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Cooperative vehicle-to-vehicle active safety testing under challenging conditions

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ABSTRACT

Cooperative vehicular communication systems are being developed to improve traffic safety and efficiency through the wireless exchange of information between vehicles and between vehicles and infrastructure units. The future deployment of cooperative active safety applications requires their prior extensive testing due to their critical nature and strict quality of service requirements. Such testing should consider challenging driving and communications conditions that could significantly impact the applications' effectiveness. In this context, this paper presents a cooperative communications testing platform implemented to evaluate the operation and effectiveness of cooperative active safety applications under challenging driving and communications conditions. The paper also reports the results of an extensive testing campaign that reveals potential limitations of cooperative technologies and applications, and discusses possible countermeasures to overcome the applications' effectiveness degradation under adverse operating conditions.

1. Introduction

Cooperative vehicular communication systems are being developed to improve traffic safety and management, while providing Internet connectivity on the move. Cooperative systems are based on the dynamic and ubiquitous wireless exchange of information between vehicles (V2V, Vehicle-to-Vehicle) and between vehicles and infrastructure units (V2I, Vehicle-to-Infrastructure). Cooperative vehicular systems will be based on the IEEE 802.11p radio access technology at the 5.9 GHz band (IEEE Standards Association, 2010) and the WAVE (Wireless Access in Vehicular Environments) family of standards (IEEE Standards Association, 2010–2012). This technology has been specifically designed for the vehicular environment, and is being adapted by ETSI (European Telecommunications Standards Institute) through the ITS-G5 standard (ETSI TC ITS, 2009a). In the European context, the operation of cooperative vehicular systems is mainly based on the exchange of three different types of messages: CAMs (Cooperative Awareness Messages), DENMs (Decentralized Environmental Notification Messages), and SAMs (Service Announce Messages). CAMs are periodically transmitted by all vehicles and infrastructure units on the so called control channel to provide and receive positioning and status information to neighboring nodes that are located within a single hop distance. DENMs provide support to event-driven applications, and are transmitted to inform neighboring vehicles of a particular event (e.g. a car's hard braking), including its nature, severity and location. Typically, upon detection of an event, the vehicle or infrastructure unit immediately broadcasts a DENM to the neighboring nodes located in a geographical area and which are concerned by the event. The transmission of a DENM is repeated with a certain frequency, and such broadcasting persists as long as the event is present. SAMs are also transmitted by vehicles and infrastructure units on the control channel to announce the services available on the so called service channels. In the US, the

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functionalities of CAMs, DENMs and SAMs are covered mainly by WAVE Short Messages (WSMs) and WAVE Service Advertisements (WSAs).

Current international activities include research, development and prototyping of cooperative V2V technologies that will lead to new products, standards and services in the coming years. However, the future deployment of cooperative vehicular systems will require the prior and exhaustive testing of their operation and effectiveness. This is particularly the case for active road safety applications that are characterized by their critical nature. Different FOTs (Field Operational Tests) are currently under development in Europe, US and Japan to test under real conditions the intended benefits of cooperative V2X[1] technologies. However, FOTs have a limited capability to test cooperative active safety applications under challenging conditions, since the tests are usually performed in the public road network and involve non-expert drivers. As a result, cooperative V2X active safety applications will need to be extensively tested in proving grounds where challenging driving conditions can be reproduced in controlled real-world environments.

The effectiveness of cooperative road safety applications depends on aspects such as the communications technology, the positioning accuracy, and the warning strategy used to alert the driver about a potential dangerous situation. These aspects have been typically tested separately in the literature. The IEEE 802.11p communications technology has been tested in different environments and operating conditions for V2V and V2I communications. For example, the work in Gallagher et al. (2006) presents a V2V and V2I measurement campaign in highways considering different transmission parameters (transmission power and data rate), and number of antennas under LOS (Line of Sight) and NLOS (Non-LOS) propagation conditions due to large blocking vehicles. In the conducted experiments, the maximum V2V range observed was 967 m with an average PER (Packet Error Rate) of 0.15%, considering a 64 B packet streaming at 6 Mbps under LOS conditions. However, the obtained results showed that NLOS links are significantly more challenging to maintain than LOS links, and are characterized by higher PER values, especially under the 5.9 GHz frequency band. The work reported in VSC-A Consortium (2011) presents a comprehensive analysis of the effect of transmission power and data rate on PER and received signal level. The study considers multiple scenarios (urban, sub-urban, rural, freeway, etc.), and uses an external power amplifier to increase transmissions power. An interesting study that evaluates the IEEE 802.11p performance under challenging communications conditions was presented in Schmidt et al. (2011). In this contribution, the authors showed that the transmission range of a vehicle could be degraded between 50% and 70% under high channel load levels due to communications interference (the experiments were conducted in a highway-like scenario using a single equipment emulating the presence of multiple interfering nodes). The authors conclude that the communications range experienced under interference conditions could be sufficiently large for time-critical applications operating in the range of 50–300 m, but do not specifically evaluate the effectiveness of any application. From a higher layer perspective, the study reported in Bai and Krishnan (2006) also analyzes V2V communications in highway environments. Based on the conducted measurement campaign, and considering fixed application performance metrics defined by the VSC (Vehicle Safety Communications) Consortium (2005), the study concludes that the IEEE 802.11p technology is a viable candidate for cooperative active road safety applications under relatively favorable conditions (highway environment with good propagation conditions, no interference, reduced positioning errors, etc.).

Other studies focus on the design and implementation of driver assistant prototypes that support cooperative V2X active road safety applications. These studies mainly focus on the architecture design, reliable road hazard detection algorithms and warning strategies, and advanced positioning mechanisms to reliably support the applications. For example, the work in Sengupta et al. (2007) was one of the first studies presenting a cooperative driver assistant system that considers different warning levels, with the warnings being triggered by parameters such as the time to collision. The platform was implemented for different applications, such as intersection collision warning or forward collision warning. Particular attention was given in Sengupta et al. (2007) to the improvement of the positioning accuracy through the integration of GPS with wheel speed encoders (a yaw rate gyro and a steering angle sensor) in order to reduce the standard deviation of positioning errors below 50 cm and be able to support reliable and consistent warnings. The study includes additional tests to evaluate the dropouts and delays produced in a car-following situation using two laptop computers equipped with a DGPS receiver and an IEEE 802.11b wireless card with power amplifiers; the conducted tests showed that good connectivity levels were maintained below 450 m. The work reported in Mitropoulos et al. (2010) also presents a driver assistant system (WILLWARN – wireless local danger warning) designed to timely warn the driver about a dangerous situation ahead by decentralized distribution of warnings and incident messages via ad hoc inter-vehicle communications. The study focused on the design and detailed analysis of hazard detection techniques (using multiple sensors, including V2V communications sensing capabilities), decentralized distribution of warnings, or position-based relevance check techniques. The tests were mainly designed for full function demonstrations and integration validations based on IEEE 802.11a technology. The study reported in Ibanez-Guzman et al. (2010) presents the implementation and basic test in an intersection scenario of an instance of the architecture developed for cooperative vehicle applications as part of the European project SAFESPOT. The study highlighted the relevant impact of obstructions on the communications performance, the importance of positioning technologies, the difficulty in creating hazardous situations in testing scenarios, and the need to adequately quantify and log results. A more recent study presented in Kianfar et al. (2012) proposes a Cooperative Adaptive Cruise Control (CACC) architecture designed and implemented as part of the Grand Cooperative Driving Challenge (GCDC) in 2011. The solution was based on communications, sensor fusion and control modules. The different modules were tested and were able to guarantee the maximum delay

[1] V2X encloses V2V and V2I communications capabilities.

and PER levels required by GCDC. In Ammoun and Nashashibi (2010), the authors describe the hardware architecture of an on-board communications unit, and the design of cooperative intersection collision warning and lane changing applications. Using IEEE 802.11g devices, the authors conducted basic experiments to evaluate the feasibility of the implemented prototype for risk assessment and collision avoidance; in particular, the study evaluated the communications performance (throughput as a function of the distance between vehicles, and latency).

Some of the reviewed studies emphasized the need to improve the positioning accuracy to reliably support cooperative V2X active safety applications. A different approach to the study of the positioning impact is that reported in Santa et al. (2010) where the authors exploit cellular communications (in particular, the UMTS standard) for cooperative applications. In particular, the authors show that the most appropriate navigation sub-system is based on a combination of motion and GNSS (Global Navigation Satellite Systems) sensors; the implemented prototype used a SBAS-capable GPS sensor, with additional inertial sensors and speedometers. Other studies evaluated the positioning error and proposed advanced positioning solutions to support cooperative V2X active safety applications, without addressing the design and implementation of complete functional driver assistant system prototypes. For example, Jihua and Han-Shue (2009) studies the impact on the capability to detect road hazards of errors in Differential Global Positioning System (DGPS)-based positioning and inter-vehicle communications. The analysis compares the actual time to collision with the estimated one using DGPS and inter-vehicle communications. The paper statistically characterizes the errors in position estimation and trajectory prediction, and incorporates simulated communication errors as part of the prediction error to determine the quality of the detection performance.

The reviewed studies represent some of the most comprehensive and innovative studies published to date regarding the evaluation of cooperative vehicular technologies. However, the studies usually concentrate on specific aspects and do not fully and repetitively evaluate cooperative safety applications under different and challenging testing conditions. Extensive tests have been conducted to evaluate the performance of IEEE 802.11p communications using metrics such as PER, received signal level, or latency. While the experiments conducted have considered varying communication parameters and different operating conditions (including challenging ones), the applications' effectiveness has not been tested. Full functional driver assistant system prototypes, that include the detailed implementation of cooperative V2X active safety applications, have been mainly evaluated from the integration and demonstration point of view, but without extensively testing the applications' effectiveness, especially under challenging conditions. The reported studies have also highlighted the importance of positioning accuracy to design reliable cooperative V2X active safety applications, but limited efforts have been conducted to test and quantify in detail the impact of positioning accuracy errors on the applications' effectiveness. To further advance the state of the art and complement the reported studies, this paper presents a cooperative vehicle testing platform that allows repetitively testing cooperative active road safety applications under challenging driving and communications conditions in controlled proving ground facilities. To the authors' knowledge, this study is one of the first initiatives testing the effectiveness of cooperative V2V applications under challenging conditions. In this context, this paper also presents the results of an extensive testing campaign that evaluates the performance of ICW (Intersection Collision Warning) and EEBL (Emergency Electronic Brake Lights) applications under different driving and communications conditions, including challenging conditions resulting from high-speed driving, physically obstructed communications, interfered communications, and various positioning accuracy levels. The main objectives of the conducted tests are (1) the performance evaluation of cooperative active road safety applications under challenging operating conditions, (2) identify potential limitations of the implemented technology, and (3) obtain indications about possible countermeasures that could be taken to overcome the applications' performance degradation under adverse operating conditions. However, it is important to highlight that the value of this work is not limited to the particular tests conducted, but also includes the methodology used to repetitively test cooperative active road safety applications under challenging driving and communications conditions and the implemented cooperative vehicle testing platform.

The rest of the paper is organized as follows. Section 2 presents the implemented cooperative V2V testing platform, including a detailed description of the implemented on-board unit, cooperative applications, and testing vehicles and facilities. Section 3 analyses and discusses the most significant results of the extensive testing campaign, while Section 4 summarizes and concludes the paper.

2. Cooperative V2X testing platform

The cooperative V2V testing platform was developed as part of a collaboration with IDIADA Automotive Technologies, an industrial leader in automotive testing engineering and services that operates the most comprehensive independent proving ground facilities in Europe (Fig. 1). Covering a surface of 370 ha, IDIADA's proving ground facilities include fully equipped laboratories and state-of-the-art test tracks, such as a high-speed circuit, an external noise track or a dry handling track. IDIADA's target is to develop a cooperative V2X active safety testing environment where cooperative applications can be tested under challenging conditions.

