Intelligent V2I-Based Traffic Management System

Vicente Milanés, Jorge Villagrá, Jorge Godoy, Javier Simó, Joshué Pérez, Enrique Onieva

***Abstract*—Vehicles equipped with intelligent systems capable of preventing accidents as collision warning system (CWS) or lane-keeping assistance (LKA) are presently in the market. Next step in the reduction of road accidents is based on the coordination of these vehicles in advance for not only avoiding collisions but also improving the traffic flow. To this end, vehicle-to-infrastructure (V2I) communications are mandatory to manage properly traffic situations. This paper presents AUTOPIA approach toward an intelligent traffic management system based on V2I communications. A fuzzy-based control algorithm that take into account a safe and comfortable distance and speed adjustment of each vehicles in order to prevent collisions has been developed. A communication study based on IEEE 802.11p to validate the proposed solution is presented. The whole system has been tested in real scenarios both in simulation and with real vehicles with a good performance.**

***Index Terms*—Road vehicles, traffic control, data communication, vehicle-to-infrastructure communication, traffic management**

I. INTRODUCTION

Advanced Driver Assistance Systems (ADAS) have become an ideal tool to improve the safety in the roads and, at the same time, reducing the pollution and traffic jams dimension, heading to a greener and smarter driving. For example, the Adaptive Cruise Control (ACC) Systems based on radar technology [1], or the traffic warning signals using artificial vision [2]. However, in a common driving environment exists additional elements that must be considered as: vehicles, pedestrians, emergency vehicles, motorists, cyclists and so on. Bearing this in mind, a short-term goal is to design and implement cooperative systems based on communications that guarantee the information exchange between all these elements in a close environment.

Several solutions to this problem have been presented. Among them, US Department of Transportation promotes, under the IntelliDrive Initiative, the development of safety and mobility applications in order to identify possible crash scenarios and prevent drivers through visual or audio warnings opportunely. These applications are based on the communication standards defined for the Wireless Access in Vehicular Environments (WAVE): IEEE 1609 [3] and IEEE 802.11p [4]. WAVE systems are composed by three elements: The Road Side Unit (RSU), designed to be installed on traffic lights, signals and others road elements; the On Board Unit (OBU), designed to be mounted on the vehicles to guarantee the connectivity; and the Service Channels (SCHs), which allows bidirectional connectivity vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) [5].

In Asia, the Universal Traffic Management Society of Japan works on Driving Safety Support Systems (DSSS) that would prevent drivers about potential dangers on the road [6] [7]. DSSS are based on Dedicated Short Range Communication (DSRC) and infrared V2I communications. Several real tests proved the effectiveness of the first DSSS on intersections. Another important program is the Ubiquitous ITS initiative, included on the e-Japan Strategy. This program works on V2V communications systems using two RF channels: one for communications, in the band between 5811.5 and 5828.5 MHz, and the other one between 669 and 679 MHz for control signals [8]. In 2008, DENSO tested these systems in public roads of Abashiri, Hokkaido (Japan) in order to measure noise while vehicles are traveling.

In Europe, the Cooperative Vehicle Infrastructure Systems project (CVIS) aims to design and develop the elements to communicate vehicles and infrastructure in a continuous and transparent way based on the Communication Access for Land Mobiles ISO standard (CALM). This architecture allows V2V and V2I communications through various access technologies: 2G/3G cellular networks, Infrared, WiFi (IEEE 802.11 a/b/g) or WAVE [9]. In the same research line, the SAFESPOT project aims to improve the roads safety by merging the information incoming from vehicles and infrastructure and representing it on Local Dynamics Maps (LDMs) [10]. Based on the dynamic maps, the safety applications will be able to detect critical situations on advance, improving the response time. On the other hand, the Co-operative Systems for Intelligent Road Safety project (COOPERS) aims to keep continuous bidirectional V2I communications, allowing vehicles to exchange relevant data for a specific segment of the road in order to improve the safety and enable the traffic management [11] [12].

Since these cooperative applications are based on communications, it is necessary to study their performance under real critical conditions, where there is a considerable exchange of information through the network due to the high number of vehicles present in the near environment. In previous works, several experiments and simulations have studied diverse test scenarios: communications delays due the node number, channel noise, and the connection fail between nodes [13] [14] [15] [16].

In this paper, an intelligent V2I-based traffic management system is described. The goal is to coordinate the traffic in a limited urban area where different driving scenarios can coexist (see Fig. 1). A control station is in charge of evaluating

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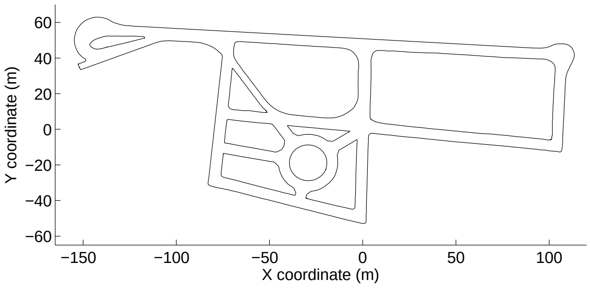

Fig. 1. AUTOPIA driving area

the traffic flow in order to prevent collisions in advance. To this end, a level of risk – that is, a collision probability – is sent to the vehicles with a recommended action to move the vehicle toward a safer state. Since communications play a key role for the operation of this system, an analysis to evaluate their requirements is carried out. The developed system has been tested not only in simulation but also in an experiment using real cars to check the performance of the V2I management system.

