An Analysis of Communication and Navigation Issues in Collision Avoidance Support Systems

José Santa [a,*] Rafael Toledo-Moreo [b]
Miguel A. Zamora-Izquierdo [a] Benito Úbeda [a]
Antonio F. Gómez-Skarmeta [a]

[a] *University of Murcia, Department of Information and Communication Engineering, Campus de Espinardo, 30100 Murcia, Spain*

[b] *Technical University of Cartagena, Department of Electronics and Computer Technology, 30202 Cartagena, Spain*

1 Introduction

The advanced driver assistance systems (ADAS) are one of the prime work lines in the field of intelligent transportation systems (ITS). With the aim of decreasing the number of deaths and injures caused by traffic fatalities, ADAS developments try to automate the traffic perception and, in general, the driving task. Collision avoidance support systems (CASS) can be considered nowadays one of the main researching lines in ADAS. These systems are designed to detect oncoming collisions and warn the user with time enough for making possible an evasive manoeuvre, or directly perform an automated control action. The relevance of CASS solutions has grown to such point that a great number of researchers take it as the reference service in the design of communication architectures in the ITS field. Nowadays, several approximations study the CASS problem from different points of view. In autonomous solutions, the subject vehicle is equipped with radars or vision sensors which provide pose information about the rest of the vehicles in the traffic environment. Although these systems can potentially offer a complete vision of the obstacles the vehicle can find on the road, they are restricted to the sensing

* Corresponding author.
Email addresses: josesanta@um.es (José Santa), rafael.toledo@upct.es (Rafael Toledo-Moreo), mzamora@um.es (Miguel A. Zamora-Izquierdo), bubeda@um.es (Benito Úbeda), skarmeta@um.es (Antonio F. Gómez-Skarmeta).

10 December 2008

capabilities, and generally are not cost efficient solutions. In distributed or cooperative solutions, on the other hand, using wireless communications, vehicles can share useful information to infer dangerous states. The concept of cooperative driving appeared in early nineties (Varaiya, P., 1993) and, gradually, more and more works started to be published. Depending on the level of cooperation among vehicles, the object vehicle can track the surrounding vehicles, in order to detect risk conditions, or directly receive or send a traffic event when it is necessary. In the first case, a periodical transmission of state messages to surrounding vehicles must be maintained; whereas in the second only one message sent by an affected vehicle (or the one which detects the problem) is sent and propagated over the network when it is necessary.

This paper is focused on a generic distributed CASS, and main requirements for any level of cooperation among vehicles will be embraced. Some works in the literature mention several technologies which has to be integrated in the on-board unit (OBU) of a CASS. Our study is focused on the relevance of the wireless network and the navigation subsystems, considered the main architectural elements of a distributed CASS. Too often, current proposals assume ideal performances of these subsystems, but the reality is very far from this assumption. In wireless communications, several transmission problems arise in a real V2V mobility scenario and, as it is further explained, the obtained performance is directly related with the technology used. Common network simulations do not consider many external factors of real mobility scenarios. The performance of the navigation subsystem in CASS solutions is even more underestimated. Although there are many collision avoidance systems that propose novel protocols for vehicle to vehicle communications (V2V), the relevance that the positioning subsystem has in the system performance has not sufficiently considered. Most of the approaches available in the literature include the GPS position in the messages broadcasted by vehicles. However, even though the messages can reach efficiently the destination, if the reported position has been distorted by external factors at the source equipment, the overall performance will be affected.

The rest of the paper will be focused on performance issues regarding the wireless network and the positioning system, and its weight in a distributed collision avoidance solution. Real tests have been carried out using on-board prototypes, with the aim of emphasizing key performance factors. Main objectives of this paper are:

- to ascertain the requirements of CASS's regarding its main two subsystems, navigation and communication,
- to analyze current solutions in the literature and address main CASS feasibility problems,
- to identify a feasible solution for communication and navigation units in the case of study,

- to analyst cellular network (CN) potential in vehicular communications and its feasibility in a CASS,
- to determine sensors contribution to the navigation subsystem according to the CASS needs,
- to validate the prototype results taking into account CASS requirements.

The paper is organized as follows: Section 2 analyzes existing works in collision avoidance systems and performance evaluation. Section 3 treats the different architectural elements of a CASS, and pays a special attention to communication and navigation subsystems. Section 4 describes the on-board unit designed for the tests, and analyzes the results obtained from real tests carried out over several traffic environments. Finally, Section 5 concludes the paper.

2 Related work

It has been stated that several technologies have been considered in the literature to deal with the requirements of a collision avoidance system. Radar sensors are one of the most extended information sources for obstacle detection in autonomous collision avoidance systems. In (Shen, S. et al., 2006) a radar-based tracking architecture enables the object vehicle to predict collisions in highways. A similar system is described in (Jamson, A.H. et al., 2008), where a study of the impact of such systems in drivers has been made, taking into account realistic scenarios through a simulator. As this work states, the usefulness of the forward collision warning system used is indisputable under any environment, and independently of the driver profile. Vision-based systems are also applied over autonomous CASS (Toulminet, G. et al., 2006). However visibility problems can degrade the performance of the system. In order to deal with this problem, hybrid solutions based on both radar and vision sensors have been developed (Amditis, A. et al., 2005).

Regarding distributed collision avoidance systems through wireless communications, many works can be found in the literature. In (Misener, J.A. et al., 2005), for example, a cooperative CASS which uses 802.11b V2V communications is given. This work presents a complete prototype where the human-machine interface (HMI) has been completely developed and tested in field trials. Ueki, J. et al. (2005) proposes another CASS based on 802.11b, and give different approaches to detect a crash, sharing state information. Authors also include a study of 802.11 transmission problems in urban canyons, which concerns the purposes of the current paper. In (Shladover, S.E., 2005) and (ElBatt, T. et al., 2006) a dedicated short range communication (DSRC) specification is used in collision avoidance systems. The latter evaluates the network performance in terms of latency and probability of reception of packets, according to several traffic conditions. The problem of routing an eventual traffic incidence through the network, where the subject vehicle is not in charge of inferring a potential collision, is evaluated in (Biswas, S. et al., 2006). Authors demonstrate how the propagation delay of the multi-hop network affects the CASS performance at some hundred meters of a collision, propoking new crashes in a convoy of vehicles.

Some authors that describe some performance issues of both communication and navigation subsystems in a CASS are (Ammoun, S. et al., 2006; Ueki, J. et al., 2004), although a detailed study of these problems is not given. (Korkmaz, G., Ekici, E., 2006) includes a deeper study about the impact of positioning problems over a location-based V2V routing protocol. Sengupta, R. et al. (2007) evaluate the navigation system used in a CASS, which consider, as our proposal, an extended Kalman filter to integrate information from several sensors. However this analysis is not directed to the CASS performance, and communication issues are not teated in detail. In (Tan, H., Huang, J., 2006), the performance of the positioning system is evaluated over the model used to predict a collision, which estimates future trajectories of surrounding vehicles. An extended Kalman filter is also used to improve the differential GPS navigation system. The impact of communication issues in the CASS performance is further considered by the authors in (Huang, J., Tan, H., 2007). Nevertheless, in these two works the communication network has been simulated, and therefore the conclusions achieved are limited.

Our work, in contrast to the previous ones, is focused on the inherent performance problems of both communication and navigation subsystems over real scenarios. For that purpose, an intensive analysis of the current literature in the field has been enriched with field trials using an on-board prototype. Different traffic environments have been chosen, obtaining further conclusions of the performance results. Furthermore, novel ideas have been proposed to improve the whole system performance. The communication system considered is based on cellular and peer to peer networks, and, to the best of our knowledge, there are no previous solutions similar to our design, although a recent work supports the ideas presented in this paper (Rybicki, J. et al., 2007). The navigation subsystem integrates information from several inertial sensors, in order to guarantee localization in conditions of lack of GPS coverage. The usefulness of position integrity for CASS applications is also explained, and an innovative integrity calculation is presented.

3 System design

A distributed collision avoidance system enables the vehicle to dodge potential crashes by means of communication technologies and on-board sensors. Since most of the traffic fatalities are caused by human errors, the support of a collision warning system may decrease the number of injures in roads. To achieve this, some **general considerations** related to CASS design must be taken into account.

- The integration of a collision avoidance system must deal with the **driver acceptance** (Jamson, A.H. et al., 2008). Distracting warnings and automatic control actions (eg. brakes), when considered, should not interfere with normal driving operation. A reasonable goal is to design a unobtrusive system which prevents collisions or reduces the severity of the unavoidable ones (Seiler, P. et al., 1998).
- The level of cooperation among vehicles. Since CASS solutions can detect potential crashes by predicting future trajectories of vehicles (Huang, J., Tan, H., 2007), the exchange of positioning and kinematic information results crucial.
- A distributed CASS should be capable of propagating eventual incidences, and not only rely on collision prediction. In such systems the effective propagation of warning messages along the network is a key issue (Biswas, S. et al., 2006).

Independently of the concrete system design, most of the CASS solutions have in common an equivalent **high-level architecture**. Fig. 1 shows the general block diagram of a generic CASS. Here, vehicles maintain a communication channel with the traffic environment in order to warn the driver about dangerous conditions. As can be seen, the architecture is composed of four main elements. The communication module is in charge of connecting the system with surrounding vehicles (and possibly the infrastructure). The navigation module provides positioning and pose information of the subject vehicle, which is shared with the rest of vehicles. By means of this data exchange, the system logic is capable of detecting or processing a collision state, and warn the driver through the human machine interface (HMI), or directly perform a control action. Current work presents a cellular network-based alternative to 802.11 solutions for the communication module. The navigation subsystem designed is based on GPS but, as it is further explained, it is hybridized with others sensors in order to assure a reliable operation under unfriendly environments. Before explaining this on-board architecture, next sections give a generic analysis of common performance issues of communication and navigation subsystems.

