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A fuzzy aid rear-end collision warning/avoidance system

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ABSTRACT

To decrease traffic accidents is a declared target of Intelligent Transportation Systems (ITS). Among them, rear-end collisions are one of the most common and constitute one of the as yet unsolved topics in the automotive sector. This paper presents an approach to the avoidance of rear-end collisions in congested traffic situations. To this end, two fuzzy controllers, a Collision Warning System (CWS) and a Collision Avoidance System (CAS), have been developed. The former is in charge of alerting the driver in case of an impending rear-end collision to prevent or mitigate the crash. The latter is in charge of generating an output control signal for the steering wheel in order to avoid the collision. Both CWS and CAS have been tested with real cars using vehicle-to-infrastructure (V2I) communications to acquire data of vehicles. A system installed in the infrastructure capable of assessing road traffic conditions in real time is responsible for transmitting the data of the vehicles in the surrounding area. The systems have been tested at the Center for Automation and Robotics (CAR)'s facilities with two mass-produced cars.

1. Introduction

Steering distractions on the part of the driver are one of the major causes of road accidents (DGT, 2009). Since driver's attention capacity plays a key role in the steering wheel management, a system capable of aiding the driver, would reduce significantly these accidents. Automatic steering wheel management constitutes a good option to face this problem. Presently, implementation of full automatic-steering control is one of the hardest disciplines in the intelligent-vehicles field, and perhaps has a long way to go before it comes to market (Dickmanns, 2002; Vahidi & Eskandarian, 2003). Among its possible applications, to prevent vehicle-to-vehicle collisions using steering avoidance maneuver is a very challenging topic in this field.

Vehicle-to-vehicle collisions can be classified as head-on crash, lateral impact, and rear-end collisions. The reduction in the number of two-way roads in Europe is causing rear-end collisions to occur with ever greater relative frequency. In Spain during 2008, for example, 44.3% of road accidents were rear-end collisions (DGT, 2009).

In order to reduce the number of accidents due to rear-end collisions, there have been important advances in the development of Collision Warning Systems (CWS). A model of human driving behavior focusing on the driver's collision avoidance maneuver was presented in Kim et al. (2005). Hillenbrand, Spieker, and Kroschel (2006) developed a multilevel collision mitigation approach to obtain a solution for the decision-making problem in rear-end collisions. A longitudinal controller using terminal sliding mode with hierarchical structure in order to minimize the safety distance error and regulate the relative velocity between two vehicles was proposed for rear-end collision avoidance in Kim, Park, and Bien (2007). In a parallel line of work, vision-based systems have been developed in order to detect a potential collision situation (Chang, Tsai, & Young, 2010). Other studies have focused on the use of laser scanners, as in Kaempchen, Schiele, and Dietmayer (2009) where a collision prediction algorithm was presented based on assessing the situation as a function of Kamm's circle. A cooperative CWS (CCWS) is presented in Sengupta et al. (2007) where five vehicles were equipped with wireless communications and global positioning systems (GPS) to know the locations and motions of all the neighboring vehicles so as to evaluate the proposed solution. Finally, Santa, Tolelo-Moreo, Zamora-Izquierdo, Übeda, and Gömez-Skarmeta (2010) presented a deep analysis about communication and navigation technology for Collision Avoidance Support Systems (CASS).

A subsequent step in rear-end collisions avoidance research was the development of automatic Collision Avoidance Systems (CAS). In this line, Adaptive Cruise Control (ACC) systems with collision avoidance capabilities using an adimensional warning index and the Time-To-Collision (TTC) were developed in Moona, Moon, and Yi (2009), where a commercial brake-by-wire system was installed in the vehicle in order to actually perform the rear-end collision avoidance. Sudeendra Kumar, Verghese, and Mahapatra (2009) implemented a CAS in an electric scaled-vehicle using a high-level protocol controller area network (CAN). The braking system of the scaled-vehicle was controlled through fuzzy logic. Vehicle collision avoidance simulation using a reactive multi-agent system in which

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agents interact with each other and the obstacles situated in the environment by using physics-inspired behaviors was presented in Yang, Gechter, and Koukam (2008). Finally, Labayrade, Royere, and Aubert (2007) developed a CWS based on stereovison sensors and laser scanners. When a warning message was received, a pressure command of 90 bars was applied on vehicle's brakes.

While braking is the last response in case of an imminent collision, if the risk is detected in advance the collision should be safely avoided by a steering change. This maneuver can be incorporated both to Lane-Change maneuvers (Naranjo, Gonzalez, Garcia, & de Pedro, 2008; Pérez, Milanés, Alonso, Onieva, & de Pedro, 2010a) or Lane-Departure Avoidances (Enache, Mammar, Netto, & Lusetti, 2010), but given the situation of a potential collision, the steering avoidance maneuver is more critical and more complicated than an autonomous lane-change. In this sense, an interesting study was developed in Chang and Tang (2001), which shows different strategies for drive assistance in emergency situations.

Some real applications have been implemented in collision avoidance systems. Choe, Hur, Chae, and Park (2008) use a laser range finder mounted on an experimental autonomous vehicle in an open area for the early detection of any obstacle, followed by modification of the path-plan to avoid the collision, and using a fixed safe distance of 1 m and its maximum speed is 10 km/h. Eidehall, Pohl, Gustafsson, and Ekmark (2007) developed an emergency lane assist (ELA) system to prevent dangerous lane departure maneuvers. It was mounted on a Volvo V70 equipped with forward-looking radar – for adaptive cruise control applications – and a vision system – for the lane tracking and vision-based object detection. A vehicle and steering wheel model designed to perform avoidance maneuvers was presented in Eskandarian and Soudbakhsh (2008). The effects of changing the initial velocity and the distance to the obstacle on the deviations from the desired trajectory were studied with different controllers.

Other applications, in the framework of Safety Warning Systems (SWS) have been developed with Interactive Intelligent Driver-Assistance and Safety Warning (I2DASW) and implemented in a real platform (Cheng, Zheng, Zhang, Qin, & van de Wetering, 2007) focusing on the sensor redundancy problem.

In the present study, an aid rear-end collision warning and avoidance system was evaluated and tested with real cars on a private circuit. Two fuzzy controllers were developed to implement the warning system – the trigger for the CAS and the avoidance controller. The autonomous vehicle – a convertible Citroën C3 Pluriel – receives data from the surrounding vehicles through a wireless network. The avoidance controller is responsible for taking the best action as a function of the traffic conditions, executing the avoidance maneuver in a rear-end collision risk situation.