2.1. Architecture

The cooperative V2V testing prototype includes an On-Board Unit (OBU) based on the DENSO WSU (Wireless Safety Unit) platform, a 400 MHz MPC5200B PowerPC with Linux OS and 128 MB DDR SDRAM (DENSO, 2009). Fig. 2 depicts the OBU's

Fig. 1. Aerial view of IDIADA Automotive Technologies' proving ground facilities in Tarragona (Spain).

logical architecture that includes: V2V communications, risk detection, warning management, HMI (Human-to-Machine Interface), and positioning modules.

The V2V communications module is in charge of the transmission and reception of packets using the IEEE 802.11p MAC and PHY available at the DENSO WSU. In particular, the V2V communications module implements functionalities for data packet construction and extraction. In addition to the DENSO WSU, the module includes a Nippon omni-directional antenna with $G = 0$ dBi, placed on top of the vehicle, and connected with an LMR240 antenna cable of 3 m length (see Fig. 3). The V2V communications module was configured to communicate on the control channel using periodic CAM and event-driven DENM broadcast packets. The packets' transmission power (P), transmission frequency (F) and data rate (R) can be configured from the V2V communications module with the following options and restrictions:

- The EIRP (Equivalent Isotropically Radiated Power) depends on the maximum transmission power of the DENSO WSU platform ($P_{max} = 20$ dBm), and the antenna cable loss and gain. The maximum EIRP permitted in the 5.855–5.925 GHz band for 10 MHz channels is equal to 33 dBm (2 W) in Europe (IEEE Standards Association, 2010). The default configuration employed in the conducted tests considered $P = P_{max} = 20$ dBm (the maximum output power of the DENSO WSU devices employed in the testbed (DENSO, 2009)), antenna gains of $G = 0$ dBi (following the technical specifications of the Nippon antenna), and antenna cable losses of 2.35 dB and 3.21 dB for each of the two OBUs implemented (the cable losses were measured using a Network Vector Analyzer at 5.9 GHz).

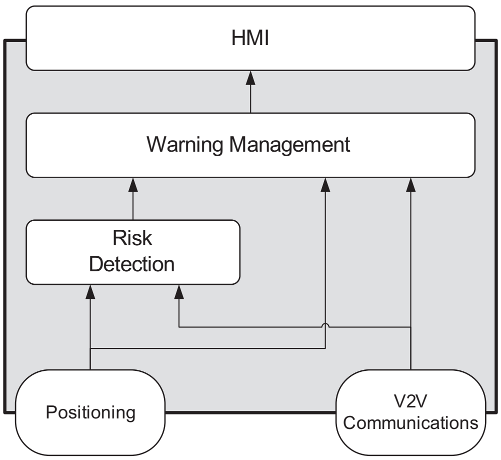


Fig. 2. Logical architecture of the cooperative V2V OBU.

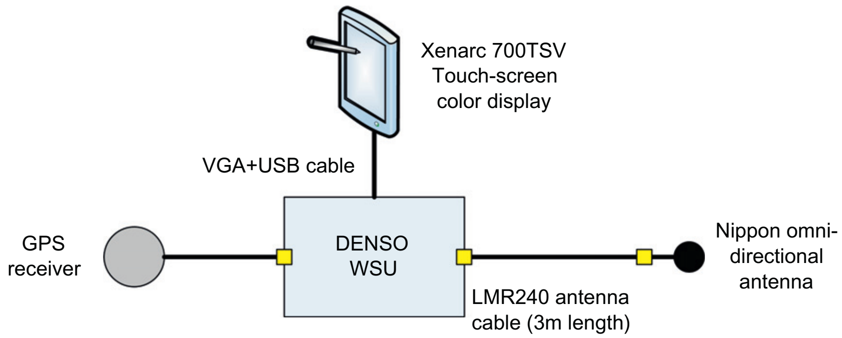


Fig. 3. Hardware architecture of the cooperative V2V OBU.

- The packet transmission frequency for periodic CAMs and event-driven DENMs in the case of active road safety applications typically varies between $F = 1$ Hz and $F = 10$ Hz (ETSI TC ITS, 2009b). However, for safety applications such as ICW and EEBL, the maximum frequency $F = 10$ Hz is recommended to reduce the latency and increase the application's reliability (VSC Consortium, 2005; ETSI TC ITS, 2009b). As a result, $F = 10$ Hz has been considered as the default packet transmission frequency.
- IEEE 802.11p includes 3, 4.5, 6, 9, 12, 18, 24 and 27 Mbps data rates. Current ETSI standards (ETSI TC ITS, 2009a) define 6 Mbps as the default transmission data rate for the control channel. As shown in Jiang et al. (2008), a 6 Mbps data rate could offer the best communications performance under different channel load levels and transmission powers, and has been here considered as the default data rate.

The risk detection module is in charge of continuously estimating the risk of collision using the information extracted from received CAM and DENM messages, and the position/speed/acceleration obtained from the GPS receiver. The implemented module detects a risk of collision when the trajectory of the vehicle is expected to intersect with the trajectory of any of the vehicles from which a CAM or DENM message has been received (considering the current speed and acceleration are maintained). The intersection point of the two trajectories constitutes the collision point, and needs to be computed taking into account their current driving direction (heading) and digital map information such as road curvatures, bridges, etc. It is important noting that different cooperative active safety applications may require different methods for estimating a risk of collision. One of the parameters that can be configured in this module is the threshold used to detect a risk of collision. It is interesting to note that, although the risk detection module does not currently support multiple applications simultaneously, it could be extended to provide basic support for multi-application scenarios. In particular, it could be extended to evaluate the risk of collision for all the different cooperative active safety applications running every time a new packet is received, although other approaches would be obviously valid. Additionally, it is important to also note that the current implementation follows a memory-less approach, in which the risk of collision is evaluated on a per packet basis, without taking into account previously received messages.

Using the output of the risk detection module, the warning management module is responsible of evaluating the level of danger, and triggering the adequate warning signals that will be shown to the driver. In order to successfully support cooperative active safety applications, it is important that the OBU is capable to reliably warn the driver when a potential hazard is detected with enough time for the driver to react and avoid the collision. In this context, a too early warning may result in the driver forgetting it or even ignoring it, and repeated warnings about the same hazard may also be ignored, in addition to causing distraction to the driver. To avoid these negative effects without compromising the applications' functionalities, the implemented warning management module uses a warning strategy that differentiates the level of danger. In particular, different warning zones have been defined depending on the remaining time to the collision point (Mitropoulos et al., 2010; PReVENT Project, 2007). Zone 1 represents the most critical area before which the driver should be warned about the danger so that he/she has sufficient time to react and stop the vehicle before the accident. In order to avoid a sudden deceleration when the vehicle enters zone 1 and the driver has not reacted to a possible risk of collision, the driver should be seriously warned of the imminent risk before reaching zone 1. This warning is triggered by the warning management module in warning zone 2. To further facilitate the drivers' reaction and avoid sudden actions, a third warning zone (zone 3) has been defined to warn the driver and allow for her/his smooth reaction, as well as taking preventive actions and avoiding critical risks. More details on the estimation of the warning zones will be provided when describing the implemented applications in the following section. However, it is important noting that the duration of zones 2 and 3 can be configured to test different warning timings and their implications.

The HMI module has been implemented using a Xenarc 700TSV touch-screen color display. The HMI can be used as the driver interface using a combination of sound and visual warnings dependent on the warning zones. In addition, the HMI module also includes a testing interface to configure the different prototype modules (e.g. the communication parameters, or the duration of warning zones 2 and 3), and visualize communications performance parameters that are not shown to the driver. The testing HMI interface is shown in Fig. 4.

The DENSO WSU platform is connected to a GPS receiver with the antenna located on top of the vehicle (positioning module). The main specifications of the different GPS receivers tested are presented in Table 1. Please note that the values shown in this table are reference values provided by the manufacturers, but the specific performance specifications are subject to ionospheric and tropospheric conditions, satellite geometry, multipath effects and the presence of intentional or unintentional interference sources. To evaluate and compare the performance achieved with different GPS receivers, different experiments were conducted simultaneously using two GPS receivers. While the first GPS receiver was connected to each DENSO WSU platform, the second one was connected to a standard laptop to continuously log the position and speed of each vehicle with different position accuracies and update frequencies.

2.2. Cooperative active road safety applications

Cooperative active road safety applications represent one of the four application classes currently defined by ETSI's Technical Committee on ITS (ETSI TC ITS, 2009b). Cooperative active road safety applications can be in turn classified in two groups: cooperative awareness applications, which base their operation in the exchange of periodic messages, and road hazard warning applications, which are event-driven applications triggered under certain conditions and following specific events. To address these two groups, this work implements one cooperative awareness application and one event-driven application.

2.2.1. Intersection collision warning

One of the cooperative awareness applications with a higher potential to improve road safety is Intersection Collision Warning (ICW). In fact, a significant percentage of road accidents occur at intersections or are intersection-related, mainly due to driver's misjudgment of the situation, inability to correctly perceive the degree of danger, lack of attention, or wrong/hidden traffic signals (US DOT, 2004), among others. The ICW application warns drivers when a potential collision at an intersection is detected. Such detection is based on the real-time exchange of CAM messages, which include information about the position of a vehicle, its speed, and acceleration, among others. While the ICW application could be based on V2V or V2I communications, the wide scale deployment of infrastructure units could be hindered by its economic cost, so it is thereby necessary that ICW applications also reliably work using V2V communications.

Fig. 5 represents an intersection scenario where two vehicles (A and B) approaching the intersection periodically transmit CAM messages, and listen to the control channel to detect each other (as well as other neighboring vehicles), monitor their position and movement, and detect in advance potential intersection risks and collisions. If vehicle A (or B) detects the other vehicle approaching the intersection, but the distance to the intersection is large and thereby an intersection risk cannot yet be identified (e.g. because there is sufficient time for any of the two vehicles to modify their speed and thereby never create any intersection risk), then no warning message is provided to the driver. On the other hand, when such risk exists, the driver must be warned. To this aim, the three warning zones for the ICW application are based on the Time to Collision (TTC) and the driver's reaction time. The TTC for the ICW application is based on the current speed and distance to the collision point (PReVENT Project, 2005), and can be computed as follows:

$$TTC_{ICW} = \frac{v_A}{d(A, C)} \tag{1}$$

where v_A represents the current speed of vehicle A, and $d(A, C)$ represents the distance between this vehicle and the collision point. The TTC computation takes into account the fact that the vehicles used in our tests move at constant speeds. If this was

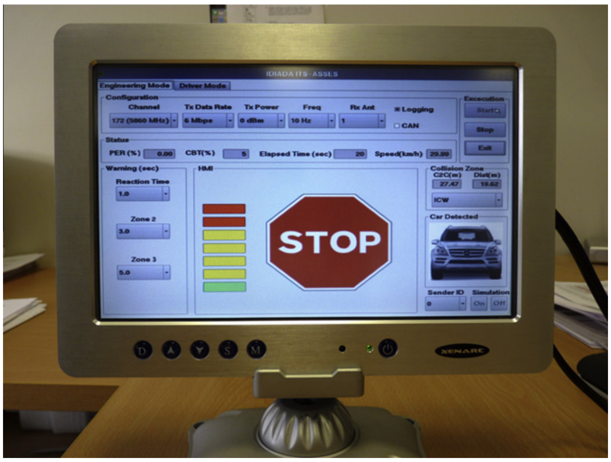


Fig. 4. HMI testing interface.

Table 1
GPS receivers.