3.1 Communication subsystem

Vehicle communications are more and more integrated in road safety solutions. However, up to now, only fleet management and tracking systems solutions can be found in the market. In last years the research community has been specially interested in architectures which, very far from a simple CN connection with a central station, use novel vehicle to vehicle and vehicle to infrastructure (V2I) communications technologies to improve the traffic efficiency and safety. Collision avoidance systems play an important role in such developments. They use V2V communications to route messages among vehicles, usually through vehicular ad-hoc networks (VANETs).

Regardless of the communication technology used, there are a set of quality parameters that must be taken into account in a vehicular network architecture. The network throughput and, overall, the availability and the edge to edge latency must be seriously attended in safety applications. In spite of the most of the vehicular network solutions in the ITS world are VANET and 802.11-based, our work, as it is further explained, is centered on a novel platform based on cellular networks. Both VANET and CN technologies are considered in the following subsections with the aim of analyzing the most important factors in vehicular communication performance.

3.1.1 Communication technology

Among all communication technologies considered in the vehicle domain (Nolte, T. et al., 2005), the most extended technology in V2V is 802.11 through VANET solutions. In collision avoidance applications, where it is necessary to receive a continuous information flow from close vehicles, the propagation delay is a key issue (ElBatt, T. et al., 2006). Nevertheless, a low delay in near vehicle to vehicle patterns does not imply a good performance when services notify unsafe situations (a car crash, icy surface, etc.) along the network. This way, not only one-hop traffic, but also multi-hop patterns must be considered in the performance of VANET approaches (Yousefi, S. et al., 2007).

On the other hand, regarding CN, recent improvements in operators' infrastructures (UMTS Forum, 2006) encourage us to consider CN not only in V2I, but also in V2V communications. The Universal Mobile Telecommunications System (UMTS) offer new capabilities which clearly improve classical GSM networks. According to recent studies (Wewetzer, C. et al., 2007), the usually obtained latencies of some hundreds of milliseconds in CN are too high to send a critical notification to an adjacent vehicle. However, if we consider distances from some hundred meters, current UMTS technology is able to give propagation times even better than some multi-hop-based VANET approaches, according to our tests.

3.1.2 Network availability

Network availability is one of the main drawbacks of CN systems. In VANET designs, a physical infrastructure is not necessary due to the inherent decentralized design. Regarding CN, operators do not offer the same service over the entire terrestrial surface. In urban environments, CN coverage is excellent, due to the vast amount of base stations where the mobile terminal can connect. In rural locations, however, CN deployment is poor, or even null in some places. This way, a vehicle equipped with a VANET system always can emit messages because the vehicle itself is part of the "infrastructure", but in CN approaches, the availability is a key issue.

In CN connections, it is also important to differentiate between two important concepts regarding network availability: coverage and capacity. Coverage can be understood as the possibility of the mobile terminal to use the network, because in this exact location an operator has deployed the necessary infrastructure. However, even under good coverage, the user can be rejected to establish a call or a data connection if the capacity of the network has been exceeded. Depending on several technological issues, such as modulation, frequency allocation, time slot scheduling, etc., this effect has a different behavior. This way, the number of users who are concurrently using the network also restricts the CN availability.

3.1.3 Mobility effects

Apart from potential access to the network, some problems arise in both VANET and CN technologies due to mobility effects. In (Wewetzer, C. et al., 2007), experimental evaluations give real results of these effects. In 802.11 transmissions, the distance between sender and receiver is an important factor, the more the distance the smaller the probability of reception of packets. In CN, handoffs between base stations are also important, due to potential decrease of performance in the process. If the mobile terminal is moving at locations far away from the UMTS Node B without performing a handoff, poor latency and throughput results can be obtained (Alexiou, A. et al., 2004).

Nevertheless, the distance between two physical edges in the communication is not the only noticeable effect of mobility. Interference with other radio equipments in the case of VANET should also be considered, due to the wide usage of the 802.11 frequency spectrum (Wewetzer, C. et al., 2007). The presence of the terminal at locations with bad orography features could also cause communication problems in both VANET and CN systems. Other external factors, like communication block due to the rest of vehicles or buildings are considered in realistic mobility patters for VANET solutions (Naumov, V. et al., 2006). More specifically, mobility patters with includes realistic urban considerations should pay attention to streets layouts, traffic behavior, independent vehicular motion, average speed, etc., which affect the network performance (Mahajan, A. et al., 2007; Ueki, J. et al., 2005).

3.1.4 Routing protocols

In VANET solutions, there are multitude of routing protocols in the literature. In collision avoidance systems, where tracking the surrounding vehicles is important, the most usually considered strategy is the broadcast (ElBatt, T. et al., 2006). However, when multi-hop transmission of critical information is considered (Biswas, S. et al., 2006), the complexity of the routing layer grows. At this point, two main types of routing protocols inherited from common ad-hoc networks arise: proactive and reactive protocols. In proactive protocols the multi-hop route is known in advance, due to periodical messages are exchanged between nodes to maintain the network topology. Reactive protocols calculate the route at the moment of requiring the network. It is clear that depending on the protocol design and the network configuration, the performance will be different. (Naumov, V. et al., 2006) includes an evaluation of the first packet delay over several protocols and scenarios, which is an important metric in multi-hop solutions. In (Biswas, S. et al., 2006), an interesting study about the propagation of safety messages using a multi-hop VANET is considered in terms of latency and reaction time of the driver. As this work shows, some collisions could arise at vehicles located 200 m. behind the transmission source and further on, due to transmission delays. Our CN-based system can solve these problems, as it is shown in the tests.

In the CN case, the situation is much more established. There are a set of low level routing protocols used at physical and MAC layers between the different elements of the network infrastructure. Several works study the impact of TCP/IP protocols over CN (Landman, J., Kritzinger, P., 2005; Alexiou, A. et al., 2004), and emphasize the problems of TCP over a the non-wired transport channel in situations where coverage is not good.

3.1.5 Penetration rate

The problem of penetration rate is well-known in VANET solutions. These require the presence of enough equipped vehicles to route messages across the network (Wisitpongphan, N. et al., 2007). Although a low penetration rate is obviously a problem in safety of life applications, such as collision avoidance, an excess of equipped vehicles also arises transmission difficulties. Due to the wireless network has a maximum theoretical capacity (Gupta, P., Kumar, P.R., 2000), when traffic density substantially increases, communication performance degrades (Naumov, V. et al., 2006). In CN, situations of dense traffic also present a problem. In these cases, a poor performance can be obtained when the time slot scheduler need to serve so much users (Landman, J., Kritzinger, P., 2005).

Solutions to penetration rate problems in VANET can be found in a better usage of network resources at the routing layer (Naumov, V. et al., 2006). At the physical level, decreasing interference levels can also alleviate the problem (Torrent-Moreno, M. et al., 2006), with the aim of decreasing packet collision rates.

3.1.6 Vehicle speed

Vehicle speed has a direct effect in topology change frequency (Wisitpongphan, N. et al., 2007). Although the fragmentation problem is a direct consequence of vehicle speed, high mobility rates in highway can be used to forward packets in the opposite direction, to reduce propagation time and fragmentation at the same time (Agarwal, A. et al., 2007).

The speed is also a noticeable issue in cellular networks (Litjens, R., 2002). At the physical level, effects such as Doppler shift, Rayleigh fading and multipath propagation limit the maximum bit rate allowable in CN at high speed. At link level, handoff issues must be considered. When a mobile terminal roams from one coverage cell to another, a handoff process is carried out. This process is mainly performed attending to the signal strength with the base station. Several types of handoff exist, although they can be summarized in soft and hard handoffs. Soft handoffs do not imply any significant change in the quality of service offered, but in hard handoffs data losses can even appear. Because the handoff process takes time (depending on the type), vehicles at high speed could have problems in places where the base station density is too high. For this reason, a high rate of base stations at highways is favorable, apart from the obvious reduction in deployment costs.

3.2 Navigation subsystem

Car navigation systems currently available in the market usually employ a single GPS receiver and digital cartography for map matching purposes. This simple combination brings many possibilities at a low cost, although some problems arise when high performance is demanded. To mitigate these problems, different sensors can be included in the on-board equipment (OBE) of the vehicle, such as GLONASS (Global Navigation Satellite System) and SBAS (Satellite Based Augmentation System) capable receivers, INS (Inertial Navigation Systems), and odometry captors. To integrate different sensors in a unique navigation unit, many options are available in the literature based on extended Kalman filters (Carlson, R., et al., 2002; Toledo-Moreo, R., et al., 2006), neural networks (Wang, J., et al., 2005), particle filters (Yang, N., et al., 2005; Gustafsson, F., et al., 2002) or sigma point filters (Shin, E., et al., 2007; Merwe, R., et al., 2004).

The performance of a navigation system dedicated to collision avoidance purposes must be much higher than those oriented to travel guidance and orientation (Toledo-Moreo, R. et al., 2007). Four parameters must be attended: accuracy, coverage, continuity and integrity. These four features and the effects of using aiding sensors to improve the system response are discussed next. From this analysis, it can be concluded that the inclusion of sensors with different features in the navigation unit may be the key to achieve high levels of performance in every aspect.

3.2.1 Accuracy

The accuracy of a navigation system can be defined as the degree of precision of its pose estimates as compared to actual values. For collision avoidance applications based on information exchange among vehicles, this feature becomes crucial, since the system relies on the knowledge of the position, orientation, velocity, etc. of the ego-vehicle and the rest involved in the scene. Solutions based on the estimation of TTC (Time To Collision) and TTR (Time To React), such as (Hillenbrand, J. et al., 2006; Ammoun, S. et al., 2006), must take into account the estimated values of accuracy in the vehicle pose.

