Experimental Evaluation of Cooperative Active Safety Applications based on V2V Communications

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ABSTRACT

Cooperative vehicular systems are expected to improve traffic safety and efficiency through the real-time exchange of information between vehicles and infrastructure nodes. To this aim, cooperative active safety applications are being designed to extend, in space and time, the drivers' awareness of the surrounding environment in order to be able to detect potential road dangers with sufficient time for the driver to react. The strict requirements of cooperative vehicular applications and the challenging vehicular environment require that cooperative active safety applications are extensively tested under real-world conditions. In this context, this paper presents the experimental evaluation of different vehicle-to-vehicle cooperative active safety applications under real world and challenging conditions where cooperative systems need to prove their real effectiveness.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design –*Wireless communication*.

General Terms

Measurement, Performance, Reliability, Experimentation.

Keywords

Vehicle-to-Vehicle (V2V) communications; cooperative vehicular systems; field tests; active safety applications.

1. INTRODUCTION

Cooperative vehicular systems are expected to improve traffic safety and efficiency through the real-time exchange of information between vehicles and infrastructure nodes. To this aim, cooperative active safety applications are being designed to extend, in space and time, the drivers' awareness of the surrounding environment in order to be able to detect potential road dangers with sufficient time for the driver to react. Cooperative active safety applications will be based on the IEEE 802.11p radio access technology [1], specifically designed for the vehicular environment, and adapted to the European context in the ITS-G5 standard [2]. Based on this technology operating the 5.9GHz band, cooperative active safety applications will be supported by the exchange of periodic 1-hop broadcast messages and event-driven messages. Periodic 1-hop broadcast messages are used to provide and receive information about presence, movement and service announcements to/from neighboring nodes. Event-driven messages are generated when a potential dangerous situation is detected in order to inform surrounding vehicles.

The strict requirements of cooperative vehicular applications and the challenging vehicular environment require that cooperative vehicular systems are extensively tested under real-world and challenging conditions. This is especially true for cooperative active safety applications due to their critical nature. Apart from studies aimed at characterizing the radio propagation conditions for cooperative vehicular systems [3][4][5][6], different studies have experimentally analyzed the vehicular communication performance using IEEE 802.11p prototypes. These studies experimentally analyze the effect of the propagation environment on the experienced V2V or V2I connectivity, normally measured in terms of PDR (packet delivery ratio). This type of experimental studies typically study the negative effect produced by obstacles that reduce the visibility conditions and attenuate the radio signal. For example, the work in [7] presents the results of a V2V communication measurement campaign in five different scenarios (open straight road, highway, urban, rural - steep crest and rural - curve with vegetation), showing the high influence of the visibility conditions on the PDR. The extensive field testing campaign presented in [8] analyzes the impact of urban characteristics, RSU deployment conditions, and communication settings on the quality of IEEE 802.11p V2I communications. The reported results show that the streets' layout, urban environment, traffic density, presence of heavy vehicles, trees, and terrain elevation, have an effect on V2I connectivity, and should be taken into account to adequately deploy and configure urban RSUs. Other studies such as [9] or [10] analyze with more detail the impact of vehicles as obstacles on the signal attenuation and PDR. In particular, the work in [9] measured the PDR experienced in a highway using one and two receiving antennas, and considering other vehicles and trucks as obstacles. The measurement campaign presented in [10] quantifies the impact of vehicular

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obstructions in terms of received signal strength and PDR in different scenarios (parking lot, highway, suburban and urban canyon).

More limited studies evaluate through field tests the impact of adverse vehicular communication conditions on the reliability of cooperative vehicular applications. These studies help better understanding and quantify the negative effects of adverse operating conditions on the applications' reliability, and design the necessary countermeasures to enable the reliable deployment of cooperative vehicular applications. One of the first studies that experimentally evaluated the reliability of cooperative vehicular applications is [11]. This study demonstrates the suitability of the IEEE 802.11p technology to improve traffic safety considering the application requirements developed by the USDOT VSC (Vehicle Safety Communications) project. Based on real-world experimental data in highways, the work analyses the performance of the emergency electronic brake lights, lane change assistance and forward collision warning applications, among others. A similar analysis was presented in [12], focusing also on particular standard road safety applications. In this case, the application reliability is evaluated through the driver warning time obtained with V2V and V2I communications. Their main objective is to compare the performance of conventional physical layer processing and a more sophisticated channel estimation and tracking, focusing on NLOS (Non-Line of Sight) communication conditions.

Despite the interesting tests conducted to evaluate cooperative vehicular systems under real-world conditions, limited studies have been carried out to analyze the negative effects of the challenging operating conditions of the vehicular environment on the applications' reliability. To this aim, this paper presents the experimental evaluation of different V2V cooperative active safety applications under real world and challenging conditions where cooperative systems need to prove their real effectiveness.

The rest of the paper is organized as follows. Section 2 presents the three cooperative active safety applications evaluated, and their requirements. Section 3 describes the experimental setup and analyzes the results obtained. Section 4 concludes the paper.

