A Cooperative Overtaking Assistance System

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***Abstract*— One of the most risky maneuvers in roads with both directions in the same carriageway and only one lane for each direction is overtaking another vehicle. To overtake becomes particularly dangerous at night, with bad weather conditions and in curves, due to the diminution of the visibility. This paper presents a system to assist the driver in scenarios of bad visibility for overtaking. The system works as follows: when a lane change of the ego-vehicle is predicted by means of a filter which employs information of the vehicle kinematics and the road shape, the communication subsystem reports this event along with the navigation data of the ego-vehicle via the cellular network. Those vehicles in an area of interest which approach the same location and drive in opposite direction are subject to study by the scene interpreter subsystem. The trajectories of both vehicles are predicted according to their kinematics and the information of the road shape stored on a digital map, and an indicator of the estimated risk of the maneuver is provided based on it. The system under consideration has been found to be useful for the problem under consideration in experiments performed in real environments.**

I. INTRODUCTION

One of the scenarios with a worse rate of road traffic accidents are minor roads which interconnect neighbor cities and only have one lane per direction. This can be the case of some national and rural roads. Although the volume of traffic through these roads is significatively smaller than on highways, the accident/traffic rate is clearly worse [1]. Many of these accidents occur when a vehicle intends to overtake another under risky conditions. The fact that vehicles at very different velocities share the same lanes makes it harder to estimate the real velocity of a car which comes in opposite direction. Accident rates become even worse during night trips or in situations with hard rain or fog due to the diminution of visibility. For valuable statistics regarding road accidents, the reader is welcome to visit [2].

Despite of its disadvantages, minor roads present some other benefits which can ease the development of a collision avoidance support system (CASS). The fact that at one point of the road there is only one lane for each direction reduces the possibilities for lane matching, resulting on an easier process of lane allocation for a vehicle. In [3] it is shown that accurate lane assignment is feasible with current GNSS (Global Navigation Satellite Systems) and aiding sensors on roads that meet certain restrictions, such as the ones under consideration in this paper. Therefore, a cooperative system based on this information could enhance the visibility of a driver who intends to overtake. However, we cannot demand from the driver to launch a system by himself or herself, especially during overtaking situations when his or her attention must be total on the maneuver. Therefore, the estimation of the risk of the maneuver must be a fully automated process which does not annoy the driver, but it gives a warning only in cases of certain risk. To achieve this, our proposal contains a subsystem that predicts lane changes. Although these predictions could be obtained by simply checking the blinkers, it is well known that drivers do not notify their maneuvers with the blinkers properly in a significant percentage of the times. Both a real-vehicle study [4] and the simulator study [5] found that drivers activated their blinkers only half of the times or less, a very poor rate which disregards this very straightforward possibility. In our method, lane change predictions are carried out by means of an interactive multiple-model (IMM) filter which employs GNSS, odometry and inertial measurements, along with a digital map of the road.

In our approach, lane changes are predicted before the four wheels of the vehicle cross the median line and with time enough to launch the trajectory predictor and risk assessment processes. These two processes employ the digital road map, and the kinematic data of the ego-vehicle and those coming in opposite direction which may cause a collision with it, in order to provide a value of the estimated risk of a scene. This estimate is based on the position of each vehicle and its uncertainty. Finally, in order to inform the user, alert limits must be settled. When tuning warning thresholds, different strategies may be followed. This aspect will be briefly discussed later in the paper.

The communication system is also of special interest in cooperative services like the one presented in this paper. Apart from vehicular ad-hoc networks (VANET), which imply a number of performance issues related to deployment limitations (penetration rate, complexity of routing protocols, etc.), cellular networks (CN) are demonstrating these days to be a good alternative [7], [8]. Our communication platform gives an overlay vehicular network specially focused on infrastructure-based communication technologies. Since 3G cellular networks are also deployed in many interurban areas, this has been the base communication technology used.

The rest of the paper is organized as follows: Section II presents the architecture of the system, and Sections III, IV and V are dedicated to the main subsystems. Section VI presents the experiments carried out to evaluate the system and the results achieved. Finally, Section VII concludes the paper.