Commonly used single GPS receivers supply position with an accuracy of 6–10 m. within the 95% of the fixes (assuming Gaussian distributions). Some of these receivers provide a number of accuracy parameters based on the geometry of the satellite signals used for the solution, such as the GDOP (Geometry Dilution Of Precision) measurements. The HDOP (Horizontal Dilution Of Precision) is specially considered in road applications, due to the relevance of the horizontal plane. Errors in the pseudorange values are not considered, and therefore the GDOP parameters only represent a part of the actual value of the accuracy error. These errors can be classified into two groups: common mode and non-common mode errors (Grewal, M.S. et al., 2001). Common mode errors are ionospheric, tropospheric, clock, and ephemeris errors. Non-common mode errors are caused by multipath effects and the noise in the receiver. While the latter depends on the very concrete position of the receiver and its local environment, common mode errors can be estimated and corrected based on the error calculations obtained in reference stations, if we assume that their value remain similar within a certain area. This is usually called differential GPS or DGPS, and is the basis of the SBAS. The European Geostationary Navigation Overlay System (EGNOS) provides corrections to those receivers capable to understand its messages, through geostationary satellites, what improves the horizontal position accuracy till 1–2 m. for the 95% of the fixes (Lucas, R., 2005).

The influence of the Russian GLONASS in the accuracy of the navigation has not been found significant in most of the studies of the current literature, although different experts provide different results depending on the test area (Toledo, R., 2005; Bruyninx, C., 2006; Kuzin, S., et al., 2006; Zinoviev, A., 2007). This is probably due to the a priori more dedication of GLONASS to higher latitudes. On the other hand, although the use of dual frequency GPS receivers improve the position accuracy until ranges of 0.1–0.5 m (Hein, G.W., 2000), prices are still not competitive for cars.

Finally, according to the literature, inertial and odometry sensors appropriate for car navigation (low cost MEM based units) cannot improve the accuracy of GNSS sensors when these are operational. Its accuracy in situations without GNSS coverage decreases as time goes by, due to the integration process required to obtain position from the acceleration measurements, and can be characterized.

3.2.2 Coverage

The data coming from four satellites (at least) are necessary to compute a GPS position, although collision avoidance support applications for cars usually focus exclusively on horizontal movements, what simplifies the position calculation. The appearance of obstacles such as trees, buildings, tunnels or near trucks may impede the direct view of satellites, provoking a total loss of GPS position or its significant degradation.

The addition of GLONASS may increase the number of satellites locked by the receiver, specially at higher latitudes (Titterton, D. H., Weston, J.L., 2004), since GPS receivers work better at mid latitudes. However, in places with very poor satellite visibility, such as tunnels, a solution exclusively based on GNSS cannot guarantee total coverage (Toledo, R., 2005). On the other hand, inertial measurements, accelerations, and rates of turn in the body-frame of the vehicle, do not depend on visibility conditions or any external reference, being its coverage performance total.

3.2.3 Continuity

Continuity can be understood as the capability of the system to provide uninterrupted pose estimates. Although in normal operation GPS service is uninterrupted, providers do not guarantee this, and non-schedule constellation failures can stop the system function.

Extra sensors must be considered to supply continuity in the positioning subsystem operation. The nature of the inertial sensors assures pose estimates, only constrained by power or mechanical accidents during operation. Moreover, the usual working frequency for an inertial sensor is 100 Hz., at least ten times higher than GPS receivers, making high dynamic motions also detectable by the navigation unit.

3.2.4 Integrity

Integrity can be defined as the capability of the system to detect performance anomalies and warn the user that the system should not be used. Currently, two different approaches to provide integrity in GPS-based navigation systems are Receiver Autonomous Integrity Monitoring (RAIM) and the use of SBAS. The RAIM technique, which is based on an over-determined solution to evaluate its consistency, requires a minimum of five satellites to detect a satellite anomaly and six or more to be able to reject it (Kaplan, E.D. , Ed.). Unfortunately, this cannot be assumed in usual traffic situations, especially in cities. The use of SBAS allows one to have integrity information through the geostationary satellite. SBASs offer to their client equipments the possibility of calculating an indicative value of position integrity that considers pseudorange errors, by means of the Horizontal Protection Level, or HPL_{SBAS}. These messages can be obtained in Europe via the geostationary satellite, by using EGNOS, or via Internet, by means of Signal In Space through Internet (SISNeT) (Toran-Marti, F., Ventura-Traveset, J., 2004). In (Santa, J. et al., 2006), the HPL_{SBAS} parameter is proven to be of high importance in liability critical applications for road transport.

However, since integrity parameters based on GNSS are provided by means of satellite signals, the same coverage and continuity issues previously described can be applied now. Moreover, some of the assumptions done in the calculation of the HPL values cannot be guaranteed in a road environment. The use of an alternative integrity parameter, uninterrupted and with total coverage is advisable for collision avoidance support purposes. In (Boysen, P.A., Zunker, H., 2004), the HTL (horizontal trust level) value is presented as a confidence estimator of the vehicle positioning, based on all the sensor variances, and not only on GNSS indexes. This HTL has been successfully applied in (Toledo, R., 2005). In this occasion, however, we have defined HIT (horizontal integrity threshold), a new integrity parameter more in accordance to the considered CASS specifications.

4 Experimental set-up

The previous analysis of communication and navigation issues in collision avoidance solutions, has been considered in the development and test of both subsystems over a real prototype. This section deals with the design details of the on-board unit, and analyse main results obtained from several field trials. Communication tests, performed with a CN-based approach, point up the effects that real traffic and environment conditions provoke in the communication performance. Potential benefits of the communication architecture are also addressed, taking into consideration the requirements of collision avoidance support applications. Navigation tests cover main aspects presented in the previous section from the point of view of the extra sensors contribution. A brief description of the on-board hardware and software platform of our prototype is firstly given.

4.1 Prototype vehicle and on-board unit

A real prototype of the on-board unit has been created and tested, using a car widely sensorized at the University of Murcia. Fig. 2 shows this car and the main components of the on-board unit. The vehicle has been enhanced with odometry captors, a gyroscope, an accelerometer, and two GPS receivers. Serial buses communicate the sensors with the PC via RS-232 and the Controller Area Network (CAN) bus. A SBAS capable Trimble Ag 132 GPS and an Ashtech GG24 GPS/GLONASS receiver are installed in the car. An embedded computer of VIA is the central processing unit, with a Linux Fedora Core 4 operating system, and a Java Virtual Machine 1.5. This computer is located at the rear part of the passenger's seat. As can be seen, the dashboard has also been modified as well to install a LCD monitor. Regarding communications, a cellular network PCMCIA transceiver has been used. The model is a Huawei E220, which allows UMTS data connections.

4.2 Communication tests

The communication architecture considered for its evaluation in a collision avoidance system is based on cellular networks. Details in depth about the communication subsystem can be found in (Santa, J., Gomez-Skarmeta, A.F., 2008).

The network infrastructure uses a P2P approach over the cellular network basis to enable vehicles to receive and send contextual information. Fig. 3 shows a general diagram of the proposed communication architecture. Traffic zones are organized in coverage areas, each one using different P2P communication groups. These zones are logical areas which do not have to fit in the cellular network cells. Information about the geometry of each area is maintained in the Group Server (GS) entity. Vehicles are able to move from one P2P group to another through a roaming process between coverage areas. This roaming is based on the vehicle location, provided by the navigation subsystem. Information about areas is received from GS using a TCP/IP link over UMTS. A local element called Environment Server (ES) manages special messages inside the area. Event notifications are sent and received by service edges, located either at the vehicle or at the road side (Environment Servers). Messages are encapsulated in P2P packages, and two different techniques of emission have been developed. Consequently, P2P messages can be broadcasted in the area or sent to a specific vehicle.

This network architecture has been developed for both vehicle and road side edges. This way, software entities at the road side execute over a a Linux-based system with an AMD Opteron multiprocessor architecture, and the described on-board unit contains the vehicle implementation. For the message propagation tests, apart from the described car, an extra laptop was used inside a second vehicle. This computer uses a Windows XP operating system with Java 1.5. An extra Novatel OEM3 receiver have been used and, both the prototype vehicle and the common one use the GPS sensor for positioning and time synchronization. A software which uses this network platform has been installed to send messages at a fixed rate of one per second; the other on-board unit inside the second vehicle receives these messages and saves a log. Both vehicles have been closely driven through the test circuits. A ZTE MF620 transceiver, and the Huawei E220 one in the prototype vehicle, have been used to connect the two terminals to the cellular network. Both devices support HSDPA (High Speed Downlink Packet Access), which improves the UMTS performance in terms of throughput and delay, as can be noted if the results obtained are compared with the ones shown in (Santa, J., Gomez-Skarmeta, A.F., 2008).

Next sections give latency results obtained in real tests carried out at the surrounding of the University of Murcia. Table 1 summaries some features about the three followed circuits, and Table 2 includes information about several tests performed over them, which start at the same point (Computer Science Faculty). Through the latency results obtained in the tests, a number of conclusions can be deducted according with the traffic environment.

4.2.1 Availability analysis

Fig. 4 shows the network performance following the C1 circuit in the test T3. As can be noted, the delay is bounded bellow 400 ms. along most of the circuit.

However network delay problems appears in the middle of the path, caused by coverage problems. Inside the university bounds the coverage is good, due to the presence of a base station at the central part; however, the problematic stretch of the path belong to a small urbanization far away of the base station. Next problems arise when the vehicles drive around the northeast edge of the campus, hidden from the base station by a small hill. After that, the path ends at the initial point.

