Controller for Urban Intersections Based on Wireless Communications and Fuzzy Logic

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***Abstract*—A major research topic in Intelligent Transportation Systems (ITS) is the development of systems capable of controlling the flow of vehicular traffic through crossroads, particularly in urban environments. This could significantly reduce traffic jams, since autonomous vehicles would be capable of calculating the optimal speed to maximize the number of cars driving through the intersection. We describe the use of vehicle-to-vehicle (V2V) communications to determine the position and speed of the vehicles in an environment around a crossroad. These data are used to estimate the intersection point, and a fuzzy controller then modifies the speed of the cars without right-of-way according to the speed of the car with right-of-way. Experimental tests conducted with two mass-produced cars on a real circuit at the IAI facilities gave excellent results.**

***Index Terms*—Inter-vehicle communication, Autonomous vehicles, Accident detection, Traffic management, Fuzzy control.**

I. Introduction

CROSSROADS are one of the major problems in controlling the flow of vehicular traffic in urban environments. Approximately 50% of all traffic collisions occur at crossroads and over 60% in urban areas [1]. There are two principal issues affecting the safety of traffic at crossroads. One is poor visibility of the minor approaches to a crossroad, so that drivers may fail to yield when they should. The other is inadequate traffic signalling in areas with continuing series of crossroads. These two problems may be a cause of vehicle collisions related to the "dilemma zone", i.e., the space from the crossroad to the point on the road where it is difficult for the driver to discern whether he should accelerate, thus passing the crossroad before the other vehicle, or decelerate to play it safe.

Intelligent transportation systems (ITS) focus on improving road safety either by improvements to the infrastructure or by acting on the vehicles themselves [2]. The last decade has seen significant progress in the automation of vehicles in this field of research. One of the pioneers in implementing a real car capable of driving for hours at a time was the University of Parma's ARGO project [3] in which a human driver performed the longitudinal control and the lateral control was carried out by an autonomous system.

A reference for today's autonomous vehicle development programs has been the USA Defense Advanced Research Projects Agency (DARPA) Urban Challenge held in California in 2007. In this event (a continuation of the DARPA Grand Challenges held in 2004 and 2005), vehicles capable of driving in traffic, performing complex manoeuvres such as merging, passing, or parking, competed in an autonomous vehicle race. The Carnegie Mellon University Tartan Racing Team's Boss [4] crossed the finish line first with a run-time of just over four hours driving, covering 85 km autonomously.

Cooperative manoeuvres among autonomous vehicles have been carried out based on different sensors. An example is the extension of cruise control (CC) known as adaptive cruise control (ACC). ACC has been implemented by Naranjo [5] using a Real Time Kinematic Differential Global Positioning System (RTK-DGPS) with a wireless network, Abou-Jaoude [6] using radar technology, and Gehrig and Stein [7] using a computer vision system. A further extension known as cooperative adaptive cruise control (CACC) has been the subject of different simulations [8,9].

Several research works in this field have tackled another cooperative manoeuvre based on lane changing – the overtaking manoeuvre. Ngai [10] proposes a reinforcement learning multiple-goal framework to solve the problem of automated vehicle overtaking. Zhu [11] proposes a robust solution with an integrated on-board monocular vision system for obstacle detection applied to overtaking. Naranjo [12] uses fuzzy controllers to carry out the overtaking manoeuvre in autonomous vehicles equipped with path-tracking and lane-change capabilities.

One of the most complex cooperative manoeuvres is the management of different vehicles approaching a crossroad. The problem of accident prevention in this situation has been attacked from different points of view. One consists of vision-based systems for monitoring traffic in real time to predict possible collisions through an innovative low-overhead collision-prediction algorithm [13]. Also dealing with vision, Kamijo [14] developed an algorithm, described as a spatio-temporal Markov random field (MRF), to model a tracking problem by examining all the pixels in an image and how they change both in space and in time. With regard to vehicle-to-vehicle (V2V) communications, Korkmaz [15] proposed two modifications of the IEEE 802.11 protocol for their management which differ in how they deal with the crossroad situation, and tested them in simulations. Other research works have studied the behaviour of vehicles approaching crossroads using neural networks [16], techniques to improve the vehicular traffic at crossroads through maximal weight matching algorithms [17], the characterization of driver behaviour at crossroads [18], and simulations of intervehicle communications applied to blind

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crossroads [19].