Receiver	Position accuracy (RMS)	Update frequency
OXTS RT3002	0.02 m (with differential corrections)	100 Hz
Novatel SMART-V1-2US-PVT	1.8 m	20 Hz
Garmin 18x LVC	15 m	1 Hz

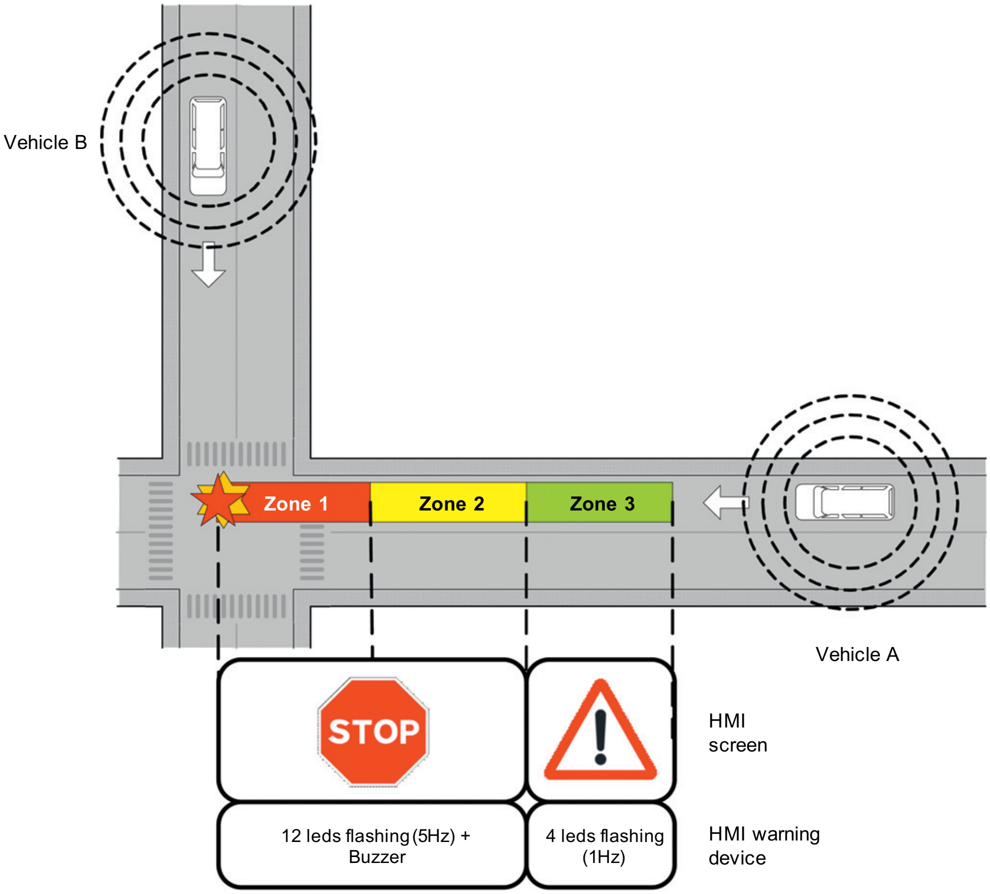


Fig. 5. ICW scenario and HMI warning strategy.

not the case, the TTC could be computed as reported in Zhang et al. (2006). The testing environment was limited to a single-lane intersection. As a result, the collision point is fixed and equal to the center of the intersection. In multi-lane intersections, the collision point should be computed taking into account the lanes at which the potentially colliding vehicles are located. The time duration of zone 1, the most critical warning zone, is computed as the braking time (current speed divided by the maximum deceleration for the ICW application) plus the driver's reaction time. Its duration is therefore equal to the time needed by the driver to react and strongly decelerate before colliding at the intersection. In the implemented applications, the reaction time used to compute the length of zone 1 has been pre-defined, but more advanced approaches would be certainly valid. In order to avoid the sudden deceleration needed to avoid an intersection collision when a vehicle enters zone 1, the driver should be seriously warned of the imminent risk before reaching zone 1 (this is illustrated in Fig. 5 as zone 2). As shown in Fig. 5, zones 1 and 2 present a strong and equal warning to the driver, although the vehicle deceleration should start before reaching zone 1 to avoid the accident at the intersection. To avoid sudden actions, when a vehicle enters zone 3, if the ICW application has detected a hazardous situation based on the positioning information received from surrounding vehicles, the driver will be warned to smoothly react and avoid critical risks. In this work, the duration of zones 2 and 3 has been fixed and pre-configured through the testing HMI shown in Fig. 4, and will be specified in Section 3.1. However, their dynamic adaptation based on the vehicle's speed, or driving context situation, could also be considered in future studies to analyze other aspects such as the human perception and system acceptance; these studies are out of the scope of this paper that focuses on V2V active safety testing under challenging conditions. Based on the proximity to the intersection and the risk of collision, the implemented HMI module considers different warning symbols and signals as shown in Fig. 5.

As previously mentioned, the methodology followed by the risk detection module to estimate if any surrounding vehicle represents a road hazard or not, is based on the calculation of the future trajectories of all detected vehicles considering that current speed, acceleration and driving direction are maintained. In particular, for the ICW application, each vehicle calculates its own TTC and the TTC of all detected vehicles that are approaching the intersection based on the received CAM messages. If the unsigned difference between its own TTC and the TTC of any of the approaching vehicles is below a certain threshold (ε), a potential hazard at the intersection is considered to be detected. The use of a low ε value would reduce the number of vehicles detected as road hazards, which could result in a reduction of false alarms, but also in a potential increase of undetected road hazards. On the other hand, a high ε value would increase the number of vehicles detected as hazards, which could create unnecessary false alarms. In this work, the following threshold value has been used by default:

$$\varepsilon = \frac{L_A}{v_A} + \frac{L_B}{v_B} \tag{2}$$

where L_A and L_B represent the length of the potentially colliding vehicles in meters. Again, other approaches could be of interest, but their study and optimization are outside the scope of this work.

2.2.2. Emergency electronic brake light

The Emergency Electronic Brake Light (EEBL) application is one of the most representative examples of road hazard warning applications. In this case, whenever a vehicle brakes hard, the EEBL application automatically sends time limited periodic DENMs to following vehicles 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. The EEBL application is typically based on V2V communications, especially given that this type of dangerous situation can ubiquitously take place. CAM messages exchanged among vehicles could also be used to anticipate and prevent rear-end collisions, since they include positioning, speed and acceleration information. However, triggering the transmission of DENMs at the occurrence of a hard-braking situation reduces the application's latency, and allows the transmission of additional and useful information such as the type of event that has occurred and its location. In addition, DENM messages can be transmitted over multiple hops through which distant vehicles can be warned of a potential road hazard.

To reliably warn the driver with enough time to react and avoid the collision without too-early warnings, the implemented EEBL application follows the warning strategy previously described. Fig. 6 presents a car-following scenario in which a collision between vehicles A and B could take place if vehicle A suddenly brakes and vehicle B is not warned with enough time to reduce its speed. In this scenario, both vehicles periodically transmit CAM messages, and listen to the control channel for detecting and monitoring surrounding vehicles. Additionally, vehicle A starts transmitting DENM messages when it suddenly brakes to rapidly inform vehicle B (and other potential following vehicles) about the dangerous situation. If vehicle A suddenly brakes but the distance between them is high, then no warning message is provided to the driver of vehicle B. However, when such risk exists, the EEBL application is also based on three warning zones that depend on the TTC and the driver's reaction time. In a car-following situation, the TTC is the time taken for the two vehicles to collide if they maintain their present speed and heading, and can be computed as follows:

$$TTC_{EEBL} = \frac{v_B - v_A}{d(A,B)} \tag{3}$$

where v_A and v_B represent the current speed of the two vehicles, and $d(A,B)$ corresponds to the distance between them. However, when the vehicle ahead (e.g. vehicle A) suddenly brakes, a more valid approach that more precisely calculates the time to collision would need to take into account the vehicle's deceleration. In this context, two situations can be produced. In the first one, the collision between the two vehicles occurs before the complete stop of vehicle A. In this case, the TTC can be computed as follows:

$$TTC_{EEBL} = \frac{-v_{rel} - \sqrt{v_{rel}^2 - 2a_A d(A,B)}}{a_A} \tag{4}$$

where $v_{rel} = v_A - v_B$, and a_A is the deceleration of vehicle A ($a_A < 0$ when braking). However, if the distance between the two vehicles is relatively high when vehicle A suddenly brakes, the collision between them could occur after vehicle A has completely stopped. In this case, the TTC computations requires first to calculate the distance needed by vehicle A to stop considering a constant deceleration:

$$d_{stop}(A) = -\frac{1}{2}\frac{v_A^2}{a_A} \tag{5}$$

The TTC is then computed as the time needed by vehicle B, moving at a constant speed v_B, to reach a distance equal to the sum of $d(A,B)$ and $d_{stop}(A)$:

$$TTC_{EEBL} = \frac{1}{v_B}\left(d(A,B) - \frac{1}{2}\frac{v_A^2}{a_A}\right) \tag{6}$$

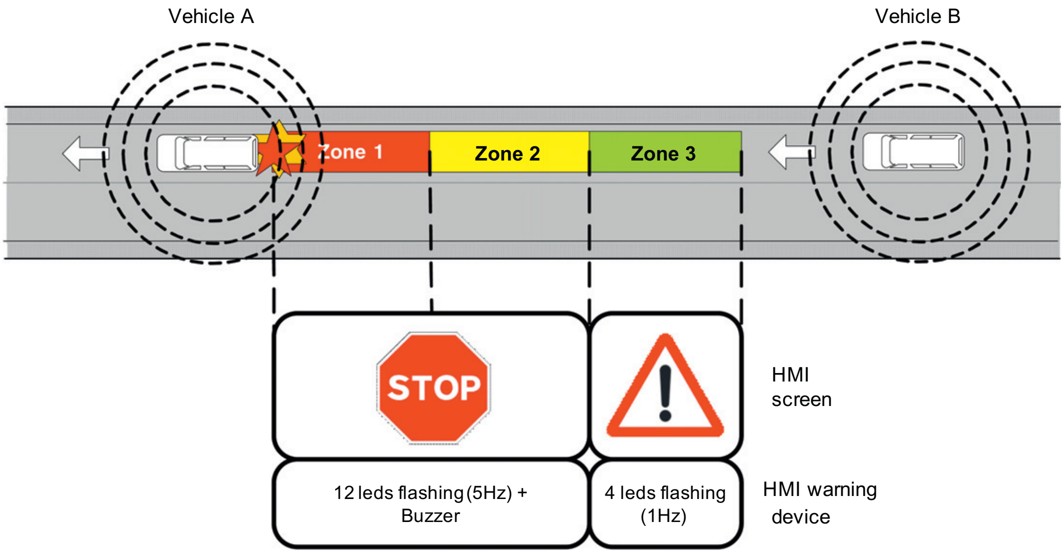


Fig. 6. EEBL scenario and HMI warning strategy.

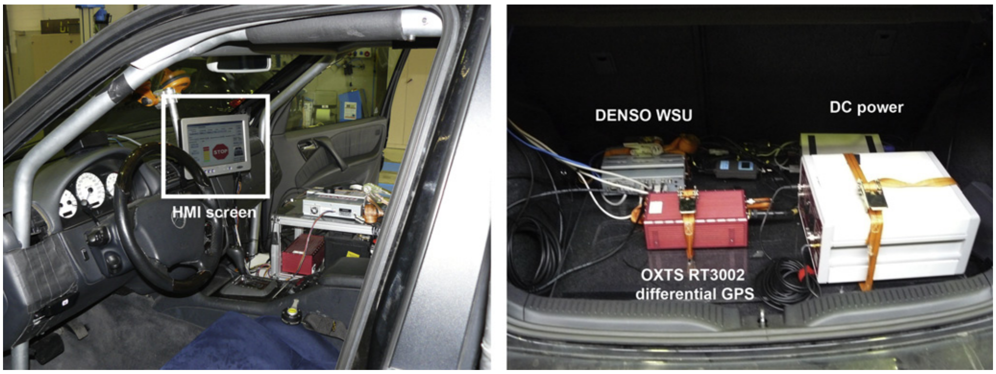


Fig. 7. Partial view of one of the vehicles used to conduct the cooperative active road safety tests.

