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Cross-Border interoperability for Cooperative, Connected and Autonomous Driving

José E. Naranjo[1], *Member, IEEE*, F. Jiménez[1], R. Castiñeira[2], M. Gil[2], C. Premebida[3], P. Serra[4], A. Valejo[4], F. Nashashibi[5], C. Magalhães[6]

[1]Instituto Universitario de Investigación del Automóvil, Universidad Politécnica de Madrid, Madrid, Spain
[2]Indra S.A., Madrid, Spain
[3]University of Coimbra, Coimbra, Portugal
[4]Laboratory for Automation and Systems, Instituto Pedro Nunes, Coimbra, Portugal
[5]Inst. National de Recherche en Informatique et en Automatique (INRIA), Paris, France
[6]Brisa – Auto-estradas de Portugal, Lisboa, Portugal

Nowadays, there is no doubt that the implantation on a massive scale of safe autonomous driving is very difficult using only the information coming from the ego-vehicles, which are subject to the limitations of their visual horizon. For autonomous driving systems to become a reality, it is essential to provide the system with two fundamental elements: connectivity and cooperative services. However, both elements are still at a very early stage of their development, both in communications technology and in the organization and generation of support information. In addition, added difficulties are presented, such as trans-national barriers to accessing services and exchanging information with other vehicles and infrastructure. This paper presents the work done within the European project AUTOCITS, where three cooperative, connected and autonomous driving pilots have been carried out in three cities belonging to the trans-European Atlantic Corridor: Madrid, Lisbon and Paris. Within these pilots, the results of cross-border interoperability are described in detail, both at the communications and at the autonomous driving level. Also, results are analyzed in order to have a set of recommendations to ensure a successful deployment of cooperative, connected and autonomous driving (CCAD) at European level.

***Index Terms*—Autonomous vehicles, V2X Communications, Pilots, Cooperative connected and autonomous driving.**

I. Introduction

CONNECTED and autonomous vehicle (CAV) technology is built around three fundamental pillars: V2X communications systems, generation of C-ITS services and autonomous driving.

Although the first autonomous driving experiences took place between the 60s and 70s, it has not been until the early 90s of the last century when the first realistic steps have been taken when carrying out a complete development of the autonomous road vehicles, where is possible to highlight the contributions of the University of Parma [1], the Bundeswehr University Munich [2], University of Southern California [3], and INRIA [4]. From the experiences of the DARPA Grand Challenge [5] at the end of the 2000s, the autonomous driving of vehicles has suffered a great boost, especially thanks to IT companies such as Google [6], which have pushed the entire sector of the automotive industry towards this type of technological development, where Volvo [7], Daimler [8] or Ford [9] stands out. This impulse has also been supported by the different national and international regulatory agencies in charge of road traffic management, which give legal coverage to the introduction of real autonomous driving into the market.

The autonomous driving capacities of the vehicles are organized in six autonomy levels (0 to 5), following the SAE J3016 standard [10]. An Automated Driving System (ADS) can be classified as level 0, 1 or 2 when the Dynamic Driving Task (DDT) is performed by the driver, totally (level 0), with driver assistances (level 1) or with partial automated systems (Level 2). When the ADS performs the entire DDT while engaged it can be classified as level 3 if the ADS performs automatically some tasks but considering the fallback-ready user in any moment. In levels 4 and 5 the ADS considers the DDT fallback without any expectation that the user will respond to a request to intervene in some or all Operational Design Domains (ODD), considering the SAE definition of ODD as the operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.

Nowadays, commercial vehicles with automated capacities are considered of level 2-3 and only research and testing vehicles are considered of levels 3-4. However, those vehicles are designed in order to carry out the DDT using the sensors and equipment installed in the ego-vehicle. This fact can improve the perception of the vehicles by the addition of a wide range of sensors, but it also is constrained due the visual horizon limit. This means that there is a large set of situations that cannot be solved by the ego-vehicle ADS with the minimum safety performance required. An example of those situations is the navigation through a roundabout with heavy traffic condition [11].

In order to solve these limitations, there are two technologies that should be enabled within the autonomous vehicles: connectivity and cooperation.

Communication technologies enable the data exchange among vehicles and with the infrastructure and any other element that is suitable to relate to the road eco-system. Those vehicular communications are commonly known as V2X (vehicle-to-any) and support the different communication means to grant access to the connected systems and services

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deployed linked to the ADS navigation geographical area [12]. Two technologies are widely used to support the communication between vehicles (V2V) and with the infrastructure (V2I): The Dedicated Short-Range Communications (DSRC) based in ETSI ITS-G5 (IEEE 802.11p) and the cellular telephony 3/4/5G. The first technology includes geo-referenced unicast/broadcast communications with the capacity to support real-time data exchange with vehicles and infrastructure. It requires an ad-hoc infrastructure and vehicles deployment but without necessarily a network operator. The second technology is provided only by licensed network operators and support communications for services that do not demand high latencies [13]. The most common approach is the hybridization of short range/cellular communications, taking advantage of the features of each. With the future upcoming of 5G cellular communications, this hybridization will be a fact in a single platform [14].