In this paper, we present an automatic fuzzy controller to manage the vehicles traversing a crossroad, allowing a vehicle either to yield to an incoming vehicle which has right-of-way, or cross if the incoming vehicle's speed permits it. Two mass-produced cars are used to demonstrate the operation of the system. A wireless network is used to communicate the information needed in order to evaluate the fuzzy decisions.

The paper is structured as follows: in Sec. II, a description is given of the automated vehicles and the sensors and communications systems used. Section III presents the decision architecture developed to activate the fuzzy controller, and the decision algorithms are described in Sec. IV. The experiments with the real cars are presented in Sec. V, and Sec. VI gives some concluding remarks.

II. Infrastructure and Equipment

A. Vehicles

This section describes the on-board systems used to perform the experiment. The cars used were a fully automated Citroen C3 Pluriel and a commercial Citroen C3 (Fig. 1). The former, named Clavileño, has been modified to drive autonomously. The main sensorial inputs are a RTK-DGPS and an inertial measurement unit (IMU). A sensorial fusion system was developed to perform the guidance of the vehicle [20]. To this end, a target route is defined and digital cartography is used to follow the reference. The actuators modified for autonomous driving are a pulse width modulator for the steering wheel, an analog output card to control the throttle, and an added electro-hydraulic pump to act on the brake. These systems are handled by an on-board industrial PC.

The other car, named Platero, is a mass-produced vehicle with unmodified actuators. It is equipped with a low-cost differential global positioning system (DGPS) with which the errors in the positioning of the car can be up to 50 centimetres. This error applies to measurements that may drift over time. The relative distance error between two consecutive measurements is similar to that of the RTK-DGPS. A laptop in the car is used to manage the position data obtained from the DGPS. Loss of the DGPS signal is treated as a communications failure. In this case, no signal is transmitted and the autonomous system is deactivated.

B. Communications

The system outlined above in Sec. II-A allows each vehicle to know its position in real time. Communications are therefore needed for the cars to be able to exchange this information with each other. To this end, we implemented a peer-to-peer Wi-Fi network. An access point, located at one of the corners of the circuit, supplies coverage to all the vehicles that are driving along the circuit. The distance from the access point to the farthest point of the circuit is about 250 metres, and the coverage of the communication system is up to 300 metres.

A Personal Computer Memory Card International Association (PCMCIA) Proxim Wireless ComboCard is installed in the PC of each car. In the experiments described here, only two vehicles were used. A check was made that the system is capable of managing more cars, a test was performed using the vehicles described above and two extra computer-generated GPS signals to simulate a situation involving four concurrent vehicles.

III. Intersection Detection System

In this work, we present a system which is capable of performing intelligent crossroad traversals. The development of this system naturally divided itself into two parts. The first, explained in this section, was a system capable of detecting the position and intention of the other cars in its vicinity. The second, which will be described in Sec. IV, was a controller to act on the throttle and brake pedals.

The detection system was designed on the basis of a local topological analysis. It stores the last positions of each car that is detected in its local area. From this data, it is thus possible to determine each car's direction vector. The autonomously driven vehicle continuously checks a circular area of up to 80 metres radius. When another vehicle is detected within this area, its direction vector is monitored to analyze its trajectory.

Article 57, Chapter 3 of the Spanish Road Circulation Code reads: "In the absence of signals that regulate the priority, drivers are obliged to yield to vehicles approaching on their right." With this premise, only vehicles coming from the right need to be taken into account to perform automatic traffic flow at crossroads. Therefore two checks must be made: whether a vehicle is driving along the perpendicular road, and whether it is entering the crossroad.