The TTC for the EEBL application is then selected as the minimum value between Eqs. (4) and (6). Based on the TTC, the definition of the three EEBL warning zones follows the reasoning previously discussed. Zone 1 represents the critical area before which the driver should be warned about the danger to provide him/her with enough time to react and avoid the accident, and its time duration is computed as the braking time (current relative speed divided by the maximum deceleration for the EEBL application) plus the driver's reaction time. Zones 2 and 3 have also been defined to facilitate the driver's reaction and avoid sudden actions. As for the ICW application, the duration of zones 2 and 3 has also been fixed for the EEBL application through the testing HMI shown in Fig. 4.

For the EEBL application, the methodology used to estimate if a vehicle represents a road hazard or not is simpler than for the ICW application. In particular, the vehicle ahead is identified as a road hazard when it is moving at a lower speed, or when it starts a hard braking maneuver.

2.3. Testing vehicles and facilities

Fig. 7 shows part of one of the vehicles that has been used to conduct the cooperative active road safety tests. In addition to the implemented cooperative V2V prototype, the professional testing vehicles include the necessary equipment to ensure the driver's safety during challenging driving conditions, as well as the repeatability of the experiments. The EEBL application was tested at IDIADA's proving ground test track (see Fig. 1). Testing EEBL applications at high speeds requires reducing the risk when a sudden deceleration of a vehicle is produced and there is a vehicle immediately behind. To avoid the collision between the two vehicles, the vehicle ahead has a lateral foam platform that represents a virtual vehicle and is used in the EEBL application testing. As shown in Fig. 8, the tests are conducted so that the vehicle behind could collide with the foam

Fig. 8. EEBL testing vehicles with foam platform at IDIADA's proving ground.

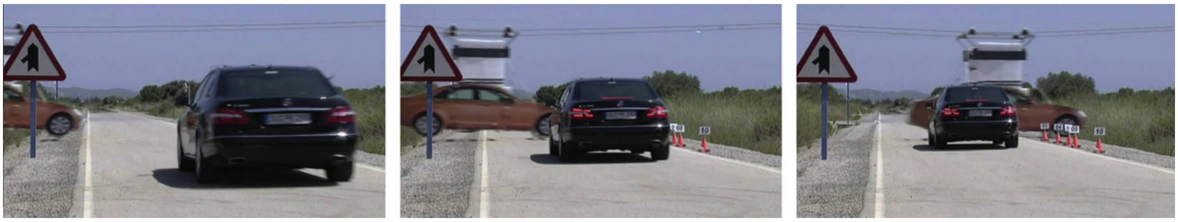


Fig. 9. Safety intersection laboratory at IDIADA's proving ground.

platform. While all the equipment except the antenna was in the vehicle, the EEBL application was configured to take into account the lateral distance between the vehicle and the foam platform.

The ICW application was also tested at high speeds at IDIADA's proving ground using the vehicles equipped with the cooperative V2V prototype. At high speeds, testing ICW applications requires the synchronization between the two vehicles approaching the intersection to create a risk of collision. To this aim, and also to guarantee the drivers' safety, ICW applications were tested at high speeds using IDIADA's safety intersection laboratory. In this laboratory, one of the vehicles approaches the intersection at the desired speed. A central processing unit measures the speed of the subject vehicle using multiple sensors deployed along the road. Based on this information, the central processing unit controls the movement of a foam car to approach the intersection and reach the intersection at the same time as the potentially colliding vehicle (Fig. 9). The tests included intersection scenarios with full visibility between approaching vehicles, and scenarios where a building partially blocked the radio signal (Fig. 10, open spaces on 3 out of the 4 corners). Finally, ICW tests were conducted with and without the presence of other interfering vehicles communicating on the control channel. The realization of the experiments in straight road segments did not require the implementation and exploitation of digital map information to obtain the collision point.

3. Cooperative active road safety testing

Using the equipment and testing facilities previously described, more than 100 experiments were conducted to evaluate the EEBL and ICW applications' effectiveness under different conditions. Each experiment was characterized by a different communications setting, driving speed, and/or operating conditions (e.g. presence or absence of obstructing building, or interference). Each experiment was repeated several times, with more than 700 runs in total.

Table 2 presents the main communications and operating parameters used in the experiments. P represents the transmission power at the DENSO WSU output connector, and the employed default value is $P = 20$ dBm (the maximum transmission power of the DENSO WSU). Congestion control policies may recommend the use of lower transmission power levels to avoid channel congestion under certain scenarios. To account for this possibility, the use of $P = 10$ dBm has also been tested. Additional experiments were conducted to increase the radiated power (without using power amplifiers) considering $P = 20$ dBm and avoiding the use of the LMR240 antenna cables[2] (Fig. 3). Unless otherwise stated, the LMR240 antenna cables are used in

[2] We have measured in an anechoic chamber that the difference in terms of received signal level between the configuration using the antenna cables, and the one in which the antennas were directly connected to the DENSO WSUs without cables, was more than 7 dB. The difference is due to the antenna cable losses and connectors.

Fig. 10. ICW testing scenario with obstructing building.

Table 2
Experimental communication and operating parameters.

Parameter	Value
P (transmission power)	10 dBm, 20 dBm
F (packet transmission frequency)	2 Hz, 10 Hz, 20 Hz
R (data rate)	3 Mbps, 6 Mbps, 9 Mbps
Driver's reaction time	1 s
Warning zone 2 duration	2 s
Warning zone 3 duration	2 s
Emergency deceleration	8.5 m/s^2

the tests. A default packet transmission frequency of $F = 10$ Hz has been used in the experiments. However, decreasing the packet transmission frequency ($F = 2$ Hz) can also be a viable option for reducing the channel load. The use of $F = 20$ Hz was also considered to combat the reduction on the applications' effectiveness experienced under certain challenging conditions. Finally, different data rates have also been tested to also analyze the impact of the modulation/coding scheme employed on the applications' effectiveness. The experiments were conducted using the default IEEE 802.11p MAC parameters (IEEE Standards Association, 2010): $CW_{\min} = 15$, $CW_{\max} = 1023$, AC_BK background access category, and AIFSN = 7 (Arbitration Inter Frame Spacing). The driver's reaction time and emergency deceleration (Biswas et al., 2006) shown in Table 2 are used to calculate the time duration of warning zone 1, and can be modified at any time based on the driver and vehicle conditions.

3.1. Performance metrics

The applications' effectiveness is mainly evaluated through the warning accuracy metric following the definitions provided in Tu and Huang (2010). As illustrated in Fig. 11, a warning can be successful or failed. A *successful warning* is defined as a correct and timely warning indication of a potential collision that provides to the driver enough time to reduce its speed and avoid the accident. Depending on the remaining time to collision at which the warning indication is triggered, two types of *successful warnings* can be identified: *effective* and *precise* warnings. An *effective warning* is produced when a smooth deceleration can be applied to avoid the accident, i.e. when the warning can be triggered at high distances (the alert is shown to the driver in zone 3). A *precise warning* is produced when the hazard is detected with reduced time for the driver to avoid the accident (i.e. when the alert is shown to the driver in zone 2; if the alert is only shown in zone 1 then the accident cannot be avoided). In this case, the driver would have enough time to stop the vehicle and avoid the accident, but a stronger deceleration would be needed. As a consequence, a dangerous situation resulting from the sudden deceleration could be produced, e.g. rear-end collisions. To better reflect its nature, *precise warnings* have been renamed in this work as *last-minute warnings*. Finally, *failed warnings* include *missed warnings* and *late warnings* (i.e. warnings triggered without sufficient time for the driver to stop the vehicle and avoid the accident). In this work, *late warnings* are produced when the first message from the potentially colliding vehicle is received at zone 1.

In addition to the warning accuracy metric, a reliability parameter has also been considered following the indications provided in Mitropoulos et al. (2010). This parameter defines the probability of a hazard to be valid, and therefore is a critical parameter that decides whether or not a driver should be informed about a specific hazard. Based on Mitropoulos et al. (2010), the reliability of an event increases when several messages describing the same event are received, and decreases

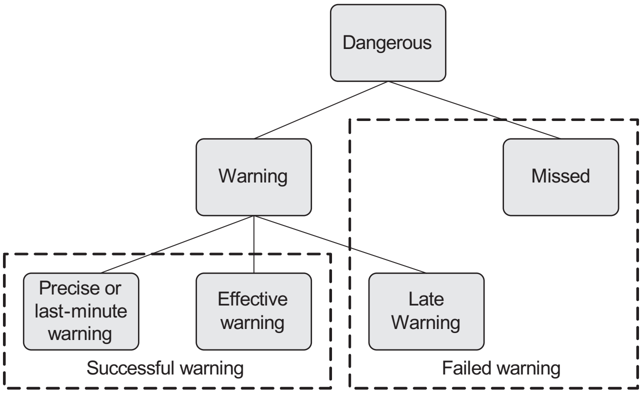
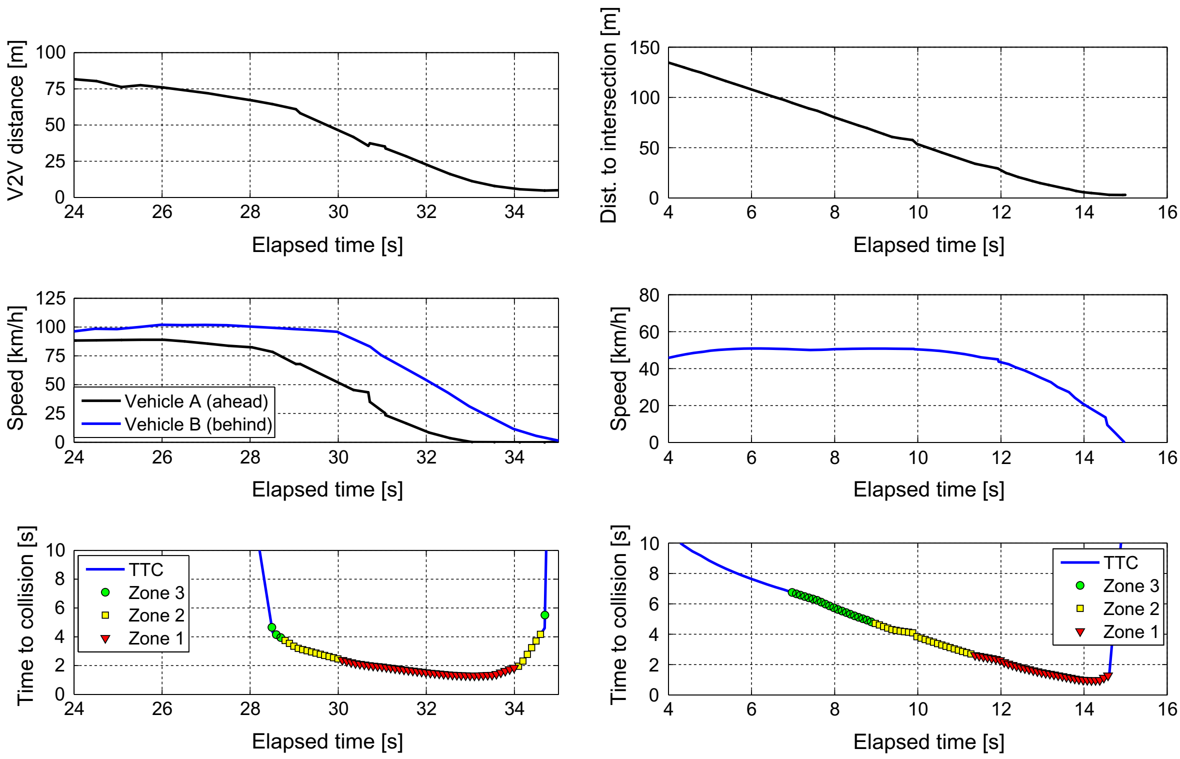


Fig. 11. Types of warning (adapted from Tu and Huang (2010)).