2. COOPERATIVE ACTIVE SAFETY APPLICATIONS

Based on the work of ETSI TC ITS (European Telecommunications Standards Institute Technical Committee for ITS) [13], USDOT VSC [14], and international research projects such as SAFESPOT (http://www.safespot-eu.org/), three cooperative active safety applications have been selected for this study based on their relevance and expected impact of cooperative technologies: overtaking assistance application, lane change assistance application, and forward collision warning application.

The applications selected are based on the periodic exchange of 1-hop broadcast messages to collect information about surrounding vehicles, and inform the driver about the suitability of an overtaking maneuver, a lane change maneuver, or a potential forward collision, respectively, to avoid any dangerous situation. Figure 1 shows the scenarios considered for each application, in which vehicles A and B represent the communicating vehicles. The operation and requirements of each application is presented below.

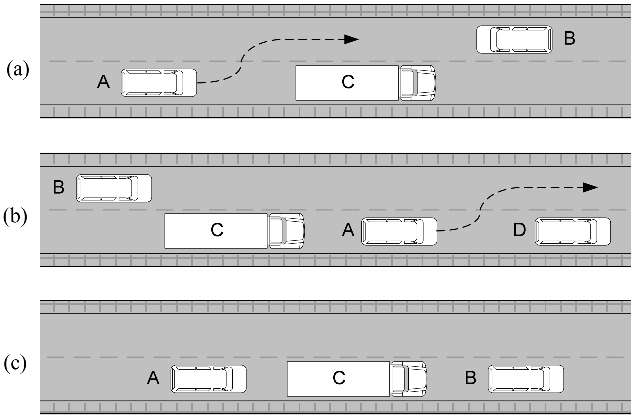


Figure. 1. Scenarios for (a) overtaking assistance application, (b) lane change assistance application, (c) forward collision warning application.

2.1 Overtaking assistance application

This application warns the driver of an oncoming vehicle before an overtaking maneuver is started, and is also known as *do not pass warning application* [12]. In the scenario depicted in Figure 1a, this application should warn the driver of vehicle A about the presence of vehicle B to avoid any dangerous situation. To this aim, vehicles A and B should communicate with each other at a distance higher than the distance needed by vehicle A to overtake vehicle C and avoid the collision with vehicle B. This distance corresponds to the warning distance (D_w) required by the application, and could be estimated based mainly on each vehicle's speed (v_A, v_B and v_C), the acceleration that vehicle A would apply during the overtaking maneuver (a_A, a_B and a_C), the time needed to change the lane (T_{ch}), and each vehicle's length (L_A, L_B and L_C) [15]. The value of the warning distance shown in Figure 2 represents the application requirement of the overtaking assistance application described. As it can be observed, this requirement notably depends on the vehicles' speed, and increases as the vehicles' speed increase.

2.2 Lane change assistance application

This application informs the driver about the suitability of a lane change maneuver based on the collection of information about surrounding vehicles. Each vehicle should detect and monitor surrounding vehicles, especially those that could represent a danger, such as fast overtaking vehicles. In the scenario illustrated in Figure 1b, vehicle B should warn vehicle A about its presence before certain warning distance to avoid any dangerous situation. Based on [15], the warning distance can be calculated based on the parameters previously described for the overtaking assistance application. However, the warning distance required to safely change the lane is notably lower than the one needed for overtaking, which can be directly observed though the comparison of Figures 2 and 3. The different application requirements are mainly due to the fact that vehicles A and B are moving in opposite directions in the overtaking assistance application scenario, resulting in a higher relative speed.

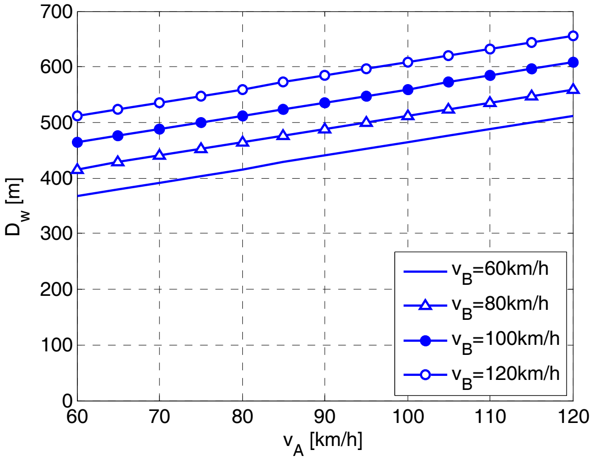


Figure 2. Distance at which vehicles A and B need to communicate to avoid a dangerous situation in the scenario illustrated in Figure 1a for the overtaking assistance application. Configuration: T_{ch}=2s, L_A=L_B=L_C=4m, a_A=4m/s^2, a_B=0, a_C=0, v_C=v_A.