To this end, three unit vectors are defined. The autonomous vehicle's direction vector, the incoming manually driven vehicle's direction vector, and the common vector defined as the unit vector from the position of the autonomous vehicle to the position of the manual one (Fig. 2). Once the other vehicle has been detected, it can be in one of eight different positions: on the same road in either the same or the contrary lane, and in each case either ahead of or behind the autonomous vehicle; or on the perpendicular intersecting road, travelling to either the right or the left, and in each case either approaching or leaving the crossroad area. Taking all this into account, three conditions have to be met in order to activate the crossroad controller illustrated geometrically in Fig. 3.

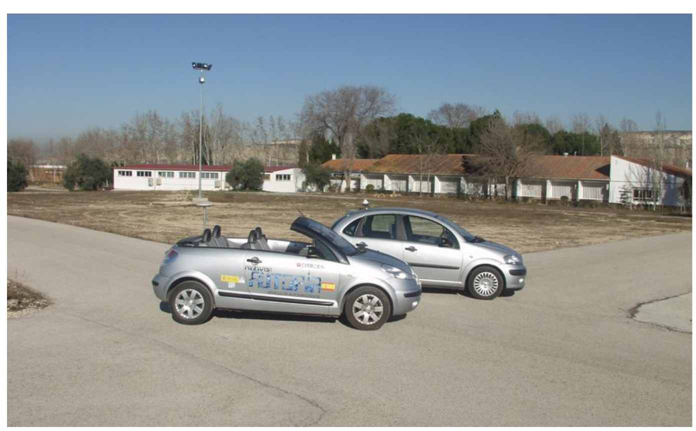

Figure 1. Clavileño and Platero at the IAI facilities.

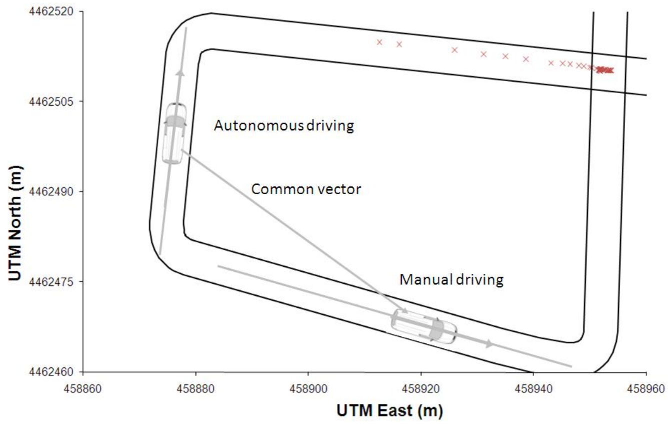

Figure 2. Behaviour of the intersection detection system.

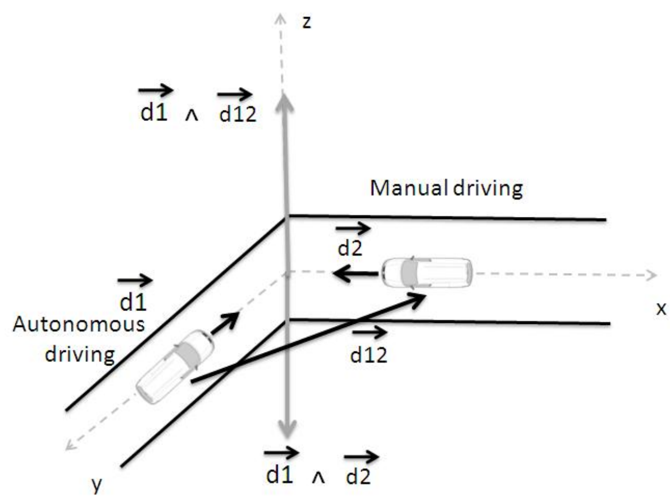

Figure 3. Vector representation in the left-handed coordinate system.

1) The absolute value of the dot product between the autonomous vehicle's unit direction vector ($\vec{d1}$) and the manual vehicle's unit direction vector ($\vec{d2}$) must be less than 0.707, i.e., the manual vehicle is travelling along the perpendicular road.
2) The cross product of the autonomous unit direction vector ($\vec{d1}$) with the common unit direction vector ($\vec{d12}$) must be positive, i.e., the manual vehicle is in the right-hand segment of the perpendicular road.
3) The cross product of the autonomous unit direction vector ($\vec{d1}$) with the manual unit direction vector ($\vec{d2}$) must be negative, i.e., the manual vehicle in the right-hand segment of the perpendicular road is approaching the crossroad.