The effect of a progressive lack of coverage can be seen in Fig. 5, that shows test T5, where the vehicles drive along the C2 path. The vehicles start the circuit at the University facilities, and arrive to a point far away from the base station coverage. At this point the connectivity is lost, and the last packet is received with a delay of more than three minutes. It can be noticed an interesting effect related to the continuous peaks observed even at the beginning of the travel. Because the path begins at a medium coverage location, and the vehicles start to drive far away the base station, the channel quality feedback send by the vehicle is not good. Hence, the UMTS channel does not become stable, as occur in the previous test T3. HSDPA includes this feedback system to dynamically modify modulation features of the data channel depending on the signal quality (3GPP, 2007).

In order to solve availability problems of CN, the only solution seems to be the improvement of the operator infrastructure through a deeper study about the number of mobile terminals which usually connect to the UMTS network at these locations. In process improvements of operators for making the most of the spectral efficiency can also impact on system performance.

4.2.2 Mobility issues

In cellular networks, mobility effects are noticeable due to the variability of signal quality. Even in good coverage conditions, and without any apparent problem, small variations in transmission delay are noticeable, as can be seen in Fig. 4. These small variations can be turned into large jitter if the UMTS scheduling algorithm cannot attend efficiently the terminal, as can be seen at the beginning of test T5 (Fig. 5).

Handoffs between base stations, and the “ping-pong” phenomenon which arises when the mobile terminal connection is alternating between different base stations, is a key problem in CN. Fig. 6 includes the test T10, where the mobile terminal cannot stabilize the network connection (like in T5), because the vehicles start to drive around a hill until reaching a big urbanization located at the north part of the campus. At this location, a new base station is detected and, although the one located at the campus is closer, the hill hides the signal reception. The bad operation of the network subsystem in the first third is due to handoffs between these two base stations, and the poor performance obtained if the connection to any of them is established. Orography problems could be solved again spreading more base stations, in order to deal with performance requirements of critical ITS services, such as collision avoidance.

4.2.3 CN eventual disconnections and delay continuity

An important issue in CN communications is the packet drop ratio. In all the tests carried out, no packet loss were appreciated. This is because under lack of UMTS coverage, and when the network start to loss packets, the P2P protocol used over the TCP/IP stack directly give up to route messages (as it is noticeable in test T5). The JXTA P2P protocol used does not appear to correctly work under eventual disconnections. This fact reveals a problem which has to be solved in P2P protocols over cellular networks, in order to consider this technology for high reliable services, such as collision avoidance. Further researching is necessary in this line, as it is proposed by Rybicki, J. et al. (2007).

Nevertheless, the suitability of the network architecture presented is demonstrated over a common environment, as the one used in the tests carried out over the circuit C1. Here, the latency results under good coverage conditions, and without availability problems, are around 400 ms. in most of the cases, as can be seen in Table 2. The application of such architecture in a collision avoidance system based on eventual transmissions of warning messages along the road, is possible with the obtained results. Although the transmission delay to a near vehicle is higher than those given by 802.11 solutions, as the distance between the source and the destination vehicle increases, a CN-based architecture becomes even preferable than some multi-hop solutions (Biswas, S. et al., 2006). Cellular networks can maintain almost the same propagation latency over a huge area.

4.2.4 Capacity problems in crowded areas

Test T4 analyses capacity problems of CN without losing connectivity in the first low coverage area of circuit C2. As can be seen in Fig. 7, three problematic zones can be extracted from the results, according to the peaks observed. The first one is obtained between messages 280 and 400, when the vehicles pass under a highway with dense traffic and drives near it for several minutes. The next set of peaks (between messages 480 and 580) are obtained when the vehicles passes over another highway. Finally, the highest peaks are found at the location where the connectivity was lost in test T5.

One consideration related to the capacity of the network which has not been taken into account up to now, is the time when the tests were performed.

Observing Table 2, if the same circuit is fixed, it can be noted a variation in the mean delay times obtained. During tests T1 and T2, the traffic density around the campus is medium, but increases until the maximum level at lunchtime. After that, the amount of connected users decrease around three o'clock (test T3), and then start to gradually increase due to the return to work of part of the university staff and students, as can be seen in test T11, T12 and T13. For the circuit C2, results reveal a worse performance in the afternoon, due to traffic jams in the two highways where the vehicles drive close. The presence of several shopping centers in the area, the Christmas period, the time close to a common end of the working day, and the fact that these highways are the access to the city of Murcia, are the main reasons of this problem. In tests carried out through the C3 circuit, the behavior is similar to C1 cases, because a half of the path is along the campus and the other half belongs to a stretch near a urbanization at work time.

4.2.5 Vehicle speed

The vehicle speed did not have a noticeable effect in the network performance, as can be seen in tests T11, T12 and T13. These tests were carried out through the C1 circuit at the maximum speed allowed on each stretch. The results of the network delay do not show big differences as compared to tests T1, T2 and T3. T11 and T3 were made at similar times of the day, and only 22 ms. more of mean delay were obtained. The results are in accordance with the expected performance. Because the density of base stations around the test place is low, the vehicle speed does not increase the number of handoffs per unit of time. Furthermore, it has been proven that vehicle speed is even favourable in some cases. In test T4 (Fig. 7), the small period of time in which the vehicles stay under bad network conditions is decisive in order to not lose connectivity, as occurred in test T5 (Fig. 5). In this last case an eventual traffic jam forced vehicles to stay for several minutes in a location of low coverage and high density of vehicles, what caused a connectivity loss.

In the future, the vehicle speed will be further analyzed, considering highway tests and higher speeds at urban locations, where the density of base stations provokes frequent handoffs. The physical channel with the base station has demonstrated to be suited to mobility scenarios, in contrast to common 802.11 technologies, and only handoffs and driving at locations far away from the base station imply serious mobility problems in CN communications.

4.3 Navigation tests

In this section the performances of different navigation sensors and configurations are tested and analyzed for the case of study, considering a DGPS/INS implementation. The estimated performance requirements for the navigation subsystem are assumed to be: a horizontal positioning error of 1.5 m. (it is expected that the system could distinguish road lanes), 99% of coverage and availability, and a frequency of the vehicle pose of 20 Hz or higher (capable to determine a road vehicle dynamics). In addition, the system should be capable to inform the user when the system should not be used (integrity) and must keep costs at the minimum.

4.3.1 GPS performance

Depending on the price of the GPS device, its position accuracy may typically vary from values of 25 m. to a few centimeters. A SBAS-capable GPS device has been selected, since these devices can currently offer values of standard deviation of 1 m., enough to fulfil the assumed requirement of 1.5 m. The use of more precise dual frequency receivers has been disregarded due to its excessive cost for a car application.

Details of the accuracy obtained in a test performed in a circuit of 6 km. with total GPS coverage are shown in Table 3. As can be seen, the mean error value in the 99% of the stamps (aimed availability), remains significantly lower than 1.5 m. However, the maximum error during the test, 1.2521 m., is not far from the proposed threshold.

Some other problems arise, such as the interruptions of the positioning due to signal blockages or low values in the satellite visibility angles. Furthermore, since GPS positions with accuracy indexes higher than the assumed threshold should not be accepted by the navigation system, all the GPS data that do not verify this constraint should be rejected, provoking more often GPS gaps.

To analyze the availability in a urban environment, we collected GPS data in the city of Murcia, accepting only the positions with an accuracy higher than a certain threshold. It is assumed for this test that the accuracy is given by the HDOP parameter, and the threshold was set to 3 m. In these conditions, GPS positions were only available during the 75% of the time. Although in highway scenarios this value usually raises up to 92%, we are still quite far from the assumed acceptable 99%, being tunnels, crossing roads and nearby trucks the most common reasons for gaps.

With respect to the positioning frequency, the GPS data was gathered at 5 Hz, what can be considered as low to determine the vehicle dynamics.

Concerning the provision of integrity, as it has been commented, GPS-based navigation can determine its value by means of the RAIM technique, using an over-determined solution. Although this technique can be found very useful in aerial navigation, where the coverage is usually good, we find its application in cars unfeasible, since the number of satellites in view may be lower in many occasions, and the assumptions valid for the aerial domain are often violated in our case.

4.3.2 SBAS and double constellation sensors contributions

A priory, the inclusion of SBAS and double constellation capabilities in the receiver may improve next features:

- The number of satellites locked by the receiver, and therefore the availability of reliable positions,
- More accurate positions due to the use of differential corrections,
- Position integrity values, such as the HPL_{SBAS} parameter.

With respect to the positioning availability, several tests were carried out with a double constellation GLONASS/GPS receiver in the same circuit that was mentioned in the previous section. The availability of positions with HDOP values equal or lower than 3 m. increased from a 75% until an 80% in the case of cities, and from a 92% till a 95% in highways. Despite of the improvements, it is advisable the inclusion of some other assistance sensors to ensure a better availability in time and space.

The use of positioning corrections through EGNOS has been found useful to improve the accuracy during our tests, obtaining mean values for the horizontal positioning error of 0.3–0.4 m, what even surpasses our expectations. However, since EGNOS messages are broadcasted by means of the geostationary satellite (PRN 120 in our tests), its availability is subject to many obstacles. To avoid this, SISNeT may be used to obtain these corrections through the Internet. In the tests performed in a combined scenario with urban and highway features, for a total of 20 km. and 2777 fixes, GPS positions were available a 93% of the circuit, being EGNOS available a 65%, and EGNOS/SISNeT an 89%. According to the results achieved by using EGNOS, it may expected a noticeable influence of GALILEO in the future satellite-based navigation. Nonetheless, the double constellation results obtained in our tests, encourage the use of aiding navigation sensors to cooperate with satellite navigation solutions for collision avoidance support.