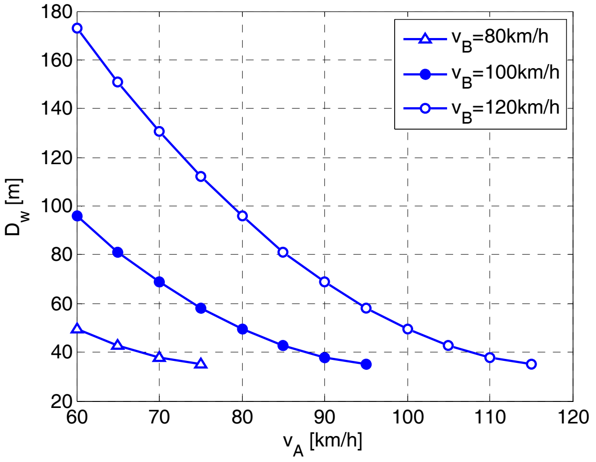


Figure. 3. Distance at which vehicles A and B need to communicate to avoid a dangerous situation in the scenario illustrated in Figure 1b for the lane change assistance application. Configuration: T_{ch}=2s, L_A=L_B=L_C=4m, a_A=1m/s^2, a_B=0, a_C=0, v_C=v_A.

2.3 Forward collision warning application

This application warns the driver when a rear-end collision danger is detected to reduce the risk of collision. This application will help following vehicles by providing an early notification of lead vehicle braking, even when the driver's visibility is limited. Contrary to the overtaking and lane change assistance application, the forward collision warning application does not require vehicles A and B in Figure 1c to communicate before reaching certain distance. Instead, vehicle A needs to constantly monitor vehicle B (and obviously C) with low latency and high packet transmission frequency requirements, while the distance between them can be nearly constant. The rear-end collision would be avoided if they are able to exchange broadcast packets at a sufficient frequency so that the packet inter-reception time is kept below certain threshold. In other words, a collision would occur if vehicle A does not receive any packet from vehicle B during a certain period of time, while vehicle B reduces its speed. To calculate the maximum inter-reception time that could avoid their collision, uniform kinematics equations can be used, following a similar approach to [15]. Considering that vehicles A and B move initially at the same speed (v_0), the initial distance between them is d_0, and that vehicle B starts decelerating at t=0, the distance between them once they have stopped can be expressed as:

$$d(A,B)\big|_{stop} = d_0 - v_0(RT + t_c) - L$$

where RT represents the driver's reaction time, L the length of the vehicles, and t_c the time at which vehicle A receives the first message from B after the deceleration starts. For simplification, this result assumes that the driver of vehicle A starts decelerating at $t=RT+t_c$ and with the same deceleration as vehicle B. The accident would be avoided if the distance between the two vehicles once they have stopped is above zero, if there was no vehicle between them (vehicle C in Figure 1c). When there is a third vehicle or a truck between vehicles A and B, the accident would be avoided if the distance between the two communicating vehicles once they have stopped is above the third vehicle's length. As it can be observed in the equation above, such distance decreases as t_c increases. The value of t_c can be affected by the packet transmission frequency of vehicle B and the PER (packet error rate) experienced. The following equation express the maximum inter-reception time t_c required by the forward collision warning application under the considered conditions:

$$t_c < \frac{d_0 - L - L_T}{v_0} - RT$$

where L_T represents the length of the truck. This equation links the application requirements in terms of packet inter-reception time to the driving and communication conditions Figure 4 plots the maximum inter-reception time t_c required for varying speeds, v_0, and distances between vehicles, d_0, considering a truck of L_T=12m between vehicles A and B.

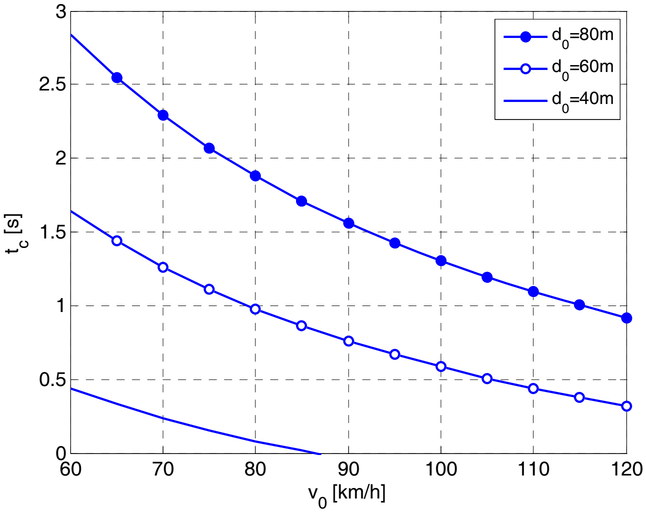


Figure. 4. Maximum packet inter-reception time needed to avoid a dangerous situation in the scenario illustrated in Figure 1c for the forward collision warning application. Configuration: L=4m, L_T=12m, RT=1s.

3. EXPERIMENTAL EVALUATION OF ACTIVE SAFETY APPLICATIONS

3.1 Equipment setup and scenarios

Two OBUs have been employed in the experiments conducted, each of them equipped with an IEEE 802.11p DENSO WSU (Wireless Safety Unit) prototype and mounted on a standard vehicle (see Figure 5). Each OBU used a single Nippon omni-directional antenna with 0dBi gain, placed on the roof of a vehicle and connected to the DENSO WSU prototype with an LMR240 antenna cable of 3m length and approximately 3dB cable loss. Each OBU employed a Novatel SMART-V1-2US-PVT GPS receiver to accurately track each vehicle's position. This receiver presents a reference positioning accuracy of 1.8m (RMS) and 20Hz maximum update rate. The most important configuration parameters used in the experiments are summarized in Table 1.