The remainder of the paper is as follows. Section II presents the problem description and the issues to be solved. Section III presents the data package specification and an analysis of the communication system to manage vehicles' information. Section IV describes the traffic management system implemented in the control station. The experiments and results are presented in section V, and some remarks and conclusions are given in section VI.

II. STATEMENT OF THE PROBLEM

Congestion in large cities is one of the major problem of transportation systems. Our approach attempts to give a response to this problem using control stations, each of them managing the traffic within its influence area. These stations should be coordinated in order to solve border problems. This section describes the missions to be accomplish by the local station and the requirements to divide each area. The goal of this paper is focused in an isolated local control area, the communications among different local control areas is out of the scope of this work. An idea of how to solve this problem is presented in [17].

Figure 1 shows a typical urban area, that will be used in the experimental phase, which includes a roundabout, T and X shape intersections, incorporations, 90^o bends, U-turns and straight stretches. A local control station capable of receiving all the information coming either from the infrastructure or the vehicles would be capable of carrying out an intelligent management of the traffic so as to prevent collisions. This station would be in charge of receiving and analyzing the information coming from the vehicles in order to send to each one a level of collision risk and a recommended action to prevent it. Taking into account the vehicle location, direction, speed and road layout, the control station is in charge of determining the collision probability.

Once the control station receives the information coming from the vehicles, its powers are:

TABLE I
PROPOSED COMMUNICATION DATA PACKAGES

Vehicle-to-Infrastructure	
Field	*Type (Size)*
Vehicle ID	Short (2B)
Timestamp	U Integer (4B)
Northing	Double (8B)
Easting	Double (8B)
Speed	Float (4B)
Reserved	X (6B)

Infrastructure-to-Vehicle	
Field	*Type (Size)*
Vehicle ID	Short (2B)
Speed warning	Short (2B)
Speed control	Short (2B)
Steering warning	Short (2B)
Steering control	Short (2B)
Reserved	X (6B)

- To classify the vehicles within the driving area.
- To identify stopped vehicles as obstacles.
- In straight stretches, to inform each vehicle about its vicinity, i.e. if exists any leading vehicle that affects to the actual speed and if it is possible to overtake it.
- In bend stretches, to inform in advance about the road layout.
- To manage each specific area using priority levels in function of the kind of vehicle to avoid potential collisions.
- To identify in advances risk traffic situations.

Assuming all vehicles equipped with a communication system, the problems to be tackled are: 1) Is the control station capable of managing all the vehicles that can be driving within its area of control? 2) How to manage the traffic in order to avoid collisions? Both questions are solved in the next two sections respectively.

III. V2I-BASED SOLUTION

As was previously stated, a control station is in charge of managing the information coming from the vehicles, processing this information and returning warning and recommended commands to the vehicles so as to improve the safety. Bearing this in mind, information exchange between the control station and the vehicles has to be as reliable as possible.

A. Data Structure

Two different data packages have been defined for the information exchange. Table I shows the fields to be sent and its size. From the vehicles to the infrastructure (see left part of Table I), five fields have been considered – identification number for each kind of vehicle; timestamp; vehicle positioning; speed and some reserved space for future variables that could be interesting to transmit, i.e. vehicle intention. From the infrastructure to the vehicle (see right part of Table I), the fields to be sent are the vehicle identification number; two next fields related to the longitudinal actions – i.e., throttle and brake pedals. The first one is in charge of sending a warning signal to the driver in function of the risk situation. The last one is responsible for sending a recommended speed to prevent the collision. This second field can autonomously act over the vehicle in case of it is equipped with automated actuators. The next two fields have the same function – warning and recommendation – but, in this case, over the lateral control – i.e., the steering wheel. Finally, some space has been reserved for future applications – i.e. road layout or weather.

B. Communication system analysis

The proposed intelligent traffic system is based on a reliable V2I communication system. The adopted solution and an analysis about its capacity to support the information exchange from the delays and packet-loss point of view are presented in this section.