V2X communications provide support for the exchange of information in vehicles, and that support will be used for the exchange of information to support the Cooperative Systems (C-ITS). These C-ITS are those that provide information services that allow cooperation between the different entities that make use of public roads, from traffic control centers to pedestrians, including vehicles and infrastructure. The C-ITS collect the necessary information from multiple sources at all levels, process it and generate the necessary messages to make the different services effective, such as traffic status warnings, weather conditions warning, emergency vehicle warning or warning of cooperative braking, among others. According to their time-to-market, these services are organized in Day-1 and Day-1.5, those that are at a level of development such that it is currently possible to deploy [15]. Day 2, basic C-ITS support services for autonomous driving. Day-3 and Day-4 are the C-ITS that will include support for autonomous and cooperative driving of the future.

In order to deploy the cooperative, connected and automated driving, it is necessary that isolated autonomous vehicles become part of the C-ITS ecosystem through two fundamental additional elements. These are the connectivity to the communications networks deployed on the road; and the modification of its Automated Driving Systems to make use of the new information that arrives through this channel, as well as the modification of its decision-making systems for this purpose.

This paper presents the work carried out as part of the European Project AUTOCITS (Regulation Study for Interoperability in the Adoption of Autonomous Driving in European Urban Nodes) whose objective is the development of the cooperative, connected and automated driving in Europe through the deployment of cross-border C-ITS based on V2I communications and autonomous and connected vehicles. For this, three pilots have been designed and executed in the urban access to the three capitals of the Atlantic Corridor of the TEN-T Trans-European road network, Madrid, Paris and Lisbon, where the deployment of a common communications architecture and C-ITS has been carried out. This deployment considers the entire value chain of C-ITS, from the road and the vehicles to the traffic control centers, in order to provide autonomous vehicles with cooperative information and allow them to increase their capacity to respond to new situations not considered to date, focusing the work to ensure cross-border interoperability. Moreover, AUTOCITS goes one step further and proposes the introduction of autonomous driving in such deployment, developing new strategies in the control systems of autonomous vehicles in order to manage the C-ITS information received through communications. This paper describes the results of these three pilots and how autonomous vehicles can manage this new information and adapt to the new communicated and cooperative environment, increasing the capacities of isolated autonomous vehicles.

II. Pilots

Within the framework of AUTOCITS and in line with other initiatives in the field of CAVs such as C-ROADS, the deployment of a complete ecosystem for connected vehicles is proposed, including traffic control centers (TMCs), C-ITS service generation, deployment of V2X communications equipment in infrastructure and connected vehicles.

When managing this information in autonomous vehicles, two fundamental factors have been considered. On one hand, the C-ITS services deployed in AUTOCITS are those corresponding to Day-1 and Day-1.5, which are currently standardized throughout its value chain. On the other hand, these services have been designed to provide information to connected, non-autonomous vehicles, in such a way that it is necessary to define specific autonomous driving strategies to respond to the reception of these C-ITS.

A. Framework architecture

Within the framework architecture of the AUTOCITS project, three functional blocks have been taken into account that, although they are independent of each other, allow to adapt to the different features and equipment available in the three countries where the pilots will be carried out, as well as guarantee the cross-border interoperability of C-ITS services and systems. These three functional blocks are: C-ITS services, deployment in infrastructure (roadside) and deployment in vehicles (onboard) (figure 1).

C-ITS services allow the generation of cooperative messages that are sent to the roadside through I2I communications system and received by vehicles connected via I2V. These services are intimately connected with the traffic management centers, being a functional module of them, and using all available internal information, as well as from external sources. Although the elements that constitute the generation of C-ITS services are the same in all pilots, their implementation varies in each country, depending on the type of TMC used, the availability of the communications system and the amount of information sources processed. Also, the TMC to C-ITS and C-ITS to Roadside communications protocols vary depending on each implementation.

The second element of the framework architecture is the roadside, consisting of all the ITS stations (roadside units - RSU), which receive the C-ITS information from the TMCs via

I2I and transmit it to the vehicles located in their geographical area via V2X.

Figure 1. AUTOCITS's framework architecture for the CCAD deployment.

The implementation of this part of the AUTOCITS architecture is identical in all pilot sites, using communications hardware compatible with the ETSI ITS G5 standard and using the DENM (Decentralized Environmental Notification Message) protocols for the transmission of C-ITS information to the connected vehicles.

Finally, cooperative, connected and autonomous vehicles equipped with V2X communications systems compatible with ETSI ITS-G5 and are capable of processing DENM messages that, depending on the information they contain, will cause certain actions within their Dynamic Driving Task. Although a total of 4 autonomous vehicles have been used in AUTOCITS, this article illustrates the results on autonomous and connected navigation of the Universidad Politécnica de Madrid's vehicle, circulating in the three CCAD pilots deployed.

The characteristics of those CCAD deployments carried out in the three pilot sites are specified below.

B. *Pilot Deployment*

1) *Spain – AUTOCITS A6 Cooperative Corridor*

The AUTOCITS A6 Cooperative Corridor is a 16-kilometer stretch of highway located in the northern access of the city of Madrid. In order to deploy C-ITS services in this area, a total of 17 RSUs have been installed to provide continuous communication throughout the route (Figure 2).

