Real-time responsive Physical and Digital Infrastructure for CCAM-enabled Traffic Management of cross-border highways

Jordi Casademont[1,2], Jordi Marias-i-Parella[2], Harilaos Vasiliadis[3], David Porcuna[3], Jacint Castells[4], Joseph Kokolo[5], William Diego[6], Ignacio López[7], Aristarco Tomas[8], Lazaros Gkatzikis[9]

[1] Universitat Politècnica de Catalunya, Spain; [2] i2CAT Foundation, Spain; [3] Abertis Autopistas España, Spain; [4] IDIADA Automotive Technology, Spain; [5] MILLA, France; [6] Retevisión, Spain; [7] Enide Solutions, Spain; [8] Tenalach Consulting, Spain; [9] Institute of Communication and Computer Systems, Greece

ABSTRACT

In this paper, we showcase a testbed implementation of the cutting-edge architecture derived from the ongoing European project PoDIUM. This project is dedicated to advancing the implementation of Cooperative, Connected and Automated Mobility (CCAM) technology. The provided use case introduces a novel system designed to facilitate collaboration between vehicles, road users, and road operators, enabling the implementation of real-time traffic strategies to ensure safe and efficient traffic flow. The Physical and Digital Infrastructure (PDI) system integrates internal and external data to create a comprehensive perception of traffic conditions along road sections. Utilizing this information, the system generates potential scenarios and formulates traffic management strategies. The primary goal is to ensure the safe and efficient flow of traffic in mixed traffic conditions. The appropriate traffic control strategies are dynamically selected in real-time, utilising information obtained from connected vehicles (CVs) and vehicle detection through video cameras equipped with image recognition capabilities. These strategies are then communicated to Connected and Automated Vehicles (CAV), which autonomously adhere to them whenever feasible. Furthermore, the infrastructure facilitates the optimal dissemination of awareness and perception information among CVs in the area, thereby enhancing safety and coordination among them.

Keywords: C-ITS, V2X, PDI, CCAM, road traffic management.

1. INTRODUCTION

Presently, we are immersed in a profound transformation of the transportation systems. At the forefront of this evolution lies the Cooperative Connected and Automated Mobility (CCAM), a paradigm that integrates cutting-edge technologies to enhance the efficiency, safety, and sustainability of transportation systems. Within this framework, Intelligent Transport Systems (ITS) applications play a pivotal role, orchestrating the seamless interaction between vehicles, infrastructure, and users. Central to this interconnected ecosystem is the concept of vehicles connected to everything (V2X), where communication networks facilitate real-time data exchange and decision-making processes. Amidst this technological revolution, it is imperative to address the needs and safety concerns of Vulnerable Road Users (VRUs), such as pedestrians and cyclists.

Under this umbrella, the ongoing European project PODIUM [1] endeavours to advance key technologies in both the Physical and Digital Infrastructure (PDI) realms to tackle the current challenges of road automation and telecommunications linked with connectivity, cooperation, data management, interoperability, and reliability of CCAM solutions. The project conducts demonstrations in real-life conditions of specific use cases in three living labs located in Germany, Italy, and Spain, spanning urban and highway environments.

In this paper, we present one of its use cases which is focussed on a traffic management system implemented in a cross-border highway scenario. This system is based in controlling and monitoring a Connected and Automated Vehicle (CAV) to efficiently and safely transport people and goods, with additional VRU safety measures in the shuttle's stops. The testbed encompasses various aspects, including devise traffic strategies to ensure safe and optimized traffic flow, gather traffic information from a hybrid environment comprising CAVs, Connected Vehicles (CV), and conventional vehicles, detect road obstacles, effectively disseminate information among the infrastructure and CAVs/CVs, address cross-border communication challenges, deploy standard protocol stacks for the infrastructure, for vehicles and for VRU's smartphones, and design a realistic service aimed at efficiently transporting users and goods via a CAV shuttle between a Spanish city and a French city.