The main contribution of this paper is the development of an aid system capable of detecting a rear-end collision situation and performing an avoidance maneuver, tested using mass-produced cars. Since CWS have been widely developed in recent years, to the best of our knowledge, the combined CWS/CAS in real roads – with real vehicles – has been not yet faced. The CAS controller is designed to perform the maneuver as soft as possible optimizing the TTC using fuzzy logic. Future trends point at wireless communications as system to detect and prevent accidents (Belanovic et al., 2010). In this sense, the data from the vehicles are acquired using a V2I system.

The structure of the paper is as follows. Section 2 describes the problem and the variables considered for the collision warning and the avoidance system. The vehicle-to-infrastructure (V2I) based communication system is presented in Section 3. The control algorithm based on fuzzy logic designed to activate the avoidance system and manage the steering wheel are described in Section 4. Section 5 describes the real cars used in the demonstrations, and the different trials at the CAR-CSIC driving circuit performed to show the feasibility of the aid system. Finally, Sections 6 and 7 presents the discussions and conclusions drawn from the results, respectively.

2. Problem description

A rear-end collision avoidance maneuver is an emergency action involving rapid movement to negotiate an obstacle. This movement can be either a steering change or hard braking. The former can be applied when the detection is made well in advance. The latter is the last solution in case of an unavoidable accident to mitigate its consequences. The present work focuses on the former case, assuming that the detection system provides recognition of the risk situation with sufficient time.

This maneuver can be divided into two steps. First, detecting the risk situation – CWS is in charge of this function. Second, performing the aid maneuver – CAS is in charge of this function. In the present study, we also seek smoothness in the steering wheel changes so as to allow the car's occupants maximum comfort.

Two situations may cause an emergency avoidance maneuver: following under ACC when there occurs sudden braking on the part of the leading car, or distraction of the driver leading to a rear-end collision situation. In order to avoid a possible accident, an activation signal has to be sent either to be shown on a display or – as in our case – to act automatically on the vehicle. Different methods have been implemented to achieve this goal. The typical parameter used to activate a CWS is the Time-To-Collision (TTC) estimate based on vision (Gormer, Muller, Hold, Meuter, & Kummert, 2009), radar (Anderson, Akdeniz, Banks, Renton, & Avery, 2009), or V2V communications using differential GPS (DGPS) (Kavitha, Bagubali, & Shalini, 2009; Tan & Huang, 2006; Ye, Adams, & Roy, 2008). Our proposal is based on the combination of TTC with the control parameter for ACC systems: the Time Gap (TG) between vehicles (Naranjo, Gonzalez, Garcia, & de Pedro, 2007). These variables permit the switching from an ACC action to rear-end collision avoidance. Once the system has been activated, the aid maneuver is executed.

Let us consider a general case in which two vehicles are driving in the same lane – the center lane (see Fig. 1) – along a straight stretch of a three-way road, or a two-way road with a wide hard shoulder. Since steering actions are permitted either to the right or to the left lane, all possible trajectories have to be considered and various parameters have to be taken into account in order to perform a safe rear-end avoidance maneuver:

- W_t indicates the width of the trailing car – the autonomous vehicle, in meters.
- W_l indicates the width of the leading car – the manually driven vehicle, in meters.
- D denotes the distance between the vehicles, in meters.
- L_d is the distance between the central axes of both cars. It is called the lateral distance and is measured in meters. It is determined in real time using the GPS positioning as shown in Fig. 1.
- S_{Ld} is a safety lateral distance. This constant measures the minimum acceptable gap between adjacent parts of the leading and trailing cars when $D = 0$, in meters.

The lateral displacement the trailing car is required to do to execute rear-end collision avoidance can be defined as

$$S_m = L_d - \frac{L_d}{|L_d|}\left[S_{Ld} + \frac{W_l + W_t}{2}\right] \quad (1)$$

where S_m is the displacement the trailing vehicle needs to perform the maneuver with success, in meters. Since W_l, W_t, and S_{Ld} are

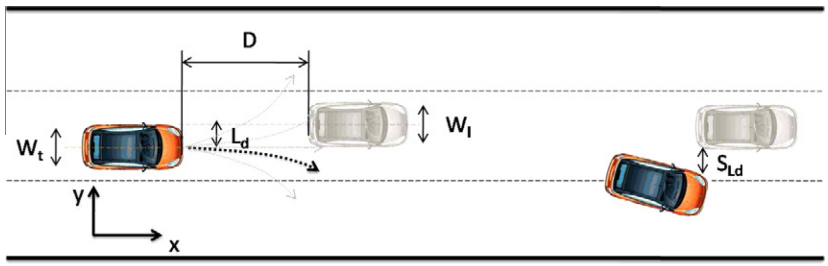

Fig. 1. Rear-end collision avoidance scenario.

constants, the action on the steering wheel depends on L_d. This value has to be re-calculated dynamically – using Universal Transverse Mercator (UTM) coordinates obtained via GPS receivers of both cars – in order to determine the best movement to achieve avoidance of the collision and maintain maximum comfort for the car's occupants. The least favorable condition – maximum steering wheel movement – occurs when the two vehicles are aligned: $L_d = 0$. In any other case, $L_d/|L_d|$ determines whether the avoidance maneuver has to be performed either to the right or to the left.

3. V2I communication system

Wireless communication systems have been extensively used for cooperative maneuvers among cars such as ACC (Yoshinori & Yoji, 2006), Stop & Go (Naranjo et al., 2007), overtaking (Naranjo et al., 2008), intersection management (Milanés, Pérez, Onieva, & González, 2010d), and CWS (Tan & Huang, 2006), showing that it is well-suited to a wide range of real traffic situations. Due to the number of solutions presented until now, the wireless vehicle communications represents a research line by its own. As a matter of fact, the IntelliDrive initiative in the United States and the Car-to-Car (Europe) are working and promoting the development of safety applications for cooperative intersections collision avoidance (CICAS), blind spot warning, automatic merging or platooning. In the present work, a V2I communication system is proposed with a local control station (LCS) that is responsible for receiving all the sensorial information coming either from the vehicles or the infrastructure, and sending the relevant information to each of the elements in the surrounding area.