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II. OVERALL SYSTEM ARCHITECTURE

The overtaking assistance system designed is compliant with the generic design of a CASS presented in [9], also covering the performance requirements here identified for this kind of systems. As it was explained in that work, two main subsystems are essential in a CASS: the navigation unit and the communication platform. Moreover, the on-board system must implement the necessary logic to offer the collision avoidance service. The overtaking assistance system presented in this work instantiates this generic design, in order to support the driver to perform this maneuver in two-way roads with a single lane for each direction. The overall architecture, together with an illustration of the common scenario, can be seen in Fig. 1. As this diagram shows, four main subsystems compose the on-board architecture:

- The communication subsystem is in charge of connecting the vehicle with the environment; hence, the ego-vehicle can exchange PVT (position-velocity-time)[1] messages with the surrounding vehicles. As it is detailed in Section IV, an overlay communication approach over the cellular network (CN) is considered.
- The navigation system provides information about the vehicle pose, what is essential in the prediction of lane change and collision. A multi-sensor navigation system is considered in the architecture, fusing information from GNSS, dead-reckoning sensors and digital maps. The final solution comprises a high-integrity navigation system, further described in [10].
- The collision detection logic comprises the intelligence of the on-board system, performing the tasks of predicting the lane change maneuver and estimating the potential collision.
- A HMI (Human-Machine Interface) is in charge of interacting with the user, in such a way that the driver can be aware of the collision danger.

The operation of the overtaking assistance system is illustrated in the lower part of Fig. 1. In the scenario, the driver intends to overtake the vehicle ahead and, when the maneuver is detected, the ego-vehicle notifies the action to surrounding vehicles. A vehicle driving in the opposite direction receives the message and infers that both cars could crash, so it notifies the problem to the other vehicle, and the on-board system of both cars raises an alarm.

The proposed collision detection algorithm follows the flowchart given in Fig. 2. After the system is started, the navigation unit continuously calculates the vehicle pose and kinematics in order to detect a lane change. After this, the communication subsystem is used to notify the surrounding vehicles about the lane change when detected, or simply to listen to this event from other vehicles. If there is no message from the surrounding vehicles, the system continues analyzing the current vehicle kinematics and keeps on estimating the probabilities of lane changes. However, if a PVT message is received from other vehicle, the collision prediction algorithm is used to analyze a potential collision. If so, the system warns the driver and send another PVT message as a response. This last notification is necessary because a vehicle not overtaking and driving in the opposite direction to the one doing so is in charge of initially detecting the problem. In case a potential collision is not detected, the vehicle continues analyzing navigation data at the beginning of the algorithm.

[1]PVT is used in the paper as a generic way to call all navigation information which is exchanged among vehicles in the system. This is the state vector of the vehicle, explained in more detail in Section III.

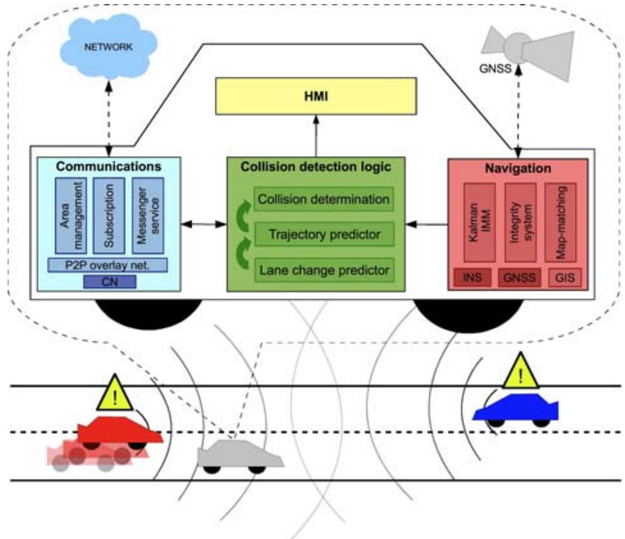

Fig. 1. Application scenario and system architecture.

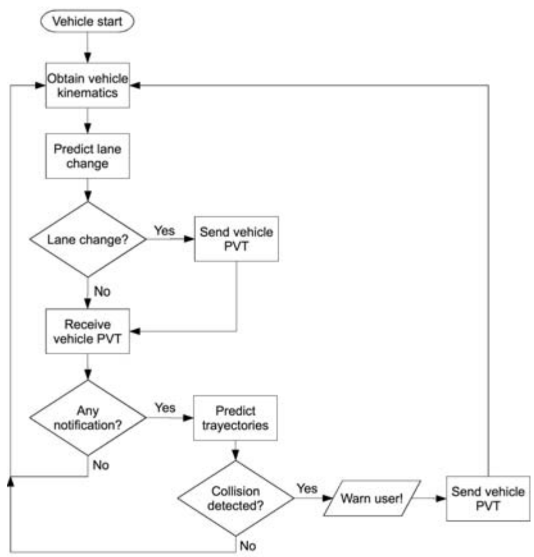

Fig. 2. Flowchart of the overtaking assistance system.