Figure. 5. Equiped vehicles used in the experiments.

Table 1. Configuration parameters

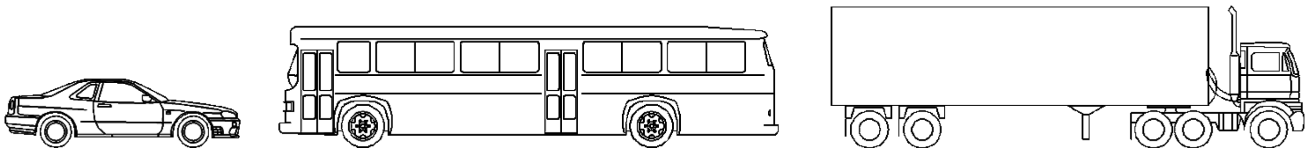
Parameter	Value
Transmission power [dBm]	5, 10, 20
Packet transmission frequency [Hz]	2, 10
Data rate [Mbps]	6
Antenna gain [dBi]	0
Channel frequency [GHz]	5.9
Packet size [bytes]	126

To evaluate the reliability of the active safety applications tested under challenging conditions, different vehicles were used as obstacles in the experiments. The most challenging conditions were experienced considering a bus and a large truck obstructing the driver's visibility and radio signal, but standard vehicles were also used as obstacles in some of the tests. Figure 6 shows a scaled drawing of these vehicles, which provides an accurate view of the different size of vehicular obstructions considered. All the experiments were performed near the city of Elche (Spain) in good weather conditions, and including urban, suburban and highway scenarios.

3.2 Overtaking assistance application

The reliability of the overtaking assistance application was evaluated in a suburban environment (straight road with few buildings and trees) through the representation of the scenario illustrated in Figure 1a under real traffic conditions. In these experiments, vehicles A and B move in opposite directions approaching to each other, and vehicle C limits their visibility, resulting in a potentially dangerous overtaking situation. To avoid any dangerous situation, vehicles A and B need to communicate at a distance higher than warning distance. In all the experiments, the speed of vehicles A and B was always between 60km/h and 80km/h, resulting in required warning distances D_w between 375m and 460m approximately. Table 2 summarizes the experiments conducted to test the reliability of the overtaking assistance application.

Figure 7 shows the distance between vehicles A and B at which packets were correctly received (RCV) or received with error (ERR) by vehicle A, as both vehicles approach to each other in the 5 experiments conducted. The two vertical lines represent the warning distance D_w at which the two vehicles should communicate to avoid dangerous overtaking situations considering both vehicles moving at 60km/h and 80km/h. The reliable exchange of broadcast messages at a distance higher than the required D_w results in that the application requirements can be satisfied. In this context, it is important to note that the reliable detection of a road hazard could require the correct reception of a number of messages before D_w (i.e. not only one) to mainly avoid false alarms [17]. Depending on the number of required messages, the application requirements would be satisfied or not. As it can be observed in Figure 7, in E1 (10dBm transmission power and no obstacles between vehicles A and B) the two vehicles were able to communicate before D_w(60km/h), but not before D_w(80km/h), which highlights the need of using high transmission power levels to satisfy the application requirements at high speeds. Experiments E2 and E3 show the effect produced by a vehicle and a truck blocking the radio signal, again with 10dBm transmission power. While the presence of a vehicle reduced the distance



(a) Standard vehicle **(b) Bus** **(c) Truck**

Figure 6. View of the different obstructing vehicles used in the tests

between vehicles A and B at which the first broadcast message was correctly exchanged to around 300m (E2), the truck reduced such distance to around 250m (E3). These results clearly show that the obstruction caused by the vehicle or the truck can reduce the application reliability, since vehicles A and B were not able to communicate before the required warning distances.

Transmission power control is one of the mechanisms that could be used to increase the overtaking assistance application reliability, especially under strong vehicular obstructions. Considering 20dBm transmission power, experiments E4 and E5 show again the effect produced by a vehicle and a truck blocking the radio signal. In this case, the use of high transmission power levels could overcome the negative effect produced by a vehicle reducing the visibility conditions (E4), resulting in an increased application reliability. However, the higher attenuation produced by the truck in E5 resulted in that the two vehicles were not able to communicate at distances above D_w(80km/h) despite using high transmission power levels.

Table 2. Overtaking assistance application experiments

Experiment	Transmission power	Obstruction
E1	10dBm	None
E2	10dBm	Vehicle
E3	10dBm	Truck
E4	20dBm	Vehicle
E5	20dBm	Truck

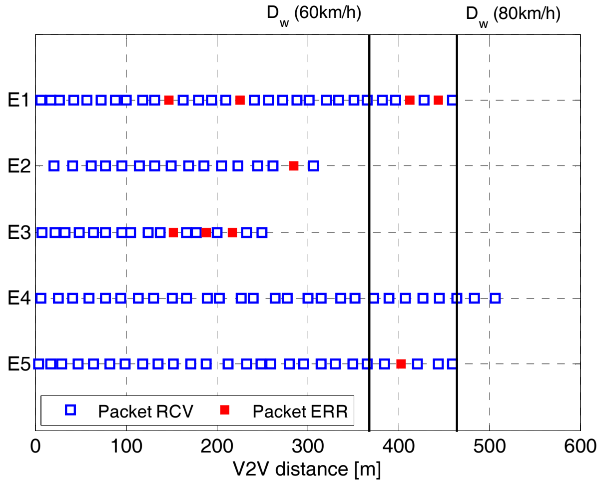


Figure. 7. Application's reliability analysis of the overtaking assistance application experiments.