(a) EEBL test at v=100km/h with hard braking (b) ICW test at v=50km/h with hard braking

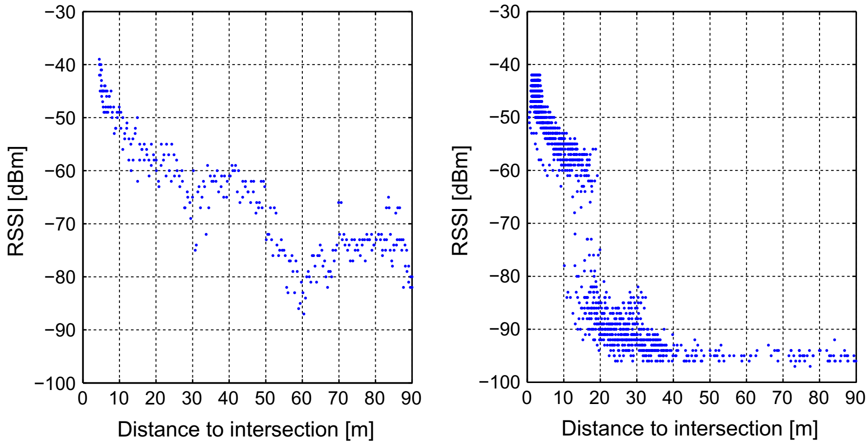
Fig. 12. EEBL and ICW testing under high vehicular speeds.

when contradictory messages are found. In this context, the conducted experiments consider that multiple packets could be needed to reliably detect a road hazard, and that the warning is triggered once *N* packets detecting the road hazard have been successfully received.

These performance metrics are aimed at evaluating the applications' effectiveness, and differ from communication metrics typically employed in field tests (e.g. PDR – Packet Delivery Ratio, PER, or RSSI – Received Signal Strength Indicator). Despite their relevance, communication metrics cannot directly be used to evaluate an application's effectiveness. Such evaluation needs defining application settings and requirements (e.g. the time or distance at which a warning must be shown to the driver) that are independent from communication aspects.

3.2. EEBL and ICW testing under high vehicular speeds

The first 70 experiments were conducted to test the implemented applications under high vehicular speeds and different driver reaction times to the received warning alerts. The EEBL application was tested at speeds between 40 km/h and



(a) LOS propagation conditions
(b) NLOS propagation conditions

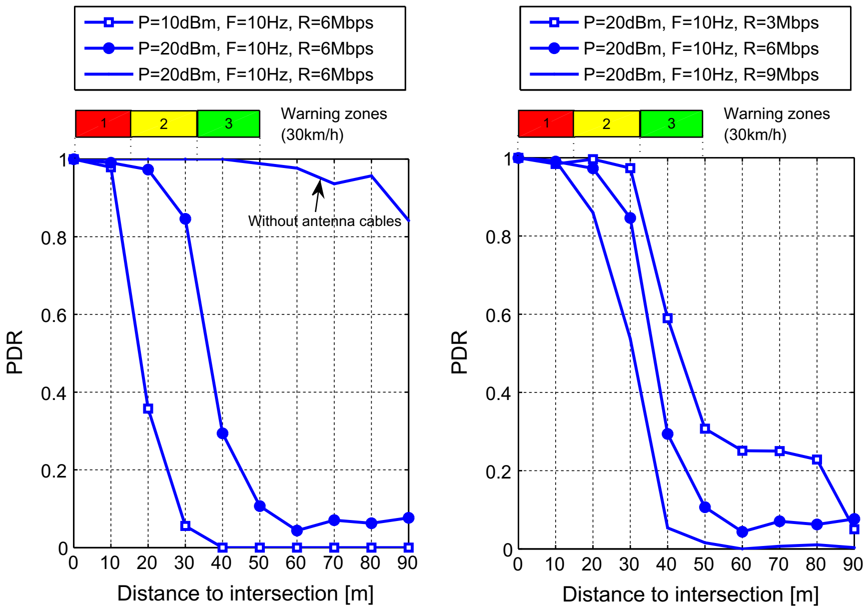
Fig. 13. RSSI experienced under LOS and NLOS propagation conditions for $P = 20$ dBm, $F = 10$ Hz and $R = 6$ Mbps.

100 km/h, and the ICW application between 20 km/h and 50 km/h. These experiments were conducted under LOS propagation conditions in IDIADA proving ground facilities using the EEBL testing vehicles and the safety intersection laboratory with the foam car. As an example, Fig. 12a shows for an EEBL test at $v = 100$ km/h, the distance between vehicles, their speed, and the TTC measured during the test. As it can be observed, the sudden deceleration of the vehicle ahead (starting at 28 s), decreased the TTC and the vehicle behind rapidly entered warning zones 3, 2 and 1. The driver of the vehicle behind did not respond to the warnings received in zones 2 and 3, and only started decelerating when approaching the frontier between zone 2 and zone 1. Once such vehicle decelerates, the danger is avoided and the TTC increases, which proves the correct operation of EEBL and its potential to improve road safety under challenging driving conditions. Fig. 12b reports the results obtained in an ICW field experiment at $v = 50$ km/h. In this case, the driver started decelerating also in the frontier between zone 2 and zone 1, and was able to avoid the accident. The favorable propagation conditions and short distances between vehicles resulted in packet error rates below 1% in all the experiments conducted; in this context, the warning accuracy was not challenged. The two experiments reported in this section represent the highest vehicular speeds tested for each application, and demonstrate the correct and safe operation of the cooperative V2V safety applications. The consideration of even higher vehicular speeds is not expected to reduce the warning accuracy given the low packet error rates experienced. Under more favorable driving conditions (e.g. at lower speeds), the conducted experiments also showed the correct operation of the applications (these results are not here reported due to their lower relevance). Challenging conditions for the EEBL application mainly result from high vehicular speeds and sudden driver's reactions. Such challenging conditions were reproduced to derive the results reported in Fig. 12a, which in fact demonstrate the effectiveness of the EEBL application. As a result, the following sections concentrate on the ICW application in an intersection scenario with a building blocking the radio signal (see Fig. 10).

3.3. ICW testing under NLOS propagation conditions

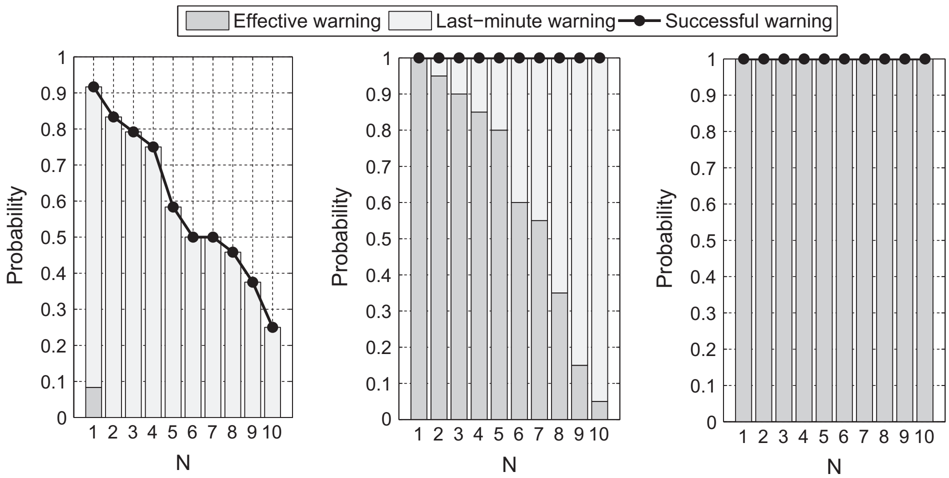
NLOS propagation conditions resulting from the presence of obstructing buildings have demonstrated to reduce the IEEE 802.11p communications performance (Gozalvez et al., 2012). It is therefore important to evaluate the effectiveness of cooperative safety applications under challenging NLOS propagation conditions due to the building obstruction. In this context, this section evaluates the ICW application in an intersection scenario with a building blocking the radio signal (see Fig. 10); each communications configuration test was repeated more than 20 times.

Fig. 13 illustrates the effect of NLOS propagation conditions on the received signal level (RSSI) measured for all correctly received packets and considering a transmission power of 20 dBm, a packet transmission frequency of 10 Hz and 6 Mbps data rate. The depicted results show that the RSSI is notably reduced under NLOS propagation conditions at distances to the intersection higher than 15–20 m. Fig. 14 shows the PDR experienced by two vehicles (A and B) approaching the intersection with a risk of collision at $v = 30$ km/h. The PDR level at a given distance is calculated as the ratio between the number of correctly received packets and the total number of transmitted packets at such distance. The conducted tests without buildings at the intersection showed that sustained connectivity levels with PDR levels higher than 95% were possible even for low transmission powers (e.g. $P = 10$ dBm, $F = 10$ Hz and $R = 6$ Mbps). However, Fig. 14 shows that the attenuation produced by buildings can notably reduce the distance to the intersection at which the two vehicles are able to reliably communicate. Fig. 14a shows that increasing the transmission power can notably increase the PDR levels at medium and high distances to the intersection. As it will be later shown, such increase could be needed for the reliable exchange of packets in warning zones 2 and 3, especially under high vehicular speeds. Fig. 14b demonstrates that the reduction of the data rate



(a) Transmission power increase (b) Data rate increase

Fig. 14. PDR (Packet Delivery Ratio) experienced by two vehicles approaching an intersection with a risk of collision at $v = 30$ km/h and NLOS propagation conditions.

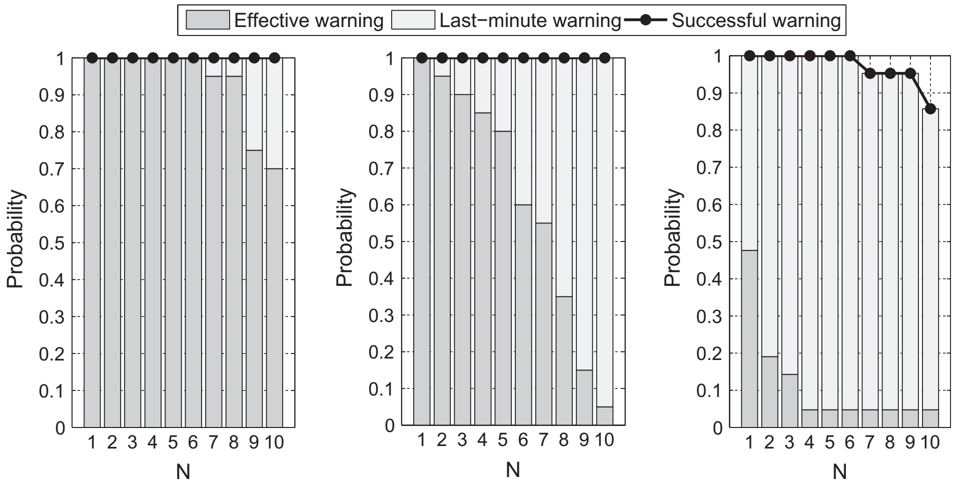


(a) P=10dBm (b) P=20dBm (c) P=20dBm (without antenna cables)

Fig. 15. ICW warning accuracy for different transmission power levels ($F = 10$ Hz and $R = 6$ Mbps).

could also benefit the experienced PDR levels, since higher data rates need a higher SINR (Signal to Interference and Noise Ratio) to correctly decode a packet as a result of their lower coding rates and less robust modulation schemes. Following the IEEE 802.11 specifications for 10 MHz channel spacing, the minimum receiver sensitivity required for 3 Mbps (BPSK, 1/2), 6 Mbps (QPSK, 1/2), and 9 Mbps (QPSK, 3/4), are −85 dBm, −82 dBm and −80 dBm, respectively. The 5 dB difference between 3 Mbps and 9 Mbps data rates is at the origin of the PDR improvement observed in Fig. 14b. Tests were also conducted varying the packet transmission frequency. In this case, the PDR levels were not modified, although as it will be later shown, the packet transmission frequency will have an influence on the number of packets that can be correctly received before reaching a certain distance, and therefore on the applications' effectiveness.