III. LANE CHANGE PREDICTION SUBSYSTEM

The prediction of lane changes in our system has been designed without considering any extra sensor to the navigation unit of the vehicle. This way, its deployment is not restricted by the addition of new sensors onboard. The measurements coming from a GNSS receiver, an accelerometer (acceleration) and a gyro (yaw rate) are fused by an Interactive Multiple Model (IMM) algorithm with two extended Kalman filters which are oriented to the possible maneuvering states of the vehicle, being in our case keep lane and change lane. The outputs of this hybridization process are therefore both the kinematic (position, velocity, heading) and the maneuvering (keep lane or change lane) states.

The decision of whether or not the vehicle is changing the lane is based on the direct comparison of the probability values of each kinematic model with a threshold. Next, these models and the way probability values are estimated are presented.

A. Kinematic models

Two kinematic models represent two possible maneuvering states of the vehicle with respect to its current lane:

1) Change lane (CL): State vector of the CL model is $\mathbf{x}_{CL/B} = (x, y, \phi, v, \omega, a, c_0, c_1)$, representing east, north, velocity angle, velocity, yaw rate of turn, and the acceleration in the center of mass of the vehicle, and the two parameters for adjusting the road shape (curvature and curvature linear rate respectively). The dynamics of this model are:

$$\dot{\mathbf{x}}_{\mathrm{CL}} = \begin{bmatrix} (v+at)\cos(\phi) & (v+at)\sin(\phi) & \omega & a & 0 & 0 & c_1 v & 0 \end{bmatrix}' + \begin{bmatrix} 0 & 0 & 0 & 0 & \eta_{\omega_{\mathrm{CL}}} & \eta_{a_{\mathrm{CL}}} & \eta_{c_{0\mathrm{CL}}} & \eta_{c_{1\mathrm{CL}}} \end{bmatrix}' \quad (1)$$

where $\eta_{\omega_{\mathrm{CL}}}$ and $\eta_{a_{\mathrm{CL}}}$ are random walk terms representing the errors due to the model assumptions of constant acceleration and constant turn, and $\eta_{c0_{\mathrm{CL}}}, \eta_{c1_{\mathrm{CL}}}$ are white noise terms representing the errors due to model assumptions of the road shape.

2) Keep lane (KL): The state vector of the KL model is the same as in the CL model. However, in this case the derivative of the angle of the velocity is assumed to follow the road shape, resulting $\dot{\phi} = c_0 v$, and the complete differential equation

$$\dot{\mathbf{x}}_{\mathrm{KL}} = \begin{bmatrix} (v+at)\cos(\phi) & (v+at)\sin(\phi) & c_0 v & a & 0 & 0 & c_1 v & 0 \end{bmatrix}' + \begin{bmatrix} 0 & 0 & 0 & 0 & \eta_{\omega_{\mathrm{KL}}} & \eta_{a_{\mathrm{KL}}} & \eta_{c_{0\mathrm{KL}}} & \eta_{c_{1\mathrm{KL}}} \end{bmatrix}' \quad (2)$$

Noise parameters of this model are different from those of the CL model, being fixed in the tuning process of the filter.

The estimate of the value of road curvature is calculated from a digital map, as presented in [11]. More details of these models can be found as well in this reference.

B. Probability estimation

In the IMM approach, the manner in which the state estimates from the individuals filters are combined depends on a Markovian model for the transition between maneuver states [12]. The equations followed for the calculation of probability values can be found in [11].

The basic idea of using an IMM based method for the calculation of probability values stems from the fact that the model which better represents the vehicle behavior presents better error features than the other. In our case, there is one model in which the value of the vehicle heading depends on its derivative (CL) and another one where the orientation must follow the shape of the road which is described by its radius of curvature (KL). The latter will be representative of the movements of a vehicle which stays on the same lane. The error considerations of this model must be such that allow small variations of the heading angle, but not those which typically lead to a lane change. In other words, the KL model must be tuned in such a way that when a vehicle performs a lane change, the innovation vector and its covariance violate its own Kalman filter (the filter is not well properly tuned for that).