In the field of vehicle safety communications (VSC), significant advances are being made worldwide. In 2006, the United States Department of Transportation defined the IEEE 1609 Family of Standards for Wireless Access in Vehicular Environments (WAVE). This standard comprises three main elements: the On Board Unit (OBU), the Road Side Unit (RSU), and the WAVE interface. Based on this principle, a communications model, management structure, security mechanisms, and physical access for wireless communications in the vehicular environment were developed. In a parallel line of work, that Department proposed an architecture for the development of Intelligent Transportation Systems. This defines four main components (travelers, centers, vehicles, and field) that are interconnected through four types of communication.

In the European Union, the Intelligent Car Initiative includes the e-safety initiative. The main goal is to achieve Intelligent Vehicle Safety Systems (IVSS) that use information and communication technologies to increase road safety and reduce the number of accidents on Europe's roads. The Co-operative Systems for Intelligent Road Safety (COOPERS) project (Piao & McDonald, 2008) is part of e-safety. Its aim is to improve the safety of a road by directing and updating the communication of the information of traffic between the infrastructure and the vehicles in a section of the road. To this end, it evaluates the different communication technologies that can be applied to V2I bidirectional communication. As part of the EU's 6th Framework Program (FP), the Co-operative Vehicle-Infrastructure Systems (CVIS) project (Singh, Singh, Langan, & Kumar, 2004) had the goal of specifying a communication architecture and a set of applications for Vehicle–Road and Vehicle–Internet communications. This architecture is based on the ISO standard CALM architecture. Another project with a similar focus on the same line is the 'Smart Vehicles on Smart Roads' (SAFESPOT) project of cooperative systems for road safety (Vivo, Dalmasso, & Vernacchia, 2007) aimed at studying how vehicles and intelligent roads can cooperate to enhance safety. The objective is to develop an assistant that anticipates accidents by detecting dangerous situations beforehand, and providing help in time and space to drivers in its environment. The assistant is a cooperative system based on V2V and V2I communications.

These architectures are too ambitious for implementation by our research group, so that we designed and developed a reduced system concordant with the characteristics of the driving circuit – of less than 300 m in length. The physical implementation uses a WiFi network to receive the vehicles' information and a Zigbee network to receive the infrastructure's data (see Fig. 2) (Milanés et al., 2010c). Thus, the LCS receives information from:

Infrastructure, to indicate emergency situations such as the road being blocked, implemented through wireless sensor networks.
Vehicles, to receive the parameters that have to be taken into account to perform cooperative maneuvers.

Since the goal is to develop a rear-end collision avoidance system, the infrastructure information is beyond the scope of the present work. For the present purposes, therefore, the V2I-based communication system is only responsible for informing the autonomous vehicle about the position, speed, and width of the

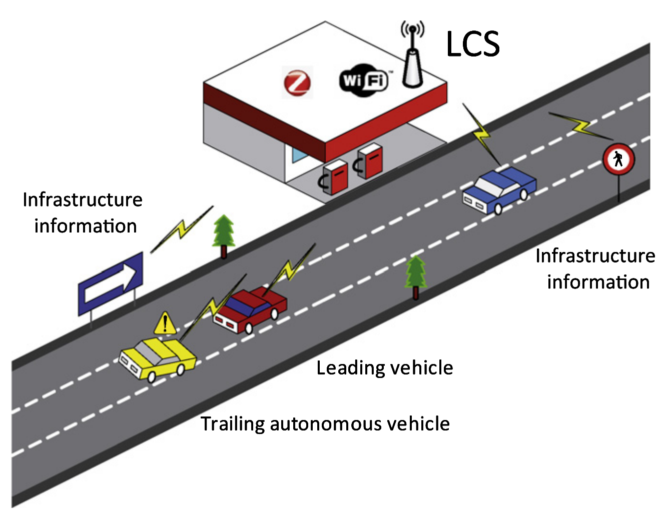

Fig. 2. The V2I communication system.

vehicles in its close environment. In accordance with the scheme shown in Fig. 1, the LCS will send information on which lanes are available to the autonomous vehicle for it to perform an avoidance maneuver. The trigger of the maneuver and the control algorithm are executed by the autonomous vehicle's on-board PC.

4. Control system

The control system to implement the aid maneuver is on board the vehicle. Two fuzzy controllers were developed, one for detecting a possible collision situation (CWS) and the other for performing the avoidance maneuver (CAS). The former is responsible for generating the collision warning signal so as to warn the driver via human–machine interface (HMI), and the latter generates the output control signal to manage the steering wheel in order to avoid the rear-end collision. That is, the CWS triggers CAS. Fig. 3 shows the relationship between both controllers.

Fuzzy logic was selected as the control technique because it is a well-tested method for dealing with this kind of system, provides good results, and can incorporate human procedural knowledge into control algorithms (Castro, Delgado, & Medina, 2011; Ganji & Kouzani, 2011). Also, it allows the designer to partially mimic human driving behavior. The min–max system was chosen to implement T-norm and T-conorm because of its computational ease. The inference engine used is Mamdani-type.

In order to determine the value of the variables needed to perform the maneuver, a reference system is defined in the autonomous vehicle – the trailing vehicle – with the x-axis along the direction of longitudinal movement of the vehicle and the y-axis is anticlockwise perpendicular to it (see Fig. 1). The position values received from the leading vehicle were transformed to refer to this coordinate system.

4.1. Trigger

Two variables were considered to trigger the rear-end Collision Avoidance System. The first is the Time-To-Collision (TTC), which is the time would take the cars to collide at their current speed. This is defined as:

$$TTC = \frac{D}{v_t - v_l} \tag{2}$$

where D is the distance between the vehicles – obtained via GPS positioning, and v_t – obtained from the CAN bus using a CANCard – and v_l – calculated reading the signal coming from the speedometer with a pulse counter card – are the speeds of the trailing and leading cars, respectively.

The second is the time gap (TG) that is the time it would take the trailing car to cover the current distance to the leading car. Time gap is introduced because as far as TTC is concerned, it only considers relative speed between vehicles. The time gap is introduced to permit the controller take into consideration the speed at which the maneuver occurs. It is defined as

$$TG = \frac{D}{v_t} \tag{3}$$

These two variables are used as inputs to the CWS fuzzy controller which generates the trigger of the CAS. The output of this controller will be a value in the interval [0,1] where 0 indicates no collision risk and 1 that a collision has already happened.

The upper part of Fig. 4 shows the membership functions for the TTC. The *Critical* linguistic label indicates a close collision situation while the *Soft* linguistic label indicates safe situations. The membership functions have been defined as symmetric, and the cross point is fixed at 4 s. As the TTC falls below 2 s, the probability of activating the system increases. Thus, the lower limit of the Soft linguistic label was set at 2 s, as also for the start of the slope of the Critical label.

