

Cross-Border interoperability for Cooperative, Connected and Automated Driving

José E. Naranjo¹, *Senior Member, IEEE*, Felipe Jiménez¹, Rodrigo Castiñeira², Mauro Gil², Cristiano Premebida³, Pedro Serra⁴, Alberto Valejo⁴, Fawzi Nashashibi⁵, Conceição Magalhães⁶

¹Instituto Universitario de Investigación del Automóvil, Universidad Politécnica de Madrid, Madrid, Spain

²Indra Sistemas S.A., Madrid, Spain

³University of Coimbra, Coimbra, Portugal

⁴Laboratory for Automation and Systems, Instituto Pedro Nunes, Coimbra, Portugal

⁵Inst. National de Recherche en Informatique et en Automatique (INRIA), Paris, France

⁶Brisa – Auto-estradas de Portugal, S.A., Lisboa, Portugal

Nowadays, there is no doubt that the implantation on a massive scale of safe highly automated driving is very difficult using only the information coming from the ego-vehicles, which are subject to the limitations of their visual horizon. For automated driving systems to become a reality, it is essential to provide the system with two fundamental elements among others: connectivity and cooperative services. Both elements are still at a very early stage of their development, in communications technology and in the organization and generation of support information. In addition, extra difficulties are presented, such as trans-national barriers to accessing services and exchanging information with other vehicles and infrastructure. This paper presents the implementation of a novel architecture to support the integration of cooperative intelligent transportation systems (C-ITS) in automated driving, including the results of cross-border interoperability tests carried out in three cooperative, connected and automated driving (CCAD) pilots that have been deployed in three cities belonging to the trans-European Atlantic Corridor: Madrid, Lisbon and Paris, under the framework of the European project AUTOCITS. These results show the performance of the CCAD architecture and have been analyzed to have a set of recommendations to ensure successful deployment of cooperative, connected and automated driving at European level.

Index Terms—Automated vehicles, V2X Communications, Pilots, Cooperative connected and automated driving.

I. INTRODUCTION

COOPERATIVE, connected and automated driving technology is built around three fundamental pillars: V2X communications systems, generation of cooperative services and automated driving.

Although the first automated driving experiences took place between the 60s and 70s, it was not until the early 1990s that the first realistic steps were taken for the complete development of Automated Driving System-operated road vehicles. Here it 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]. With the experiences of the DARPA Grand Challenge [5] at the end of the 2000s, Automated Driving System-operated vehicles received a significant boost, especially thanks to IT companies such as Google [6] that pushed the entire sector of the automotive industry towards this type of technological development, where Volvo [7], Daimler [8] and Ford [9] are major players. This jump forward has also been supported by the different national and international regulatory agencies in charge of road traffic management, which give legal coverage for the introduction of real automated driving into the market.

There are six automated driving levels for road vehicles (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. When the ADS performs the entire DDT while engaged, it can be classified as level 3 if the ADS performs some tasks automatically but the driver must act as the fallback-ready user

at any moment. In general terms, in levels 4 and 5 there is no expectation by the ADS that the user will take back the driving task, within the current Operational Design Domain (ODD) or in every driving operations respectively, which is defined under the SAE J3016 standard [10] as “the specific conditions under which a given driving automation system or feature thereof is designed to function”. Those conditions include the driving modes, and the environment limitations related to the specific vehicle operation.

Nowadays, commercial vehicles with automated capacities are considered level 2-3 and only research and testing vehicles are considered levels 3-4. However, those vehicles are designed to carry out the DDT using the sensors and equipment installed in the ego-vehicle. A wide range of sensors can improve the perception of the vehicles, but these are constrained by the limits of the visual horizon. Thus, there is a large number of situations with high uncertainty that can be hardly solved by the ego-vehicle ADS respecting required safety levels so the ODD is forced to be reduced. An example of this is navigation in a roundabout with heavy traffic [11].

To solve these limitations, there are two technologies that should be enabled within the automated vehicles: connectivity and cooperation.

Communication technologies enable vehicles to exchange data among themselves, and with the infrastructure and any other suitable element in the road eco-system. These vehicular communications are commonly known as V2X (vehicle-to-everything) and they support the different ways of providing access to the connected systems and services deployed in the

navigation geographical area of the ADS [12]. Two technologies are widely used to support communication between vehicles (V2V) and with the infrastructure (V2I): The Dedicated Short-Range Communications (DSRC) based on ETSI ITS-G5/IEEE 802.11, and 3/4/5G cellular telephony. 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 vehicle deployment but not necessarily a network operator. The second technology is provided only by licensed network operators and it supports communications for services that do not demand low latencies (10 ms range) [13]. The most common approach is the hybridization of short range/cellular communications to leverage the features of each. With 5G cellular communications, this hybridization will be a reality 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 intelligent Transportation 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 management 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 warnings on traffic status, weather condition, emergency vehicles and cooperative braking, among others. Using their time-to-market, these services are classified as Day-1 and Day-1.5, those that are at a level of development that they can be deployed now [15]. Day 2 includes basic C-ITS support services for automated driving. Day-3 and Day-4 are the C-ITS that will include support for automated and cooperative driving of the future.