On the other hand, the CL model allows changes in the orientation of the vehicle which do not match the road shape. Therefore, it is clear that this model represents well the kinematics of a lane change. Although it is true that the CL model can also represent the kinematics of the vehicle when it simply keeps on the same lane, it is the authors claim that between two models which can represent well the kinematics of one vehicle, it results better the one with a larger value of certainty. Indeed, probability values for each model depend on innovation vectors and covariances. When the vehicle does not change the lane, both models may present good innovation vectors, but the covariances of the KL are lower, becoming consequently higher its probability value. More details can be found in [11].

IV. OVERLAY VEHICULAR NETWORK

The communication architecture considered in the system is based on an overlay network which operates over the CN basis. Details in depth about the communication subsystem can be found in [13].

The network infrastructure uses a P2P (peer to peer) approach to enable vehicles to receive and send contextual information inside communication areas. 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 (Universal Mobile Telecommunication System). 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.

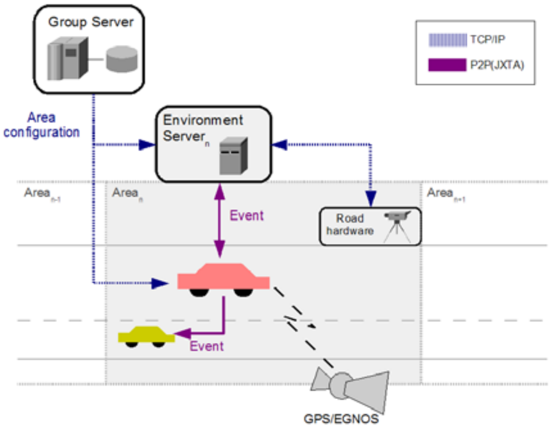

Fig. 3. Overlay vehicular network used in the system.

In the overtaking support system, vehicles take advantage of the group-based communication approach to limit the propagation of messages in the whole cellular network. This way, a communication technology widely deployed in road networks is used, also avoiding routing complexities and penetration rate problems of VANET proposals.

Two specific messages have been defined inside a new communication service defined for the overtaking assistance system:

- `Lane_Change_Notification`. This message notifies the rest of vehicles in the communication area about the start of an overtaking maneuver. It includes the navigation state vector of the vehicle performing the overtaking.
- `Collision_Warning`. By using this message, a vehicle driving in the opposite direction warns the vehicle performing the overtaking about a potential collision. The message includes the navigation state vector of the vehicle which detects the problem.

V. TRAJECTORY PREDICTOR AND RISK ASSESSMENT

The subsystems in charge of the trajectory prediction and the estimation of the risk of the overtaking maneuver are currently under development, and are introduced next.

A. Trajectory prediction

In the literature there are several works focused on predicting future trajectories using vehicle kinematics and Kalman filtering [15]. Of special interest for our case is the work presented by Salvucci in [14]. On it, the prediction of the trajectory of a vehicle is studied based on lane changes. Following this philosophy, we support the prediction of the trajectories of the vehicles of interest according to the lane on which they are allocated. Indeed, the position of a vehicle and its uncertainty can be bounded by the shape of the lane, since only when two vehicles share the lane there is risk of collision. To do it so, the kinematical status of the vehicle and its lane allocation, along with information descriptive of the road shape obtained from a digital map, are employed for the predictions. Estimates of the road curvature can be now applied to predict a trajectory that follows the road shape. These data are employed as the inputs of a KL filter. The filter is run in open-loop mode providing estimates of the trajectory of the vehicle a certain safe time ahead. The estimates are updated as new measurements are collected.

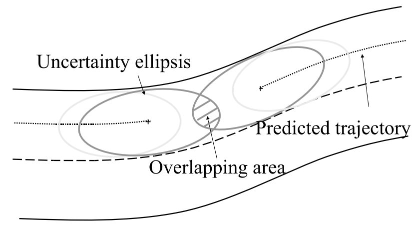

Fig. 4. Graphical view of the risk assessment principle.