Figure 2. AUTOCITS Madrid Pilot deployment of RSUs.

The architecture of this corridor has been designed with the aim of guaranteeing maximum communications coverage while minimizing the cost of deployment. In this way, 2 Cohda MK5 RSUs have been installed through 3G or fiber optic connectivity with the traffic control center, one at the beginning of the corridor and another at the end. The rest of the RSUs are relay stations, which resend the information when necessary without the need for external connectivity. The relay units have been integrated and deployed by the Universidad Politécnica de Madrid and their cost is a fraction of the cost of a Cohda RSU, considering that the range of all stations is around 1000 m. The distribution of the RSU has been carried out based on the orography of the road, with distances between them ranging between 300 and 1200 meters, in order to maintain a continuous connectivity for the vehicles that circulate through the corridor, in such a way that a message issued by one of the RSU tailing is guaranteed to reach any Onboard unit (OBU) that circulates at any point along the route. The Cohda RSUs receive messages from the C-ITS Service Center, located in the Spanish Traffic Agency (DGT). This C-ITS Service Center allow the Traffic Management Center of DGT to send incidents or events to the connected and to the autonomous vehicles to enhance the information sent to the drivers through the variable message signs. It is important to note that this pilot site has been incorporated into the ERTRAC Connected and Automated Driving Roadmap 2019 as one of the European Reference Test sites for CCAD [16].

The steps followed in the implementation of the service generation is defined next:

- Step 1: Collection / generation of incidents (planned traffic cuts, accidents, weather information, etc.). The control center collects and generates this kind of information and publishes it through DATEX II, information that is sent to the C-ITSs.
- Step 2: The C-ITS analyzes the information provided by the TMC and converts the incidents in events. Based on the location of the incident one RSU is selected to disseminate the event and a specific message using the Cohda protocol is sent to this RSU.
- Step 3: As long as the event is active the RSUs disseminates Geo-Broadcasts messages with the useful information for every service in a specific geographical area using the ETSI ITS-G5 standard and the DENM protocol. The vehicles within the area of diffusion receive the information through their OBUs.
- Step 4: The OBU filters the relevant events using its own vehicle information (type vehicle, GPS position, direction, speed, etc…). The vehicle takes this information and executes the relevance action, notify/alert the driver (through HMI), or slow down, change lane, among others.

2) *Portugal*

The deployment concerning to the Lisbon Pilot was carried out in the A9 - CREL motorway (Circular Regional Exterior de Lisboa), between "Radial de Pontinha" (at A9 km 10) and "Radial de Odivelas" (at A9 Km 17). Six RSUs have been installed in this infrastructure in the positions shown in the figure 3. Those RSUs manufactured by A-to-Be are connected through the optic fiber (or 3G/4G) of BRISA, the road operator of this infrastructure, and managed from the C-ITS service center of the TMC of Brisa. One of the aims of this deployment is to test the reception of the messages by the vehicles using the AUTOCITS architecture in cross border tests. The BRISA C-ITS service center and the RSUs use the CoAP protocol (Constrained Application Protocol [16]) to interchange information.

Figure 3. AUTOCITS Lisbon Pilot deployment of RSUs

The following steps describes the data workflow and how it is integrated with C-ITS services:

- Step 1: Collection/generation of events.
- Step 2: Then ATLAS platform, used by BRISA as TMC, publishes the events through DATEX II to the C-ITS platform.
- Step 3: The C-ITS platform and the RSUs will use the Constrained Application Protocol (CoAP - RFC 7252) to communicate, using an IP architecture.
- Step 4: Then the RSU units, using ETSI ITS-G5 standard, convert the events to DEN messages and geoBase them in the location of the event, selecting a specific RSUs to

disseminate the information. As long as the event is taking place the RSUs disseminates the messages in a specific area. The vehicles within the area of diffusion receive the information through their OBU.

- Step 5: The OBU filters the relevant events using own vehicle information (type vehicle, GPS position, direction, speed, etc…). The vehicle takes this information and executes the relevant action, notify alerts to the driver (though HMI), or slow down, change lane etc…, in the case of autonomous driving tests.

3) France

The deployment in Paris was held in Rocquencourt, France, using a single YoGoKo RSU, using YoGoKo Y-Cloud architecture. YoGoKo ITS architecture provides full integration of all ETSI defined C-ITS services. The following steps describes the data workflow during the French pilot tests using C-ITS services:

- Step 1: Collection/generation of events (Manually or automatically by external source).
- Step 2: Then YoGoKo Y-Cloud platform connected to a Tablet HMI will operate as a Traffic Management Centre, which can publish any events to the ITS platform.
- Step 3: The ITS platform and the RSUs will use the YoGoKo protocol to have inter- communication.
- Step 4: Each of YoGoKo RSU will in real-time convert the triggered events to DENM standard messages.
- Sep 5: Any connected or autonomous vehicles within the area of event will receive the information through its OBU.
- Step 6: The integrated computer in each vehicle will filter and process the relevant events and extract data such as (Event Cause, SubCause, type vehicle, GPS position, direction, speed).
- Step 7: The vehicle takes this information and executes the relevant action, notify alerts to the driver (through HMI), or slow down, change lane, in the case of autonomous driving tests.