Those C-ITS are being tested in several cooperative corridors. In Europe, the C-ROADS initiative covers the aspects of design and interoperability of the national C-ITS corridors, acting as a framework to unify the European initiatives. Thus, the European Joint Cooperative Corridor links three countries (The Netherlands, Germany and Austria) to support communication between vehicles and roadside infrastructure. In the UK, four infrastructure projects are available, using open road, testbeds in the West Midlands and London to test C-ITS. In Spain, there are two C-ITS corridors fully developed: Siscoga and AUTOCITS-A6, joined through the framework of C-ROADS Spain that includes four additional corridors under development. In Finland the Aurora testbed C-ITS corridor is also part of the C-ROADS ecosystem. Outside of Europe, in the USA, US DoT has designated 10 C-ITS testbed proving grounds focusing on CCAD [16]. There are also similar experiences in Japan, South Korea, China or Singapore [17], focusing in the C-ITS services deployment.

To deploy cooperative, connected, and automated driving, it is necessary that isolated automated vehicles become part of the C-ITS ecosystem through two key additional elements. The vehicles need connectivity to the communications networks deployed on the road; and modifications must be made to both

the Automated Driving Systems to make use of the new information that arrives through this channel and the decision-making systems for this purpose.

This paper presents the framework architecture to support this C-ITS integration in automated driving, providing cross-border functionality to the CCAD and its deployment in three pilots. This architecture has three main novelties: it integrates the C-ITS information to enrich the capabilities of the automated vehicles; the C-ITS management is transparent to the TMC infrastructure due its ability to obtain the information from multiple sources; and it is interoperable, independently of the TMC, the country or the connected and/automated vehicles.

This is 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 automated and connected vehicles. For this, three pilot projects have been designed and conducted in urban access roads in the three capitals of the Atlantic Corridor of the TEN-T Trans-European Transport network, Madrid, Paris and Lisbon, where a common communications architecture and C-ITS has been deployed. This includes the entire value chain of C-ITS, from the road and the vehicles to the traffic management centers, to provide automated vehicles with cooperative information and allow them to increase their capacity to respond to new situations that have not been considered to date, with a focus on ensuring cross-border interoperability. Moreover, AUTOCITS goes one step further and proposes the introduction of automated driving and the development of new strategies in the control systems of automated vehicles to manage the C-ITS information received through these communications [18, 19, 20]. This paper describes the framework architecture, the deployment of V2X technology, the results of these three pilot projects and how automated vehicles can manage this new information and adapt to the new communicated and cooperative environment, increasing the capacities of isolated automated vehicles.

II. PILOTS

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

When managing this information in automated vehicles, two key 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-automated vehicles, in such a way that it is necessary to define specific automated driving strategies to respond to the reception of these C-ITS.