B. Risk assessment

The collision detection subsystem is in charge of estimating the risk of a collision between two vehicles. In our proposal, we assume 3.5 m as the standard width of a lane in the European road network, although this value could be also obtained from the digital map in the future. Constraining the position uncertainty of the trajectory predictions to the lateral dimensions of the lane allows us to compare not only the positions predicted for the vehicles, but also the corresponding regions of uncertainty, being the final solution not affected by unrealistic areas which represent no risk since they belong to another lane. The overlapping rate of the regions of the position uncertainty of both vehicles is used to estimate the risk of the scene. This idea is visually presented in Fig. 4. It is the authors' claim that the use of the uncertainty ellipsis of the positions appears to be a better option for risk estimation than comparing only the positions, since in this case not only the position of each vehicle matters, but also its reliability.

In order to inform the driver when a maneuver is not advisable, warning thresholds must be settled. Two variables determine the risk of the maneuver at instant $t = t_1$: time to collision, $t_c^{t_1}$, and risk rate rr^{t_1}. There are three typical approaches in the literature to adjust alerts of an ADAS [6]:

- to minimize the false alarm rate (FAR),
- to minimize the missed-detection rate (MDR), and
- to maximize the overall correct detection rate (OCDR) which can be estimated following the expression OCDR = 1 - FAR - MDR.

Among these three options, we will tune the system following the first option. However, it can be claimed that a safety system should minimize missed-detections, even at the expense of false positives. It is therefore to the users choice the final setting of the system.

Finally, let us briefly present our approach to two important issues which were not discussed previously: the reference time and the communication delays. The reference time issue is solved by using the GPS atomic clock to reference all the trajectories. With regard to the communications delay, a real time measurement is considered as input in the algorithm. Since all messages transmitted contain a time stamp, each vehicle receiving a message is able to compute the current communication latency.

VI. EXPERIMENTS

Both the lane change prediction and the communication units have been evaluated under real conditions. These are two key subsystems of the cooperative overtaking assistance system presented in the paper. This way, two main inputs required in our CASS architecture are validated. The estimators of the vehicles' trajectories and risk assessment are being tested at the moment.

A. Set-up

A real prototype of the on-board unit has been created and tested. The hardware architecture of the OBE is based on a standard single-board computer of VIA, with a Linux Fedora Core 4 operating system. This computer is located at the rear part of the passenger's seat. Moreover, the dashboard has also been modified to install a LCD monitor. Serial buses communicate the sensors with the PC via RS232 and controller area network (CAN) bus. The inertial measurement units (IMUs) tested are the low-cost MEMS-based MT9B by XSens and IMU400 by Xbow. Thanks to the assumptions of the models, only one gyro and one accelerometer are employed. A Trimble DGPS Pathfinder Office version 3.0. was used to evaluate the system performance with a position accuracy of 15 cm. Nevertheless, the Global Navigation Satellite System (GNSS) inputs to the filter were only single uncorrected GPS positions, which results in the assumed ground truth being ten times more accurate. Details of the sensor specifications can be found in [11].

Additionally, to cover the overlay network necessities, the necessary software/hardware modules have been included 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 on-board unit contains the vehicle implementation. For the message propagation tests, two cars were used to assess the performance of the vehicular network. Apart from the prototype vehicle, a common car with an equivalent set-up was considered. Both of them use the navigation system for positioning and time synchronization. A software which uses this network platform has been installed in one vehicle to send messages at a fixed rate of one per second, while the other receives these messages and saves a log. The modems used have been a ZTE MF620 and a Huawei E220. 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 presented in this work are compared with the ones shown in [13].

B. Lane Change Prediction Results

Fig. 5 shows the probability values during a test with seven lane changes. The time of response (t_r) before the actual beginning of the lane change maneuver was found to be between 0.3 and 0.4 s. The time of prediction (t_p) before the four wheels of the vehicle were on the other lane was typically between 1 and 1.5 s. This corresponds to standard lane changes with a duration of around 2 s. A sharp lane change launches the predictor but it shortens its t_p value. On the contrary, a very smooth lane change which is completed after more than 7 s, may pass undetected by the system. With a normal maneuvering style the system was found to work well with no missed detections or false alarms, except for the obvious case of lateral reversal in the middle of the maneuver. This subsystem have been tested in straight and curved trajectories showing good results.