In Fig. 2, an example is shown of the behaviour of the crossroad detection system at the IAI private driving circuit. For this test, the idea was to check the evolution of the point of intersection. The vehicles start moving, simultaneously, from the position in the picture. The points were calculated at the GPS rate, 5 Hz. To this end, the limitation of 80 metres to detect a car was disabled, and as soon as the three conditions above were matched, the system began to calculate the point of intersection. The first points, far from the point of intersection, correspond to the moment when the manually driven vehicle is coming out of the bend, and the automatic vehicle is already heading straight for the intersection point. The crossroad system is activated but the manual car is not yet heading completely straight for the crossroad. Once both cars are in the straight parts of their trajectories, the point of intersection converges to the centre of the crossroad. Given the error associated with the DPGS installed in the manual driving vehicle, the errors in the determination of the point of intersection are insignificant.

Different tests performed to check the behaviour of the detection system gave good results. The digital cartography is thus only needed for the guidance of the autonomous vehicle. The designed detection system is independent of the shape of the roads. When a vehicle is detected, the point of intersection is calculated in real time, and then the determination of the distances of the cars to the point of intersection is immediate.

IV. Fuzzy Controller

Fuzzy logic is a powerful technique to control processes which are difficult to model and linearize. The AUTOPIA program at the IAI-CSIC, of which this work forms a part, has long experience in the use of fuzzy logic. This technique has been used for the control of systems as diverse as helicopters [21] and the air temperature and humidity of greenhouses [22]. For this reason, it was regarded as a good potential solution to the problem of controlling unmanned vehicles.

In earlier work [23], we had developed ORBEX (Experimental Fuzzy Coprocessor) which is an inference motor with a straightforward, natural language based, input language. ORBEX functions with Mamdani's inference method, with singleton-type membership functions to codify the output variables, and allows control decisions to be made very rapidly and very precisely – essential qualities for real-time systems. Its application to the present control problem is described in this section.

The fuzzy controller developed will be responsible for managing the throttle and brake pedals (i.e., the longitudinal control) in making decisions about reducing, maintaining, or increasing the autonomous vehicle's speed when the two cars are approaching the crossroad. This controller consists of a rule base containing expert knowledge and a set of variables representing the linguistic values considered. Functionally, the fuzzy reasoning is done in three stages – fuzzification, inference, and defuzzification.

1) Fuzzification: In this step, the actual "crisp" numerical values of the input variables are transformed into "linguistic" values that can be processed by the fuzzy compiler. This transformation assigns a degree of truth to each of the input fuzzy values. In our case, we define three input variables named dist-self, dist-other, and dif-speed representing the distance in metres of the cars from the intersection point (dist-self for the automated car and dist-other for the manually driven one) and the speed difference between the cars in kilometres per hour. The definitions of these variables are shown in Fig. 4.

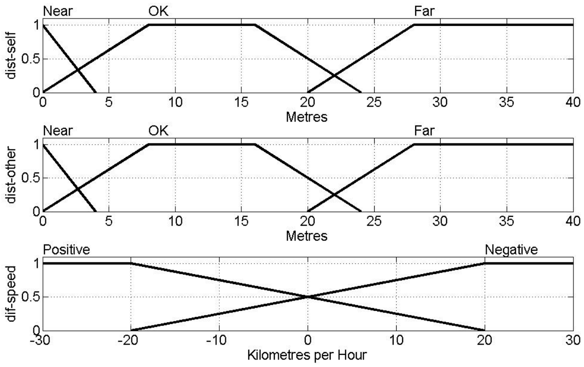

Figure 4. The definitions of the membership functions for the input fuzzy variables.