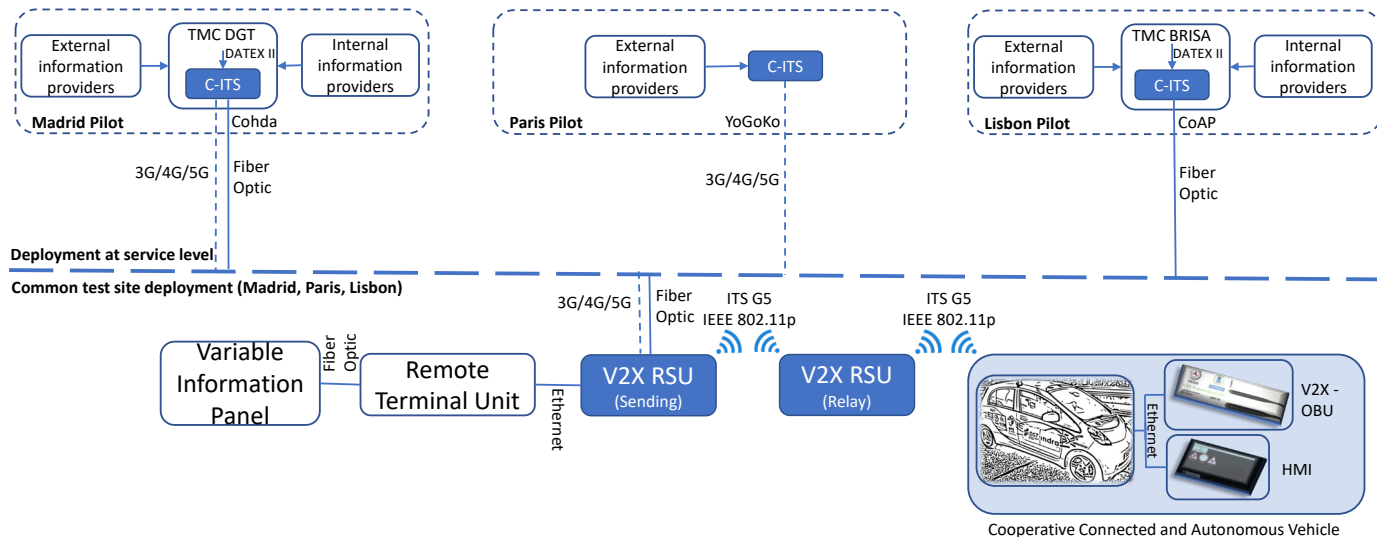


Figure 1. AUTOCITS's framework architecture for the CCAD deployment.

The information flow of those Day-1 and Day-1.5 services selected to be implemented and tested is downstream, from TMC to vehicles. However, the V2I upstream communication is possible and enabled, as well as the data interchange through V2V. This design enables a set of new behaviors in the ADS of the automated vehicles, that can be extended in function of the addition of new C-ITS services.

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, enable adaptation to the different features and equipment available in the three countries where the pilots will be carried out, as well as guaranteeing 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 Infrastructure-to-Infrastructure (I2I) communications systems and received by vehicles connected via V2X. 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 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.

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 automated vehicles are 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 four automated vehicles have been used in AUTOCITS, this article shows the results of automated and connected navigation for the Universidad Politécnica de Madrid's vehicle, which was used 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 on one of the northern access roads in the city of Madrid. To deploy C-ITS services in this area, a total of 17 RSUs were installed to provide continuous communication throughout the route (figure 2).

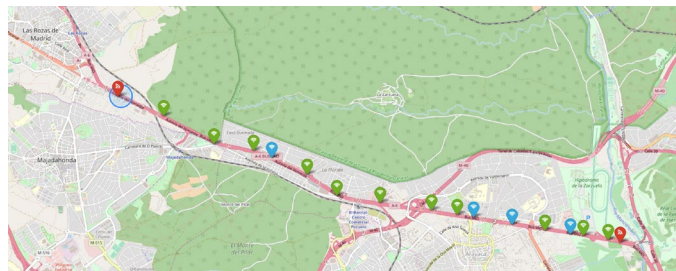


Figure 2. AUTOCITS Madrid Pilot deployment of RSUs.

The architecture of this corridor was designed with the aim of guaranteeing maximum communications coverage while minimizing the cost of deployment. In this way, two Cohda MK5 RSUs were installed through 3G or, optionally, fiber optic

connectivity with the traffic management 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 were 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 was carried out based on the topography of the road, with distances between them ranging between 300 and 1200 meters. This maintains continuous connectivity for the vehicles that circulate through the corridor, in such a way that a message issued by one of the RSUs is guaranteed to reach any Onboard unit (OBU) that circulates at any point along the route. The Cohda RSUs receive messages from the Indra C-ITS Service Center, connected to the Spanish Traffic Agency (Dirección General de Tráfico - DGT) via DATEX II. This C-ITS Service Center allows the DGT Traffic Management Center to send information about possible incidents or events to the connected and/or automated vehicles that are circulating in a specific geographical area, following a similar philosophy than 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 are defined below:

- Step 1: Collection / generation of incidents (planned maintenance works, 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 into 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 disseminate Geo-Broadcast 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 of vehicle, GPS position, direction, speed, etc.). The vehicle takes this information and executes the relevant action, notify/alert the driver (through HMI), or slow down, change lanes, etc.

2) Portugal

The deployment for 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 the positions shown in figure 3. Those RSUs manufactured by A-to-Be are connected with optic fiber (or 3G/4G) of the operator of the infrastructure, BRISA, and managed from the C-ITS service center of the BRISA’s TMC. 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 [21]) to interchange information.

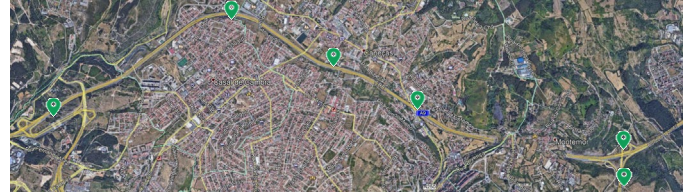


Figure 3. AUTOCITS Lisbon Pilot deployment of RSUs

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

- Step 1: Collection/generation of events.
- Step 2: The ATLAS platform, used by BRISA as a TMC, then 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: The RSU units, using ETSI ITS-G5 standard, then convert the events to DEN messages and geo-reference them in the location of the event, selecting specific RSUs to disseminate the information. For as long as the event is taking place the RSUs disseminate the messages in a specific area. The vehicles within the area of diffusion receive the information through their OBUs.
- Step 5: The OBU filters the relevant events using the vehicle information (type of vehicle, GPS position, direction, speed, etc.). The vehicle takes this information and executes the relevant action, sending alerts to the driver (through HMI), or slowing down, changing lanes, etc., in the case of automated driving tests.

3) France

The deployment in Paris was conducted 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 describe 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 on the ITS platform.
- Step 3: The ITS platform and the RSUs will use the YoGoKo protocol for intercommunication.
- Step 4: Each YoGoKo RSU will convert the triggered events in real time to DEN standard messages.
- Step 5: Any connected or automated 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 of vehicle, GPS position, direction, speed).
- Step 7: The vehicle takes this information and

executes the relevant action, send alerts to the driver (through HMI), or slow down, change lanes, etc. in the case of automated driving tests.

C. C-ITS

C-ITS services are structured around the generation of information between vehicles and infrastructures, allowing safety and efficiency on the road to be enhanced. 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 road transport applications that demands cooperation among different road entities, following different communication protocols depending on the focus application such as Cooperative Awareness Messages (CAM), Decentralized Environment Notification Message (DENM), Map Data (MAP) and Signal Phase And Timing (SPAT) [22]. In the AUTOCITS architecture, the considered data flow is downstream from TMCs to vehicles using DENM and attached messages. The structure of those messages is described in figure 4.

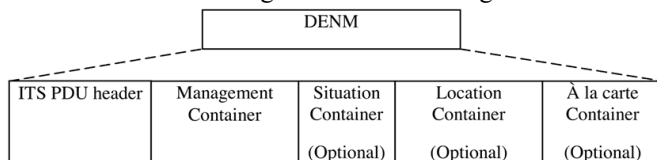


Figure 4. General DENM structure [19].

This DENM message structure is divided into containers that separate the different types of information, and are specified in the standard ETSI TS 102 637-3, [23]:

- 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 (e.g. 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 is an open data field designed to include additional specific information related with the current C-ITS service.

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 provides information regarding possible hazardous conditions related with weather (fog, rain, wind, ice, etc). This service is directly linked to the prevention of unsafe situations related to inadequate speed, recommending the best speed in function of the weather condition of the geographical area of circulation. Additionally, in situations extreme weather conditions, the service can also warn the driver. 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 provides information about road works in the circulation area, considering also possible traffic restrictions and the reduction of speed limits. 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. ADS EQUIPPED VEHICLE

The testbed automated vehicle used in the three pilots is the UPM’s automated Mitsubishi iMIEV; it includes 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 (Robotic Operative System) environment, where a navigation module was developed to maintain the route and perform maneuvers, while the decision-making module takes the appropriate driving decisions depending on the environment perception and the communications data. This module has been modified to comply with the requirements of the AUTOCITS project and to extend the capabilities of the automated 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, which receives and manages all those V2X messages.



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

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 automated vehicles. This is not a simple task because the C-ITS were not 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.

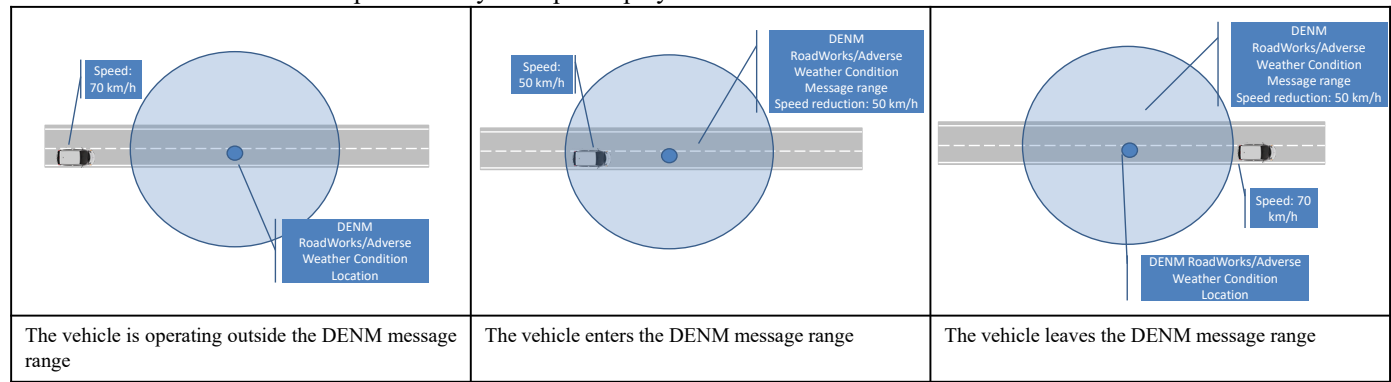


Figure 6. Example of operation of DENM messages under CCAD.