Fig. 15 shows the probability of providing a successful, last-minute and effective warning to the driver for different ICW experiments. This probability is illustrated as a function of the number of messages (N) considered to reliably identify the potentially colliding vehicle as a road hazard. It is assumed that the warning is triggered after the correct reception of N



(a) R=3Mbps (b) R=6Mbps (c) R=9Mbps

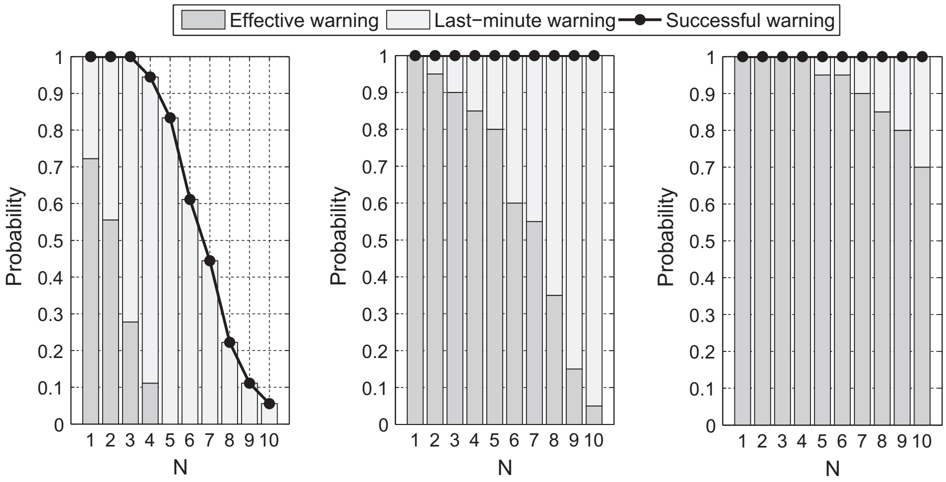
Fig. 16. ICW warning accuracy for different data rates (P = 20 dBm and F = 10 Hz).

packets detecting the road hazard, and each bar in the figure represents the probability of triggering such warning in zone 2 (last-minute warning), or in zone 3 (effective warning). A successful warning is produced when the warning is triggered either in zone 2 or in zone 3. The figure presents the results obtained for three different transmission power levels, while the data rate and packet frequency were fixed at the default values (F = 10 Hz, and R = 6 Mbps). As it can be observed, the use of a low transmission power (Fig. 15a) results in a reduced probability of successful warning due to the attenuation produced by the obstructing building, especially when a high number of N messages is needed to reliably trigger the alert. Fig. 15a also shows that only a reduced part of the successful warnings were due to effective warnings; in fact, no effective warnings were experienced during the tests for N higher or equal to 2. As a result, most of the warnings triggered using a low transmission power level were shown to the driver with reduced time to react and avoid the accident at the intersection (last-minute warnings). To overcome these limitations, a higher transmission power could be used. Fig. 15b and c shows that increasing the transmission power can notably improve the ICW application's effectiveness as the probability of triggering effective warnings increases importantly. The obtained results show that a successful warning could be obtained in all the conducted experiments with medium and high transmission power levels for the N values analyzed. However, a 100% probability of launching effective warnings was only observed under high transmission power levels (Fig. 15c).

Different studies have shown that 6 Mbps data rate offers the best communications performance under different channel loads, transmission power, and packet sizes (Jiang et al., 2008). However, the observations reported in Fig. 14b suggest that reducing the data rate could improve the ICW application's effectiveness under challenging propagation conditions. Fig. 16 shows the probability of providing successful (effective and last-minute) warnings for different data rates. The reported results show that varying the data rate has mainly an impact on the probability of launching effective warnings, while the probability of successful warning is maintained almost at the maximum level for the three data rates tested. In any case, it is important to remember that effective warnings would enable a smooth driver reaction, and thereby reduce, for example, the probability of rear-end collisions. It is also important noting that the benefits of using low data rates shown in Fig. 16 could be reduced under: (1) congested channels due to the higher probability of packet collisions with longer packets (this effect will be shown in Section 3.4), or (2) strong fading environments with short coherence times that can reduce PER for long packets.

As previously discussed, varying the packet transmission frequency did not modify the observed PDR levels. However, augmenting the packet transmission frequency increases the number of packets that can be received at a given distance to the intersection for a fixed transmission power and data rate. Fig. 17 shows that the probability of effective warning can be increased with F = 20 Hz, and therefore the ICW performance can be improved, especially when a high number of packets N is required to reliably trigger the warning. The figure also shows that the use of low packet transmission frequencies could be unfeasible for critical active safety applications (e.g. ICW). It is important to note that the one of the methods to control channel congestion is through the variation of the packet transmission frequency. While congestion control policies might recommend the use of low packet transmission frequencies to reduce channel congestion, the obtained results have experimentally shown that decreasing the packet transmission frequency can notably affect the applications' effectiveness.

The results reported in this section have shown through field experiments that the use of high transmission powers, low data rates or high packet transmission frequencies can help overcoming the limitations resulting from challenging propagation conditions caused by obstructing elements such as buildings. However, it is important to note that the reported results in this section did not yet consider interfering neighboring vehicles. In scenarios with neighboring vehicles it might not always be possible to modify the communication parameters due to the resulting high channel load.



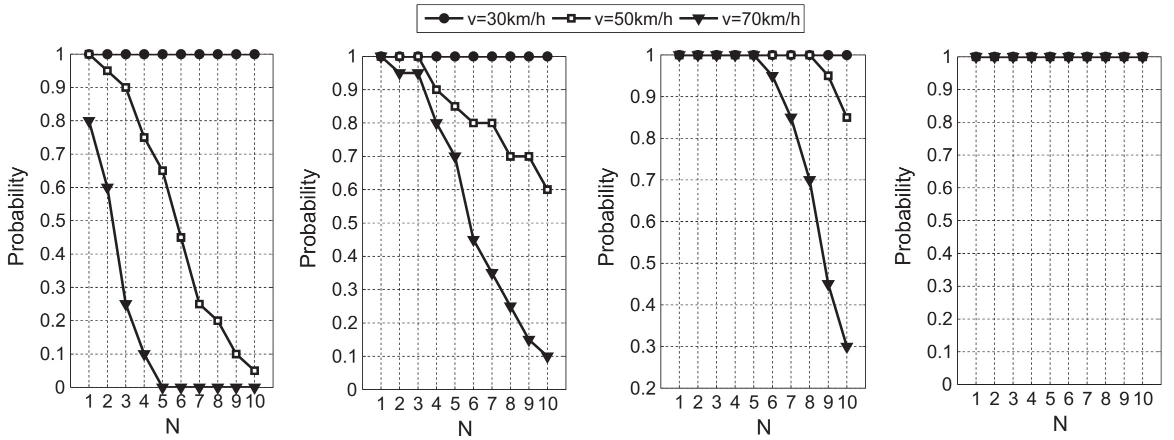
(a) F=2Hz (b) F=10Hz (c) F=20Hz

Fig. 17. ICW warning accuracy for different packet transmission frequencies (P = 20 dBm and R = 6 Mbps).

The obtained results showed that good ICW performance levels can be achieved at v = 30 km/h under challenging propagation conditions with high transmission powers, low data rates, or high packet transmission frequencies. The performance is only degraded when requiring a very high, and probably unreasonable, road hazard reliability. Increasing the vehicles' speed augments the distance needed to stop the vehicle, and therefore the distance to the intersection at which the warning needs to be shown to the driver. Experimental tests were not conducted at higher speeds for safety reasons (the building was blocking the visibility between the two approaching vehicles). However, the different warning probabilities that could be expected under higher speeds have been derived using the PDR traces obtained at v = 30 km/h. In particular, vehicles approaching the intersection at higher speeds have been simulated to determine the distances to the intersection at which each packet would be transmitted. For each transmitted packet, the PDR traces obtained at v = 30 km/h have been used to simulate whether the packet was correctly received or not by the potentially colliding vehicle; the two vehicles are assumed to be at the same distance to the intersection. The probability to provide a successful, last-minute and effective warning can be computed using the distance to the intersection at which packets are correctly received and the new warning zones derived for higher speeds. Fig. 18 illustrates the successful warning probability for different speeds, and the four communications configurations that offer the best ICW performance. As it can be observed, while a perfect probability of successful warning is achieved with all configurations for v = 30 km/h, higher speeds notably reduce this probability, especially under the default communication parameters (P = 20 dBm, F = 10 Hz, R = 6 Mbps). The degradation of the probability is overcome with higher transmission power levels, independently of the road hazard reliability. Increasing the packet transmission frequency and decreasing the data rate also improves the successful warning probability. The probability of effective warning is depicted in Fig. 19 for the four different communications configurations. The degradation of the probability as the speed augments is much higher, although again a variation of the communications configuration can help and partially mitigate such degradation. In any case, it is clear that high vehicular speeds under challenging propagation conditions require high transmission power levels and a relaxation in the number N of packets that need to be correctly received to estimate as reliable a road hazard detection.

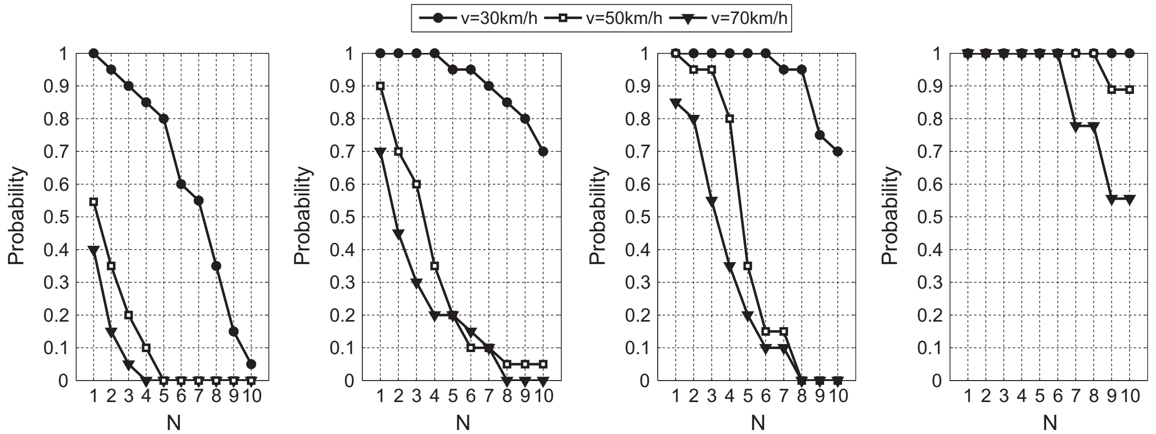
3.4. ICW testing under interference conditions

The adequate operation of cooperative active road safety applications does not only depend on the driving and propagation conditions, but also on the communications channel load and potential interference levels. To evaluate the ICW application's effectiveness under interference conditions, different communications channel load levels have been generated. The metric used to measure the channel load level is the CBT (Channel Busy Time), which can be defined as the average fraction of time that the channel is sensed as busy. Due to equipment limitations, the interference was generated by a static interfering node configured to periodically transmit a broadcast packet with P = 10 dBm, F = 200 Hz and R = 3 Mbps. Packet payload lengths of 1500 B, 1000 B and 500 B were used to generate radio channel load levels of CBT = 84%, CBT = 57% and CBT = 30%, respectively. As shown in Le et al. (2009), the selected channel load levels can be experienced in intersection scenarios. The interference generated using a single interfering node transmitting longer packet does not exactly reproduce the precise interference conditions that could be experienced in a real scenario with multiple vehicles transmitting short packets from different positions. However, the conducted study still provides very valuable indications about the impact of interference on the applications' effectiveness.