Of special interest in the inclusion of SBAS is the capability to provide an integrity parameter for the positioning solution, the HPL_{SBAS}, and to inform the user whether the navigation system can be relied or not, anytime. The HPL_{SBAS} has been logged around the facilities of the University of Murcia.

The results achieved in this test are shown in the upper image of Fig. 5. As can be seen, a regular performance is obtained along almost all the test. The peaks in the HPL_{SBAS} are due to locations where the GPS visibility is low (see coverage graph in lower image). Changes in the satellite geometry affect the HPL_{SBAS} calculation. Steps as those at instants 1540 and 1730 s., appear due to changes in the error estimates of some satellites. When a new EGNOS message is received, individual corrections for several satellites are updated, varying the value of the HPL_{SBAS}. From instant 1820 s., the performance degrades mainly due to a poor reception of EGNOS messages. The visibility of the geostationary satellite is low in this area, and corrections become obsolete, provoking the linear increase which can be seen in the image.

4.3.3 Aiding motion sensors

Aiding sensors can compensate the GNSS navigation deficiencies, providing total availability and coverage at a value of accuracy that can be characterized.

Among the many possibilities for fusing the information coming from different sensors, we have implemented a set of extended Kalman filters with different vehicle models suitable for different dynamics. These filters are combined in one by using interactive multiple model (IMM) techniques. This allows to apply the model that better represents the vehicle behavior anytime, improving the filter solution as compared to single model solutions. Further details of the developed IMM-EKF filter and its results can be found in (Toledo-Moreo, R. et al., 2007). The kinematic model employed in the tests presented in this paper is a simplified bicycle model, in which the orientation of the acceleration and velocity are assumed to be equal. The results achieved using this model have been compared with implementations of unscented Kalman filters and some other Kalman filter based solutions reported in the literature, showing good performance.

The results obtained by the implemented multisensor filter during the same test of 6 km. presented in Section 4.3.1 are now shown in Fig. 6. In this case, several GPS masks have been simulated to evaluate the performance of the system under absences of satellite visibility. In Fig. 6(a) three masks of 2 s. each were applied. Although the 2-σ envelope increases noticeable, the errors during these periods remain with similar values as those obtained with GPS coverage, below 0.8 m. most of the time. Fig. 6(b) shows the positioning errors during the same circuit with simulated masks of 5 s. Still, error values do not augment significantly during the gaps. However, the confidence on the position, estimated by the value of the 2-σ envelope, exceeds the 2 m. with values higher than the 1.5 m. threshold proposed. In this case, the navigation unit should inform that the position may have unacceptable accuracy errors. Fig. 6(c) shows same situation under 10 s. masks. As expected, the accuracy is lower, reaching a maximum positioning error of 3.15 m. Table 4 summaries main error indexes for these experiments. As can be seen, the values obtained are very good as compared to some other solutions available in the literature, with mean values below 0.5 m. even with a GPS absence of 30 s. Fig. 6(d) shows the vehicle trajectories along a two-lane circuit. An ellipsis of confidence on the position defined by the value of 2-σ_x and 2-σ_y at every filter step, has been overprinted in solid blue. As can be seen, the assumed true reference lies into the ellipses, that consider the 95% of the values if normal distributions are verified.

The frequency of the inertial measurements is 100 Hz., what can be considered enough to estimate the vehicle dynamics. Furthermore, since there is no need of any external reference, it can asserted that the availability is total. Nonetheless, due to the degradation of the positioning value in the periods of inertial navigation, the user should be continuously informed about the integrity of the system performance. For that purpose, our navigation system provides the HIT parameter, whose value depends on the sensor variances and the covariance of the state anytime. Monitoring the system integrity with the HIT have three main benefits, as compared to RAIM or $\mathrm{HPL_{SBAS}}$:

(1) It supplies uninterrupted integrity information, even during the absences of GPS and EGNOS signals,
(2) Its value depends on the vehicle dynamic state anytime, and it is not affected by external factors,
(3) It is representative of the whole multisensor solution, as compared to satellite-based integrity, in which only the errors in the satellite positioning are considered.

On the other hand, main disadvantage can be its dependency on the filter tuning process, what can make difficult the comparison of approaches with different filter adjustment.

The value of HIT can be calculated following:

$$\mathrm{HIT} = 3\sqrt{\frac{\sigma_x^2+\sigma_y^2}{2}+\sqrt{\left(\frac{\sigma_x^2+\sigma_y^2}{2}\right)^2+\sigma_{xy}^4-\sigma_x^2\sigma_y^2}}$$

where σ_x, σ_y and σ_{xy} are the covariance values of the filter. The factor 3 represents a probability of mis-detection close to 0.01. More details of its calculation can be found in (Toledo-Moreo, R., et al., 2008).

In Fig. 7, the value of the HIT during a test with 9 simulated GPS masks of 3 s. each, has been compared to the position error and the 2-σ envelope. As it was expected, the HIT value strongly depends on the GPS availability, resulting a convenient confidence estimator under any circumstance of the trial. During the periods of GPS coverage, its value never surpassed 1 m., becoming higher when the confidence on the positioning must decrease, and being consistent with the errors obtained. In our tests, the percentage of errors within the HIT area remain over the 99%.

5 Conclusions

An analysis of the communication and navigation subsystems, essential for main ITS applications, and specifically for cooperative collision avoidance support systems, has been made. Main issues addressed in the paper can be summarized as:

- State of the art in the subsystems oriented to the problem under consideration,
- Feasibility requirements of communication and navigation for cooperative collision avoidance support,
- Suitability of networks and sensors,
- Validation of a prototype including both subsystems and tested in common unfriendly conditions,
- Provision of an integrity value to determine the reliability of the system for the intended application.

Regarding to communication issues, an exhaustive study about the key performance factors of VANET and cellular networks through literature has been made. This study presents an original point of view in contrast to partial performance studies carried out in VANET literature. Current deployment status of CN, and its feasibility in vehicular environments overall, have been specially considered. In this line, a novel CN-based communication architecture has been proposed and tested. P2P networks are applied over the CN basis in order to create a group-based communication approach. Such groups bound the message propagation in the CN. This network design is able to give good performance results for implementing collision avoidance systems where vehicles use the communication channel to avoid eventual crashes on the road. Several key factors are taken into account for choosing the test places, in order to deal with stressful communication conditions. The network availability has been proved to be a key issue for CN data connections, and it has been treated in terms of coverage and maximum capacity of the network. Mobility effects have been exemplified through the set of tests, and orography and handoff problems have been analyzed at specific locations. Due to the rich set of tests, the time and date of tests have been found as a key factor in the network performance expected. New tests are planned in pure urban environments, in order to analyse the effects of frequent handoffs, and at extreme speeds, to cover a realistic case of highway crash. Additionally, a further study of P2P reliability under frequent disconnections is also considered to improve the reliability of the system. Nevertheless, current operator infrastructure is still found as the main limitation for the implementation of a more efficient collision avoidance system, according to obtained results.

A navigation subsystem based on a combination of motion and GNSS sensors has been found the most appropriate solution. A SBAS-capable GPS sensor is considered in our prototype. The addition of inertial sensors and speedometers gives benefits in three of the four navigation features under consideration: coverage, availability and integrity. Although in good conditions of satellite visibility, aiding sensors cannot improve the accuracy of the system, they provide excellent estimators for rejecting degraded GNSS positions, for example due to multipath effects. In addition, since inertial measurements do not need any external reference, they are not affected by GPS jamming, blockages or any other disturbances. However, the need of an integration process to compute the position from acceleration measurements diminishes the accuracy of the positioning during GNSS gaps. A study of how this influences the system performance is presented in the paper. The results show that the most common short interruptions do not impede a safe estimation of the navigation system. However, as time goes by, these drifts become higher. For this reason, our approach includes the provision of an integrity parameter capable to represent the navigation subsystem performance anytime.

Acknowledgements

The Authors would like to thank the Spanish Ministerio de Fomento and the Ministerio de Ciencia e Innovación for sponsoring these research activities under the grants FOM/2454/2007, TIN2008-06441-C02-02 and AP2005-1437. Last one in frames of the FPU program. This work has been carried out inside the Intelligent Systems group of the University of Murcia, awarded as an excellence researching group in frames of the Spanish Plan de Ciencia y Tecnología de la Región de Murcia (04552/GERM/06).

References

3rd Generation Partnetship Project, 2007. High Speed Downlink Packet Access (HSDPA) Overall Description. 3GPP TS 25.308. 3GPP, Valbonne.

Agarwal, A., Starabinski, D., Little, T.D.C., 2007. Exploiting Downstream Mobility to Achieve Fast Upstream Message Propagation in Vehicular Ad Hoc Networks. Mobile Networking for Vehicular Environments, Anchorage, 6–12 May, pp. 13–18.

Alexiou, A., Bouras, C., Igglesis, V., 2004. Performance Evaluation of TCP over UMTS Transport Channels. International Symposium on Communications Interworking, Ottawa, 29–1 November/December.

Amditis, A., Polychronopoulos, A. Floudas, N., Andreone, L., 2005. Fusion of infrared vision and radar for estimating the lateral dynamics of obstacles. Information Fusion 6(2), 129–141.

Ammoun, S., Nashashibi, F., Laurgeau, C., 2006. Real-time crash avoidance system on crossroads based on 802.11 devices and GPS receivers. IEEE Intelligent Transportation Systems Conference, Toronto, 17–20 September, pp. 1023–1028.