2. USE CASE DESCRIPTION

The baseline application service in this use case involves a CAV shuttle bus tasked with ferrying passengers between two cities situated across the border. Operating on a demand-driven model, this service is managed by two cloud-based servers (see Figure 1). The first server is responsible for managing user requests, devising routes, and establishing schedules for the shuttle's operation. Users interact with this server through a dedicated smartphone application. Conversely, the second server is administered by the company owning the CAV shuttle and serves as the recipient of route directives from the first server. Additionally, it fulfils functions related to fleet management, including real-time acquisition of shuttle data and emergency response capabilities.

This use case encompasses scenarios where this shuttle navigates along a highway with other vehicles, which may vary in their connectivity and automation levels, so a third service, the Traffic Management Centre, becomes necessary to improve traffic flow and safety. These vehicles could range from fully connected and automated (CAV), solely connected (CV), to conventional vehicles without any connectivity. CAVs and CVs exchange Cooperative Intelligent Transport Systems (C-ITS) messages, adhering to the European Telecommunications Standards Institute (ETSI) standards, both among themselves (Vehicle-to-Vehicle, V2V) and with the infrastructure (Vehicle-to-Infrastructure, V2I). For these communication purposes, two radio technologies are employed. Each vehicle is equipped with one 5G cellular network interface and one Cellular Vehicle-to-Everything (C-V2X) interface following standard LTE-PC5. 5G communication is advantageous due to its expansive coverage, which, with the support of the infrastructure module "C-ITS Information Distributor," it enables the dissemination of awareness and perception information among vehicles, adopting a Vehicle-to-Infrastructure-to-Vehicle (V2I2V) approach. However, this approach introduces a certain latency. Hence, specific ITS applications necessitate the faster side-link C-V2X approach, namely V2V communication. As a result, vehicles concurrently utilize both technologies. Moreover, in areas where cellular network coverage is deficient, or in cross-border regions where vehicles encounter that roaming between different cellular operators leads to intermittent unavailability, communications to the infrastructure through C-V2X Road Side Units (RSU) offer a viable alternative. These units seamlessly replace cellular services during periods of unavailability, ensuring uninterrupted communication.