(a) P=20dBm, F=10Hz, R=6Mbps
(b) P=20dBm, F=20Hz, R=6Mbps
(c) P=20dBm, F=10Hz, R=3Mbps
(d) P=20dBm, F=10Hz, R=6Mbps (without antenna cables)

Fig. 18. ICW successful warning probability for different speeds and communications configurations.



(a) P=20dBm, F=10Hz, R=6Mbps
(b) P=20dBm, F=20Hz, R=6Mbps
(c) P=20dBm, F=10Hz, R=3Mbps
(d) P=20dBm, F=10Hz, R=6Mbps (without antenna cables)

Fig. 19. ICW effective warning probability for different speeds and communications configurations.

Two interference scenarios have been tested. In the first one, the interfering node was located at the intersection, and therefore had direct visibility with the two vehicles (vehicles A and B) approaching the intersection. As a result, the IEEE 802.11p CSMA/CA protocol avoids packet collisions, and the PDR experienced by the two vehicles does not significantly vary and is only decreased at short distances to the intersection (see Fig. 20a). In the second scenario, the interfering node was located at 95 m from the intersection, immediately behind the point at which vehicle A starts moving. In this scenario, only vehicle A has direct visibility with the interfering node. The interfering node and vehicle B do not detect each other's transmissions, and therefore can simultaneously transmit and produce packet collisions at vehicle A. We verified in this scenario that the interfering node and vehicle B did not detect each other's transmissions by measuring the CBT they experienced. This effect is known as the hidden terminal problem, and results in a significant decrease of the percentage of packets that vehicle A is able to receive from vehicle B, as shown in Fig. 20b. These results experimentally highlight the importance of the position of the interfering nodes with respect to the transmitting/receiving nodes when analyzing the effects produced by interference.

Fig. 21 shows the effective and successful warning probabilities experienced with $P = 20$ dBm, $F = 10$ Hz, $R = 6$ Mbps, and various channel loads for the first interference scenario (interfering node located at the intersection). As it can be observed,

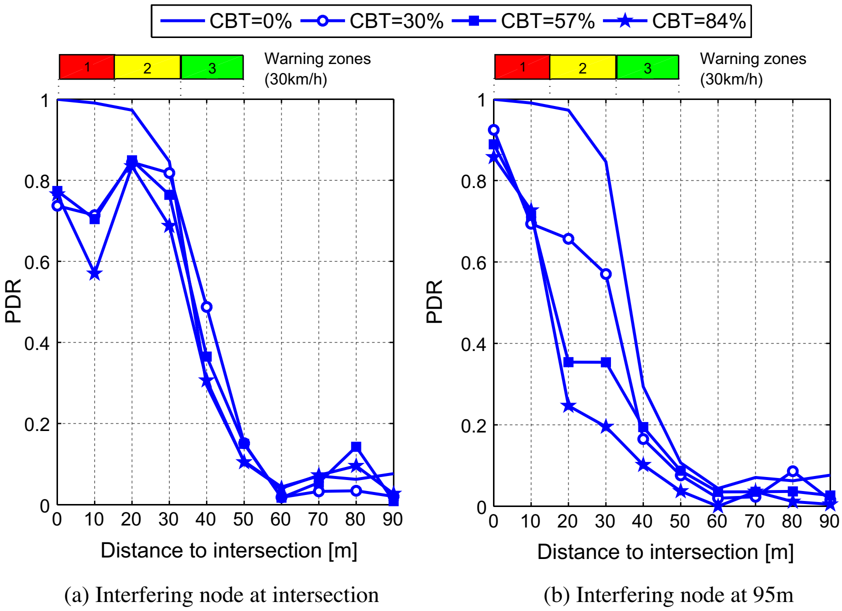


Fig. 20. PDR (Packet Delivery Ratio) experienced by vehicle A when approaching an intersection with a risk of collision with vehicle B, NLOS propagation conditions, v = 30 km/h and different channel load levels (P = 20 dBm, F = 10 Hz, R = 6 Mbps).

the successful warning probability was not affected by the interference generated, and the probability of effective warning was only slightly reduced due to small packet collisions. As shown in the previous section, this reduction could be compensated by increasing the packet transmission frequency or reducing the data rate.

Fig. 22 shows the effective and successful warning probabilities experienced with the same communication parameters, and various channel loads for the second interference scenario (interfering node located at 95 m from the intersection). In this case, the reduction of the PDR as a result of packet collisions (Fig. 20) notably decreases the ICW application's effectiveness. It is important to note that differently from the impact of NLOS propagation conditions, the presence of interference not only strongly impacts the effective warning probability but also the successful warning probability. This probability is significantly reduced under high channel load levels, which would require a reconfiguration of the communication parameters of the potentially colliding vehicles. In addition, the obtained results demonstrate the importance of congestion control protocols that limit the channel load generated by quantifying its potential impact on the application's effectiveness. In fact, the application of a congestion control protocol in the intersection scenario could decrease the CBT from e.g. 84% to 57%, which could notably improve the ICW application's effectiveness as shown in the conducted tests. It is also important highlighting that in the second interference scenario, vehicle B did not experience the hidden terminal problem since vehicle A and the interfering node detected each other's transmissions and did not simultaneously transmit. As a result, vehicle B did not experience a significant degradation of the PDR and the ICW application's effectiveness in the presence of interference.

Fig. 23 shows the impact on the ICW application's effectiveness at vehicle A of varying the communication settings of vehicles A and B under the second interference scenario. The depicted results show that augmenting the packet transmission frequency at only the potentially colliding vehicles increases the effective and successful warning probabilities as a result of providing additional communication opportunities between both vehicles. A similar improvement has been observed with the reduction of the data rate as a result of its better robustness to radio propagation losses and interferences. In particular, the PDR experienced by vehicle A when using R = 3 Mbps increases the effective and successful warning probabilities, in particular for low values of N. Following the results discussed in previous sections, increasing the transmission power, and thereby the transmission range, could improve the ICW application's effectiveness. The hidden terminal problem was avoided in the proposed intersection scenario with a single interfering node when vehicles A and B used a 20 dBm transmission power without the antenna cables. This is the case because the interfering node was able to detect/receive messages from vehicle B. Although increasing the transmission power could help avoiding the hidden terminal problem in this particular scenario, this outcome might not be directly applicable to other scenarios with interfering nodes distributed along the road or located at farther distances to the intersection. These scenarios could not be reproduced due to equipment limitations, which limited the capability to accurately represent the impact of varying transmission power levels on the hidden terminal problem. It is important noting that the application of the proposed countermeasures needs a careful analysis. One option to avoid further increasing the channel load and interference would be the adoption of opportunistic schemes that selectively apply the countermeasures only to vehicles approaching the intersection with a risk of collision (see for example Sepulcre et al., 2011a,b).

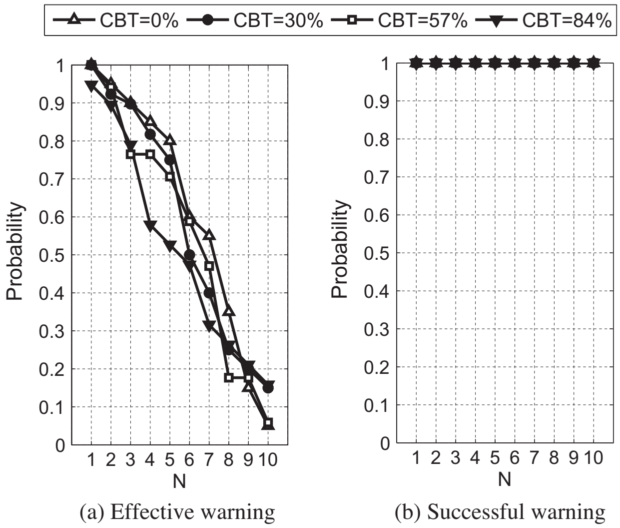


Fig. 21. ICW effective and successful warning probabilities for different channel load levels (P = 20 dBm, F = 10 Hz, R = 6 Mbps). Interfering node located at the intersection.

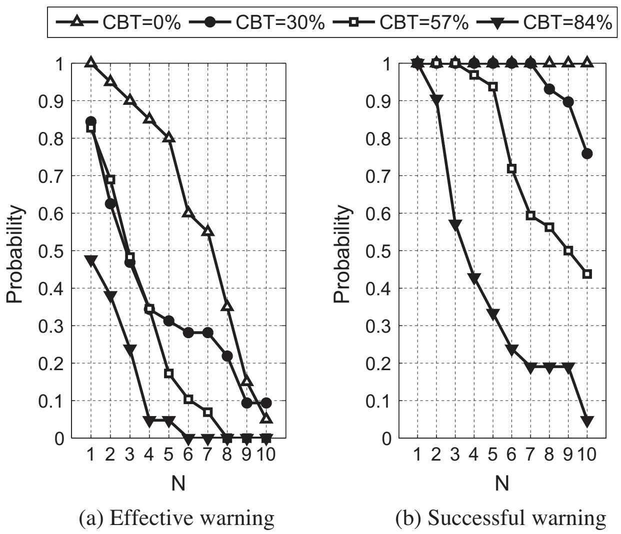
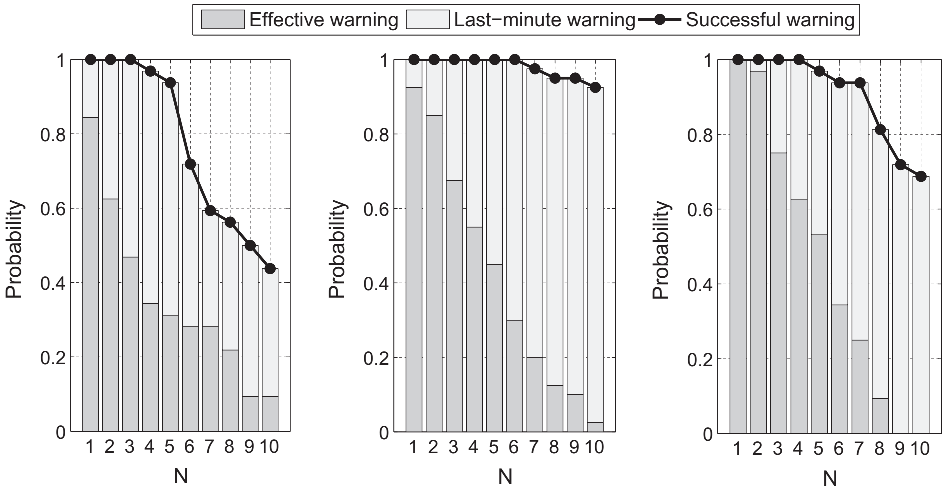


Fig. 22. ICW effective and successful warning probabilities (at vehicle A) for different channel load levels (P = 20 dBm, F = 10 Hz, R = 6 Mbps). Interfering node located at 95 m from the intersection, immediately behind the point at which vehicle A starts moving.