Biswas, S., Tatchikou, R., Dion, F., 2006. Vehicle-to-Vehicle Wireless Communication Protocols for Enhancing Highway Traffic Safety. IEEE Communications Magazine 44(1), 74–82.

Boysen, P.A., Zunker, H., 2004. Low Cost Sensor Hybridisation and Accuracy Estimation for Road Applications. ESA Conference Navitec 2004, Noordwijk, 8–10 December, pp. 541–548.

Bruyninx, C, 2006. Comparing GPS-only with GPS+GLONASS positioning in a regional permanent GNSS network. GPS solutions DOI 10.1007/s10291-006-0041-9.

Carlson, C.R., Gerdes, J.C., Powel, J.D., 2002. Practical position and yaw rate estimation with GPS and differential wheelspeeds. International Symposium on Advanced Vehicle Control, Hiroshima, 9–13 September.

ElBatt, T., Goel, S.k., Holland, G., Krishnan, H., Parikh, J., 2006. Cooperative collision warning using dedicated short range wireless communications. International Workshop on Vehicular Ad Hoc Networks, Los Angeles, 25–30 October, pp. 1–9.

Grewal, M.S., Weill, L.R., Andrews, A.P., 2001. Global Positioning Systems, Inertial Navigation and Integration. John Willey & Sons, USA.

Gupta, P., Kumar, P.R., 2000. The capacity of wireless networks. IEEE Transactions on Information Theory 46(2), 388–404.

Gustafsson, F., Gunnarsson, F., Bergman, N., Forssell, U., Jansson, J., Karlsson, R., Nordlund, P.-J., 2002. Particle filters for positioning, navigation, and tracking. IEEE Transaction on Signal Processing 50(2), 425–437.

Hein, G.W., 2000. From GPS and GLONASS via EGNOS to Galileo - Positioning and Navigation in the Third Millennium. GPS Solutions 3(4), 39–47.

Hillenbrand, J., Spieker, A.M., Kroschel, K., 2006. A Multilevel Collision Mitigation Approach - Its Situation Assessment, Decision Making, and Performance Tradeoffs. IEEE Transactions on Intelligent Transportation Systems 7(4), 528–540.

Huang, J., Tan, H., 2007. Impact of Communication Reliability on a Cooperative Collision Warning System. IEEE Intelligent Transportation Systems Conference, Seattle, 30–3 September/October, pp. 355–360.

Jamson, A.H., Lai, F.C.H., Carsten, O.M.J., 2008. Potential benefits of an adaptive forward collision warning system. Transportation Research Part C 16(4), pp. 471–484.

Kaplan, E.D. (Ed.), 1996. Understanding GPS: Principles and Applications. Artech House, USA.

Korkmaz, G., and Ekici, E., 2006. Effects of Location Uncertainty on Position-Based Broadcast Protocols in Inter-Vehicle Communication Systems, Annual Mediterranean Ad Hoc Networking Workshop, Lipary, 14–17 June, pp. 152–159.

Kuzin S., Revnivykh S., Tatevyan S., 2007. Advances in Space Research, 39 (2007) pp. 1539-1544.

Landman, J., Kritzinger, P., 2005. Delay analysis of downlink IP traffic on UMTS mobile networks. Performance Evaluation 62 (1–4), 68–82.

Litjens, R., 2002. The impact of mobility on UMTS network planning. Computer Networks 38 (4), 497–515.

Lucas, R., 2005. ESA Projects on EGNOS Applications. Workshop on EGNOS performance and Applications, Gdynia, 27–28 October, pp. 55–76.

Mahajan, A., Potnis, N., Gopalan, K., Wang, A., 2007. Modeling vanet deployment in urban settings. ACM Symposium on Modeling, Analysis, and Simulation of Wireless and Mobile Systems, Chania, 22–26 October, pp. 151–158.

Merwe, R., Wan, E.A., Julier, S., 2004. Sigma-point Kalman Filters for Nonlinear Estimation and Sensor-Fusion: Applications to Integrated Navigation. AIAA Guidance, Navigation and Control Conference, Rhode Island, 16–19 August.

Misener, J.A., Sengupta, R., Krishman, H., 2005. Cooperative Collision Warning: Enabling Crash Avoidance with Wireless Technology. World Congress on ITS, San Francisco, 6–10 November.

Naumov, V., Baumann, R., Gross, T., 2006. An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces. ACM International Symposium on Mobile Ad Hoc Networking and Computing, Florence, 22–25 May, pp. 108–119.

Nolte, T., Hansson, H., Lo Bello, L., 2005. Wireless Automotive Communications. Euromicro Conference on Real-Time Systems, Palma de Mayorca, 6–8 July, pp. 35–38.

Rybicki, J., Scheuermann, B., Kless, W., Lochert, C., Fallahi, P., Mauve, M., 2007. Challenge: Peers on Wheels - A Road to New Traffic Information Systems. ACM International Conference on Mobile Computing and Networking, New York, 9–14 September, pp. 215–221.

Santa, J., Ubeda, B., Skarmeta, A.F.G., 2006. Monitoring the Position Integrity in Road Transport Using SBAS/EGNOS and Communication Issues. Location Magazine 2(1), 38–42.

Santa, J., Gomez-Skarmeta, A.F., 2008. Architecture and evaluation of a unified V2V and V2I communication system based on cellular networks. Computer Communications, 31(12), 2850–2861.

Seiler, P., Song, B., Hedrick, J.K., 1998. Development of a Collision Avoidance System. International Congress & Exposition, Detroit, 23–26 February, pp. 97–103.

Sengupta, R., Renzaei, S., Shladover, S.E., Cody, D., Dickey, S., Krishnan, H., 2007. Cooperative Collision Warning Systems: Concept Definition and Experimental Implementation. Journal of Intelligent Transportation Systems, 11(3), 143–155.

Shen, S., Hong, L., Cong, S., 2006. Reliable road vehicle collision prediction with constrained filtering. Signal Processing 86(11), 3339–3356.

Shin, E., El-Sheimy, N., Unscented Kalman Filter and Attitude Errors of Low-Cost Inertial Navigation Systems. Navigation Journal 54(1), pp. 1–10.

Shladover, S.E., 2005. Effects of traffic density on communication requirements for cooperative intersection collision avoidance systems (CICAS), San Francisco, 6–12 November.

Tan, H., Huang, J., 2006. DGPS-Based Vehicle-to-Vehicle Cooperative Collision Warning: Engineering Feasibility Viewpoints. IEEE Transactions on Intelligent Transportation Systems 7(4), 415–428.

Titterton, D. H., Weston, J.L., 2004. Strapdown Inertial Navigation Technology (2nd Edition). Institution of Electrical Engineers, London.

Toledo-Moreo, R., 2005. A High Integrity Navigation System for Vehicles in Unfriendly Environments. PhD. Thesis. University of Murcia, Murcia.

Toledo-Moreo, R., Zamora-Izquierdo, M.A., Gomez-Skarmeta, A.F., 2006. A Novel Design of a High Integrity Low Cost Navigation Unit for Road Vehicle Applications, IEEE Intelligent Vehicles Symposium, Tokyo, 13–15 June, pp. 577–582.

Toledo-Moreo, R., Zamora-Izquierdo, M.A., Ubeda-Miarro, B., Gomez-Skarmeta, A.F., 2007. High-Integrity IMM-EKF-Based Road Vehicle Navigation With Low-Cost GPS/SBAS/INS. IEEE Transactions on Intelligent Transportation Systems 8(3), 491–511.

Toledo-Moreo, R., Santa J. Zamora-Izquierdo, M.A., Bubeda B., Gomez-Skarmeta, A.F., 2008. A Study of Integrity Indicators in Outdoor Navigation Systems for Modern Road Vehicle Applications. IROS 2008 2nd Workshop on Planning, Perception and Navigation for Intelligent Vehicles.

Toran-Marti, F., Ventura-Traveset, J., 2004. The ESA SISNeT Project: Current Status and Future Plans. European Navigation Conference GNSS, Rotterdam, 16–19 May.

Torrent-Moreno, M., Santi, P., Hartenstein, H., 2006. Distributed Fair Transmit Power Adjustment for Vehicular Ad Hoc Networks. IEEE Sensor and Ad Hoc Communications and Networks, Reston, 25–28 September, pp. 479–488.

Toulminet, G., Bertozzi, M., Mousset, S., Bensrhair, A., Broggi, A., 2006. Vehicle Detection by Means of Stereo Vision-Based Obstacles Features Extraction and Monocular Pattern Analysis. IEEE Transactions on Image Processing 15(8), 2364–2375.

Ueki, J., Tasaka, S., Hatta, Y., Okada, H., 2005. Vehicular-Collision Avoidance Support System (VCASS) by Inter-Vehicle Communications for Advanced ITS. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences E88-A(7), 1816–1823.

Ueki, J., Mori, J., Nakamura, Y., Horii, Y., Okada, H., 2004. Development of vehicular-collision avoidance support system by inter-vehicle communications - VCASS. Vehicular Technology Conference Spring, Milan, 17–19 May, pp. 2940–2945.

UMTS Forum, 2006. 3G/UMTS Evolution: towards a new generation of broadband mobile services. White Paper, UMTS Forum, London.

Varaiya, P., 1993. Smart Cars on Smart Roads: Problems of Control. IEEE Transactions on Automatic Control 38(2), 195–207.

Wang, J., Yang, G., 2005. GPS-based Land Vehicle Navigation System Assisted by a Low-Cost Gyro-Free INS Using Neural Network. Journal of Navigation 57(3), 417–428.

Wewetzer, C., Caliskan, M., Meier, K., Luebke, A., 2007. Experimental Evaluation of UMTS and Wireless LAN for Inter-Vehicle Communication. International Conference ITS Telecommunications, Sophia Antipolis, 6–8 June, pp. 287–292.

Wisitpongphan, N., Bai, F., Mudalige, P., Tonguz, O.K., 2007. On the Routing Problem in Disconnected Vehicular Ad-hoc Networks. IEEE International Conference on Computer Communications, Anchorage, 6–12 May, pp. 2291–2295.

Yang, N., Tian, W.F., Jin, Z.H., Zhang, C.B., 2005. Particle filter for sensor fusion in a land vehicle navigation system. Measurement Science and Technology 16(3), 677–681.

Yousefi, S., Bastani, S., Fathy, M., 2007. On the Performance of Safety Message Discrimination in Vehicular Ad Hoc Networks. Fourth European Conference on Universal Multiservice Networks, Toulouse, 14–16 February, pp. 377–390.

Zinoviev, A., 2005. Using GLONASS in Combined GNSS Receivers: Current Status. ION GNSS 18th International Technical Meeting of the Satellite Division, 13–16 September 2005, Long Beach, CA, 1046–1057.

Abstract

Collision avoidance support systems (CASS) are nowadays one of the main fields of interest in the area of road transportation. Among the different approaches, those systems based on vehicle cooperation to avoid collisions present the most promising perspectives. Works available in the current literature have in common that the performance of such solutions strongly relies on the operation of two on-board subsystems: navigation and communications. However, the performance of these two subsystems is usually underestimated when the whole solution is evaluated. Collision avoidance support applications can be considered among the most critical vehicular services, and this is the reason why this paper focuses on the performance issues of these two subsystems. Main issues regarding navigation and communication performance are discussed along the paper, and a study of the literature in the field is completed with the evaluation of different system prototypes. Communication and navigation tests in real environments yield further conclusions discussed in the paper.

Figures

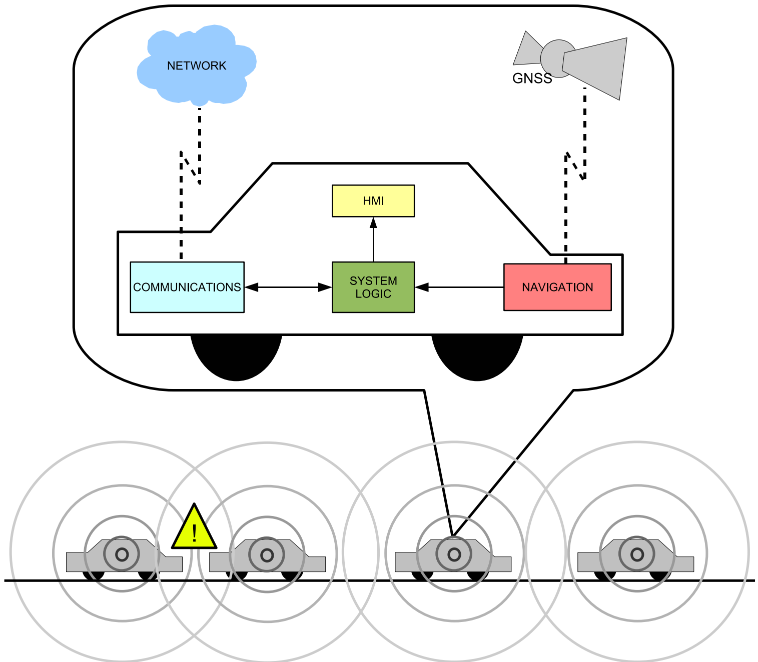


Fig. 1. Generic design of a distributed collision warning system.

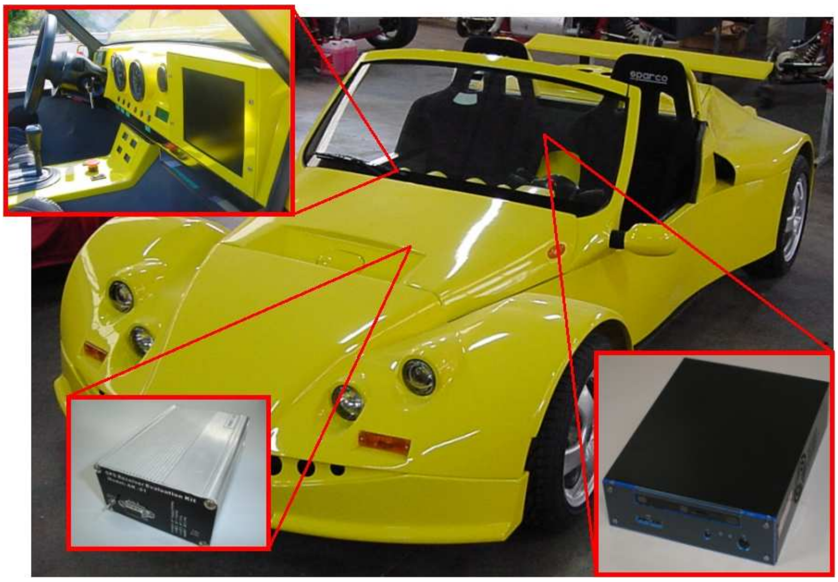


Fig. 2. Prototype vehicle and key components.

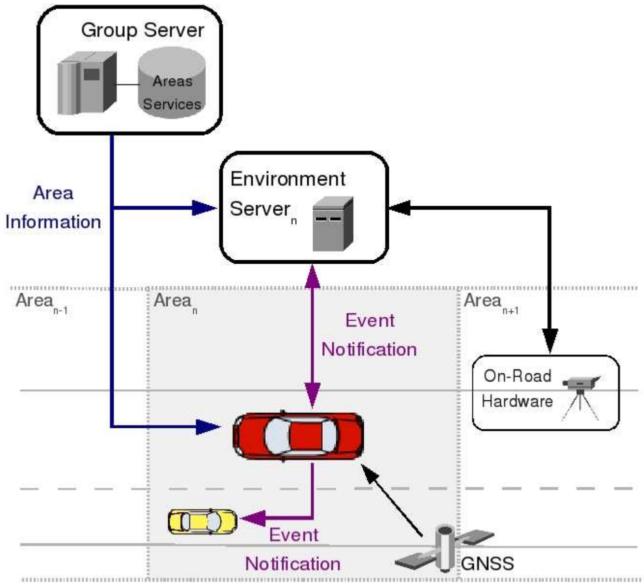
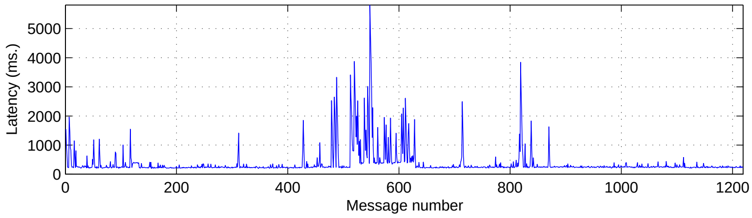
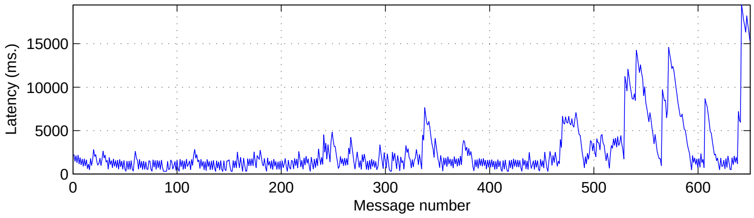


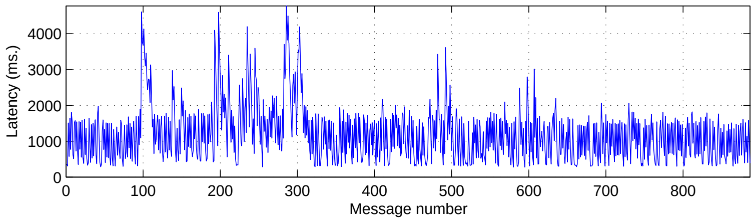
Fig. 3. Main elements and interactions of the CN-based network design.



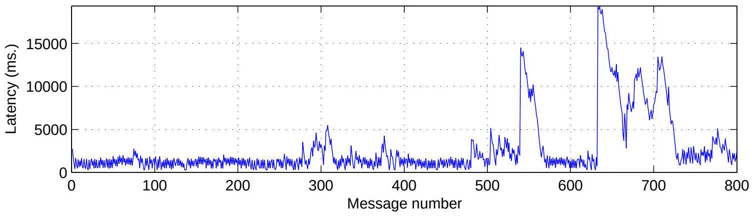
(a) Good UMTS coverage conditions (test T3).



(b) Gradual loss of UMTS coverage (test T5).



(c) Driving around a hill that reduces the UMTS coverage (test T10).



(d) Poor UMTS coverage and high density traffic (test T4).

Fig. 4. Network performance under different scenarios.