The obtained results demonstrate that, especially at high speeds and with strong vehicular obstructions, the high application requirements could not be satisfied even considering high transmission power levels. As a result, more advanced solutions would be needed to enable the reliable deployment of the overtaking assistance application. Apart from the use of advanced receivers [12], the consideration of heavy vehicles as relays could enable the reliable deployment of this application in the proposed scenario. In particular, a controlled multi-hop beaconing mechanism could be used so that heavy vehicles dynamically detect the presence of potentially colliding vehicles and forward their broadcast messages to enable their communication at high distances with reduced transmission power levels. In the proposed scenario, vehicle C (heavy vehicle) would continuously monitor all broadcast messages received from surrounding vehicles. When vehicle C detects the presence of vehicle B approaching in the opposite direction, it would forward its beacons so that vehicle A would be able to detect the presence of vehicle B with sufficient time to avoid any dangerous situation. This approach would enable the reduction of the transmission power needed mainly due to the higher antenna height on top of heavy vehicles, and therefore their better visibility conditions with surrounding vehicles.

3.3 Lane change assistance application

The reliability of the lane change assistance application was evaluated in a highway environment through the representation of the scenario illustrated in Figure 1b under real traffic conditions. In this case, vehicle B is on the left lane, moving at a higher speed than vehicle A. Again, vehicle C limits their visibility, resulting in a potentially dangerous lane changing situation. In the lane change assistance application experiments, the speed of vehicle B was always around 120km/h, while vehicle's A speed was between 70km/h and 80km/h, resulting in required warning distances D_w between 100m and 125m approximately. The conducted experiments considered different transmission power levels and vehicular obstructions. The transmission power levels tested were lower than those considered for the overtaking assistance application experiments, given the lower warning distance required. Table 3 summarizes the lane change assistance application experiments conducted.

Figure 8 shows the distance between vehicles A and B at which packets were correctly received or received with error by vehicle A in the 3 experiments conducted to test the lane change assistance application. The two vertical lines represent the warning distance D_w considering vehicle moving at 120km/h and vehicle A moving at 70km/h and 80km/h. As it can be observed in E6, with 10dBm and a vehicle limiting the visibility conditions, a reliable communication could be established between vehicles A and B at a distance higher than the required warning distance. However, the presence of a truck blocking the radio signal in E7 notably increased packet losses at short distances between vehicles A and B and therefore reduced the possibility of reliably exchange certain number of messages before the required warning distance. Depending on the defined number of messages required to reliably detect a road hazard, the application requirements would be satisfied or not with the presence of the truck in E7. Finally, as it could be expected, the negative effect produced by the presence of heavy vehicles can be even worse for low transmission power levels in E8. The use of low transmission power levels could be imposed by congestion control mechanisms to avoid overloading the wireless channel under high traffic density conditions. These results highlight the need of taking into account the vehicle-specific application requirements when adapting the communication parameters following congestion control policies, as extensively discussed in [18].

Table 3. Lane change assistance application experiments

Experiment	Transmission power	Obstruction
E6	10dBm	Vehicle
E7	10dBm	Truck
E8	5dBm	Truck

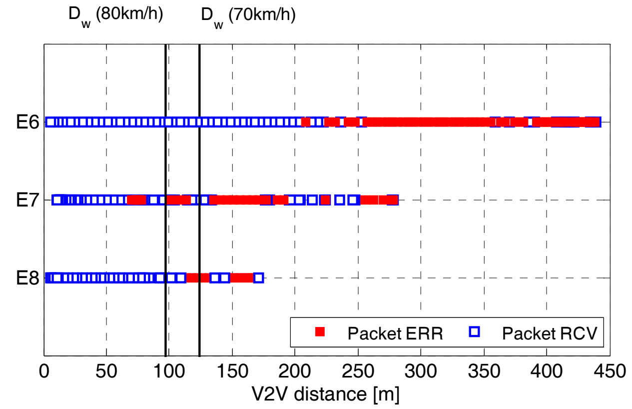


Figure. 8. Application's reliability analysis of the lane change assistance application experiments.

3.4 Forward collision warning application

The reliability of the forward collision warning application was evaluated under real traffic conditions in an urban and a highway environment through the representation of the scenario illustrated in Figure 1c. In this case, the visibility between vehicles A and B was obstructed by either a bus or a truck in the different experiments to evaluate their influence on the packet reception rate and application's reliability. While in the urban environment their speed was always between 0km/h and 40km/h, the highway scenario permitted testing the application at around 90km/h. Table 4 summarizes the forward collision warning application experiments performed.