The V2I-based intelligent management traffic system is based on WAVE for the V2I communications. WAVE is based on the IEEE 802.11p standard for PHY (physical layer) and MAC (medium access control), and on additional standards of the IEEE 1609 family that solve logical link control, multichannel management, security and other issues. IEEE 802.11p is an amendment to the IEEE 802.11-2007 standard that proposes EDCA (Enhanced Distributed Channel Access) for the MAC and a PHY similar to IEEE 802.11a but using channels of 10 MHz. EDCA defines four different traffic classes or ”access categories” that are given different priorities: AC_VO (Voice Access Category), AC_VI (Video Access Category), AC_BE (Best-Effort Access Category) and AC_BK (Background Access Category). Depending on the priority that a certain packet should have, it must be queued for the corresponding access category (see [18] for details). Another important characteristic of WAVE is the multichannel feature. There are several 10 MHz channels in the DSRC (Dedicated Short-Range Communication) band that can be used. One of them is the CCH (control channel) and the rest of channels are SCH. All the stations – vehicles – must listen to the CCH, where packets can be sent and received without any previous association, but only stations that have joined a WBSS (Wireless Basic Service Set) may exchange packets over an associated SCH. Time is slotted in 100 ms super-frames, and each one starts with about 50 ms of contention in the CCH, followed by a similar time in which stations belonging to a WBSS may exchange packets in a SCH. See [5] and [19] for good tutorials about WAVE.

Regarding the use of EDCA, Mora et al. [20] demonstrated that, under heavy load conditions – even using the traffic differentiation – real-time traffic may suffer from unacceptable packet loss and high delays. They also suggest that dynamic adjustments of the contention window size for all access categories can significantly improve the performance, which is further demonstrated by [21].

A scenario very similar to ours is studied by Bohm and Jonsson [22] but they avoid the contention for the channel by implementing a polling mechanism. As we will demonstrate below, standard EDCA can be enough for our application to handle critical traffic under heavy load conditions, but Bohm and Jonsson’s proposal would be reasonable in other more complex scenarios.

TABLE II
PARAMETERS FOR SIMULATIONS AND EXPERIMENTS WITH EDCA

Parameter	Value assigned
Channel width	10 MHz
MACHeader	232 bits
PHY Overhead	13 symbols ($8 \mu s/symbol$)
BasicBitRate	3 Mbps
BitRate	6 Mbps
Propagation Time	up to $2 \mu s$
SIFS	$32 \mu s$
Slot Time	$13 \mu s$
$AIFSN_0$ *(AC_VO)*	2
$AIFSN_2$ *(AC_BE)*	6
$AIFSN_3$ *(AC_BK)*	9
$CW_{min,0}$	4
$CW_{max,0}$	8
$CW_{min,2}$	16
$CW_{max,2}$	1024
$CW_{min,3}$	16
$CW_{max,3}$	1024
WSMP Header	11 bytes

Although the previous comments seem to show that EDCA may not be well suited for our application, the values proposed for EDCA parameters in 802.11p have a very special quality: when AC_VI access category is not used, AC_VO is not only highly prioritized, but also protected deterministically from any possible collision with AC_BE and AC_BK traffic, at least at the first transmission attempt. Even in case of collisions among AC_VO packets, retransmissions still get a very high priority. As far as the number of stations transmitting AC_VO traffic is kept low, delay and packet-loss are supposed to be kept under certain limits for that prioritized traffic no matter what happens with less prioritized traffic classes [22]. Hence, if only the RSU and very few vehicles at special situations – emergencies, breakdown vehicles and so on – are allowed to use AC_VO traffic, and AC_VI is generally not used, we will guarantee that vehicles always receive real-time packets from the infrastructure. The problem will be then how to keep delay and packet-loss probability under certain limits for uplink traffic, whose intensity depends on the number of vehicles within the coverage area.

For critical message dissemination, Eicher [23] suggests that a higher layer mechanism must be built on top of the WAVE stack in order to manage the network in such a way that the number of vehicles contending for the channel in this kind of scenarios never exceeds a certain limit that must be carefully measured. With this premise, we have assumed that all vehicles send packets as described in the previous section every 100 ms and then we have measured the number of vehicles beyond which delay and packet-loss grow too much. We have simulated our scenario with one RSU – traffic control station – and an increasing number of vehicles, delay and packet-loss have been estimated. WLS EDCA simulator has been used[1], respecting in all simulations the values of parameters as indicated in Table II.

The results of the simulations[2] clearly show (see Fig. 2) how RSU packets maintain the quality of service even with a very high number of vehicles, as expected. On the other hand, less prioritized traffic coming from vehicles keep low delays and insignificant collision probabilities only for less than 40 stations. Beyond that limit, as the number of vehicles generating traffic increases, the quality of service worsens very quickly.

These results imply that an application level mechanism

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[1] G. Bianchi and I. Tinnirello [18] developed the WLS simulator in order to have a simulator that exactly implements EDCA. WLS has been extensively validated by the authors and by other researchers

[2] RSU sending short AC_VO packets every 50 ms and a minimum of 20 vehicles sending AC_BE traffic

TABLE III
AVERAGE DELAY, STANDARD DEVIATION OF DELAY, AND PACKET-LOSS PROBABILITY FOR LESS PRIORITY TRAFFIC.