The maximum TTC was set at 2 s because this is a generally accepted value at which to trigger this kind of system, since TTC values less than 1.5 s are considered critical (van der Horst, 1990) and less than 1 s as unavoidable (Shiller & Sundar, 1998). Since real vehicles were used in the experimental phase, 0.5 s was added to the TTC to protect the cars in the experimental phase.

The TG membership functions are shown in the middle part of Fig. 4. They are similar to those of TTC, also with two linguistic labels defined. The cross point is set at 2 s which was the TG value used as the referent in previous studies (Naranjo et al., 2007). The *Low* linguistic label will be used to mark when the TG value is greater than 2 s so as to decrease the value of the activation signal. TG values of less than 2 s will increase the weight of the *High* linguistic value, until at 0 s it indicates an unavoidable collision (Lin, Hwang, & Green, 2009).

Fig. 5 shows the control surface for the output variable – trigger – as a function of the fuzzy input variables – Time-To-Collision and Time Gap – according to the fuzzy rules given in Table 1. The fuzzy output variable membership function shapes are defined using Sugeno singletons (see lower part of Fig. 4). In this controller, we have defined three different singletons: *Deactivate* whose value is equal to zero, *Medium* whose value is equal to 0.5 and indicates that one is closer to activating the emergency system, and *Activate* equal to 1. Values greater than 0.5 activate the rear-end collision avoidance system.

Thus the intuitive meaning of all this is clear. TTC values lower than 2 (label Critical equals 1) trigger the CAS no matter what the other variable might be. If the TTC is between 2 and 6, then TG plays a key role in the CAS activation. Specifically, if TG equals 2 it has no influence, from this point onwards, the higher the TG value, the lower the probability of CAS activation.

4.2. Control algorithm

CWS activation causes a collision avoidance maneuver by steering to be performed under another fuzzy controller. This second

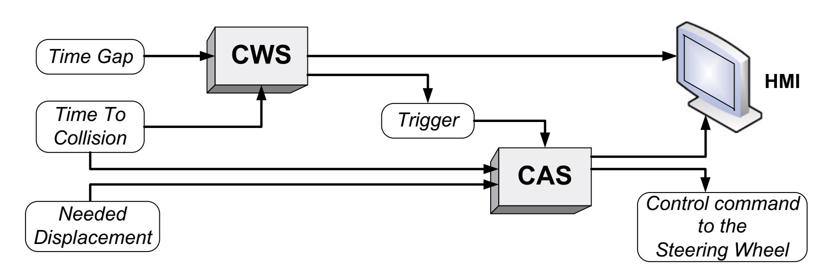

Fig. 3. Overview of the connection between the two controllers (CWS and CAS).

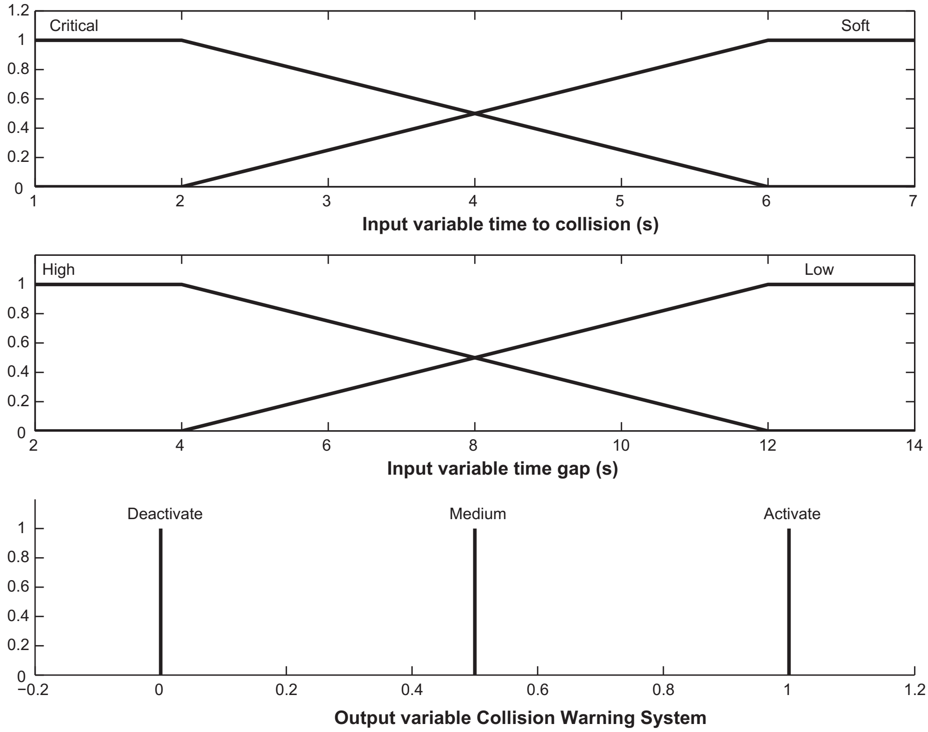

Fig. 4. Definitions of the trigger system membership functions for the input fuzzy variables.

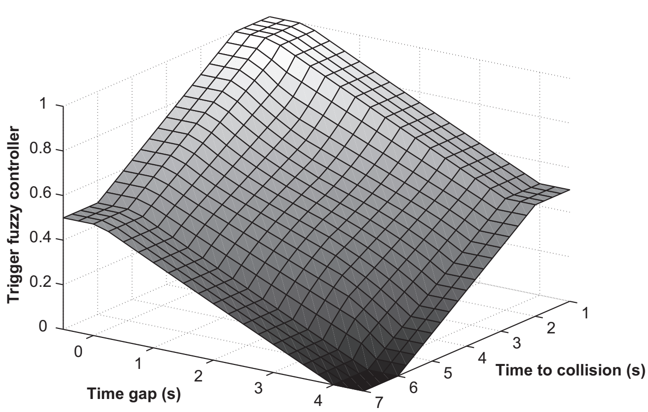

Fig. 5. Control surface for the Collision Warning System.

Table 1
Rule base for the rear-end CWS.

TG/TTC	Critical	Soft
Low	Medium	Deactivate
High	Activate	Medium

controller is designed to manage the steering movement needed to prevent a rear-end crash.