Table 4. Forward collision avoidance application experiments

Experiment	Transmission power	Obstruction	Environment
E9	10dBm	Bus	Urban
E10	10dBm	Truck	Highway
E11	20dBm	Truck	Highway

Figure 9 shows the driving conditions and communications performance experienced in experiment E9, conducted in the city of Elche with 10dBm transmission power and a bus blocking the visibility between vehicles A and B. The figure shows that communications at V2V distances between 15m and 50m were required to support the forward collision avoidance application in this scenario. The minimum distances between the communicating vehicles were mainly produced at the bus stops and traffic light stops. With regards to the communications performance, the urban environment produced high RSSI (Received Signal Strength Indicator) variations, even for similar V2V distances and short time intervals, possibly due to the multipath effect typically present in urban environments. Despite the high signal variability, the PER experienced was always low except in the area of around 200s elapsed time, in which the communicating vehicles and the bus entered a roundabout with reduced visibility.

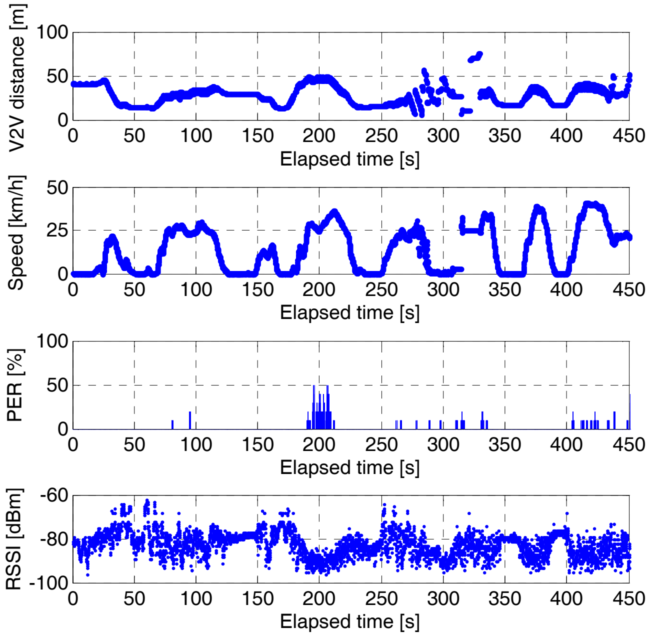


Figure 9. Driving conditions and communications performance experienced by vehicle A in E9 (10dBm, bus, urban environment).

Figure 10 depicts the driving conditions and communications performance experienced in E10, conducted in a highway with 10dBm transmission power. In this experiment, vehicles A and B had direct visibility during the initial 760s. As it can be observed, during this initial phase almost no packet losses were produced (i.e. PER almost null) due to the favorable propagation conditions and short V2V distances. The RSSI variability observed was lower than the one experienced in the urban environment, given the reduction of the multipath effect in open environments such as highways. The negative effect produced by the truck can be observed after the initial 760s. At around 760s of elapsed time, a truck blocked the visibility between vehicles A and B, and was maintained during the rest of the experiment. As shown in Figure 10, the truck drastically produced a signal attenuation of around 12dB, which resulted in a notable increase of the PER levels experienced. These results clearly demonstrate the decrease of the communications performance due to heavy vehicles in highway environments even at short distances, which could result in a decrease of the application's reliability.

The operating conditions of E10 were reproduced in E11, but using a higher transmission power (20dBm). In E11, the truck started blocking the visibility between vehicles A and B at around 480s elapsed time. As in E10, a signal attenuation of around 12dB was produced by the truck. Although the use of higher transmission power in E11 prevented high packet losses, a non-negligible PER was observed due to the truck obstruction.

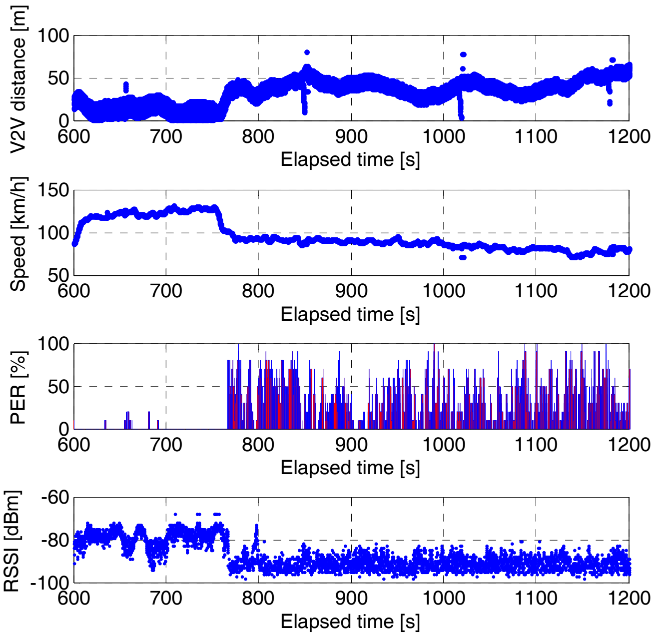


Figure 10. Driving conditions and communications performance experienced by vehicle A in E10 (10dBm, truck, highway environment).