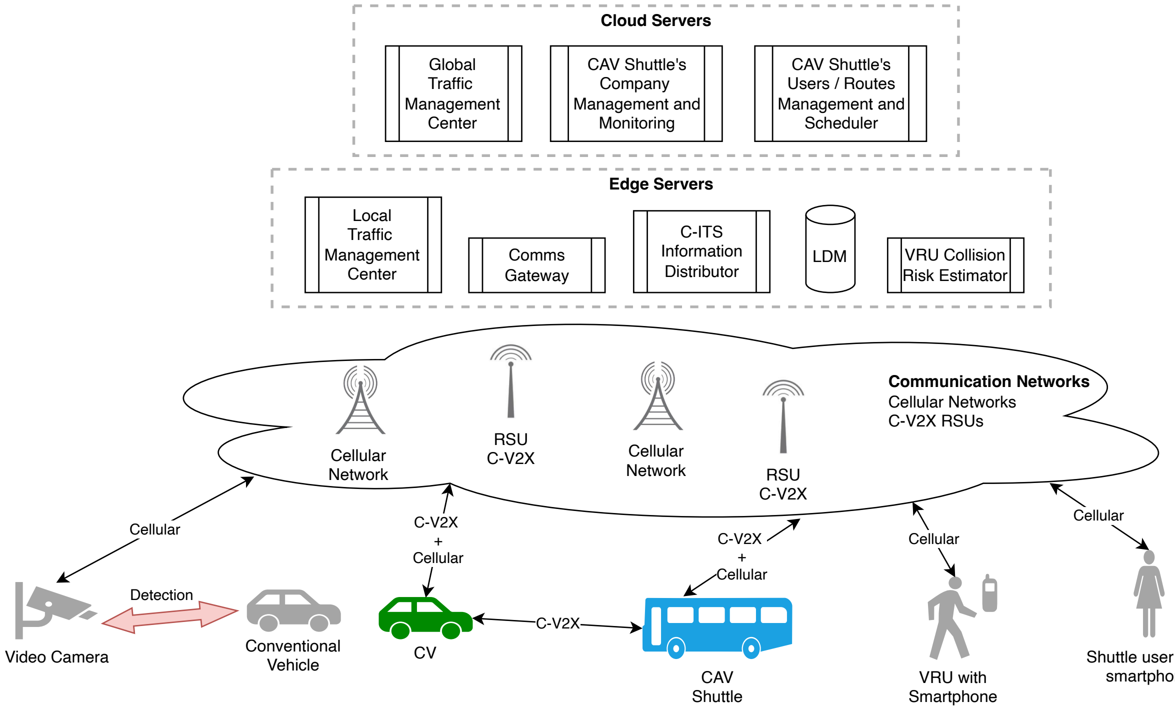

Figure 1. General view of the testbed components.

The fixed infrastructure to facilitate collaboration between vehicles, road users, and road operators, enabling the implementation of real-time traffic strategies to ensure safe and efficient traffic flow, is divided in two levels: the edge level and the cloud level. At the edge level, the focus is on addressing situations within a localized area, whereas the cloud level extends its oversight to encompass strategies across broader regions.

The edge infrastructure operates by collecting and integrating internal traffic data obtained through video cameras distributed alongside the highway, with external data generated by CAVs and CVs, that reaches the edge via the Communications Gateway, which integrates the two types of communications previously described. Upon reception, the data is initially stored in a dynamic database known as the Local Dynamic Map (LDM) before being disseminated to relevant applications that require access to it.

From this point on, three primary applications are operational within the system. The first application involves disseminating the gathered data to connected vehicles, thereby enabling these vehicles to execute various Intelligent Transport System (ITS) services internally. These services may include defining scenarios for automated manoeuvres or conducting collision detection functions. The second application focuses on detecting potential collisions between Vulnerable Road Users (VRUs) and connected vehicles. Upon detecting such situations, both the VRU and the driver involved are promptly alerted. The VRU receives an alert via his smartphone, while the driver is notified through the Human to Machine Interface (HMI) of the vehicle. Lastly, the third function revolves around the Traffic Management Centre (TMC) creating a comprehensive understanding of traffic conditions along each road section. Leveraging this information, the TMC generates potential scenarios and devises traffic management strategies. The testbed explores two different situations where the strategies of the TMC are required: i) normal driving conditions, where traffic strategies are focussed on enhancing traffic efficiency and are communicated to CAVs/CVs, and ii) safe driving, which addresses scenarios where an obstacle is detected on the road and traffic strategies communicated to CAVs/CVs prioritize safely navigating around the obstacle. The TMC leverages the hierarchical structure of the system, utilizing both the Local TMC and the Global TMC, deployed in the edge and in the cloud respectively. These components collaborate seamlessly to enhance the computation of optimal traffic strategies.

3. SYSTEM ARCHITECTURE

The developed modules comprising the road infrastructure are depicted in Figure 2, and it provides two different functionalities. The first one is to estimate the traffic situation and provide traffic management strategies, and the second one is to distribute C-ITS messages among all the actors of the system, using the ETSI ITS communications protocol architecture over two radio technologies, C-V2X and cellular networks.