2) Inference Engine: The inference engine propagates the matching of the conditions to the conclusions, generating the contribution of each rule to the final output, in this case the control action. We use Mamdani's inference method [24] (min-min-max) to solve the implication. Application of the inference engine yields the values of the output fuzzy variables.
3) Defuzzification: This last step consists of transforming these output fuzzy values into crisp values that can be used to output control intentions. In this case, we use the centre-of-area (CoA) method:

$$y_{CoA} = \frac{\int B \cdot y dy}{B dy}, B = \cup \omega_i B_i \quad (1)$$

where $\omega_i$represents the membership degree resulting from the inference of the i-th rule, and B_i is the membership function for the different values of the output variables of the i-th rule.

We defined fuzzy output variable membership function shapes using Sugeno's singletons [25] which are based on monotonic functions. In this case, a modified CoA equation is applied:

$$y\prime_{CoA} = \frac{\sum \omega_i B_i}{\sum \omega_i} \quad (2)$$

Therefore, for the speed control, we generate two output values, Throttle and Brake $\in [0, 1]$, which represent the normalized pressure to apply to the two corresponding pedals and are shown in Fig. 5. Our results with empirical studies suggested that values over 0.5 produce accelerations of the car which are so sharp as even to be dangerous for the vehicle's occupants. Thus, the singletons used for these two variables were restricted to t00, t01, t02, t03, t04, and t05 for the throttle, and b00, b01, b02, b03, b04, and b05, representing normalized pressures on the pedal of 0 (no pressure), 0.1, 0.2, 0.3, 0.4, and 0.5, respectively. The implementation of the rule base is given in Table I where T and B indicate Throttle and Brake output values, respectively.

V. EXPERIMENTAL RESULTS

Two experiments were performed at the IAI facilities' private driving circuit, using the crossroad shown in Fig.

dif-speed=positive	dist-other		
dist-self	Near	OK	Far
Near	T=t00 B=b04	T=t00 B=b03	T=t02 B=b00
OK	T=t00 B=b02	T=t03 B=b00	T=t02 B=b00
Far	T=t01 B=b00	T=t03 B=b00	T=t02 B=b00

dif-speed=negative	dist-other		
dist-self	Near	OK	Far
Near	T=t00 B=b02	T=t00 B=b01	T=t03 B=b00
OK	T=t00 B=b01	T=t00 B=b01	T=t03 B=b00
Far	T=t02 B=b00	T=t01 B=b00	T=t04 B=b00

Table I
THE RULE BASE.

2, to check the behaviour of the fuzzy controller that had been developed. The first consisted of testing whether the autonomous vehicle was capable of reducing speed in order to let the vehicle approaching the crossroad from the right pass without problem. The second was to check whether the autonomous vehicle was capable of increasing speed to traverse the crossroad before the other vehicle reached it.

Since safety is the overriding parameter in traversing a crossroad, one cannot approximate the vehicles by points, and a safety distance must be added. Two considerations must be taken into account in calculating the distance of each car from the intersection point. First, the crossroad is approximately a square of 8×8 metres, with the intersection point located in its centre. Second, as can be seen in Fig. 1, the GPS antenna is located on the rear-end of the cars, and the length of the vehicles is around four metres. Consequently, eight metres are added to the distance of each car to the intersection point.

Henceforth, gray symbols will be used to correspond to the autonomous vehicle, and solid black to the manually driven one. The crosses correspond to times when the intersection conditions were not fulfilled. The open discs correspond to times after the crossroad situation had been detected. Continuous-line segments indicate the periods when the intersection detection system was not activated, and dashed-line segments when it was activated.

Figure 6 shows the behaviour of the autonomous vehicle when another car is detected and is approaching the crossroad. In this first experiment, as the two vehicles approach the

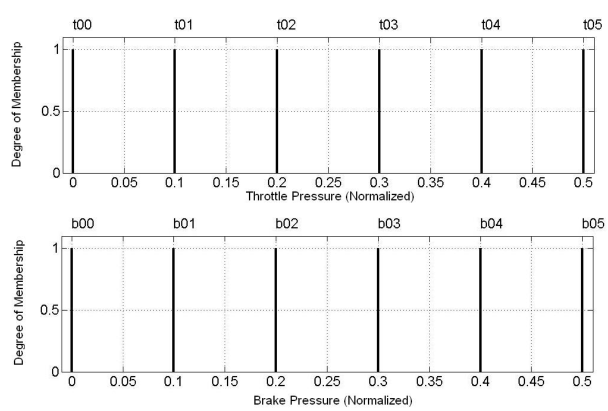

Figure 5. Output variable membership functions for throttle and brake pedals.