We aim to develop autonomous systems able to mimic human behavior. If one analyzes how a driver performs an avoidance maneuver, he/she considers the distance to the obstacle, vehicle's speed, obstacleŽs speed (if proceeds) and how he/she has to act upon the steering to avoid the obstacle. The TTC reflects the first three variables and the needed displacement (S_m in Fig. 1) the last one. In this way, we can develop the fuzzy controller writing the rules intuitively so it performs as drivers would do. Of course the full development of the controller requires a fine tuning, what in our case is done experimentally modifying the linguistic labels.

We assume that the vehicle is being driven on a straight stretch of road, and the main goal is to avoid vehicle-to-vehicle collision. Two variables are used as inputs for our fuzzy controller. The *Needed displacement* (S_m in Fig. 1) in meters, defined as the distance that the trailing car has to cover to avoid the accident, and the time to collision. The membership function definition for the input variables are shown in Fig. 6.

The fuzzy input variable *needed displacement* contains three membership functions for each of its three associated linguistic labels. As was noted above, which is the best way to avoid the collision depends on the distance along the *y*-axis between the center points of the two cars. The Left linguistic label indicates the leading vehicle is driving in our same lane but slightly to the left of the trailing car's position. The steering wheel has therefore to be moved to the right. Similarly, the Right linguistic label is used for the cases where the leading car is slightly to the right. Finally, a Center linguistic label is defined to correct the action on the steering wheel when the required lateral displacement needed to avoid collision has been attained. In this way, the system is not only capable of avoiding a rear-end collision but also of maintaining the car on the road.

The other fuzzy input is the *time to collision*. New membership functions different from those of the CWS were defined. In order to perform a safe maneuver and with the maximum comfort for the car's occupants, there are three membership functions, Close, Middle, and Far, to reflect how close the cars are.

Finally, the output of the controller is the steering wheel action defined as Sugeno singletons (see lower part of Fig. 6). There are five such singletons: Mleft (−1) and Mright (1) to indicate maximum action on the steering; Left (−0.5) and Right (0.5) to cover the cases where the TTC is large; and Center (0) to return the steering wheel to the initial position. The rule base is presented in Table 2, and, Fig. 7 depicts the relationship between the input and output variable as a control surface.

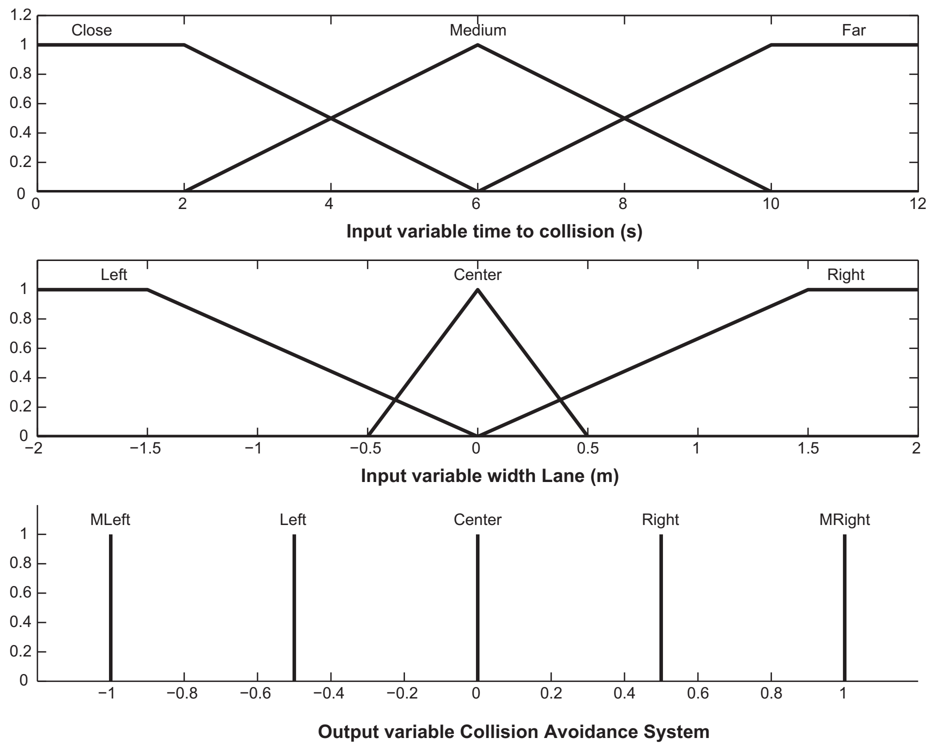

Fig. 6. Definitions of the avoidance system membership functions for the input fuzzy variables.

Table 2
Rule base for the rear-end CAS.

Needed displacement/TTC	Close	Medium	Far
Left	Mleft	Left	Left
Center	Center	Center	Center
Right	Mright	Right	Right

4.3. Evaluation of the algorithm

To evaluate the proposed control algorithm, a simulation study was carried out in order to quantify the algorithm performance. To this end, two vehicles were considered with an initial separation between them – this initial distance represents the moment in which the central station begins to send information about the leading vehicle to the trailing one (*distance* $\in$ [0–60] m). Initially, leading and trailing vehicle's speeds have values for urban environments (*speed* $\in$ [0–50] km/h). Trailing vehicle speed is maintained constant during each simulation and leading vehicle decelerations varying from 9 m/s^2 to 0 were considered. Initial conditions in which leading vehicle speed is higher than trailing vehicle speed were ruled out.

The trailing vehicle applies the fuzzy CWS algorithm described in this communication. Once the CWS was activated – output value higher than 0.5 – the lateral displacement of the trailing vehicle is started. The simulation is finished when the distance between the rear-end of the leading vehicle and the front of the trailing one is equal to zero. The test is successful if the lateral deviation is enough to prevent the crash. For all the tests, both vehicles were aligned at the beginning of the simulation so as to consider the most unfavorable case. In this situation, Horiuchi, Okada, and Nohtomi (2004) proposed the next formula for the maximum lateral displacement of a vehicle (H)

$$H \leqslant \frac{\gamma_{max} D^2}{2V^2} \quad (4)$$

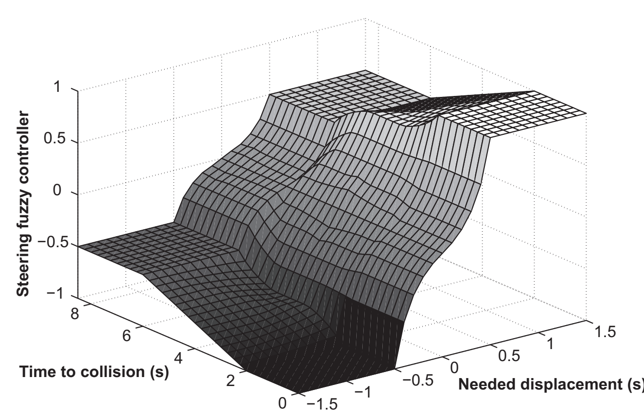

Fig. 7. Control surface for the Collision Avoidance System.