Thus, from the point of view of an automated vehicle it is necessary to include in the ADS a response to the different types of C-ITS messages available. In this way, when receiving a speed reduction message due to roadworks in 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. Additionally, when the vehicle receives messages such as “strong storm” that do not involve any specific associated instruction, the ADS of the vehicle must be extended with the response to that message, that must be a reduction in speed, exactly as human drivers would.

That is why the control systems of these vehicles must be adapted 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 address the orders received from the traffic management centers through V2X.

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

The decision module is in charge of taking the high-level driving decision in the ADS of the 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 automated 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.

An example of the task performed 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 according to this new information. In the event that 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. If the event has a target speed higher than

the target speed of the route tracking system, the vehicle will maintain its speed.

TABLE I
DECISION MAKING RULES ADDED IN THE AUTOMATED VEHICLE ADS
DEPENDING ON THE RECEPTION OF THE DENM MESSAGES

Pilot	C-ITS Service	Cause (code)/Sub-cause (code)	Action of the ADS
<i>Paris</i>	Works Information Service	RoadWorkWarning (3) / ShortTermStationaryRoadWorks (4)	The ADS reduces the speed of the vehicle by 50% with respect the current speed limit ^{*,**}
<i>Madrid</i>	Weather information service	AdverseWeatherCondition - Adhesion (6) / iceOnRoad (5)	The ADS reduces the speed of the vehicle to 40 km/h ^{**}
<i>Lisbon</i>	Weather information service	AdverseWeatherCondition - Visibility (18) / HeavyRain (4)	The ADS reduces the speed of the vehicle to 50 km/h ^{**}
<i>Lisbon</i>	HazardousLocation	SurfaceCondition (1) / Rock falls (1)	The ADS reduces the speed of the vehicle to 50 km/h ^{**}

* In case of C-ITS messages overlapping, the ADS only applies one reduction.
** In case of C-ITS messages overlapping, the ADS applies the lowest speed

In this way, the C-ITS Day-traffic management center 1 and 1.5 messages have been programmed together with their subsequent responses in the UPM automated vehicle, as shown in table I.

Table I specifies the detailed behavior and actions of the automated vehicles as a response to the C-ITS messages. Specifically, four different behaviors have been defined depending on 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 in kilometer per hour (km/h)
- Speed reduction to a percentage of the current speed
- Lane change
- Vehicle Stop

Note that 20 C-ITS services have been implemented in the automated vehicle, but only four, the C-ITSs and related automated behavior (speed reduction), are shown in this paper. The lane change and stopping behaviors have been also implemented and tested as part of AUTOCITS project. In this case the speed limits have been selected empirically to demonstrate the performance of the complete architecture in different countries, infrastructures, and conditions.

Figure 6 shows an example of the response and actions of a connected and automated vehicle when it receives 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 roadworks or adverse weather conditions warning depending on the information retrieved by multiple sources. Once the warning is generated, the C-ITS module sends a message with the corresponding information to the RSUs installed in the geographical area concerned, including the geodata of the position of the event and the range (relevant distance) of event validity, from the center to the limit of the event.

The OBU captures this message and sends it to the high-level ADS to report the situation. In this way the vehicle can perform all these actions independently from the previously designed plan on the route tracking system. The received event points out to the vehicles that they must reduce the speed of the automated vehicle to a specified value and/or use a certain lane. Then, as represented in figure 6, the vehicle approaches 70 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 implementation and deployment of the AUTOCITS framework architecture to support cross-border CCAD, conducted through pilot tests conducted in Paris, Madrid, and Lisbon. One of the key contributions of this architecture is the extension of the capabilities of the automated 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 cross-border interoperability.