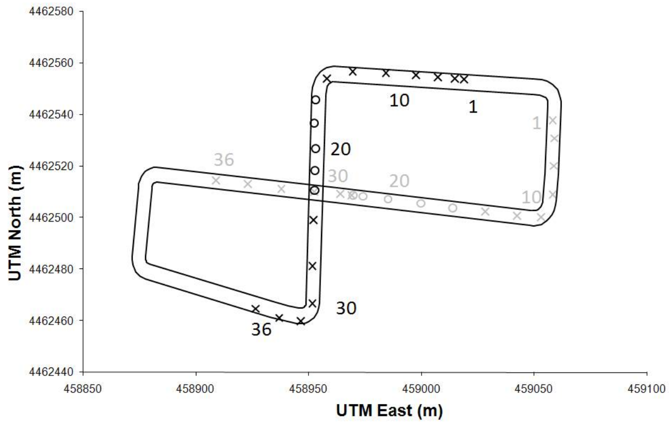

Figure 6. Position of each car during the first experiment.

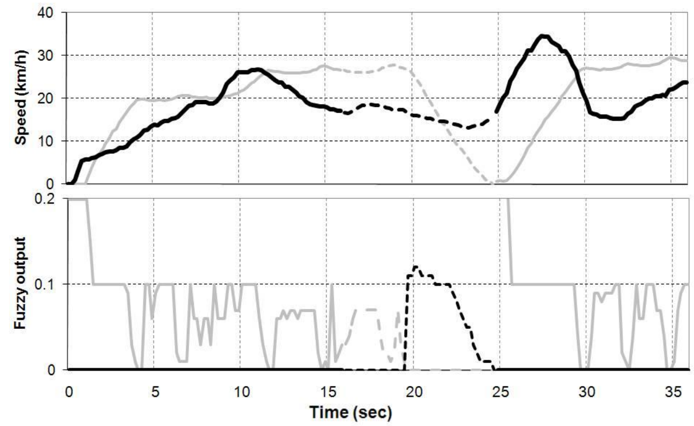

Figure 7. Speeds and fuzzy output during the first experiment.

crossroad, when the autonomous vehicle detects the other it reduces speed until the manual one has traversed the crossroad. Each mark corresponds to a GPS position plotted every two seconds.

At the beginning, each car advances in different directions and the intersection detection system remains inactivated. Around second 15, the autonomous vehicle detects the presence of another vehicle approaching the crossroad, and the fuzzy controller is activated. One observes that after second 20, the next three positions are very close together, reflecting the reduction in speed. In this way, it permits the manually driven vehicle to traverse the crossroad with no problem. The autonomous vehicle then recovers its reference speed in normal driving and continues on its path.

Each car's speed during this experiment is shown in the upper part of Fig. 7. The lower part shows the normalized output of the fuzzy controller, with the gray line corresponding to the throttle and the black line to the brake. The autonomous vehicle's speed increases up to the reference speed set at 20 km/h by second 10, and then to 27 km/h from second 10 until the end of the experiment. The fuzzy controller is activated at around second 15. At first, the autonomous vehicle maintains its speed until it detects the proximity of the manual vehicle to the crossroad at around second 20. Then, a force is exerted on the brake in order to permit the manual vehicle to traverse the crossroad. The output of the fuzzy controller acting on the brake is shown in the lower part of Fig. 7. Once the manual vehicle has traversed the crossroad, the autonomous vehicle sets about recovering its target speed and continuing on its route.

The second experiment was a continuation of the first. The two vehicles went around the circuit and came back to the same crossroad with the manual vehicle again having priority (Fig. 8). In this case, we tested the option when the manual car is moving slowly and the automated one decides to traverse the crossroad in order to improve traffic flow.

The fuzzy controller to handle the crossroad situation is activated after second 10. The decision of the autonomous vehicle is to try to maintain a speed similar to that of the manual one. At around second 18, the manual vehicle slows down, and this is followed by the controller's decision to increase speed and traverse the crossroad before the manual vehicle.