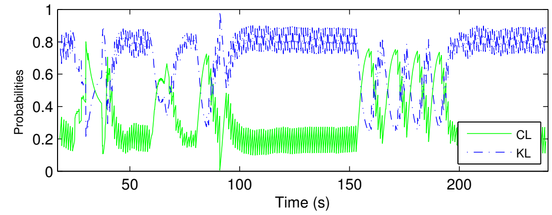

Fig. 5. Probability values of both KL (dash-dotted blue) and CL (solid green) models during a test.

C. Communication tests

Many communication tests have been performed using the vehicular network previously presented. In this Section, a representative trial with both vehicles, the prototype and the common one, driving closely around the University Campus of Espinardo (University of Murcia) is analyzed. Fig. 6 summarizes its results. The first graph shows the delay values for each message. At a first glance, it is noticeable how mobility conditions, which affect both the uplink and downlink channels of the cellular network, provoke continuous delay peaks. There are three main problematic zones. The first one is noticeable in the peaks observed between times 0 s and 120 s. This stretch belongs to the initial part of the circuit, where vehicles drove in a parking area near a building which blocked the signal with the base station. The second problematic area is more evident, between times 440 s and 640 s. The vehicle reaches the farthest position from the base station located in the middle of the campus, and several buildings also block the line of sight with the UMTS B-Node. After leaving this area, the vehicle comes back to the campus, where the network performance is better. However, new problems arise when the car goes across a third problematic area. At this location, a small hill between the vehicle and the base station decreases the channel quality. The graph which illustrates the cumulative distribution function (CDF) of the delay results, shows that values between 200 and 400 ms comprise near the 90% of collected delays. The rest of latency values are distributed in a quasi-logarithmic trend, although a small fluctuation appears between 400 and 500 ms. These values match with the frequent small peaks noticeable in the upper graph, which are due to signaling

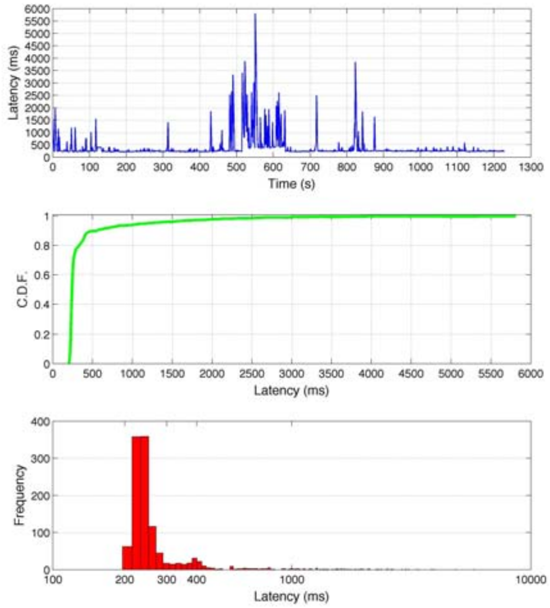

Fig. 6. Measuring the performance of the communication subsystem.

traffic when the terminal comes from low-power mode. The last graph clearly illustrates this distribution of values, showing a histogram plot of the latency values. Containers are situated in a logarithmic scale on the abscissas axis. Most of the values are between 200 and 300 ms.

VII. CONCLUSIONS

This paper presents a system capable to diminish the risk of overtaking maneuvers in carriageways with single lanes for opposite directions, which are particulary dangerous according to the literature. The system under consideration claims to a certain originality at several fronts:

- The sensing onboard unit consists of only vehicular navigation sensors, such as a GNSS receiver, an accelerometer and one gyro.
- Outputs of the sensors are fused (not only matched) with a digital map.
- Cellular networks are exploited as a means to share data of interest for avoiding an inter-vehicular collision.

The tests carried out with the two main subsystems (lane change predictor and communication platform) give good results in the trials performed in real environments. For the case of the communication platform, for instance, performing the tests around the University Campus of Espinardo implies a number of issues, due to the deployment of 3G infrastructure is still low in several areas. On the other hand, since lane changes are detected by means of navigation sensors and map information, it is clear the importance of the accuracy of the map. In concrete, local errors and missed contents may affect remarkably the accuracy of the curvature estimate.

Current investigations in the line of this paper are mainly focused on the development of the trajectory prediction and risk assessment subsystems, apart from an exhaustive analysis of the overall system performance. Moreover, an ongoing work deals with the integration of the overtaking assistance capabilities in a final application, using a suitable HMI to warn the driver about a potential collision.

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