N. AC_BE flows *N. AC_BK flows*	20 0	40 0	60 0	20 20	20 40	20 60
AC_BE Delay (Mean)	213,00 μs	437,03 μs	1613,23 μs	408,45 μs	1111,8 μs	4975,35 μs
AC_BE Delay (Standard Deviation)	2,44 μs	14,69 μs	152,57 μs	9,49 μs	58,41 μs	142,32 μs
AC_BK Delay (Mean)	-	-	-	562,26 μs	2538,70 μs	32546,49 μs
AC_BK Delay (Standard Deviation)	-	-	-	19,71 μs	179,97 μs	335,89 μs
Packet-loss Prob.	0,000	0,000	0,000	0,000	0,000	0,364

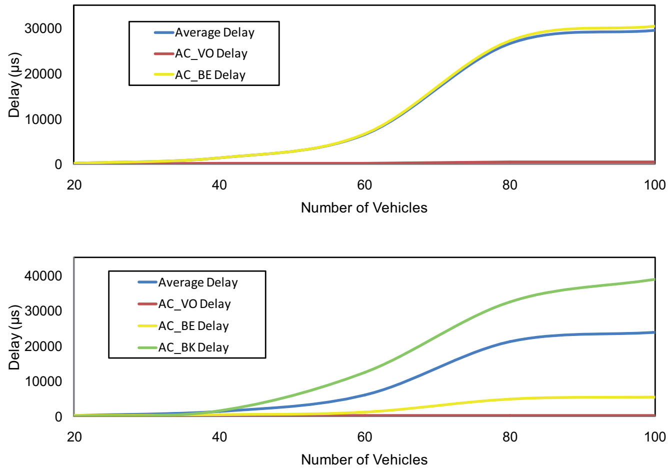

Fig. 2. (a) One RSU and a variable number of vehicles sending 1 packet/super-frame each (b) One RSU, twenty vehicles with AC_BE traffic and a variable number of vehicles with AC_BK traffic sending 1 packet/super-frame each.

that preserves a low number of stations contending for the channel for safety-critical traffic has to be proposed. This is not necessary at all for our experiment presented in the following sections, but the problem must be solved theoretically so that our proposals may be of general application. Considering WAVE specifications, the RSU can announce a WBSS (wireless basic service set) during the CCH so that stations can join it in a SCH just by internally deciding to do so. Invitations for the WBSS may be generally broadcast packets with information that permits the stations to decide whether to join it or not, or may also be unicast packets if necessary. As opposed to the CCH, traffic in the WBSS during the SCH comes only from the RSU and from those vehicles that have joint the WBSS. The packet protocol used in the CCH is WSMP (more suited than its alternative IPv6), and it would also be used for the WBSS for efficiency.

Hence, if the RSU invites certain vehicles during the CCH to join a safety-critical WBSS, either with broadcast packets or with unicast packets to certain vehicles, a limited number of vehicles may exchange traffic on the SCH without any interference from the rest of the vehicles. The high level application in vehicles is in charge of observing packets sent during the CCH informing about the coordinates and size of the critical area, and use those informations and their own coordinates to decide whether they must join the announced safety-critical WBSS in the SCH or not. Using this solution we are fully within the limits of the standards and, following our simulation results, packet drop probabilities and delays are kept under reasonable levels (see Table III).

Simulations results have also verified than the number of AC_VO transmissions may be ten times higher than expected or more without a significant increase in AC_VO packet-drop probability and delay. For up to 10 stations producing each one the same amount of traffic as the RSU, the packet-loss probability remains null and the average delay with up to 100 stations contending for the channel stays at 515 μs. This illustrates that our system tolerates the presence of some emergency vehicles in the area using AC_VO in the CCH with very low impact in the quality of service.

For the experimental part of this work that will be described in Section V, 802.11p has been hardware-emulated with 802.11a radios by adjusting as adequate several parameters (see Table II). However, due to the low number of vehicles involved in the experiment, old 802.11e EDCA, simple contention in the CCH or the complete solution proposed here are all of them valid solutions.

IV. TRAFFIC MANAGEMENT SYSTEM

Once the feasibility of the proposal has been shown from the communication point of view, the other question to be solved is how to avoid collisions.

The traffic control station has to manage all the information coming from the vehicles and, in function of the environment, returning a warning signal with the collision probability and a recommended action. A detailed description of its powers was presented in sec. II. One can appreciate the fields to be sent by the control station in the right part of Table I. For the sake of simplicity, this study is focused in the longitudinal actions so only recommended speeds are sent to the vehicles.

With these premises, the two bytes reserved – *Speed warning* and *Speed control* – are used to send the level of risk and the recommended speed for each car respectively. Specifically, the *Speed warning* signal is used to codify the level of risk between 0 and 100%. With respect to the *Speed control*, this field is in charge of sending the reference speed for each vehicle to prevent collisions. If the vehicle is equipped with automatic systems (ACC capabilities for the longitudinal control), this command can be automaticly applied.

A. *Management solution*

The main difficult arise from the fact that the control station has to be capable of properly managing all the traffic circumstances in a safe way. Our approach is based on recent results shown in [24], that was previously outlined by the partners of Advanced Transportation TecHnology (PATH) program – see Lu *et al.* [25], based on magnetic markers.