where $\gamma_{max} = \mu g$ – with μ representing the tyre-road coefficient of friction; D is the required longitudinal displacement to obtain a H lateral deviation – in this simulation D is the distance the trailing vehicle covers from the moment CWS is activated to the moment the test is finished – and V is the velocity of the vehicle. Fig. 8 depicts the simulation results. One can observe how for initial distance values higher than 50 m, the system is capable of avoiding the leading vehicle independently of speed and acceleration of the leading vehicle. For values lower than 50 m, the higher the deceleration, the higher the collision probability and the lower the initial separation the higher the collision probability. Note that some unrealistic situations, where crashes are unavoidable, have been computed too – i.e. initial separations lower than 5 m and decceleration for the leading vehicle greater than 7 m/s^2.

Using any V2I system proposed in Belanovic et al. (2010), a distance higher than 50 m is easily obtained. So the algorithm is capable of solving any situation if the central station begins to send information from the leading to the trailing vehicle with at least

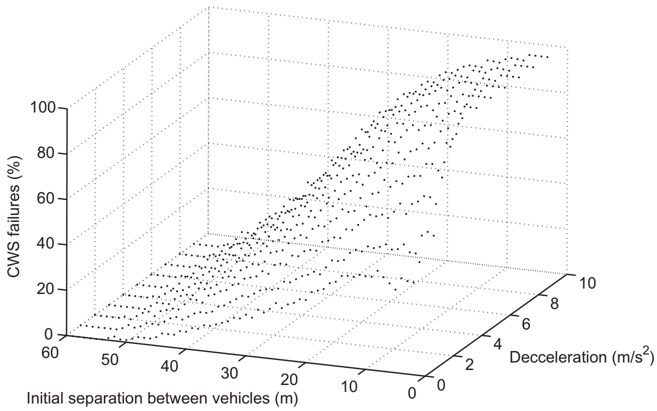

Fig. 8. Probability of succesful CWS detection.

50 m of separation. Furthermore, trailing vehicle decelerations has not been considered, so results for low initial distance should be improved.

5. In-circuit trials

The demonstration trials were performed at the CAR-CSIC private driving circuit using a street with a length of about 200 m.

5.1. Vehicles

Two Citroën cars were used for the trials (see Fig. 9). One of them is a convertible C3 Pluriel model that is a dual-mode vehicle with automatic driving capabilities. An analog I/O card is responsible for managing the throttle (Milanés, Onieva, Pérez, de Pedro, & González, 2009), and an electro-hydraulic braking system has been installed to brake the car (Milanés, González, Naranjo, Onieva, & de Pedro, 2010a). The steering wheel is controlled via the I/O card connected to a servoamplifier which manages the motor, using several classical control and fuzzy controllers in a cascade architecture (Milanés et al., 2012). The car is equipped with a real-time kinematic DGPS (RTK-DGPS) and an inertial measurement unit (IMU) to obtain vehicle's position (Milanés, Naranjo, Gonzalez, Alonso, & de Pedro, 2008). Vehicle's speed is obtained from the CAN bus (Milanés, LLorca, Vinagre, González, & Sotelo, 2010b). An IEEE 802.11 standard PCMCIA Proxim Wireless ComboCard is used for wireless communication.

The other car is an electric Citroën Berlingo van equipped with an RTK-DGPS and a differential Hall effect sensor coupled to a cog-wheel attached to one of the forward wheels to provide positioning and speed respectively (Pérez et al., 2010b). Both sensors are connected via RS-232 to a laptop with a PCMCIA Proxim Wireless ComboCard to send the data to the LCS. This van also follows the automatically driven C3 Pluriel car's architecture (Pérez et al., 2009), with automatic driving capabilities. But, to make the demonstrations as close to a real traffic situation as reasonably possible, the van was driven by a human driver during the trials. It was assumed during the trials that the adjacent lanes were free, so that the LCS was only responsible for sending the data coming from the leading car to the trailing car.

5.2. Demonstrations

Several trials were conducted to validate the proposed system. This section will describe two of them, the first being an avoidance maneuver to the left, and the second an avoidance maneuver to the right. In both trials, we assume lanes of 3 m width – from −1.5 to 1.5 as shown in the fourth plot of the two respective figures – and at least 1.5 m more on each side of the lane.

Fig. 9. Real vehicles used for the trials.

Each of the two Figs. 10 and 11 shows the evolution of the following variables. The three upper plots depict the CAS activation. The first from the top is the time gap between the cars. The second is the evolution of the time to collision. The third indicates the variation in the trigger value, with values greater than 0.5 triggering the CAS. The fourth shows the lateral positions of both the leading and the trailing cars, the lateral displacement until CAS is triggered and the needed displacement to perform the rear-end avoidance maneuver. The fifth represents the speed of each car. The bottom plot shows the distance between the cars over the course of the demonstration.

Fig. 10 shows the first test carried out on our circuit. The two vehicles are in the same lane. During the first 7 s, the speed of the leading car is greater than that of the trailing car. This is reflected in the TTC whose values are negative, and by the time gap with values between 3 and 3.5 s. At the beginning, the lateral distance between the central points of the rear-end of the leading vehicle and the front of the trailing one is close to 1 m (see gray dashed line of the fourth plot in Fig. 10). But as the demonstration proceeds, the two vehicles come closer to a lateral position of zero indicating that the cars are in the center of the lane. After second 7, the speed of the trailing vehicle increases to 20 km/h. When its speed surpasses that of the leading car, TTC changes sign, with a discontinuity appearing in the graph, because the lower the difference in speeds of the two cars, the higher the TTC values. The trigger then starts to increase up to the point of the CAS activation signal (second 11.5). At that moment, the variable needed displacement is updated to reflect the need of avoiding the leading vehicle. In this demonstration, the safer maneuver is to move the steering wheel to the left. The car then moves laterally to avoid the rear-end collision. One observes that the needed displacement lowers and eventually becomes zero as the lateral displacement of the trailing vehicle with respect to the center of the lane increases in value.