C. C-ITS

C-ITS services are articulated around the generation of information among vehicles and infrastructures, allowing to increase safety and efficiency on the road. This flow of information depends on the generation of standardized protocols that can be understood by all the actors in the cooperative environment and are organized around the ITS Facilities. ITS Facilities are a collection of functions to support applications for various tasks. The facilities provide data structures to store, aggregate, and maintain data of different types and sources, following different communication protocols in function of the focus application such as Cooperative Awareness Messages (CAM), Decentralized Environment Notification Message (DENM), Map Data (MAP) or Signal Phase And Timing (SPAT) [18]. In the AUTOCITS architecture, the considered data flow is downstream from TMCs to vehicles using DENM facility and attached standardized messages. The structure of those messages is described in figure 4.

Figure 4. General DENM structure [19].

This DENM message structure is divided in containers that separate the different types of information:

- The ITS PDU (Protocol Data Unit) header is specified in ETSI TS 102 894-2, and represents protocol specific control information ;
- The Management Container holds the information about the message itself, and is used to control the repetition interval, time to live, etc.;
- The Situation Container holds the information about the situation itself, like the cause and sub-cause codes (eg. Code: visibility, sub-code: fog);
- The Location Container holds the information about the location of the occurred event, with regards to position, heading, etc.;
- The "À la carte" Container contains additional information that is not provided by other containers, providing the possibility for ITS-S application to include application specific data in a DENM message.

In the case of AUTOCITS, two C-ITS services have been selected for CCAD pilots: Weather Conditions and Roadworks Warning [19].

The C-ITS service Weather conditions informs the driver of hazardous weather conditions, such as fog, rain and ice. It would be especially beneficial if the service is linked to in-vehicle speed limits, thereby informing the driver and vehicle of the appropriate speed for the weather condition he or she is driving in. In addition, the system would warn for those dangerous weather conditions which are hard to be visually perceived by the driver, such as wind gusts. This service covers specific cause codes regarding Adherence (cause code 6), ExtremeWeatherCondition (cause code 17), Visibility (cause code 18) and Precipitation (cause code 19), and sub cause codes like Fog (sub cause code 1), Smoke (sub cause code 2), HeavySnowFall (sub cause code 3), HeavyRain (sub cause code 4), HeavyHail (sub cause code 5), etc.

The C-ITS service Roadworks warning inform drivers about upcoming road works, including possible restrictions and lowered speed limits. It will therefore improve the safety for the workers, especially if the lower speed limits around the work site are communicated to the vehicles' Intelligent Speed Assistance systems. Those messages only consider the cause code RoadWorkWarning (cause code 3) and sub cause codes like MajorRoadWorks (sub cause 1), RoadMarkingWork (sub cause 2), SlowMovingRoadMaintenance (sub cause 3), ShortTermStationaryRoadWorks (sub cause 4), StreetCleaning (sub cause 5) or WinterService (sub cause 6).

III. AUTONOMOUS VEHICLE

The testbed autonomous vehicles used in the three pilots is the UPM's automated Mitsubishi iMIEV, that include speed (accelerator and brake pedals) and steering control, environment perception and a communication onboard unit (OBU) to receive the C-ITS data (figure 5). The closed-loop control of the speed is completed by measuring the speed obtained from the CAN BUS of the vehicle, a signal acquired at a sampling frequency of 50 Hz. The ADS has been implemented using the ROS environment, where a navigation module was developed to maintain the route and perform maneuvers, while the decision-making module takes the appropriate driving decisions in function of the environment perception and the communications data. This module has been modified in order to comply with the requirements of the AUTOCITS project and to extend the capabilities of the autonomous vehicle incorporating communication between vehicles and road infrastructure as well as to understand the V2X incoming data. Thus, the ROS architecture implements this new module that receives and manages all those V2X messages.

This extension of the capabilities is not trivial, since it relies on enabling the C-ITS as a source of information for the control systems of the autonomous vehicles. This is not a simple task since the C-ITS have not been originally designed as a source of information for this type of vehicle, but to be transmitted to users of connected vehicles and presented by a simple display. That is why, from the point of view of an autonomous vehicle it is necessary to "teach" it to act in response to a C-ITS message of the different types available. In this way, before a message of speed reduction due roadworks on the path of the vehicle, the ADS must associate the message reception to a physical reduction of the speed, without losing at any time the expected level of driving safety . Also, when the vehicle receives messages that do not involve any specific associated instruction, such as "strong storm", the vehicle should learn that the response to that message must be a reduction in speed, exactly as human drivers would react.

Figure 5. UPM Autonomous vehicle participating in one of the AUTOCITS pilots.

Figure 6. Example of operation of DEMN messages under CCAD.

An example of the task carried out by this module is the case in which the vehicle is following a route at a certain speed and a DENM message is received. The decision module must determine the speed the vehicle should have at that moment in function of this new information. In case the travel speed is greater than the one notified in the event, the decision-making module will assign the priority to the speed marked in the event and decrease the vehicle speed to the target speed marked in the event. Otherwise, if the event has a target speed higher than the target speed of the route tracking system, the vehicle will maintain its speed.