It consists on the projection of the vehicles over the same lane, independently in which driving situation they are involved, that is, all the vehicles are considered to be involved in a virtual adaptive cruise control (ACC). In this way, if four vehicles are approaching to an intersections, they are projected over the same lane and they are treated as a platooning so a recommended distance and speed are generated for each one of them. With this projection, both the level of risk and the recommended speed can be sent for each car. The same reasoning can be applied for any traffic situation – see [24] for details.

Bearing this idea in mind and once the priority for each car was assigned based in the Circulation Code or following a basic criteria on the part of the control station (transport vehicles have priority with respect to production vehicles), references – in speed and distance – can be generated by the management system both to generate the recommended speed and to be used as input for the control system.

B. Reference speed and distance generation

The goal of the traffic management system will be to coordinate vehicles to track as precisely as possible a reference distance between vehicles d_r and a target relative velocity v_r. A reference model proposed by [26] will provide these two variables (see [27] or [28] for recent implementations using such model).

The reference distance is related to the safe nominal interdistance d_0 -maximum distance at which the control algorithm will be activated-, and the critical distance d_c -minimum distance between cars, that is only attained when they are stopped. Note also that the dynamic reference model used in this work will provide a reference inter-distance lower than the classical 2 seconds distance rule, that is besides extremely complex to compute and handle at low speeds.

The inter-distance reference model is expressed as follows

$$\begin{aligned} v_r &= \frac{c}{2}(d_0 - d_r)^2 + \dot{x}_l(t) - V_{max} \\ \dot{d}_r &= v_r \end{aligned} \tag{1}$$

where $\dot{x}_l$ is the preceding vehicle speed, V_{max} is the maximum allowable speed and c is a design parameter. Equation (1) describes the dynamics of a virtual vehicle, which is positioned at a distance d_r (the reference distance) from the leading vehicle, and such that the following comfort and safety constraints are fulfilled:

- $d_r \geqslant d_c$, with d_c the minimal inter-distance.
- $|\ddot{x}_r| \leqslant \gamma_{max}$, where γ_{max} is the maximum attainable longitudinal acceleration.
- $|\dddot{x}_r| \leqslant J_{max}$, with J_{max} a bound on the driver desired jerk.

Note that this reference velocity depends upon the leading vehicle, distance d_0 and parameter c, which is, in turn, an algebraic function of safe and comfort parameters d_c, V_{max}, γ_{max} and J_{max} [26].

C. Level of risk

To evaluate the traffic situation, a fuzzy traffic management system has been developed. Fuzzy logic is considered a good control technique in case of treating with systems whose definition is not very precise and has been widely applied in industrial applications in recent years [29]. In this case, the control station has to advise the driver about future possible risk situation but, how much level of risk in each case?

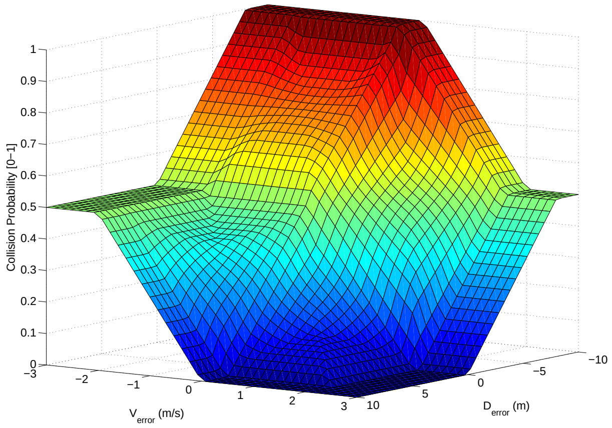

Fig. 3. Control surface to evaluate the level of risk

Considering the information available in the control station, the actual and reference distances between vehicles and the actual and recommended speeds for a vehicle involved in a risk situation are known. So the errors in both the distance (D_{error}) and the speed (V_{error}) are used as inputs for the fuzzy controller. As output, the level of risk is sent to the vehicles. The output of the controller is codified using three singletons located at 0, 0.5, and 1, representing respectively, collision probability of 0, 50 and 100%.

Note that the described system has been developed to be applied in urban environments so the maximum allowed speed is set at $50km/h$. Taking into account errors – with respect to the reference distance and speed – are evaluated to determine the level of risk, three symmetrical triangular membership functions are defined for each one of the input variables. For the speed, triangles have the centers situated at -2, 0 and 2 m/s, representing membership functions named $High$, $Moderate$ and Low risk probability. In the same way, triangles defined to codify the distance have centers at -8, 0 and 8 m, named as the previous one ($High$, $Moderate$ and Low risk probability). Values outside the range (± 2 for the speed and ± 8 for the distance) have degree of membership one for the correspondent membership function. The control surface generated by the fuzzy controller is shown in Fig. 3.

