11 Cumulative Distribution Function of the transmission power needed to receive the first broadcast message before $CD + ED$ for a target $p = 0.9999$ using SUMO with traffic density D2 and RT = PT = 0.75 s

4 Conclusions

The design of effective vehicular communications requires a careful analysis of the applications' requirements, in particular in the case of active road safety applications. Despite the interaction or dependencies that certain active road safety applications might exhibit, few studies have investigated them, as well as their impact on the dimensioning and configuration of vehicular communications. In this context, this paper has demonstrated the importance of such dependencies, and has proposed a context-based methodology to design vehicular communications considering the requirements of simultaneous applications exhibiting certain dependencies. The proposed approach exploits the knowledge of traffic context information to efficiently design V2V communications while minimising the impact of individual decisions on surrounding vehicles.

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