In this way, the C-ITS Day 1 messages implemented, and its subsequent response has been programmed in the UPM autonomous vehicle, as shown in table I.

That is why the control systems of these vehicles must be adapted in order to manage the information coming from the C-ITS, associating each message with a specific type of action that must be equivalent to that carried out by human drivers.

Upon the reception of C-ITS DENM messages, the vehicle's decision-making system must be able to interpret the information received, establish the priorities and activate certain behavior to solve the orders received from the traffic management centers through V2X.

A. Modifications to include C-ITS in the Autonomous Driving System

The decision module is in charge of taking the high-level driving decision in the ADS autonomous vehicle while executing the Dynamic Driving Task, taking into consideration the information provided by the low-level controller, the route tracking system, the sensors and the V2X messages.

The ADS decision making module is directly linked to the low-level control of the actuators and is the only module of the autonomous vehicle architecture that can send orders to this layer. This module is also linked with the other high-level modules, and acts as a filter in case of contradictory commands, indicating different speed commands, for example.

TABLE I
DECISION MAKING RULES ADDED IN THE AUTONOMOUS VEHICLE ADS IN FUNCTION OF THE RECEPTION OF THE DENM MESSAGES

Pilot	C-ITS Service	TC ID	Cause (code)/Sub-cause (code)	Action of the autonomous vehicle
Paris	Works Information Service	6	RoadWorkWarning (3) / ShortTermStationaryRoadWorks (4)	The autonomous vehicle receives this message and decides to reduce its speed by 50%
Madrid	Weather information service	1	AdverseWeatherCondition - Adhesion (6) / iceOnRoad (5)	The autonomous vehicle receives the message and decides to reduce its speed to 40 km / h
Lisbon	Weather information service	4	AdverseWeatherCondition - Visibility (18) / HeavyRain (4)	The autonomous vehicle receives the message and decides to reduce its speed to 50 km/h
Lisbon	HazardousLocation	9	SurfaceCondition (1) / Rock falls (1)	The autonomous vehicle receives the message and decides to reduce its speed to 50 km/h

The table I specifies the detailed behavior and actions of the autonomous vehicles as response of the C-ITS messages. Specifically, there have been defined four different behaviors in function of the DENM C-ITS message received, the information included in its payload and the operation range defined for it. The four behaviors are:

- Speed reduction to a pre-defined
- Speed reduction to a percentage of the current speed
- Lane change
- Vehicle Stop

Figure 6 shows an example of the response and actuation of a connected and autonomous vehicle (CAV) in case of the reception of a warning message generated by the C-ITS control center that causes an action of speed reduction and/or change to a free lane. In this case, the C-ITS module of the TMC generates a warning of roadworks or adverse weather condition in function of the information retrieved by multiple sources. Once it generates the warning, the C-ITS module sends a message with the corresponding information to the RSUs installed in the concerned geographical area, including the geodata of the position of the event and the range (relevant distance) of event validity.

The OBU captures this message and sends it to the high-level ADS to communicate the situation. In this way the vehicle can perform all these actions independently of the previously designed plan on the route tracking system. The received event points out the vehicles that they must reduce the speed of the autonomous vehicle to a specified value and/or use a certain lane. Then, as represented in the figure 6, the vehicle approaches 90 km/h enters the relevant distance of the event and reduces speed. Once the vehicle has passed this event it resumes the journey in the normal way.

IV. Results and Discussion

This section describes the results of the pilots carried out in Paris, Madrid and Lisbon, within the AUTOCITS project involving CCAD. One of the fundamental contributions of the AUTOCITS project is the extension of the capabilities of the autonomous vehicles with connectivity, allowing them to make use of the information coming from the cooperative systems (C-ITS) generated from the TMCs, focusing on guaranteeing of the cross-border interoperability.

In this regard, the C-ITS architecture of AUTOCITS has been implemented in the 3 participating pilot sites, so that, at the vehicle level, the geographical location in which it is located to perform the CCAD is completely transparent.

The results presented in this section summarize an important part of the work done in the project, structuring the pilots with autonomous vehicles and organized in three phases according to their level of complexity. The first pilot presented is the one carried out in Paris, where the interoperability of the C-ITS AUTOCITS architecture is checked in a controlled environment. Second, it takes place in Madrid, where the pilot is carried out in real conditions and public roads, but with a controlled environment, in order to test the complete AUTOCITS system functionality in real situations. Finally, the Lisbon pilot is carried out in real situations of shared traffic, executing the complete AUTOCITS architecture and with real autonomous vehicles. In total, these pilots have traveled more than 6000 km in connected, cooperative and autonomous driving mode.

A summary of the quantitative results of the tests are presented in table II showing that in every case the time from the 1st DENM reception until the autonomous vehicle maneuver starts is less than 100 milliseconds, so the actuation of the message reception over the control system is considered as “real-time”. Regarding the DENM transmission rate, the RSUs in Madrid and Paris send the messages at a frequency of 10 Hz, and the RSUs of Lisbon at 100 Hz. This last rate is clearly excessive, but it has been selected in order to test the communication systems in limit conditions. In any case, the results of the tests show that, once the vehicle is inside the RSU coverage area, the lost DENM packets are less than 1 %. Those results will be further analyzed in the next sections.