The fuzzy traffic management system implemented in the local control station is designed to follow the Circulation Code. Under special circumstances, Circulation Code can be neglected. It is widely accepted than emergency services – like ambulances – have the highest priority [30]. Then, public transport systems – buses and taxis – have the priority in case of conflicts [31], [32]. So, for non-signalized areas this convention will be followed.

V. RESULTS

Some test results both in simulation and in real environments are presented in this section. For these tests, an intersection has been selected as region of interest since it represents the most difficult scenario in which the V2I-based traffic management system has to work. A scenario in which four vehicles are coming simultaneously to the intersection is analyzed. Assuming the intersection is not signalized and three production vehicles and a bus are approaching to the crossroad, the highest priority is assigned to the bus and the priority of the rest of the vehicles are assigned following the Circulation Code. Concerning the communication system for this scenario, Table IV shows the communication system behavior in each case, including collision and packet-drop probabilities.

TABLE IV
COMMUNICATION RESULTS FOR THE SIMULATION AND REAL EXPERIMENTS

	4 vehicles
Service Time (mean) [us]	482.19
Service Time (std) [us]	85.76
Service Time (min) [us]	424.67
Service Time (max) [us]	1336.91
Collision probability	0.002
Packet-drop probability	~1E-019

A. Simulation experiment

The traffic management system has been implemented on a simulator, where four vehicles dynamics will be recreated using a dynamic model detailed in [33]. The same longitudinal PI controller -$K_p = 0.3$ and $K_i = 0.1$- is used in each vehicle to track the desired speed. In each vehicle, GPS positioning and vehicle measurement are artificially perturbed with a white Gaussian noise. Moreover, the sampling rate is constrained by the GPS frequency ($T_s = 0.2$s).

Besides, variables x used in V2I communications are modeled as

$$x(t_k) = x(t_k - \tau) + u(t_k),$$
$$\begin{cases} u(t_k) = -x(t_k - \tau) + x(t_{k-1} - \tau) \text{ if } p(d < d_c) \\ u(t_k) = 0 \text{ if } p(d \geqslant d_c) \end{cases} \qquad (2)$$

where τ is the service time, d is the packet drop probability and d_c is the critical value, whose values are detailed in table IV.

To illustrate the algorithm's ability to evaluate the collision risk of each vehicle, a scenario where 4 vehicles approach to a X-shape intersection has been implemented. In the simulated experiment, all four vehicles will track a straight line path, starting at similar distances to the intersection point. As a consequence of this, the traffic management system must handle not only the priority order, but also the way each vehicle safely crosses the intersection. Therefore, a recommended speed and distance to the preceding vehicle has to be provided to the 3 vehicles following the public bus -the one with the highest priority.

The first vehicle is running at a constant speed –10 km/h, the second one tracks the desired velocity sent by the control station; the third vehicle simulates an aggressive manual driving, such that the vehicle speed is always over the reference. Finally, a fourth vehicle always runs under the target speed, so that a conservative manual driving is emulated.

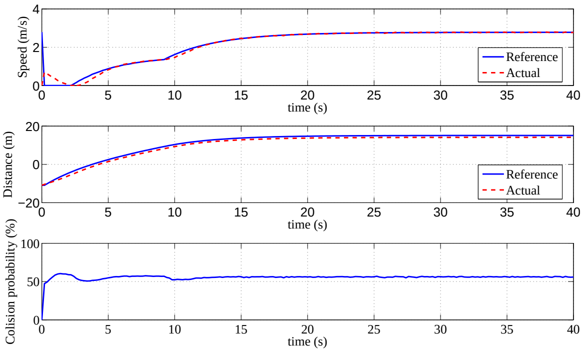

Fig. 4. Second vehicle with right-of-way approaching to the intersection. Simulation results

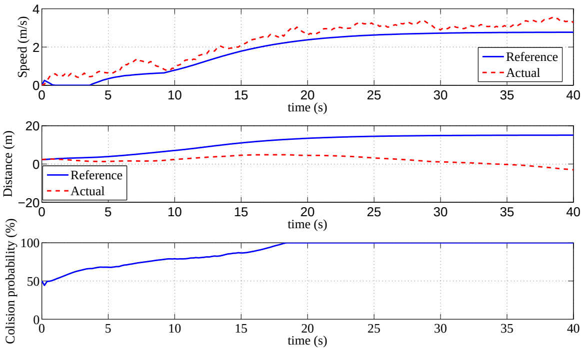

Fig. 5. Third vehicle with right-of-way approaching to the intersection. Simulation results

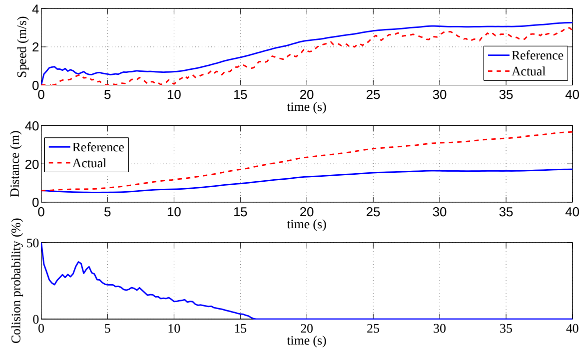

Fig. 6. Fourth vehicle with right-of-way approaching to the intersection. Simulation results