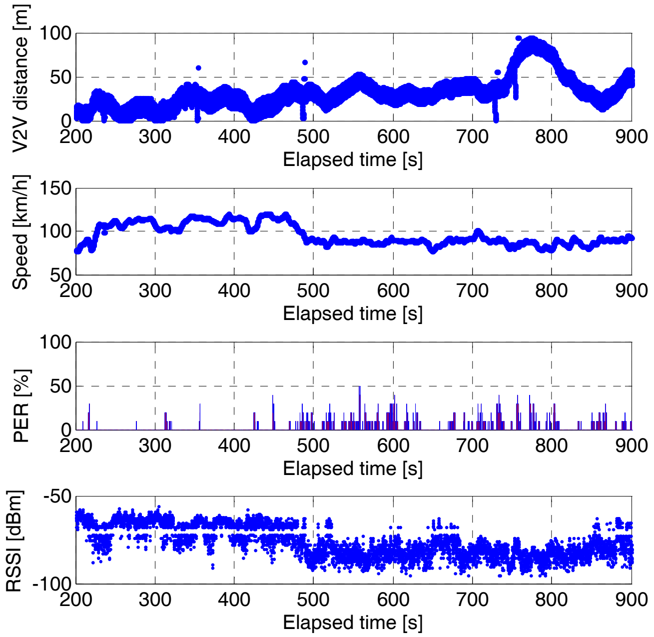


Figure 11. Driving conditions and communications performance experienced by vehicle A in E11 (20dBm, truck, highway environment).

As shown in section 2.3, the main communication performance parameter that affects the forward collision warning application is the packet inter-reception time, i.e. the time between consecutive packets correctly received. To avoid the potential collision, the packet inter-reception time needs to be below the threshold previously defined, that depends on the vehicles' speed and length, the distance between them and the driver's reaction time. Figure 12 shows the CDF of the packet inter-reception time measured in experiments E9, E10 and E11. As it can be observed, the presence of a bus in the urban environment using 10dBm (E9) and the presence of a truck in the highway using 20dBm (E11) did not significantly increase the packet inter-reception times experienced. However, such time was increased in around 20% of received packets in E10 due to the presence of a truck and the use of low transmission power.

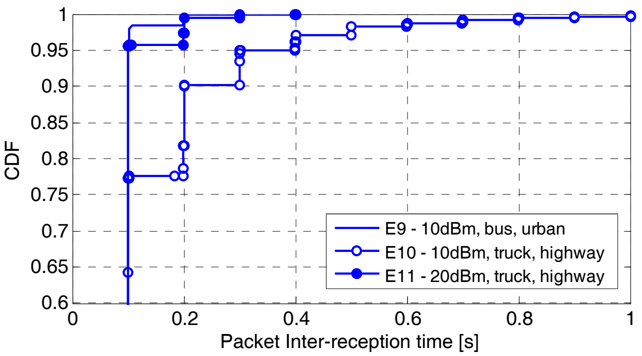


Figure 12. CDF of packet inter-reception time for the forward collision avoidance experiments.

Based on the experiments conducted, the forward collision warning application reliability can be estimated considering the vehicles' speed and V2V distances, and the established application requirement previously defined based on the packet inter-reception time. Such reliability is presented in Table 5 as the percentage of time during which the application's requirement is satisfied, for two different driver's reaction time values. As it was expected, the reliability of the application in experiment E9 is notably high, given the low packet inter-reception times and low vehicular speeds experienced. In particular, the obtained results show that in more than 96% of the time, vehicle B would receive an alert from vehicle A with enough time for the driver to react and avoid the dangerous situation. In E10, the application's reliability was decreased due to the higher vehicular speeds permitted in the highway and the lower communication performance due to the presence of the obstructing truck. The increase of the transmission power to 20dBm in E11 improved the application's reliability compared to E10, thanks to the improvement of the PER and packet inter-reception time. However, despite the high reduction in packet inter-reception times and PER levels in E11, the higher speeds experienced in E11 prevented an even higher improvement of the application's reliability. In this case, higher application's reliability could only be obtained with an increase of the packet transmission frequency, which was 10Hz in the experiments (and therefore the minimum packet inter-reception time was fixed to 0.1s).

The obtained results clearly show the potential impact of obstructing elements on the communications performance and, most significantly, on the application's reliability. This is especially true for high driver's reaction time values, with which the application's reliability decreased to 50%-55%. Moreover, the experiments conducted also highlight the high dependence of the application requirements and reliability on the driving conditions and communications performance. The direct comparison of the results obtained the different experiments reveals that the improvement of the communications performance does not directly imply a high improvement of the application's reliability, in this case because an insufficient packet transmission frequency.