TABLE II
Analytics results of the three AUTOCITS pilots. Each row indicates the average results for C-ITS messages transmission from each single RSU. For Lisbon pilot, return trip is included

Test ID	Time from AV maneuver start until AV maneuver finish (ms)	Distance to the center of DENM in the 1st reception (m)	Distance to the center of DENM in the last reception (m)	Relevant Distance of DENM (m)	Reference speed (km/h)	DENM speed (km/h)
Paris	24	49.38	50.4	50	20	10
Madrid	28	156.4	186	200	70	40
Lisbon RSU 4	10	-80	220	500	60	50
Lisbon RSU 3	29	220	161	500	60	50
Lisbon RSU 2	64	450	498	500	70	50
Lisbon RSU 2	77	485	514	500	60	50
Lisbon RSU 3	44	141	501	500	70	50
Lisbon RSU 4	31	499	409	500	70	50

A. Paris Pilot

The first round of Interoperability validation was conducted in the facilities of INRIA-Rocquencourt, were a replication of the roadside equipment was installed in their testbed track. In those facilities, INRIA and UPM teams tested the interoperability of the complete C-ITS value chain, generating warnings from the internal TMC and sending those warnings as DENM messages that were broadcast to the selected area. The autonomous and connected car of UPM received the C-ITS information, acting in consequence and responding to the messages as part of the automated driving.

For interoperability and border-crossing tests, the following scenarios were performed where data were recorded at INRIA-Rocquencourt site:

- Full autonomous slow-down speed for roadworks DENM messages.
- Full autonomous Emergency breaking for Damaged vehicles and accident DENM messages.

- V2V and I2V data recording of DENM messages exchanged between vehicles and RSUs for interoperability validation.

The following figures show the results of the interoperability testing of CCAD in Paris pilot. The figure 7 represents the route tracked by the autonomous vehicle, indicating the speed in function of its color. In this case, one RSU is installed at INRIA facilities, and is transmitting the DENM message Works Information Service (6), RoadWorkWarning (3), ShortTermStationaryRoadWorks (4). This message is received by the autonomous vehicle and causes a speed reduction by 50% in case of the vehicle is circulating into the range (relevant distance) of the message. In the figure are also represented the position and the range (20 meters of radius) where the DENM message is defined. The position where the first and the last DENM is received indicates that the selected range has full coverage of V2X communications. As shown, the speed of the autonomous vehicle is automatically reduced when it enters in the range of the message. Similarly, the previous reference speed is recovered when the vehicle leaves this area.

Figure 7. Route tracked by the autonomous and connected vehicle in the Paris pilot, indicating the position of the DENM message and its range. The center of the messages matches with the position of the RSU location.

This speed reduction is detailed in the figure 8, where is represented the speed profile of the autonomous vehicle in this test, maintaining the same colors than figure 7. The dotted square represents the area within the range of the DENM message, where the speed of the autonomous vehicle is reduced from 20 km/h to 10 km/h.

Figure 8. Speed profile of the autonomous vehicle route in the Paris pilot. In the dotted square is represented the area inside the range of the DENM message.

As shown in table II, the results of the tests of Paris pilot indicate successful results in the implementation and deployment of this first pilot, receiving the C-ITS information perfectly in the entire relevant area and acting automatically in consequence as response to this new data.

B. Madrid Pilot

In this pilot, the complete value chain of AUTOCITS architecture has been tested, generating automatically C-ITS messages from the DGT Traffic Management Center and sending them to the geographically selected RSUs to geo-broadcast the DENM messages to the position and range indicated. The AUTOCITS A6 Cooperative Corridor has been used in the Madrid Pilot and in this paper is shown the response of the autonomous vehicle to a Weather information service (1), AdverseWeatherCondition - Adherence (6), iceOnRoad (5), located in the kilometer 15 of this Corridor and within a relevant distance of 200 meters of radius.

This action of the ADS is activated as response to a Weather information service message, generating a new behavior of the decision-making rules of the ADS as defined in table 1. Only one dedicated lane is required, and the behavior activates once the autonomous vehicle enters in the DENM message range, defined by default to 200 meters around the message position.

The default circulation speed of the autonomous vehicle is 70 km/h. In figure 9 is shown the representation of one of the tests carried out in the Madrid pilot test, representing the route of the autonomous vehicle and its speed profile during the test, as well as the position of the center of the DENM message and a representation of its range (relevant distance). Two aspects must be highlighted as outcomes of this test. First, this is a real deployment in real infrastructures and conditions. That means that, due to the distribution of the infrastructures, may be areas without or with bad V2X coverage, causing delays in the actuation of the autonomous and connected vehicles. Second, once the messages are received, the response of the vehicle is immediate, acting in consequence during the navigation into the relevant distance range.

Figure 9. Route tracked by the autonomous and connected vehicle in the Madrid pilot, indicating the position of the DENM message and its range. The center of the messages matches with the position of the first RSU location of the corridor.