Figures 4, 5 and 6 show the evolution of speeds and distances between vehicles -both the reference and actual values- for the second, third and fourth vehicles. Remark that in Fig. 4, the vehicle is driving autonomously and speed and distance targets are correctly tracked. As a result of this, the risk of collision is quasi-constant around a value of 50%. This

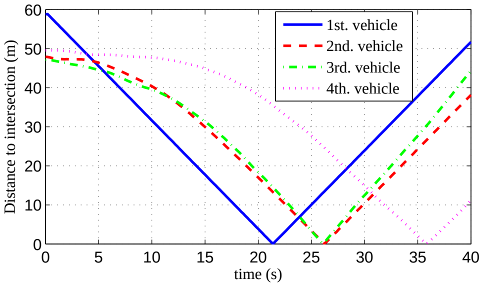

Fig. 7. Distance to the intersection point for each vehicle. Simulation results

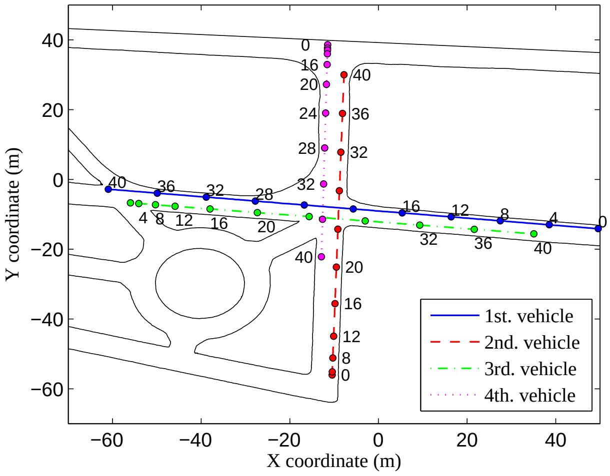

Fig. 8. Vehicles' positions in the simulation

value can be seen as the best trade-off between security and a smooth traffic flow.

In Fig. 5, the recommended speed is always exceeded, so that tracking distance error monotonically increases until the vehicle crashes its predecessor. This situation is reflected in the bottom plot of this graph, where the collision probability is estimated at 100% from instant $t = 18$ s, 5 ahead the real collision instant – see also Fig. 7. Finally, Fig. 6 shows that the conservative behavior of the last vehicle leads to a risk of collision equal to 0 from instant $t = 15$. In this respect, Figures 7 and 8 show that while the first 3 vehicles end their maneuver at a considerable distance of the intersection point, the last one has scarcely passed trough it.

The evolution of the four vehicles is plotted on Fig 8, where the crash between the second and third vehicle can be easily deduced.

B. Real results at a crossroad: a case of study

The trials using real vehicles were performed in the private driving circuit at the CAR's facilities (see Fig. 1). The central intersection was used. Since only four vehicles are available for this test, the input coming from the roundabout is neglected. The goal of this test is to evaluate in a real environment how the control station is capable of managing a traffic situation in which four vehicles coincide in a crossroad.

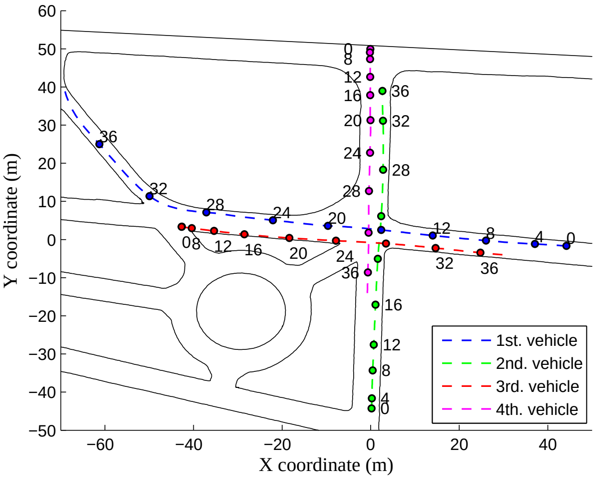

Fig. 9. Vehicles' positions during the experiment

1) Description of the vehicles: Four different vehicles were used. Two fully-automated gas-propelled production cars – one of them a convertible, an electric van and an electric minibus were used. To make the experiments as close as possible to vehicles in the market, only warning signals are allowed and the drivers – via a head-up display – can monitored the collision probability and recommended speed. Details about vehicles' equipment and facilities can be found in previous works [34], [35], [24], [36].

2) Experimental results: The real scenario is identical to the one presented in the simulation results. Figure 9 shows the evolution of the vehicle during the experiment and the distance of each vehicle to the cross point is represented in Fig. 10.