The system was activated due to a sudden change in the speed of the leading car at about second 11.5. This caused a significant change in the time gap as well as in the TTC, and this is reflected in the trigger value. A collision would have occurred close to second 13.5, when the distance between cars and the TTC are both zero, and the trigger value is equal to unity. At that moment, the lateral distance between cars is close to 1.6 m, and rear-end collision avoidance has been accomplished. One observes now that the needed displacement value has become positive. This indicates that the avoidance has been completed, and the steering wheel has to be turned in the other direction to maintain both a safety distance from the leading car and the autonomous vehicle in the road.

The second trial (see Fig. 11) represents a rear-end avoidance maneuver to the right. During this test, the speeds of the two vehicles were similar up to second 16. This is reflected in the TTC

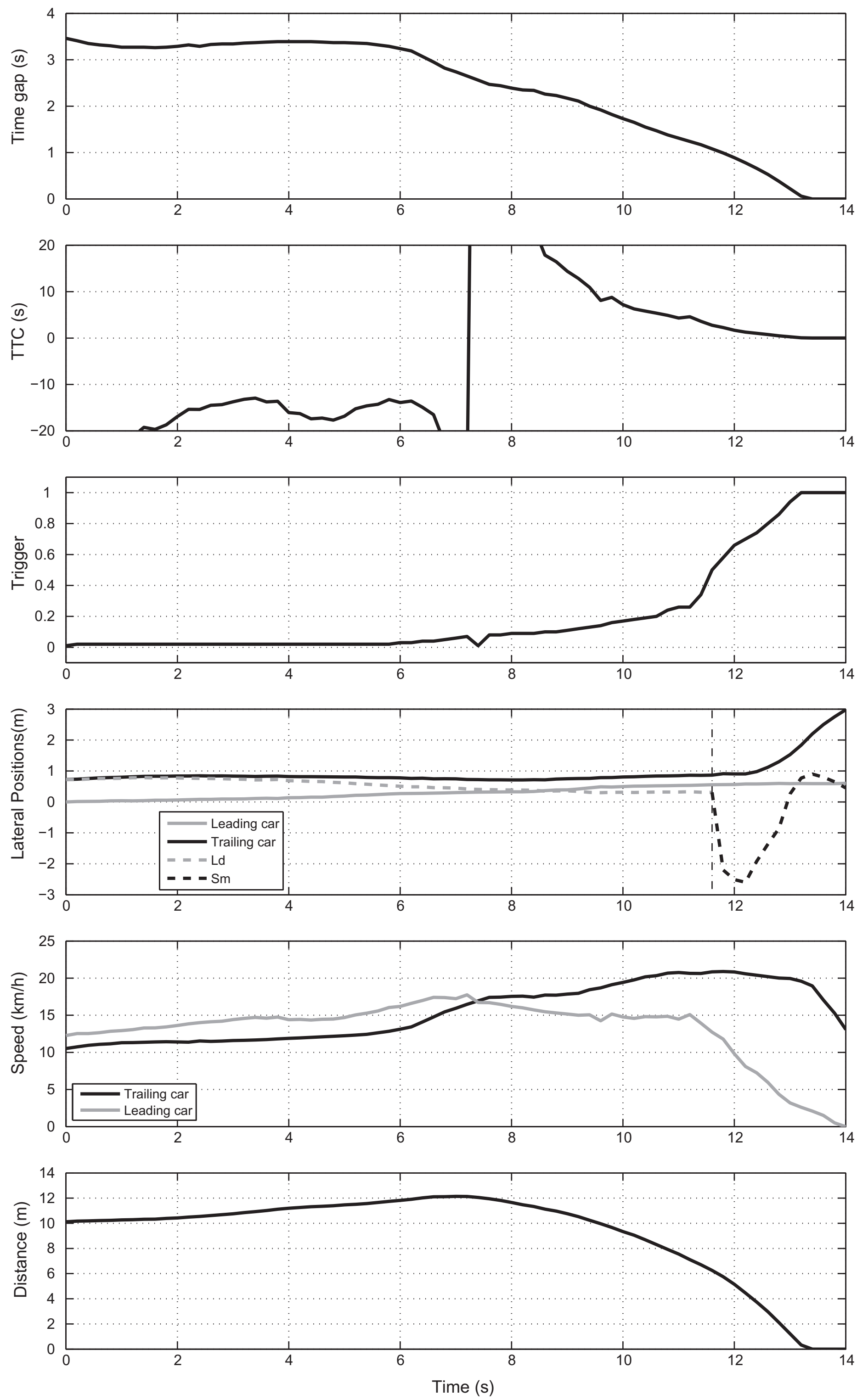

Fig. 10. First demonstration of a rear-end collision avoidance maneuver. Top three graphs show the evolution of inputs and ouput for the CWS. Bottom three graphs show the evolution of the vehicles.

variable with continual changes between positive and negative values. Then, the leading vehicle brakes, and the CAS is activated. In this trial, one can appreciate how the lateral distance between the cars is slightly greater than in the first trial. The needed displacement is therefore slightly lower than in the first test.

On all trials conducted – up to 50, leading and trailing vehicles velocity was limited between 5 and 25 km/h, having a media of 20 km/h for the trailing vehicle velocity at the moment CAS was triggered. The system was tested in straight stretches with leading vehicle's decelerations up to 2 m/s^2. Analyzing the results, the