3.5. ICW testing for varying positioning accuracy levels

Recent advances in GPS receivers and positioning sensors have demonstrated that positioning and tracking accuracy can be improved. However, limited efforts have been made to analyze the importance/need for good positioning accuracy in order to ensure the effectiveness of cooperative active safety applications. Testing GPS receivers and cooperative active safety applications separately cannot provide reliable indications about the impact of positioning accuracy on the applications' effectiveness, in particular under adverse operating conditions. In this context, the implemented platform can be used to test the effectiveness of cooperative active safety applications with different GPS receivers (and positioning accuracy) and operating conditions. To demonstrate the importance of positioning accuracy to design efficient cooperative active safety applications, the implemented applications have been tested using two off-the-shelf GPS receivers with different positioning accuracy. To this aim, the experiments reported in Sections 3.3 and 3.4 considered the simultaneous use of two GPS receivers (Novatel SMART-V1-2US-PVT and Garmin 18x LVC, see Table 1), although only the positioning information acquired with the Novatel receiver was used for the performance evaluation in previous sections. This section exploits the information acquired with the Garmin receiver to analyze the impact of the GPS positioning accuracy on the ICW application's



(a) P=20dBm, F=10Hz, R=6Mbps (b) P=20dBm, F=20Hz, R=6Mbps (c) P=20dBm, F=10Hz, R=3Mbps

Fig. 23. ICW warning accuracy for CBT = 57%. Interfering node located at 95 m from the intersection, immediately behind the point at which vehicle A starts moving.

effectiveness. To this aim, the performance indicators measured with the Novatel receiver have been used as a reference, and have been compared with those achieved with the Garmin receiver.

Reducing the GPS receiver's accuracy and update frequency can result in the wrong identification of road hazards and warning zones. To evaluate if a road hazard or a warning zone has been successfully identified by the low performance Garmin GPS receiver, its results are compared on a per-packet basis with the results obtained with the reference Novatel GPS receiver. To this aim, for each experiment, the percentage of packets correctly identifying the road hazard was computed using the Novatel GPS receiver as a reference. To evaluate the correct identification of a road hazard, three mutually exclusive categories have been defined:

- Correct: this category represents the situations where a risk of collision is correctly identified despite the use of low accuracy GPS receivers.
- Missed: this category represents the situations where a dangerous situation is missed.
- False alarm: this category represents the situations where a false alarm is produced and there is no real risk of collision.

Fig. 24a depicts the overall average probability of correctly detecting a road hazard, and of false and missed alarms when using the low performance GPS receiver. False alarms would reduce the user acceptance due to inadequate warnings issued to the driver, whereas missed alarms would result in relevant warning alert not being shown to the driver. The figure also represents the 5% and 95% percentiles to illustrate the variability experienced during the conducted tests. It is interesting to note that the intersection collision hazard was correctly identified on average in more than 90% of the received packets. However, the figure also reveals that in some experiments, the percentage of received packets that correctly identified the intersection collision hazard decreased below 70% (illustrated as the 5% percentile of correct hazard detection), thereby reducing the ICW application's effectiveness. To evaluate the correct identification of the warning zone, different categories have been defined:

- Correct: this category represents the situations where the warning zone identified by the low performance Garmin GPS receiver matches with the warning zone detected by the reference Novatel GPS receiver.
- Farther/closer: this category represents the situations where the warning zone identified by the low performance GPS receiver is a warning zone at a farther/closer distance to the intersection than the zone identified by the reference Novatel GPS receiver.

In this context, identifying a farther zone can provoke dangerous situations due to the late issue of the warning to the driver (e.g. the system detects the vehicle in warning zone 3, but it is actually in zone 2). On the other hand, identifying a closer zone can generate too many early warnings that might distract the driver and minimize user acceptance. In this context, the early warnings produced by low performance GPS receivers could negatively impact user acceptance of cooperative applications. Fig. 24b shows the average probability of correctly identifying a warning zone, and the average probability of identifying a warning zone as farther/closer than the correct one. The obtained results show that the use of a low

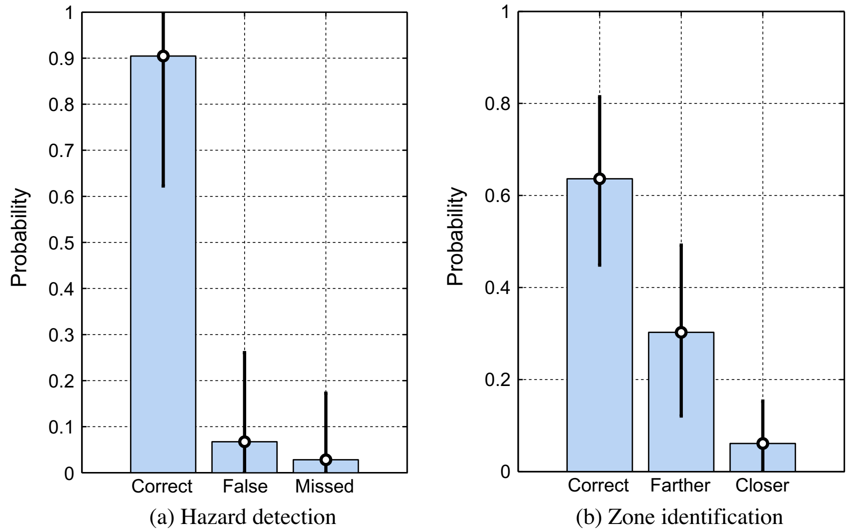


Fig. 24. Probability of correctly identifying road hazards and warning zones using a low performance GPS receiver.

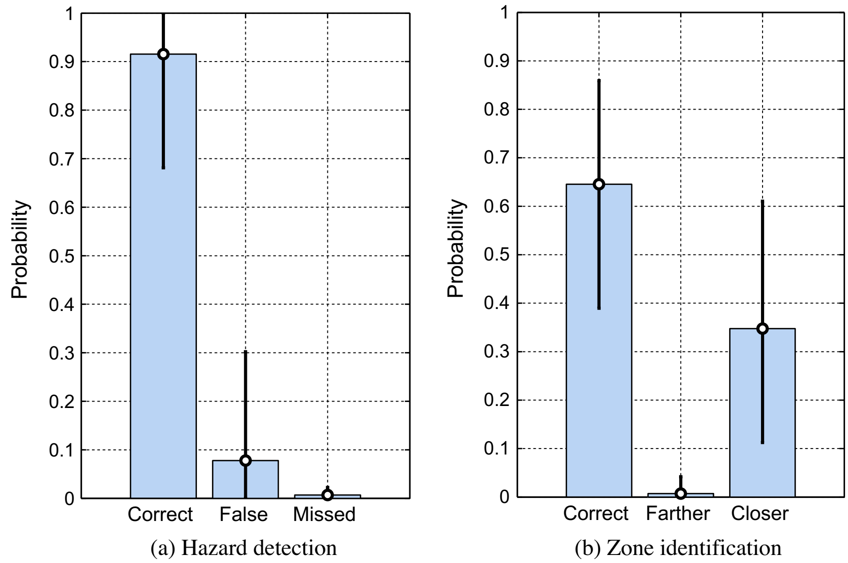


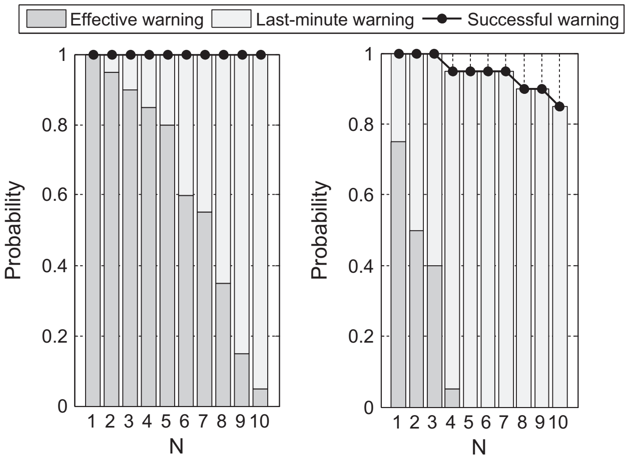
Fig. 25. Probability of correctly identifying road hazards and warning zones using a low performance GPS receiver with $GPS_a = 15$ m.

performance GPS receiver can provoke a relatively low probability of correctly identifying the warning zone (this probability was in average around 65%). Moreover, in around 30% of the tests, the warning zone identified was located at a farther distance than the actual one, which would degrade the ICW application's effectiveness.

To overcome the limitations exhibited by the low performance GPS receiver, a possible and very simple approach could be using the GPS positioning accuracy (GPS_a in Table 1) in the identification of road hazards and warning zones. In particular, the threshold used to identify a vehicle as a road hazard could be modified based on the GPS accuracy as follows:

$$\varepsilon = \frac{L_A}{v_A} + \frac{L_B}{v_B} + \frac{GPS_a}{v_A} + \frac{GPS_a}{v_B} \tag{7}$$

In addition, the length of warning zone 1 could be increased by GPS_a to reduce the percentage of cases in which the warning zone identified is at a farther distance than the actual one (zones 2 and 3 would also be displaced from the intersection by GPS_a). Comparing the results depicted in Fig. 25 using GPS_a, with the ones presented in Fig. 24, it can be observed that introducing GPS_a can decrease the number of dangerous situations thanks to the reduction of the probability of having missed alarms (Fig. 25a vs. Fig. 24a) and the identification of warning zones at farther distances than the correct ones (Fig. 25b



(a) Novatel, GPS_a=1.8m (b) Garmin, GPS_a=15m

Fig. 26. ICW warning accuracy for different GPS receivers (P = 20 dBm, F = 10 Hz, R = 6 Mbps).

vs. Fig. 24b). This positive effect is achieved at the expense of potentially decreasing user acceptance as a result of increasing false alarms (Fig. 25a) and the identification of warning zones at closer distances than the correct ones (Fig. 25b). In any case, it is also important to note that using the GPS_a parameter increases the distance to the intersection of warning zones, and thereby requires higher transmission ranges to reliably support the ICW application. Fig. 26 shows an example of ICW application performance experienced at two vehicles with different GPS receivers, and therefore different GPSa values; the figure has been obtained following the same approach as used for Fig. 25. As it can be observed, higher GPS_a values (i.e. lower GPS accuracy levels) in Fig. 26b decrease the effective and successful warning probabilities (the reduction is quite significant in the case of the effective warning probabilities). In this context, more sophisticated mechanisms to improve the GPS accuracy, or a reconfiguration of the communication settings would be needed to mitigate the ICW performance degradation.

4. Conclusions

This paper presents a cooperative V2V platform implemented to extensively test active safety applications under challenging driving and communication conditions. In addition, the paper reports the results of an extensive testing campaign of cooperative ICW and EEBL applications. Contrary to other studies reported to date, the cooperative applications have been tested under challenging conditions. To the authors' knowledge, the study reported in this paper represents to date the most comprehensive real-world experimental testing of cooperative active safety applications under challenging conditions openly released to the research and engineering communities.

The obtained results show that the applications can adequately operate under high speeds and good propagation conditions. However, the performance can be significantly degraded under NLOS propagation conditions. In this context, this paper has experimentally demonstrated that modifying the communication parameters (transmission power, packet transmission frequency and data rate) can help overcome this performance degradation. If these parameters need to be limited, for example due to congestion control, hardware restrictions or regulations, cooperative active safety applications might not be reliably supported under challenging NLOS propagation conditions, even at low vehicular speeds. Even when modifying the communications setting, the experiments conducted under NLOS conditions show that the applications' effectiveness can be compromised under high speeds, and more advanced solutions would be necessary, such as the consideration of advanced receivers with improved signal processing capabilities. The conducted study has also shown that interference, in particular when experiencing the hidden terminal problem, can significantly degrade the applications' effectiveness. In this context, the conducted experiments helped identifying maximum channel load levels that could be permitted by congestion control schemes to ensure the reliable operation of cooperative active safety applications. Modifying the communication parameters can also help partially overcome the degradation resulting from the presence of interference. However, more advanced protocols would be necessary in this case to avoid, for example, increasing the interferer's range as a result of the use of higher transmission power levels. The GPS positioning accuracy and update frequency have also been shown to have a significant impact on the hazard detection and warning zone identification, and thereby on the applications' effectiveness.

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