Since the electric minibus has the right-of-way, information about traffic circumstance is neglected for this vehicle. Figures 11, 12 and 13 show the evolution of the second, third and fourth vehicle, respectively, approaching to the crossroad. The upper plot shows the actual speed – dashed line – and the reference speed – solid line. The middle plot depicts the actual distance between each vehicle and its leading car – dashed line– and the reference distance with respect to that car – solid line. The lower plot shows the collision probability, that is, the level of risk in real time – this value is shown in the head-up display.

All the vehicles are started at the same time and at the same distance with respect to the intersection. From that moment, the drivers try to follow the reference speed that is shown in the head-up display. One can appreciate how the second vehicle starts with a speed higher than the reference velocity and the collision probability is significantly increased. Close to second 2, the speed is readjusted and the collision probability is reduced. During the rest of the experiment, the risk of collision remains under 50% so as to advise the driver about another vehicle is approaching to the crossroad with right-of-way.

Behavior of third and fourth vehicles are similar to the second vehicle. Once the drivers are capable of tracking the

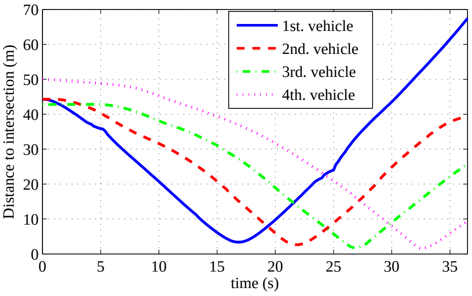

Fig. 10. Distances of the vehicles to the cross point

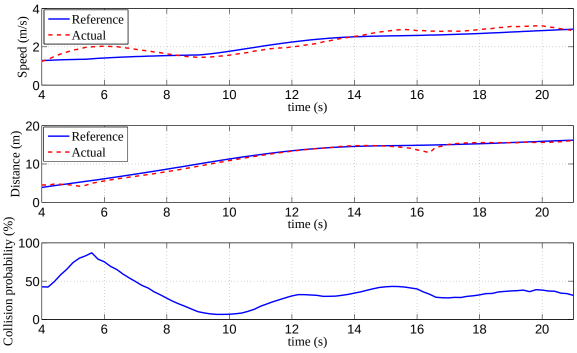

Fig. 11. Second vehicle with right-of-way approaching to the intersection

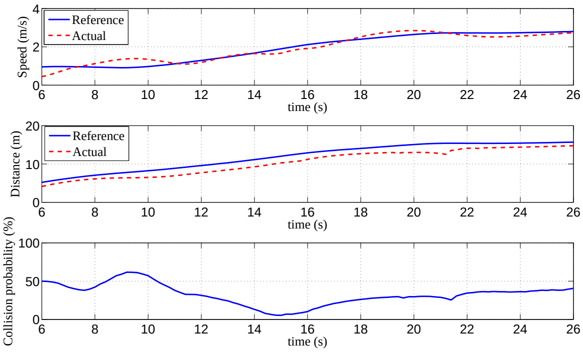

Fig. 12. Third vehicle with right-of-way approaching to the intersection

reference speed, the risk of collision is lower than 50%, specially if the vehicle's speed is lower than the recommended one and the distance to the leading vehicle is higher than the reference one.

Numerous trials were performed to evaluate the behavior of the controller in case of sudden acceleration and/or deceleration of the vehicles involved in the maneuver and, in all the cases, the level of risk was properly estimated.

VI. CONCLUSION

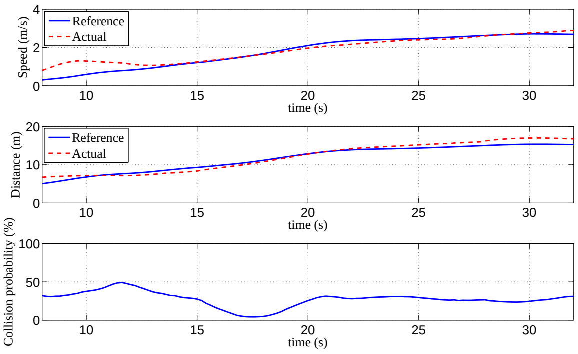

Fig. 13. Forth vehicle with right-of-way approaching to the intersection

We here present a V2I-based traffic management system with a twofold goal. On one hand, our approach proposes a solution to regulate traffic flow in urban areas where different bottleneck areas can coexist. Secondly, it advices in advance about possible collision that can occur so as to prevent accidents.

An intelligent control system based on a reference safety distance and an adequate speed are used as fuzzy inputs for the controller. As output, the risk of collision is sent to the vehicles. For the sake of simplicity, only longitudinal actions are advised in this communication.

The system has been tested in both simulation and real test tracks showing its good performance. This work constitutes a starting point for a complete fully-traffic control system. Authors want to remark that this paper present the first result involving four real vehicles at an intersection and how to manage them. As future works, new challenging scenarios including traffic lights control and lateral maneuvers will be studied.

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