Figure 9 shows the speeds of each car and the outputs of the fuzzy controller in the upper and lower parts of the figure, respectively. The target speed of the autonomous vehicle was set at 12 km/h during the first five seconds, and 9 km/h after that time until the fuzzy controller was activated. The two vehicles then maintain similar speeds, until, around second 18, the speed of the manual vehicle decreases slightly and the controller of the autonomous car decides to traverse the crossroad. The vehicle is accelerated significantly to ensure traversal of the crossroad before the manual car reaches it.

VI. Conclusions and Future Perspectives

We have presented the implementation of the idea of an intelligent crossroad traversing system aimed at improving traffic flow. The purpose of the work has been twofold: first, to develop and test a system to detect the presence of another vehicle approaching the crossroad, and second, to work towards implementing a real system capable of making the best decision in driving a vehicle through an intersection point as a function of the traffic conditions, and based on fuzzy logic. Thus, our system is capable not only of stopping the vehicle should another vehicle be entering the same intersection point, but also of crossing the intersection if the speed of the other vehicle is too slow even if it is approaching with right-of-way.

A low cost system using a DGPS and Wi-Fi communications was installed in a commercial car to permit information exchange by V2V communication. The fuzzy logic decision algorithm based on unit direction vectors gave excellent results in estimating the point of intersection without needing cartographical knowledge of the area.

In sum, we have designed a fuzzy controller aimed at managing traffic flow at crossroads in response in real time to the actions that other cars are taking. Experiments to check the behaviour of the system with two vehicles, one manually driven and the other fully automated with the designed system installed, gave excellent results.

The next steps in our research program will focus on the inclusion of more vehicles at the crossroad including more autonomous vehicles, in order to test the response of

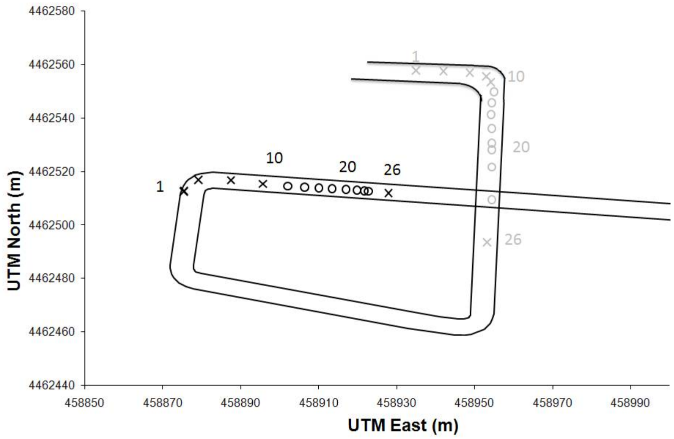

Figure 8. Position of each car during the second experiment.

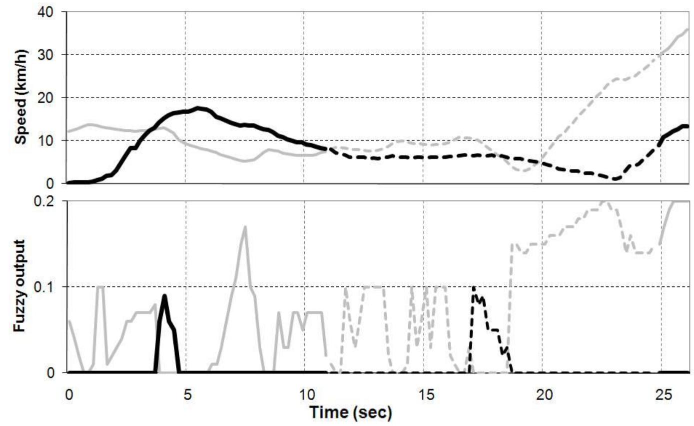

Figure 9. Speeds and fuzzy output during the second experiment.

the controller. In particular, in order to permit turns at the crossroad, the intention of each car approaching the crossroad to turn left, turn right, or go straight through is to be included in the V2V communication information package.

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