Those facts are perfectly represented in figure 9, and detailed in figure 10, obtaining the results shown in table II, with the reception of the first DENM message 43.6 meters after entering in the range area. However, in this moment, the speed of the autonomous vehicle is automatically reduced to 40 km/h until it leaves the range of the message, when recovering its previous preset speed.

Figure 10. Speed profile of the autonomous vehicle route in the Madrid pilot. In the dotted square is represented the area inside the range of the DENM message

In total, in the Madrid pilot a set of 20 different C-ITS services have been tested, including the modifications of the decision-making mechanisms of the ADS in order to deal with this new information.

C. Lisbon Pilot

The Lisbon Pilot deployment of AUTOCITS C-ITS architecture, comprised six RSUs installed in the A9-CREL highway, each of them with direct connectivity with the C-ITS service module of the Traffic Management Center of Brisa, the road operator. The 6th RSU, installed on a Toll plaza and used by the CTAG autonomous vehicle, is out of the scope of this paper. The route tracked by UPM autonomous vehicle starts in the RSU 5, follows to the West until RSU 1 and returns to the RSU 5 in the opposite sense of the highway. The tests have been carried out in free flow shared traffic with the support of the Portuguese Highway Patrol. Seven C-ITS services have been tested in this pilot and, specifically, in this paper are shown the results of two of them: Weather information service, that is located in the position of the RSUs 3 and 4, and HazardousLocation, located in the position of RSU 2, shown in figure 11.

Figure 11. Route tracked by the autonomous and connected vehicle in the Lisbon pilot, indicating the position of the DENM messages and its range. The center of the messages matches with the position of the RSU locations.

As shown in this figure, the speed of the vehicle automatically adapts as response to the DENM messages, reducing the speed from 70 to 50 km/h. Figure 12 represents the speed profile of the autonomous vehicle in one of the routes of the tests. As shown, the relevant distance of RSU 3 and RSU 4 is overlapped. This means that, independently they are launching DENM in different locations, the action of the autonomous vehicle is continuous during this section of the route. Those messages have also been defined bidirectionally, so they are addressed by the ADS in both directions of the highway. Since this is a real deployment, the RSUs coverage suffer multiple limitations in their coverage in function of the topography of the highway as well as the different infrastructures included, like bridges, gantries or changes of grade. This causes, for example, that the first message received from the RSU 4 in East-West navigation is received 580 meters within the relevant distance area (blue dot), and the last message, 339 meters before leaving this area, as shown in table II. Upon the loss of the connectivity for 5 seconds, the vehicle returns to the reference speed until it receives the first message of the RSU 3, as is shown in the figure 12 from 2000 to 3500 tenth of a second. The same situation of signal occlusion happened in the last part of the RSU 3 message range. Conversely, in the opposite sense route, the coverage is continuous between both RSUs. In the figure 13 is presented the detail of the C-ITS testing in the RSU 2 during the same route. In this case, the coverage of the V2X communications is continuous during the entire range of the DENM message and the autonomous vehicle adapts immediately its speed during the entire relevant area in both directions, as shown in figure 12.

Figure 12. Speed profile of the autonomous vehicle route in the Lisbon pilot. In the dotted squares are represented the area inside the range of the DENM messages in function of the transmitting RSU. The figure shows the route in the two directions of the highway, where the turn back occurred around the time instant 5500 sec.

Figure 13. Detail of the autonomous vehicle route in the Lisbon pilot, depicting the response of the autonomous vehicle to a Hazardous location event in the RSU 2.

In short, and in view of the results of the tests, it can be affirmed that the deployments of the AUTOCITS architecture are totally equivalent, regardless of the country or the infrastructure where they have been carried out, guaranteeing the cross-border operability. In this way, the results are similar, from the standpoint of the autonomous vehicle and its behavior, both in the tests in a controlled environment in Paris, as the tests in a semi-controlled environment in Madrid and, finally, the tests in Lisbon shared traffic. The main conclusion obtained in view of the results is that it is essential to rethink the deployment of RSUs based on the topography of the land to avoid areas of loss of coverage, an element that is not always possible to manage since, being infrastructure previously built, in most cases the installation points are not adaptable.

V. Conclusions

The main objective of the AUTOCITS Project is the development of a C-ITS cooperative systems support architecture that is interoperable and with cross-border capability to guarantee the supply of V2X information from traffic control centers to vehicles, passing through the value chain of road transport communications. These services are focused on connected vehicles, whether manned or unmanned, in order to develop cooperative, connected and autonomous driving. Within this scope, the architecture has been deployed in three cooperative corridors located in the three capitals of the European Atlantic corridor TEN-T, Paris, Madrid and Lisbon, including the installation of RSUs based on ETSI ITS-G5 technologies capable of sending DENM messages within this paper, the result of the CCAD pilots in these three locations is presented, using an autonomous and connected vehicle of the Universidad Politécnica de Madrid, which has carried out autonomous driving tests at the three pilot sites. The result of these tests is that it is confirmed that the AUTOCITS architecture can support the generation of C-ITS information and sending it to the infrastructure, as well as providing information to support CCAD independently of the geographical area or country. This has been demonstrated by the corresponding tests, which show the performance of the autonomous vehicle in the different cooperative corridors, which is capable of modifying its behavior in response to a series of DENM messages, integrating communications with its decision-making system, as detailed in the results section.