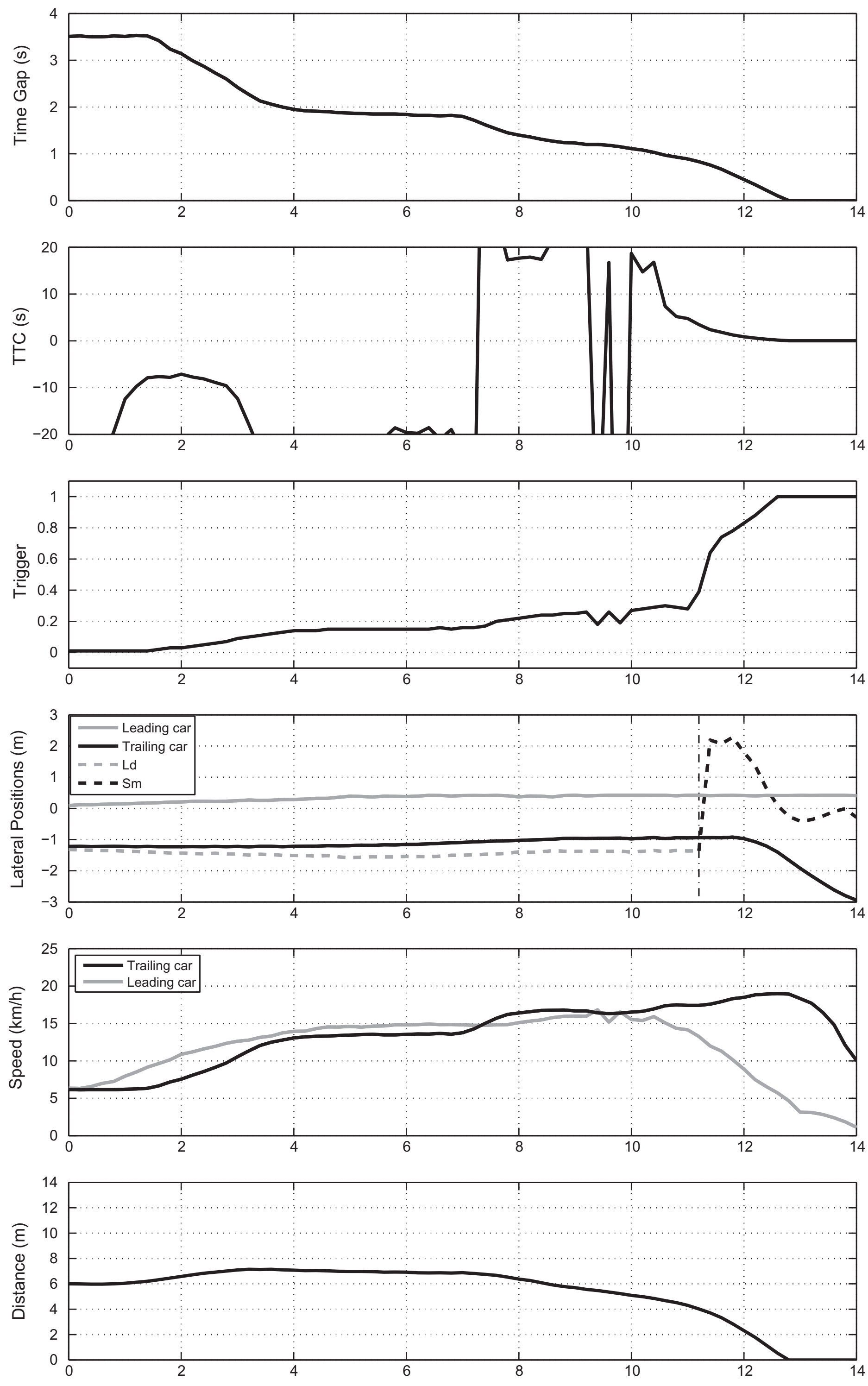

Fig. 11. Second demonstration of a rear-end collision avoidance maneuver. Top three graphs show the evolution of inputs and ouput for the CWS. Bottom three graphs show the evolution of the vehicles.

lateral distance between the cars when the distance gap is zero have a media value close to 0.2 m.

6. Discussion

This paper reflects a work framed in the subject of driverless vehicles. Even if the long term goal is a utopia, we aim to obtain systems capable of aiding in driving-related tasks. In this case, we are dealing with an approach for collision avoidance systems, tested using real mass-produced vehicles. As far as we know, literature provides very little hints of real demonstrations in rear-end collision avoidance systems. Although the proposed approach provides very encouraging results, from a real-world application perspective, where the traffic conditions are certainly more complex a significant effort is still necessary to quite solve this important problem.

The results here shown depend on infrastructure to vehicle communications to provide data sharing among many vehicles in real time situations. V2I is used as a tool in this work and the authors consider that the trend for the future will be based on vehicle-to-vehicle and vehicle-to-infrastructure communications, not only for collision mitigation but for many ITS applications. Specifically, communications systems will play a key role in CAS in the medium term (Ashtaiwi & Hassanein, 2010; Taleb, Benslimane, & Ben Letaief, 2010).

Concerning the positioning system, GPS/IMU system would be improved using sensorial fusion, that is, camera, ultrasound, lidar or radar systems to carry out a more accurate positioning both the leading and the trailing cars.

The developed fuzzy logic controllers have been validated as capable of performing both CWS and CAS. Rule base was selected trying to mimic human behavior. Since the main goal was to show the CAS, safety values were added to the membership functions both TTC and TG when triggering conditions were selected to detect the risk collision in advance.

Experimental set-up demonstrates the proposed algorithm works well at CAR's facilities, but the trials are limited by the size of the track. More tests with a greater range of surfaces and speeds have to be conducted to further validate the proposed systems.

Steering control has not received much coverage in the literature (Naranjo et al., 2008). The proposed system can be used as active ADAS controlling the steering wheel in commercial cars. This work constitutes a good starting point to continue the study of more complex scenarios.

7. Conclusions

Rear-end Collision Warning Systems have been developed by automotive manufacturers to be implemented in their commercial vehicle models in recent years, with acoustic or visual warning signals given to the driver. The next generation in safety vehicle systems is represented by Collision Avoidance Aid Systems to handle the car in order to avoid a rear-end crash.

This paper has presented a fuzzy rear-end collision avoidance system using as main inputs the time to collision and the needed displacement in order to avoid the accident. The system detects a potential collision, and, according to the position of each car, decides which is the better side on which to perform the aid maneuver without leaving the road. The system thus not only avoids the collision as its prime objective, but also maintains the vehicle on the road. To activate the system, another fuzzy controller was developed based on the time gap and the time to collision to trigger the aid avoidance system. This controller can operate as a warning system by itself.

The proposed system was tested with real cars in real situations using a vehicle-to-infrastructure communication system with a local central station to exchange information between the leading and the trailing cars. Several trials were conducted, showing the system to present good behavior.

This system can be used in two ways. First, for values of the trigger below 0.5, it can warn the driver of a possible collision, thus operating as a collision warning system. Then, for values of the trigger above 0.5, it can turn the steering wheel autonomously to avoid the accident, operating as a collision avoidance system.

Although achieved results are promising, there are still several questions in need of further investigation. Leading vehicle's movements are limited to braking actions without steering changes. Indeed, bend stretches are not consider in this study. In addition, a deep study about false alarms and successful alarms including a wide range of real traffic situations will be studied in future researches.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.eswa.2012.02.054.

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