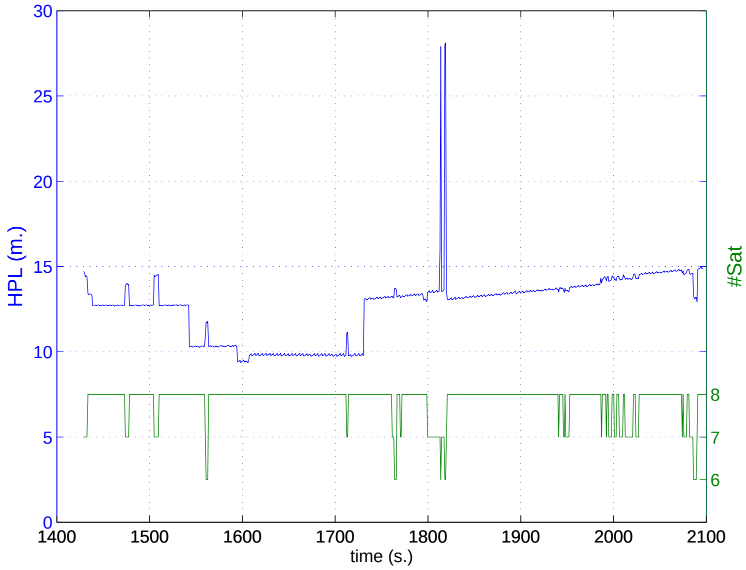
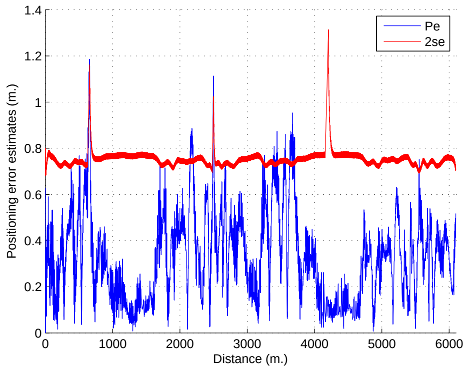
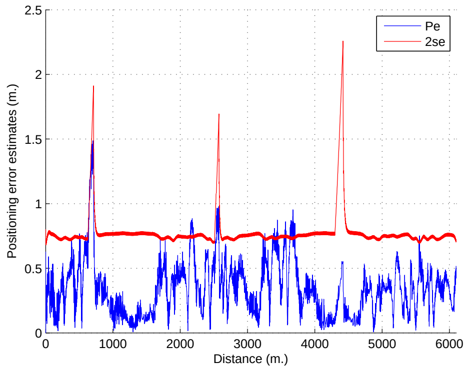


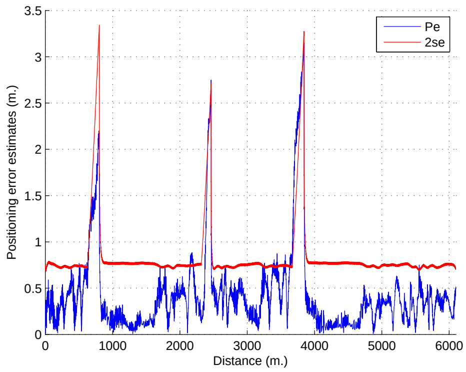
Fig. 5. HPL_{SBAS} test results and GPS coverage.



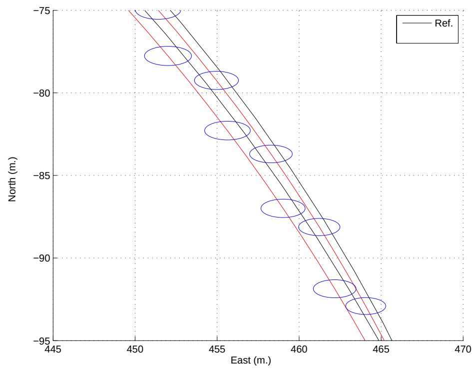
(a) Three GPS masks of 2 s.



(b) Three GPS masks of 5 s.

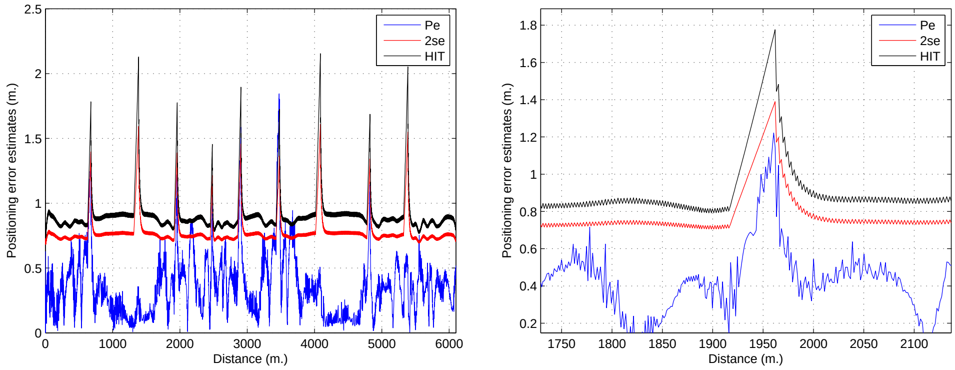


(c) Three GPS masks of 10 s.



(d) 2-σ envelope over the estimated vehicle trajectory in two lanes.

Fig. 6. Position error estimates and 2-σ envelope during a circuit stretch.



(a) Nine GPS masks of 3 s. (b) Zoom of 350 m. at the beginning of the study

Fig. 7. Analysis of position error estimate, 2-σ envelope and HIT during a circuit stretch.

Tables

Table 1
Circuits followed in the network tests.

Circuit	Distance	Traffic load	Details
C1	6.18 km	Med	Two zones of medium coverage
C2	4.7 km	Med/Hi	Towards a null coverage zone
C3	4.58 km	Lo/Med	A big zone of low coverage

Table 2
Network tests.

Test	Circuit	Speed	Time	Delay mean (ms.)	STD
T1	C1	17–25 km/h	11:22–11:43	464.33	903.09
T2	C1	17–25 km/h	11:48–12:09	489.62	814.31
T3	C1	17–25 km/h	15:43–16:04	378.93	475.92
T4	C2	17–35 km/h	16:00–16:13	2759.9	3465.37
T5	C2	17–35 km/h	17:53–18:05	4288.22	15630.92
T6	C2	17–35 km/h	10:32–10:43	2527.76	15065.64
T7	C3	17–25 km/h	11:35–11:48	963.34	906.25
T8	C3	17–25 km/h	12:12–12:26	998.24	782.72
T9	C3	17–25 km/h	12:42–12:56	1203.58	767.77
T10	C3	17–25 km/h	15:50–16:06	1392.28	1374.42
T11	C1	17–60 km/h	15:59–16:12	400.37	357.28
T12	C1	17–60 km/h	16:13–16:26	412.55	375.44
T13	C1	17–60 km/h	16:32–16:45	415.7	339.45

Table 3
Horizontal position error with total GPS coverage (m.).

STD	Mean	Max.	Mean (99)
0.2173	0.3925	1.2521	0.3403

Table 4
Horizontal position error applying GPS masks (m.).

N. of masks	Duration	STD	Mean	Max.	Mean (99)
3	2 s.	0.1923	0.3461	1.1862	0.2991
3	5 s.	0.2096	0.3596	1.4876	0.3148
3	10 s.	0.4653	0.4485	3.1509	0.3557

Figure captions

Fig. 1 Generic design of a distributed collision warning.

Fig. 2 Prototype vehicle and key components.

Fig. 3 Main elements and interactions of the CN-based network design.

Fig. 4 Network performance under different scenarios.

Fig. 5 HPL_{SBAS} test results and GPS coverage.

Fig. 6 Position error estimates and 2-σ envelope during a circuit stretch.

Fig. 7 Analysis of position error estimate, 2-σ envelope and HIT during a circuit stretch.

Table captions

Table 1 Circuits followed in the network tests.

Table 2 Network tests.

Table 3 Horizontal position error with total GPS coverage (m.).

Table 4 Horizontal position error applying GPS masks (m.).

Keywords

Collision avoidance support

Vehicular communications

Navigation

V2V

INS

Cellular networks

DGPS

VANET

Vitae

José Santa received the M.S. degree in Computer Science Engineering from the University of Murcia, Spain. Since 2004 he is a Ph.D. candidate with Department of Information and Communication Engineering, at the same university. Research interests are vehicle communications, location-based services, positioning systems, electronic vehicle identification, and the intelligent transportation systems (ITS) field in general.

Rafael Toledo-Moreo received the M.S. degree in automation and electronics engineering from the Technical University of Cartagena (UPCT), Cartagena, Spain, in 2002 and the Ph.D. degree in computer science from the University of Murcia (UMU), Murcia, Spain, in 2006. He is currently with the Department of Electronics and Computer Technology, UPCT, while he also collaborates with UMU in a number of projects concerning navigation systems applied to terrestrial vehicles. His main fields of interest are navigation systems, satellite and inertial navigation, and data fusion in road vehicle applications.

Miguel A. Zamora-Izquierdo received the M.S. degree in automation and electronics and the Ph.D. degree in computer science from the University of Murcia (UMU), Murcia, Spain, in 1997 and 2003, respectively. In 1997, he was with the Department of Engineering and Systems, Technical University of Valencia (UPV), Valencia, Spain. Since 1999, he has been an Associate Professor with the Department of Information and Communication Engineering, UMU, where he works on several projects related to the ITS field and is especially focused on navigation systems for road vehicles.

Benito Úbeda received the Bachelor's degree in telecommunication engineering and the Master's degree from the Technical University of Madrid, Madrid, Spain, in 1984 and 1992, respectively, and the Ph.D. degree in computer science from the University of Murcia, Murcia, Spain in 2006. In 1987, he was with the Department of Signal Theory and Communications, UPM, where he was an Associate Professor. Since 1998, he has been with the Department of Information and Communication Engineering, University of Murcia, where he is currently an Associate Professor. His main fields of interest are communications systems, global navigation satellite systems, and their applications in the ITS field.

Antonio F. Gómez-Skarmeta received the M.S. degree in Computer Science from the University of Granada, Spain, and the B.S. (Hons.) and the Ph.D. degrees in Computer Science from the University of Murcia. Since 1993, he is Assistant Professor with Department of Information and Communications Engineering at the same university. Research interests include mobile communications, GNSS location-based services and ITS. He has published over 50 international papers.