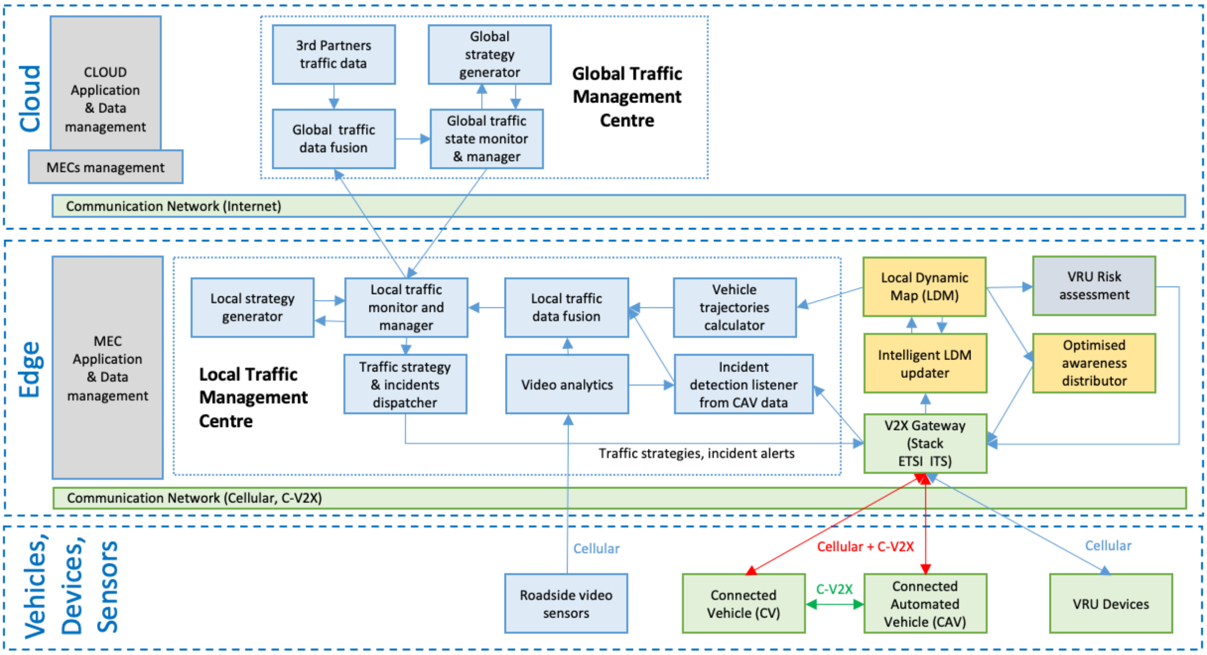

Figure 2. Architecture view.

To fulfil the first functionality, in the Edge, the *Video analytics* software module receives in real-time the raw video footage and associated metadata from the traffic video cameras. The frame-based data is analysed on the fly using Machine Learning object identification and visual analysis algorithms. It transforms this feed into a stream of processed data that contains information about the vehicles viewed on the image, lane occupancy and their velocity. This stream of traffic data is then analysed by the *Local Traffic Management Centre* (LTMC). The data is processed in two functions i) a traffic analyser to obtain the density of vehicles and average traffic speeds in the road section, and ii) a video event detection functionality to identify obstacles (stopped vehicles) on the highway. Next, the LTMC generates traffic management strategies for the road section that it handles, which are then dispatched to the CVs via the *V2X Gateway*. These strategies are: i) limit speed (lower than the normal legal speed limit of the road section), ii) increase distance from vehicle in front (for safety reasons and to avoid rough braking), and iii) avoid lane (because of blockage e.g. in case of an obstacle, like a stopped vehicle or road works).

Internally to the LTMC, the *Local traffic monitor and manager* module monitors the local traffic flow state. By combining real time and historical data, it is capable to detect an evolving agglomeration (potential traffic jam) in comparison to the previous traffic state. In that event, the *Local strategy generator* generates optimal traffic management strategies to ensure safety and reduce the speed of evolution of the traffic jam, e.g. early on, start reducing the speed of incoming vehicles and increase the distance in order to obtain a smoother traffic flow with less abrupt braking. Additionally, the *Local Traffic Monitor and Manager* listens for any road hazards / incidents / obstacles coming from the processed data of the *Video analytics* and from the LDM. The LDM stores the data from the connected vehicles and informs about detected obstacles on the road by some CAV. Additionally, self-emitted distress messages from vehicles that have a technical issue and need to make an emergency stop can also be taken into account in the same way.