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José E. Naranjo was born in Orense, Spain in 1975. He received the B. E. and M. E. degree in Computer Science engineering from the Technical University of Madrid (UPM), Spain, in 1998 and 2001 respectively. He got the Ph. D. in Computer Science at UPM in 2005. From 1999 to 2007 he was with the Instituto de Automática Industrial (CSIC). In 2007, he obtained a position as associate professor in the School of Computer Science of the Universidad Politécnica de Madrid (UPM) and became part of Region of Madrid Excellence Group SEGVAUTO (Safety in Automobile Vehicles with special interest in Reduced Mobility Persons). Presently, he is Vice-Director of the Intelligent Systems Department of the UPM. His research interests include intelligent systems, fuzzy logic control, ITS, usability and accessibility.

Felipe Jiménez obtained his Master's Degree in Industrial Engineering from the Polytechnic University of Madrid (UPM), his Master's Degree in Physical Science from the National University of Distance Education of Spain and his PhD in Mechanical Engineering from the UPM in 2001, 2005 and 2006, respectively. Currently, he is Associate Professor at the UPM and Head of the Intelligent Systems Unit of the University Institute for Automobile Research of the UPM. He has been involved in several research projects and has developed engineering studies for relevant national firms. His fields of interest are the automotive industry, vehicle safety, mechanical design, driver assistance systems and intelligent transport systems. He is author of several papers in relevant scientific journals and has participated in several national and international congresses.

Dr Cristiano Premebida is Assistant Professor in the department of electrical and computer engineering at the University of Coimbra, Portugal, where he is part of the Institute of Systems and Robotics (ISR-UC). His main research interests are autonomous vehicles, autonomous robots, robotic perception, cooperative/connected intelligent transport systems (C-ITS), ADAS, machine learning, and sensor fusion. C. Premebida has collaborated on research projects in the areas related to C-ITS, autonomous driving, and applied machine learning, including national and international projects. He is IEEE-ITS society member, been serving as AE in the flagship conferences ITSC and IVS, and has regularly organized international workshops on automated driving, AI/ML perception, and C-ITS. Google-Scholar profile: https://scholar.google.co.uk/citations?hl=en&user=RuHUvNMAAAAJ

Pedro Serra, senior researcher and responsible of Autonomous Vehicles area on IPNlas. Graduated in Electrical Engineering, Automation area, in University of Coimbra. His main experience is in autonomous shuttles technology and in development of automated and robotic systems. Was project manager of MOVE Project, where the goal was to develop and install a mobility system, based on fully autonomous electric vehicles, with two vehicles in operation at Rovisco Pais Hospital since March 2010 and a third one in Deltapark Hotel in Switzerland since March 2016. On his management curriculum have also some European Projects (p.e. AutoCITS/CEF, Dorothy/FP7, FI-WARE/FP7 and eLearningDTN/FP7).

Alberto Valejo is currently project manager in Laboratory for Automation and Systems of Instituto Pedro Nunes. He has a MSc. in Electrical and Computer Engineering from the University of Coimbra. In 2003 project manager/researcher he was involved in the genesis of the IPNlas autonomous shuttles system, precursor of MOVE project, through his participation on CyberCars - Cybernetic Cars for a New Transportation System in the Cities (2001-2004; FP5) and CyberMove - Transportation Systems for the Cities of Tomorrow (2001-2004; FP5). Later, he continues his involvement on projects related with transport industries as follow: Dorothy - Development Of RegiOnal clusTers for researcH and implementation of environmental friendlY urban logistics (2013-2016; FP7); AUTOC-ITS - Regulation study for interoperability in the Adoption the Autonomous Driving in European Urban Nodes (2016-2019; CEF-T).

Fawzi Nashashibi, 53 years, is a senior researcher and has been the Program Manager of RITS Team at INRIA (Paris-Rocquencourt) since 2010. Fawzi Nashashibi has a MSc Degree in Automation, Industrial Engineering and Signal Processing (LAAS/CNRS), a PhD in Robotics from Toulouse University prepared in (LAAS/CNRS) laboratory, and a HDR Diploma (Accreditation to research supervision) from University of Pierre et Marie Curie (Paris 6). His main research topics are in environment perception and multi-sensor fusion, vehicle positioning and environment 3D modeling with main applications in Intelligent Transport Systems and Robotics. He is the author of numerous publications and patents in the field of ITS and ADAS systems. Since 1994 he has also been a lecturer at several universities (Mines ParisTech, Paris 8 Saint-Denis, Leonard de Vinci Univ. -ESILV professor, Telecom Sud Paris, INT Evry, Ecole Centrale dElectronique) in the fields of image and signal processing, 3D perception, 3D infographics, mobile robotics and C++/JAVA programming. IEEE member, he is also member of the ITS Society and the Robotics & Automation Society and member of AHB30 committee of the TRB. He is an Associate Editor of several IEEE international journals and conferences such as IV, ITSC, ICARCV and Journals.