In this regard, the C-ITS architecture of AUTOCITS has been implemented in the three 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 automated vehicles, and organized in three phases according to their level of complexity. The first pilot test presented is the one carried out in Paris, where the interoperability of the C-ITS AUTOCITS architecture is checked in a controlled environment. The second took place in Madrid and was conducted in real conditions and on public roads, but under a controlled environment, to test the complete AUTOCITS system functionality in real situations. Finally, the Lisbon pilot was carried out in real situations of shared traffic, executing the complete AUTOCITS architecture and with real automated vehicles. In total, these pilot tests covered more than 6000 km in connected, cooperative, and automated 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 automated vehicle maneuver starts is less than 100 milliseconds (ADS reaction time), so the intervention of the message reception on the control system is considered as “real-time”.

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 (s)	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)
<i>Paris</i>	24	49	50	50	20	10
<i>Madrid</i>	28	156	186	200	70	40
<i>Lisbon RSU 4</i>	10	-80*	220	500	60	50
<i>Lisbon RSU 3</i>	29	220	161	500	60	50
<i>Lisbon RSU 2</i>	64	450	498	500	70	50
<i>Lisbon RSU 2</i>	77	485	514	500	60	50
<i>Lisbon RSU 3</i>	44	141	501	500	70	50
<i>Lisbon RSU 4</i>	31	499	409	500	70	50

*The first message is received after the vehicle has crossed the center

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 to test the communication systems in extreme 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.

A. Paris Pilot

The first round of Interoperability validation was conducted in the facilities of INRIA-Rocquencourt, where a replication of the roadside equipment was installed on 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 DEN messages that were broadcast to the selected area. The UPM’s automated and connected car 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 the INRIA-Rocquencourt site:

- Full automated slow-down speed for roadworks DENM messages.
- Full automated Emergency braking 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 the Paris pilot. Figure 7 represents the route tracked by the automated vehicle, indicating the speed depending on its color. In this case, one RSU is installed at the

INRIA facilities, and is transmitting the DENM message Works Information Service (6), RoadWorkWarning (3), ShortTermStationaryRoadWorks (4). This message is received by the automated vehicle and causes a speed reduction of 50% if the vehicle is circulating in the range (relevant distance) of the message. In the figure the position and the range (a 20 meters radius), where the DENM message is defined, are also represented. The position where the first and the last DENM is received indicates that the selected range has full coverage of V2X communications.

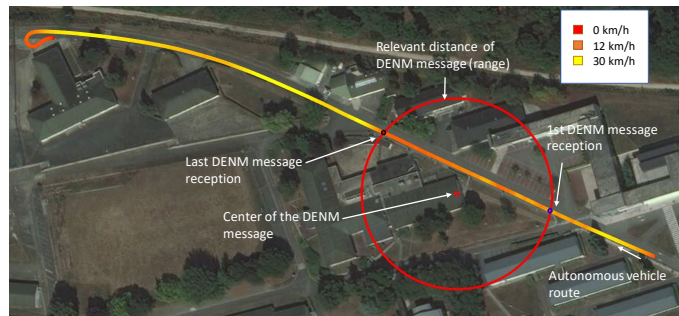


Figure 7. Route tracked by the automated and connected vehicle in the Paris pilot, indicating the position of the DENM message and its range. The center of the messages matches with the position of the RSU location.

As shown, the speed of the automated vehicle is automatically reduced when it enters the range of the message. Similarly, the previous reference speed is regained when the vehicle leaves this area.

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

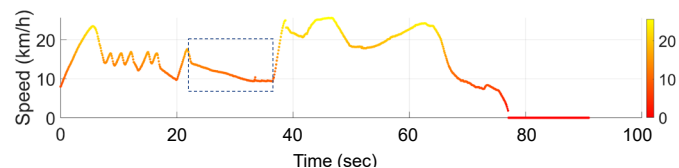


Figure 8. Speed profile of the automated vehicle route in the Paris pilot. In the dotted square the area inside the range of the DENM message is represented.

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

B. Madrid Pilot

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

distance radius of 200 meters.

This ADS action is activated as a 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 automated vehicle enters in the DENM message range, defined by default as 200 meters around the message position.



Figure 9. Route tracked by the automated 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.

The default circulation speed of the automated vehicle is 70 km/h. Figure 9 shows the representation of one of the tests carried out in the Madrid pilot, representing the route of the automated vehicle and its speed profile, 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, there may be areas without or with poor V2X coverage, causing delays in the actuation of the automated and connected vehicles. Second, once the messages are received, the response of the vehicle is immediate, acting in consequence during the navigation within the relevant range.

Those facts are 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 the range area. At this moment, the speed of the automated vehicle is automatically reduced to 40 km/h until it leaves the range of the message, when it returns to its previous preset speed.

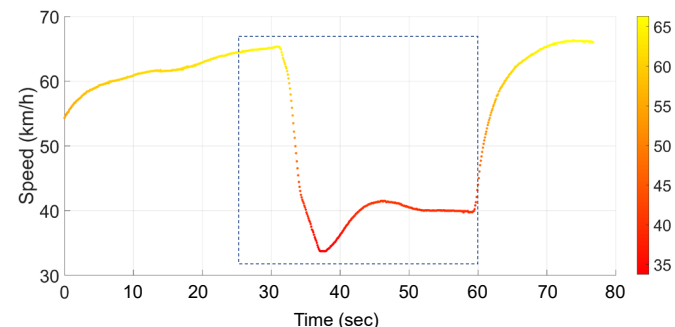


Figure 10. Speed profile of the automated vehicle route in the Madrid pilot. In the dotted square the area inside the range of the DENM message is represented

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 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 is installed on a Toll plaza and is used for other purposes beyond the scope of this paper. The route tracked by the UPM automated vehicle starts at RSU 5, continues west as far as RSU 1 and returns to RSU 5 in the opposite direction of the highway. The tests were carried out in semi-free flow shared traffic with the support of the Portuguese Highway Patrol. Seven C-ITS services were tested in this pilot and, specifically, this paper shows the results of two of them: Weather information service, located in the position of RSUs 3 and 4, and HazardousLocation, located in the position of RSU 2, shown in figure 11.

As shown in this figure, the speed of the vehicle automatically adapts in response to the DENM messages, reducing the speed from 70 to 50 km/h. Figure 12 represents the speed profile of the automated 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, regardless of whether they launch DENM in different locations, the action of the automated vehicle is continuous along this section of the route.



Figure 11. Route tracked by the automated 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.

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 suffer multiple limitations in their coverage depending on the topography of the highway as well as the different infrastructures therein, such as bridges, gantries and changes of grade. This means, 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, 280 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

from RSU 3, as shown in figure 12 between 250 and 350 seconds.

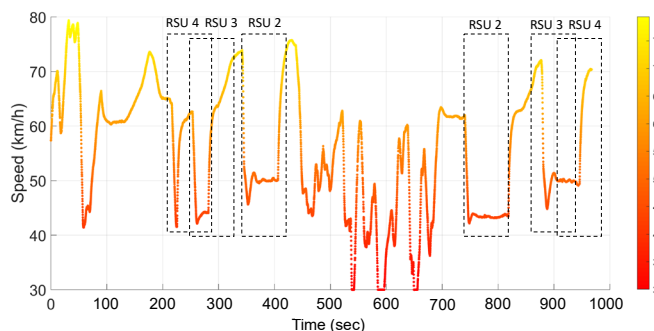


Figure 12. Speed profile of the automated vehicle route in the Lisbon pilot. The dotted squares represent the area inside the range of the DENM messages depending on the transmitting RSU. The figure shows the route in the two directions of the highway, where the turnback occurred around the time instant 550 seconds.

The same situation of signal occlusion happened in the last part of the RSU 3 message range. Conversely, in the opposite direction, the coverage is continuous between both RSUs. Figure 13 shows 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 automated vehicle immediately adapts its speed along the entire relevant area in both directions, as shown in figure 12.



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

In short, and in view of the results of the tests, it can be asserted that the deployments of the AUTOCITS architecture are totally equivalent, regardless of the country or the infrastructure where they have been carried out, guaranteeing cross-border operability. In this way, the results are similar, from the standpoint of the automated vehicle and its behavior, both in the tests in a controlled environment in Paris and 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 with a loss of coverage, an element that is not always possible to manage since, being previously built

infrastructure, in most cases the installation points are not adaptable. Some of the cross-border barriers found during the project execution are the different C-ITS and traffic management centers implementations, the information sources format, interpretation and providers, the RSU installation and deployment philosophy, multiple legal barriers, as well as many technical details not covered in standards

V. CONCLUSIONS

The main objective of this paper is to present a novel framework architecture to support CCAD, integrating the C-ITS information provided by the traffic management centers in a V2X ecosystem that includes automated vehicles and guarantees cross-border interoperability and the supply of V2X information from TMCs to vehicles, passing through the value chain of road transport communications. These services are for connected manned or unmanned vehicles to develop cooperative, connected, and automated driving, and are part of the European Project AUTOCITS. 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. This paper presents the result of the CCAD pilots in these three locations, using an automated and connected vehicle from the Universidad Politécnica de Madrid, which has conducted automated driving tests at the three pilot sites. These tests confirm that the AUTOCITS architecture can support the generation of C-ITS information and send it to the infrastructure, as well as provide information to support CCAD regardless of the geographical area or country. This has been demonstrated by the corresponding tests, which show the performance of the automated vehicle in the different cooperative corridors and that it is capable of modifying its behavior in response to a series of DENM messages, integrating communications within its decision-making system, as outlined in the results section.

Finally, the relevance of C-ITS to the ODD of the highly automated vehicles is clearly stated as a tool to enable the cooperative, connected, and automated driving. C-ITS services support the information exchange between vehicles and infrastructure, extending the specific conditions under which the automation systems are designed by adapting the ADS behavior considering the road condition in order to get a safer and more efficient road transport.

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José E. Naranjo 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 was awarded with a Ph. D. in Computer Science at UPM in 2005. From 1999 to 2007 he was a member of the Autopia Group of the Spanish Research Council (CSIC). In 2007, he obtained a position as associate professor in the School of Computer Science of the Universidad Politécnica de Madrid (UPM). His research interests include Intelligent Transportation Systems, artificial intelligence, V2X communications, C-ITS, usability and accessibility and CCAD. In addition, Prof. Naranjo is a member of several scientific and editorial committees, including his role as associate editor of IEEE Transactions on ITS, belonging to the organizing committees of the major conferences in the sector, such as the IEEE Intelligent Vehicle Symposium and the IEEE Intelligent Transportation Systems Conference, while also being a senior member of IEEE ITS Society, serving as Vice President of the ITS Society Spanish Chapter.



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 Full 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 the author of several papers in important scientific journals and has participated in several national and international congresses.



Rodrigo Castiñeira has a B.A. in Telecommunications Engineering (UVA –Valladolid, Spain). He works for the R&D group at the Transportation Business Unit department in INDRA sistemas as R&D Coordinator. He is the coordinator of several European projects related to digitalization in the transport sector, such as Transforming Transport, AUTOCITS, HARMONY, etc. He is also head of other R&D projects where Indra has implemented several pilots related to digitalization in the construction sector, such as Mire3D (BIM),

TEDS4BEE (Energy Efficiency) and Arrowhead (IoT Framework). Rodrigo also participates in several European platforms as representative and expert (DTLF, CCAM, C-ROADS, etc.) providing input as an expert. He is now coordinating the COMP4DRONES project related to UAVs applied to different domains.



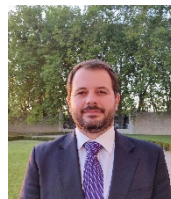
Mauro Gil has a Bachelor's degree in Industrial Engineering from Universidad de Navarra and is Senior Systems Engineer - R&D Manager at INDRA Sistemas. He oversees coordination of and participation in the complete cycle of R&D projects: project proposal, development and execution phase, mainly in the field of intelligent transport systems (ITS), Smart Cities and connected vehicles



Cristiano Premebida is Assistant Professor in the department of electrical and computer engineering at the University of Coimbra, Portugal, where he is a member 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 an IEEE-ITS society member, has served as AE in

the flagship conferences ITSC and IVS, and has regularly organized international workshops on automated driving, AI/ML perception, and C-ITS.



Pedro Serra, senior researcher and manager of the Autonomous Vehicles area in IPNlas. Degree in Electrical Engineering, Automation area, from University of Coimbra. His main experience is in autonomous shuttles technology and in the 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. His management curriculum also features a number of European Projects (p.e. AutoCITS/CEF, Dorothy/FP7, FIWARE/FP7 and eLearningDTN/FP7).



Alberto Valejo is currently project manager in the Laboratory for Automation and Systems of the Instituto Pedro Nunes. He has a MSc. in Electrical and Computer Engineering from the University of Coimbra. In 2003 as project manager/researcher he was involved in the genesis of the IPNlas autonomous shuttles system, the precursor of MOVE project, through his participation in 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 continued his involvement in projects related with transport industries such as: Dorothy - Development Of Regional clusters for research and implementation of environmentally 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 d'Electronique) in the fields of image and signal processing, 3D perception, 3D infographics, mobile robotics and C++/JAVA programming. IEEE member, he is also a member of the ITS Society, the Robotics & Automation Society and the AHB30 committee of the TRB. He is an Associate Editor of several IEEE international journals and conferences such as IV, ITSC, ICARCV and Journals.

Conceição Magalhães is the Head of Cadastre Management Service of



BRISA's Infrastructure Management and is completing her PhD in Transportation Systems, at Massachusetts Institute of Technology Portugal. She has a degree in Civil Engineering from Instituto Superior Técnico, Lisbon University and a postgraduate degree in business management from Lisbon Catholic University. Her research work aims to define a framework to deal with the operational integration of autonomous and conventional vehicles on motorways. Her main experience is motorway capital and operational expenditure planning and management as well as road designing. She is very eager to study and support emergent technologies market penetration and to contribute to increasing their public acceptability.