Table 5. Forward collision avoidance application's reliability

Experiment	RT=1s	RT=1.5s
E9	97.7%	96.5%
E10	81.1%	50%
E11	85.1%	55.2%

4. CONCLUSIONS

This work presents the experimental evaluation of three different V2V cooperative active safety applications under real world and challenging conditions. The conducted study analyzes the communications performance that can be achieved under different driving and operating conditions, and also studies the applications' reliability levels that can be obtained based on detailed application-specific performance metrics. The experiments conducted have revealed the impact of vehicular obstructions and transmission power level on the applications' reliability in different propagation environments. The obtained results have experimentally shown the strict relationship among application requirements and reliability, driving conditions and communications performance, and have shown certain limitations produced at high vehicular speeds, given the higher requirements imposed by cooperative active safety applications. In particular, the transmission range or packet inter-reception time demanded by certain applications under challenging conditions could require the design of adaptive and advanced communication techniques that dynamically adapt their operation to the operating conditions to efficiently satisfy the applications' requirements.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] IEEE 802.11p-2010: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments, IEEE Standards Association, 2010.

[2] ETSI TC ITS, "Intelligent Transport Systems (ITS); European profile standard on the physical and medium access layer of 5 GHz ITS", Draft ETSI ES 202 663 V0.0.6, October 2009.

[3] Kukshya, V.; Krishnan, H.; "Experimental Measurements and Modeling for Vehicle-to-Vehicle Dedicated Short Range Communication (DSRC) Wireless Channels", *IEEE 64th Vehicular Technology Conference VTC-2006 Fall*, 25-28 Sept. 2006, pp.1-5. DOI=http://10.1109/VTCF.2006.61.

[4] Lin Cheng. et. al, "Highway and rural propagation channel modeling for vehicle-to-vehicle communications at 5.9 GHz", *IEEE Antennas and Propagation Society International Symposium (AP-S)*, 5-11 July 2008, pp.1-4. DOI=http://10.1109/APS.2008.4619037.

[5] Sen, I.; Matolak, D.W., "Vehicle–Vehicle Channel Models for the 5-GHz Band", *IEEE Transactions on Intelligent Transportation Systems*, vol.9, no.2, June 2008, pp.235-245. DOI=http://10.1109/TITS.2008.922881.

[6] Mangel, T.; Klemp, O.; Hartenstein, H., "A validated 5.9 GHz Non-Line-of-Sight path-loss and fading model for inter-vehicle communication", *11th International Conference on ITS Telecommunications (ITST)*, 23-25 Aug. 2011, pp.75-80. DOI=http://10.1109/ITST.2011.6060156.

[7] Böhm, A.; et. al., "Evaluating CALM M5-based vehicle-to-vehicle communication in various road settings through field trials", *IEEE 35th Conference on Local Computer Networks (LCN)*, 10-14 Oct. 2010, pp.613-620. DOI=http://10.1109/LCN.2010.5735781.

[8] Gozalvez, J.; Sepulcre M.; Bauza, R., "IEEE 802.11p Vehicle to Infrastructure Communications in Urban Environments", *IEEE Communications Magazine*, 2012.

[9] Gallagher, B.; Akatsuka, H.; Suzuki, H., "Wireless communications for vehicle safety: Radio link performance and wireless connectivity methods", *IEEE Vehicular Technology Magazine*, vol.1, no.4, Dec. 2006, pp.4-24. DOI=http://10.1109/MVT.2006.343641.

[10] Meireles, R., et. al, "Experimental study on the impact of vehicular obstructions in VANETs", *IEEE Vehicular Networking Conference (VNC)*, 13-15 Dec. 2010, pp.338-345. DOI=http://10.1109/VNC.2010.5698233.

[11] Fan Bai; Krishnan, H., "Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications", *IEEE Intelligent Transportation Systems Conference (ITSC)*, 17-20 Sept. 2006, pp.355-362. DOI=http://10.1109/ITSC.2006.1706767.

[12] Alexander, P.; Haley, D.; Grant, A., "Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials", *Proceedings of the IEEE*, vol.99, no.7, July 2011, pp.1213-1235. DOI=http://10.1109/JPROC.2011.2105230.

[13] ETSI TC ITS, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions", *ETSI TR 102 638 V1.1.1*, June 2009.

[14] VSC consortium, "Vehicle safety communications project task 3 - Final Report: Identify intelligent vehicle safety applications enabled by DSRC", *DOT HS 809 859*, 2005.

[15] Sepulcre, M.; Gozalvez, J., "On the importance of application requirements in cooperative vehicular communications", *International Conference on Wireless On-Demand Network Systems and Services (WONS)*, Jan. 2011, pp.124-131, DOI=http://10.1109/WONS.2011.5720180.

[16] Treiber, Martin, et. al, "Congested traffic states in empirical observations and microscopic simulations", *Physical Review E* 62 (2), 1805-1824, DOI=http://10.1103/PhysRevE.62.1805

[17] Mitropoulos, G.K., et. al, "Wireless Local Danger Warning: Cooperative Foresighted Driving Using Intervehicle Communication", *IEEE Transactions on Intelligent Transportation Systems*, vol.11, no.3, Sept. 2010, pp.539-553. DOI=http://10.1109/TITS.2009.2034839.

[18] Sepulcre, M.; Mittag, J.; Santi, P.; Hartenstein, H.; Gozalvez, J.; "Congestion and Awareness Control in Cooperative Vehicular Systems", *Proceedings of the IEEE*, vol.99, no.7, pp.1260-1279, July 2011. DOI=http://10.1109/JPROC.2011.2116751.