At the cloud level, the *Global Traffic Management Centre* (GTMC) is the application-level component that has the full view of the traffic status from all the road sections managed by different LTMCs in the edges. To achieve this, every LTMC remits the local traffic data and incidents information, as well as any locally generated traffic strategies, to the GTMC. Using this information, the GTMC is able to implement traffic management strategies with a global view of road traffic. Additionally, the GTMC in one country takes responsibility for alerting its counterpart in the neighboring country of those events that may pose a risk (such as a stalled car or a traffic jam) to vehicles that, although they have not yet crossed the border, are approaching the location of the hazardous event. On the other hand, the first challenge for the distribution of C-ITS messages among all the actors of the system using cellular networks, relays in the fact that these messages were originally designed to be transmitted over a broadcast-oriented network such as C-V2X (LTE-PC5) and possess a non-Internet Protocol (non-IP) nature. To transmit these non-IP C-ITS messages over a cellular network, which operates on an IP-based infrastructure, it becomes imperative to introduce an additional layer of software comprising a client-server architecture. This layer essentially encapsulates the C-ITS messages within an IP datagram while they traverse through the Internet, and upon reception, removes the IP headers. Furthermore, since vehicles transmit messages using both technologies and there are RSUs deployed to cover cellular network coverage gaps, it's plausible that identical messages may arrive duplicated at edge modules. In response, our project has developed the *V2X Gateway* module, which addresses both challenges effectively. Acting as a server for both the reception and transmission of C-ITS messages over IP, it also eliminates duplicates. For a more detailed understanding and demonstration, refer to [2]. Furthermore, it implements the ETSI ITS communications protocol stack, that is the GeoNetworking protocol, the Basic Transport Protocol (BTP) and the Facilities layer messages CAM, DENM, MAPEM, IVIM, CPM and MCM. The second challenge we must tackle revolves around the scalability of the V2I2V approach in distributing awareness and perception information among connected vehicles. Cooperative Awareness Messages (CAM) convey vital details regarding a vehicle's position and dynamics, while Collective Perception Messages (CPM) relay information about objects detected by vehicles. When vehicles transmit CAMs and CPMs via a cellular network, these messages are directed to the *V2X Gateway* at the edge, where their data is stored in the LDM. This data is dynamically updated by the *Intelligent LDM updater*, which provides short-term estimations of vehicle positions in instances where CAMs are not received at the expected frequency. Subsequently, the *Optimized awareness distributor* is tasked with disseminating this awareness information effectively back to connected vehicles. However, transmitting this information solely in the form of CAM messages, with one CAM message for each known vehicle, would inevitably saturate the radio channel. To address this, we propose aggregating the information from numerous CAM messages into a select few CPM messages, which are then transmitted to specific groups of vehicles and can also be personalized based on characteristics of the receiving vehicles. Yet, this approach presents challenges such as determining the content to include in a CPM, establishing the frequency of generating new CPMs to ensure up-to-date information without saturating the communication channel, and determining the optimal size of CPMs. For further insights into this process, please refer to [3].

4. CONCLUSIONS

This paper presents a testbed implementation derived from the ongoing European project PoDIUM, dedicated to advancing CCAM technology. It specifically introduces a use case of novel system aimed at fostering collaboration among vehicles, road users, and road operators to ensure safe and efficient traffic flow in real-time. By integrating internal and external data, it perceives traffic conditions, generates potential scenarios and proposes traffic management strategies accordingly, which are communicated to CAVs. Additionally, the system optimizes the dissemination of awareness and perception information among CVs, further enhancing safety and coordination on the roads. Finally, it implements a system to alert VRUs of potentially critical situations of collisions with a vehicle.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "PODIUM project: PDI connectivity and cooperation enablers building trust and sustainability for CCAM". EU HORIZON Program. https://podium-project.eu (accessed April 2023).

[2] J. Marias-i-Parella, A. Pino, B. Cordero, J. Casademont, E. Carmona-Cejudo, F. Vázquez-Gallego. "Demo: Interoperability between Cellular and V2X Networks (802.11p / LTE-PC5) under a Cloud Native Edge Scenario," IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), 2023.

[3] J. Marias-i-Parella, J. Casademont, F. Vázquez-Gallego and E. Lopez-Aguilera. "Awareness Information Dissemination using Aggregation into Collective Perception Messages for Connected Vehicles". 2023 23rd International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania.