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Evaluation platform for 5G vehicular communications

Jose Santa [a,b,*], Konstantinos V. Katsaros [c], Luis Bernal-Escobedo [b], Sadeq Zougari [d], Marta Miranda [e], Oscar Castañeda [f], Benoit Dalet [d], Angelos Amditis [c]

[a] *Department of Electronics, Computer Technology and Projects, Technical University of Cartagena, Calle del Hospital, 1, Cartagena, 30202, Murcia, Spain*
[b] *Department of Information and Communication Engineering, University of Murcia, Facultad de Informatica, Campus de Espinardo, Murcia, 30100, Murcia, Spain*
[c] *Institute of Communication and Computer Systems, Iroon. Polytechniou, 9, Zografou, 15773, Athens, Greece*
[d] *AKKA High Tech, Boulevard Henri Ziegler, 7, Blagnac, F-31700, Midi-Pyrenees, France*
[e] *CTAG, Poligono Industrial a Granxa, Porrino, 36400, Pontevedra, Spain*
[f] *DEKRA Testing and Certification, Severo Ochoa, 2, Campanillas, 29590, Malaga, Spain*

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ABSTRACT

Cellular vehicle to everything (C-V2X) communications is presented as the cornerstone for next-generation connected vehicles. C-V2X can support efficient vehicle to vehicle and vehicle to infrastructure data transmission, and is said to be a key enabler of cooperative connected and automated mobility (CCAM). Performance of 5G New Radio (5G-NR) is expected to address bandwidth and delay requirements of services for autonomous vehicles. This is the theory and what particular research works have showed through simulation or limited prototypes. On the contrary, this work focuses on evaluating real 5G deployments (including 5G-NR) of network operators in CCAM scenarios, with particular emphasis on cross-border settings and service continuity under inter-operator handovers. The paper presents an evaluation platform to gather cross-layer measurements, homogenise results, perform comparative assessment of figures of merit, and calculate network and CCAM key performance indicators (KPIs). The platform is evaluated through implementing a use case for autonomous overtaking, involving two 5G-NR operator deployments at the Spanish-Portuguese border. Results reveal good network performances and correct operation of the service, thanks to 5G-NR and edge servers, although significant impact of handovers is detected on network and overtaking KPIs.

1. Introduction

The advent of 5G has implied the evolution of cellular networks to embrace connected scenarios up to now covered by other wireless technologies. This is the case of Intelligent Transportation Systems (ITS) and vehicular networks [1,2], a field in which 3rd Generation Partnership Project (3GPP) technologies had been used only for applications requiring continuous Internet access with low performance and non-stringent delay requirements [3], such as fleet management, vehicle monitoring, route guidance, road tolling or remote telemetry. The improvement of Long Term Evolution (LTE - 4G) in 3GPP Release 14 came with the so called Cellular Vehicle to Everything (C-V2X) service [4], which opened a new range of vehicular applications requesting high data rates and low (and very low) delays [5]. C-V2X includes an improved radio link and a vehicle-to-vehicle (V2V) channel [6], called sidelink or PC5. This marked a milestone in the evolution of 3GPP technologies to cover delay-sensitive applications such as those in the safety segment [7] and reaching the requirements of Connected, Cooperative and Automated Mobility (CCAM) [8]. The 3GPP Release 15 [9] set the basis of a new radio scheme that would improve QoS, called 5G New Radio (5G-NR) [10], which is now under worldwide deployment. 5G-NR is a key technology for the evolution of C-V2X in the CCAM domain [11], offering real starting latency of around 10 ms and data rate above 100 Mbps. These performances enable the deployment of applications withing the 5G automotive vertical [12], whose main services fall within remote driving, advanced driving, vehicle platooning, extended sensors and vehicle QoS support [13]. The requirements of these services, in the range of 10-25 ms for delay and maximum data rate of 65 Mbps, can be accomplished with the 5G Non-Standalone (NSA) mode, which still maintains the control plane of LTE. The next step is a pure 5G network with both evolved data and control planes, through the Standalone (SA) mode. At this moment, we are in the need of evaluating the 5G advances in CCAM scenarios.

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[*] Corresponding author at: Department of Electronics, Computer Technology and Projects, Technical University of Cartagena, Calle del Hospital, 1, Cartagena, 30202, Murcia, Spain.
E-mail address: jose.santa@upct.es (J. Santa).

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Table 1
Discussed works about 5G testing and vehicular evaluation platforms, with abbreviations for experimental evaluation (exp. eval.), evaluation methodology (ev. meth.), hop-by-hop measurement (HbH meas.), and data and control (D+C) evaluation planes.

	Exp. eval.	5G KPIs	Multi layer	Ev. meth.	HbH meas.	D+C planes	Cross border
[17]	*	*	*			*	
[18]		*	*		*	*	
[19]		*	*		*	*	
[21]	*	*	*	*			
[22]	*	*					
[23]	*	*	*	*	*	*	
[24]		*		*			
[25]		*	*		*	*	
[26]	*	*		*			
[27]	*	*		*	*		*

[18,19,25,26] are not focused on vehicular scenarios.
[22,27] use a 4G network deployment.

While evaluating 5G-NR in real vehicular settings is a challenge by itself, CCAM implications and the added value of cross-border present new challenges [14] in terms of involved administrations, network QoS assurance, security and privacy [15,16], which need the involvement of different operators supporting 5G, development of network configuration and solutions to cope with service continuity, inter-administration management, and real driving conditions for automated vehicles, among others. Going a step further, CCAM scenarios involve vehicles integrating sensing technologies and automation capabilities that are difficult to find and manage. Moreover, an essential part of evaluating vehicular communications when real and confident measurements are aimed is to design an evaluation methodology and a set of post-processing tools that provide significant results in terms of Key Performance Indicators (KPIs). When the objective is as challenging as evaluating 5G-NR in CCAM through different setups, services, network operators and driving areas, it is necessary to support alternative ways to conduct data gathering, a common way of saving measurements, assure data quality, and provide comparative analysis of results and homogenised data access to compute significant KPIs to promote cross-comparison. This work presents an evaluation framework that deals with these issues, developed in the project 5G for Cooperative & Connected Automated Mobility on X-border Corridors (5G-MOBIX).[1] 5G-MOBIX is the flagship project for evaluating 5G C-V2X across Europe, and it is focused on the deployment and evaluation of 5G-NR capabilities on CCAM services in a cross-border fashion.

There are works in the literature that partially deal with the testing and evaluation capabilities required for 5G experimental campaigns. These are included in Table 1, indicating their key aspects integrated in our work. The work in [17] includes a comprehensive evaluation of 5G-NR, attending to network parameters such as Round-Trip Time (RTT), throughput and handoff frequency, but also considering application-level metrics and energy impact. Two 5G deployments from real operators are considered in the evaluation. KPIs to be used in 5G evaluation have received attention in the literature. The authors in [18,19] review through simulation the KPIs marked by the IMT-2020 guidelines [20] over the 5G-NR technology. The proposal in [21] focuses on the KPIs and Quality of Service/Experience (QoS/QoE) expected by users when using several vehicular services. The work in [22] considers KPIs for both network and 5G slicing functions, while the one in [23] includes a measurement tool that evaluates a subset of the network KPIs considered in the project 5G-MOBIX. A tool to extract performance measurements and compute QoE KPIs is presented in [24], while the work in [25] particularly focuses on latency, and presents a common approach to measure it along with a set of improvements to reduce network delay. The importance of automating tests in 5G is discussed in [26], presenting a testing methodology to easily extract and aggregate results at user-level. A more complete evaluation framework is presented in [27], considering experimental evaluation of V2X and processing of results in a common platform through a set of network KPIs and using a common logging format [28].

The work presented here is based in part on the advances of the previously cited works, especially considering the principles related to 5G network KPIs [17–19,21–27]; evaluation of multiple network layers [17–19,21,23,25]; integration of an overall evaluation methodology and data flow [21,23,24,26,27]; in-detail study of KPIs in a hop-by-hop basis across the network [18,19,23,25,27]; adding of the network control plane in the study [17–19,23,25]; and consider a cross-border evaluation scenario [27]. However, none of the previous works focuses on autonomous mobility nor cope with the difficulty of gathering and process results from real 5G-NR deployments involving different operators and setups. There are no works particularly addressing KPIs for applications within the 5G automotive vertical [12]. Also, as far as the authors know, key aspects such as the experimental evaluation of CCAM test cases and cross-border issues in 5G-NR operation are not considered at all in the literature, and the evaluation methodologies and platforms reviewed lack a proper harmonisation of results while assuring data quality and presenting human-readable KPIs. These are inherent features considered in the evaluation platform presented in this paper, whose main advances are:

- A 5G evaluation framework for CCAM is presented and validated using 5G-NR technology.
- A set of KPIs for measuring both network performance and CCAM application operation is presented.
- 5G performance analysis considering radio access network (RAN), transport protocols and application level, following end-to-end and hop-by-hop evaluation for both control and data planes.
- Experimental evaluation of an autonomous driving service using a cross-border 5G-NR deployment involving two network operators.

The paper firstly describes in Section 2 the overall evaluation approach and the KPIs considered for real CCAM tests. The methodology developed to collect and process evaluation data is detailed in sections 3 and 4, respectively. Section 5 takes as reference example a set of trials performed in the Spanish-Portuguese test site to validate the evaluation platform through analysing key network and CCAM KPIs. Finally, Section 6 concludes the paper synthesising the main findings.

2. Evaluation approach

The challenge of this work is assessing 5G capabilities in CCAM scenarios, including the effects of roaming/handover (HO) events on the delivery of timely, continuous and seamless services in cross-border environments. Essential 5G concepts such as the different nodes in the network (including MEC), especial signalling, or direct V2V connectivity, require an especial evaluation approach for 5G vehicular networks. Moreover, the final network deployment, operator interconnection, road side equipment, edge computing services, on-board vehicle components, as well as application design, influence on the observed end-to-end (E2E) performance. In order to address this complexity, the evaluation approach shown in Fig. 1 has been defined. A series of cross-border issues has been defined, enumerating and analysing the various factors expected to

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[1] https://www.5g-mobix.com.

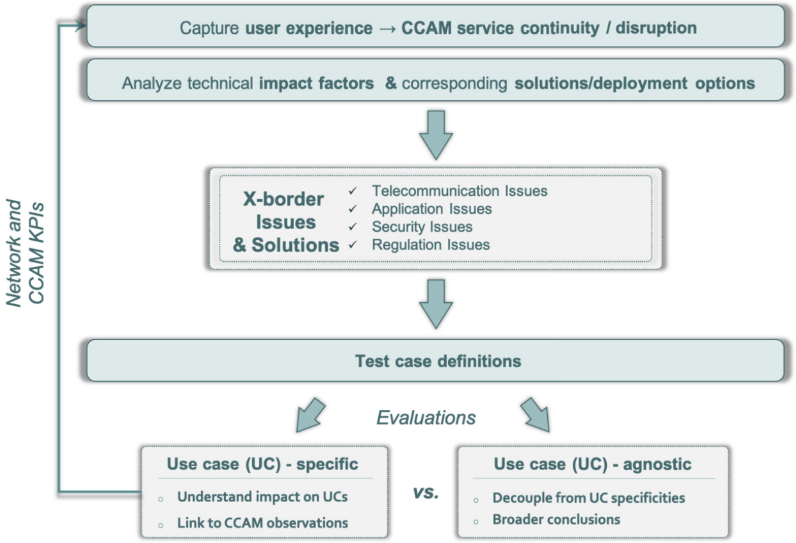


Fig. 1. High-level evaluation approach.

present an impact on the seamless provisioning of CCAM services in cross-border environments. Then a set of technical solutions have been proposed and must be evaluated. An initial shortlisting of cross-border issues has been reported in [29], with focus on four broad classes: telecommunication, application, security and privacy, and regulation issues. Taking this effort as the baseline, the concrete evaluation approach considers a series of test cases, which drive the final trials to be carried out, as depicted in Fig. 1. Each test case is meant to ultimately assess/evaluate one or more cross-border issues and solutions, following the methodology described in Section 3. Two major sets of test cases servicing different aspects of the evaluation are considered: Use Case (UC) specific and UC agnostic.

UC-agnostic test cases form the basis for the network verification/validation process, which follows the completion of a deployment activity and precedes the evaluation of services, i.e., UC-specific test cases. These test cases only support a network-level performance evaluation using synthetic traffic flows, and include scenarios with limited traffic as well as stressing conditions. Differently, UC-specific test cases are defined based on the operation of a specific CCAM application. In these cases, network traffic is generated by the applications to assess the impact of 5G solutions and deployment options on the CCAM application. The next UC categories are considered: advanced driving, focused on manoeuvres to enable autonomous driving while assuring safety; vehicle platooning, which particularly considers convoy formation and management; extended sensors, to gather and manage data from the road network to enhance autonomous operation; remote driving, which aims at operating vehicles through a network connection; and vehicle QoS support, which tests on-board high-bandwidth multimedia services.

2.1. KPIs considered

Two main groups of KPIs are defined in the evaluation platform: network KPIs and CCAM KPIs. Network KPIs focus on 5G performance figures of merit, attending to different abstraction levels or transport planes, while CCAM KPIs include measurements capturing application characteristics, e.g., number of accelerations or multimedia stream cuts. Both of them are used to evaluate the various design decisions on CCAM applications and network deployment, as a result of dealing with cross-border issues. Nevertheless, agnostic tests only consider network KPIs, whereas UC-specific evaluations consider both of them. The assessment of the 5G system performance on CCAM applications will build on the comparison of the measured KPI values against target KPI values dependant of each application. Network KPIs considered are listed in Table 2. They derive from the IMT-2020 guidelines [20], selecting the ones directly related with 5G-NR vehicular communications. CCAM KPIs considered are listed in Table 3. All CCAM KPIs are associated to at least one network KPI, identifying key network performance aspects expected to have an effect on the CCAM level performance indicators selected/defined. It is important to note that each CCAM application has particular expected behaviours, such as completing a manoeuvre safely, receive a video streaming seamlessly, or accelerate/decelerate smoothly, which can lead to a correspondingly large set of CCAM KPIs. Moreover, measurement methods for CCAM KPIs are not common, given the different nature of applications considered.

Table 2
Network KPIs, with abbreviations for latency (lat.), reliability (rel.), handover (HO), interruption (int.), accuracy (acc.), capacity (cap.) and mobility (mob.)

KPI	Description	Unit
^{1}User data rate	Data rate as perceived at the application layer	bps
^{2}Throughput	Instantaneous data rate/throughput as perceived at the network layer	bps
^{3}E2E lat.	Time since a message is transmitted until it is received, at application layer	ms
^{4}Network lat.	Time since a data packet is transmitted until it is received, at network layer	ms
^{5}RAN lat.	Time since a data packet is transmitted until it is received, at RAN layer	ms
^{6}Control plane lat.	Control plane latency to move from idle state to active state	ms
^{7}Network rel.	Amount of application/network layer packets successfully delivered	%
^{8}Position acc.	Deviation of measured position using UE 5G positioning service	m
^{9}Network cap.	Maximum data volume transferred over a dedicated area	bps
^{10}RAN HO rel.	Ratio of successfully completed handover events within the RAN	%
^{11}App HO rel.	Ratio of successfully completed application level handovers for maintaining a session	%
^{12}Mob. int. time	Time a user terminal loses connectivity during HOs	ms

Table 3
CCAM KPIs and related network KPIs, with abbreviations for acceleration (acc.), interruption (int.), perception (per.) and autonomous (aut.)

KPI	Unit	Related network KPIs											
		1	2	3	4	5	6	7	8	9	10	11	12
Advanced driving													
Instantaneous acc.	#			*		*		*					
Encroachment time	s			*		*		*					
Minimum headway	m/s			*		*		*					
Minimum time to collision	ms			*		*		*					
Extended sensors													
Speed and acc. variations	#	*		*				*				*	
Aut./manual driving	A/M	*						*					
Time to stop	ms	*	*	*		*		*			*	*	
Delay of video starting	ms	*	*	*		*		*			*	*	*
Service migration delay	ms			*				*				*	*
Map service outage	ms	*		*				*					*
Target variations	#	*		*				*				*	
Platooning													
Manoeuvre failures	#			*				*	*				*
Video streaming int.	%		*	*				*					*
Per. message failures	%			*		*		*					
Remote driving													
Instantaneous acc.	#	*		*		*		*			*	*	*
Video streaming int.	#	*						*			*	*	*
Session loses	%	*		*				*					*
Manoeuvre delay	ms			*				*					*
Video streaming quality	1-10	*		*				*					*
Per. of remote operator	1-10												
Control delay	ms	*		*				*				*	
Per. of users	1-10	*		*				*					*
Vehicle QoS Support													
Duration of video int.	ms	*		*				*			*	*	*

Table 4
Measurement (meas.) facets and the network KPIs considered for each one.

Measurement facet	Related network KPIs											
	1	2	3	4	5	6	7	8	9	10	11	12
E2E meas.	*		*				*	*				
Layered meas.		*		*	*		*		*			
Per network segment meas.		*		*	*		*					
Control plane meas.						*				*	*	*

2.2. Measurement facets

In order to calculate the previous KPIs, especially the network ones, it is necessary to take measurements targeting different aspects of the network, considering this as a black box in an E2E fashion, but also analysing its internal operation. This constitutes a set of different measurement facets included in Table 4, which indicates the network KPIs used for each one from Table 2. An explanation of the different facets is included next:

E2E measurements These focus on the performance perceived at application level in communicating end points e.g., onboard unit (OBU) and application server.

Layered measurements These capture the performance at various protocol layers, inspecting their impact in the overall E2E performance. The levels considered are: level 0 (access), considering radio access network parameters (signal strength, cell identification, etc.); level 1 (transport) studying network capabilities (throughput, delay, etc.); and level 2 (application), focused on obtaining relevant measurement data at application level (E2E latency, user experienced data rate, reliability).

Per network segment measurements These are intended to observe performance in a hop-by-hop basis. The network segments considered are: UE/OBU - gNodeB (gNB), gNB - Packet Gateway (PGW), and PGW-MEC or PGW - cloud.

Control or data plane Measure the impact of control plane operation on the E2E performance, attending to UE/network signalling.

3. Evaluation methodology

During the execution of trials, numerous measurements are performed following the previous facets, in order to compute the final network and CCAM KPIs. Given that different network setups can be in play and several evaluation perspectives must be considered, an evaluation methodology has been developed as depicted in Fig. 2 to regulate the process.

Measurements are taken from the System Under Test, which refers to the vehicle, with its communication transceiver, and all the components of the network(s). Within the system under test, we have identified a set of Points of Control and Observation (PCOs), which are specific parts at which either an observation (measurement) is recorded, or traffic is injected. These PCOs can be mapped with the different network levels considered, i.e., access, transport or application.

When tests involve synthetic network traffic, this is generated in the next stage in Fig. 2, i.e. Raw Data Injection. This traffic can

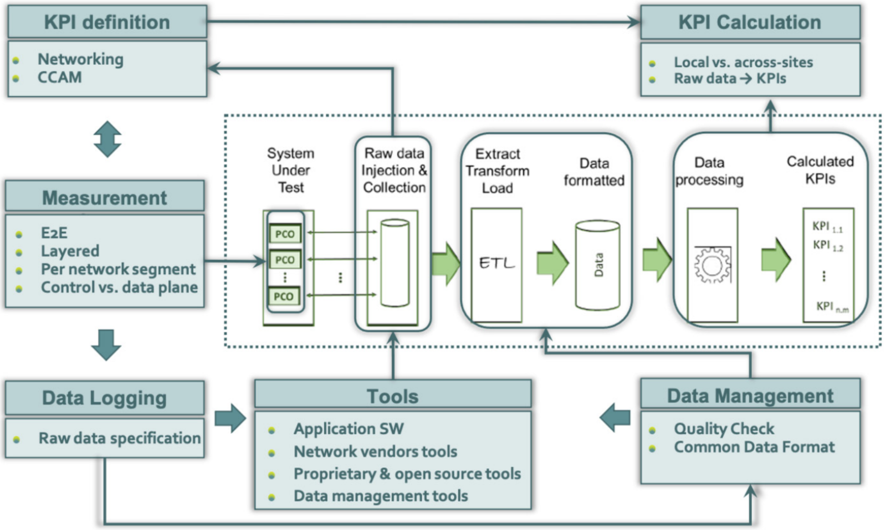


Fig. 2. Evaluation methodology.

be generated due to UC-agnostic test cases or because background traffic is desired to stress (overload) the network. Synthetic traffic can involve from periodical messages to measure network latency and reliability (packet losses), to high-load transmissions to measure maximum bandwidth. Different protocols such as UDP, TCP or RTP can be used, marking traffic with time stamps at different PCOs. Then, data collection is applied on particular traffic flows, when it comes to the data plane KPIs. The remainder KPIs are built on the collection of control plane raw data, regardless of the particular data traffic flows in place. The exact raw data required to be logged so that the selected KPIs can be subsequently calculated can be attributed to the different stack levels (a detailed list of parameters logged is included in [30]): Level 0 (Access) involve radio access network parameters, provided by the 5G transceiver, such as RAT mode, cell ID or signal strength; Level 1 (Transport) refers to network and transport related information, including instantaneous measurements such as throughput, jitter, one-way-delay, round-trip-time, and packet loss rate; and, finally, Level 2 (Application) contains application information such as terminal speed, data flow direction, communication protocol or message type, including Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM), among others. Additionally, two cross-layer data groups are gathered, the run-time conditions, about terminal settings and positioning, and handover events, with details about base station transitions and other 5G radio and network signalling.

The stage about Extract, Transform and Load in Fig. 2 deals with raw data handling to enable further data processing and calculation of the KPIs. It includes the translation of raw data into the Common Data Format (CDF), building log files that ensure comparability and consistency across different testing sites. The CDF considers different files to be created for each stack level previously described: access, transport, application and, additionally, handover events. All data contained for the first three are aggregated in one-second time windows, for the sake of space and processing performance, while handover events are saved asynchronously. All logged measurements are timestamped and geographically located. The CDF conforms a standard comma-separated value (CSV) structure, with a header naming the measured parameters. The complete list of fields for each CDF file is omitted for the sake of space, but some of them are included in Table 5.

Table 5
Common Data Format (incomplete list of data fields).

Field	Range	Unit	Mandatory
	Access		
ratmode	‘NR_NSA’, ‘NR_SA’ ...	N/A	Y
cellid	$[0, 2^{28} - 1]$	N/A	N
signalpower	[-156, -31]	dBm	Y
snr	[-23, 40]	dB	N
...			
	Transport		
protocol	‘UDP’, ‘BTP’, ‘TCP’ ...	N/A	Y
throughput	[0, 100000]	Mbps	Y
packetlossrate	[0, 100]	%	Y
e2elatency	[0, 5000]	ms	Y
...			
	Application		
messagetype	‘CAM’, ‘DENM’, ‘CPM’ ...	N/A	Y
messagestx	[0, 2100000]	packets	Y
messagesrx	[0, 2100000]	packets	Y
speed	[0, 300]	m/s	Y
...			
	Handover		
hosuccess	TRUE/FALSE	N/A	N
hoperiod	$[0, 2^{42} - 1]$	ms	N
...			

4. Data processing

The last stage in the evaluation methodology is the data processing. Its overall operation is shown in Fig. 3. Measurements correctly formatted using the CDF are collected from different network setups and then packaged to be sent to the Central Test Server (CTS). From here, data needed to compute final KPIs according to particular needs, can be downloaded through an SQL interface. The first logical unit to operate is the Data Builder, which is a common tool developed in Java and dedicated to create test data archives. It allows filling information required for a complete description of each test and the related measurements in CDF. The user can check the compliance of data files with the CDF specification, including the correctness of data, by using the Data Quality Check Tool (DQCT). The Data Builder generates an XML description file of the test and a data quality report, which are joined to the archive, as it is shown in Fig. 3.

The CTS includes a Web application to show the CDF files and sanity status of each test. Upon the arrival of testing archives to

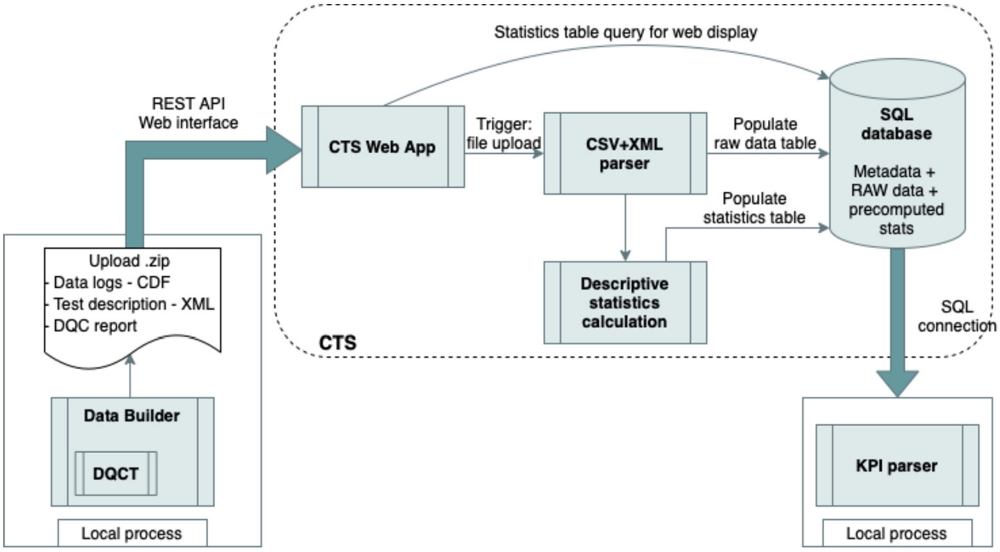


Fig. 3. Data processing flow.

the CTS, a Python script tool ($CSV + XML\ parser$) is used to assure conformance with data format and coherence, such as all measurements are within the same time frame and geographical coordinates of the referred test. Then, the tool populates a relational database implemented in PostGreSQL with CDF fields from logs and metadata, enabling programmatic access to the data. This way, further data analytics can be performed easily. A first processing of data is carried out in the same CTS, calculating KPIs directly observable from measurements in the form of descriptive statistics for the user.

5. Reference evaluation

This part presents an indicative example of how all the above processes are carried out within one of the real test cases under study in the 5G-MOBIX project.

5.1. Test case

The test case analysed belongs to the overtaking user story (advanced driving use case category), within the Spanish-Portuguese cross-border corridor. In this case a vehicle in autonomous mode performs an overtaking manoeuvre by using the information collected from the surrounding vehicles through the CAM messages exchanged. Given the safety nature of the application, low latency and high reliability features are sought in the network service.

As it is depicted in Fig. 4, vehicles exchange CAM messages by means of a Message Queuing Telemetry Transport (MQTT) broker. This way, the vehicle performing the manoeuvre (ES-PT_UE_03 in the figure) receives the position and speed of the rest of vehicles and decides how to proceed. CAM information received is fused with local data from on-board sensors (camera and LiDAR) to provide the inputs for the control algorithm.

The results showed in the paper come from a set of cross-border tests carried out at the union of the Spanish A-55 and Portuguese A-3 motorways. The gNodeB base stations used are located next to the motorways at Tuy (Spain) and Valenca (Portugal), deployed by Nokia Spain and Nokia Portugal, and integrated in the network by Telefonica and NOS, respectively. 5G-NR communications are used with NSA configuration. The MQTT broker is installed in a MEC server connected within the network domain of the Telefonica's deployment at the A55 motorway in Galicia (Spain). It is a Nokia edge computing solution based on multiprocessor architecture. Three connected vehicles were used in the tests [31]: two Citroen C4 Picasso (ES-PT_UE_01 and ES-PT_UE_02) and one Volkswagen Golf (ES-PT_UE_03). One of the Citroen vehicles and the Volkswagen one are provided with Level 4 autonomous driving features (longitudinal and lateral control), while the remaining Citroen one is only used as connected vehicle. The OBU mounted on the vehicles is a Hybrid Modular Communication Unit (HMCU) from CTAG, provided with a Trimble BD920 GPS receiver and a Quectel 5G RM500Q-GL modem with a Poynting PUCK-2 antenna.

Messages sent by ES-PT_UE_01 and ES-PT_UE_02 to the MEC (uplink traffic) are aggregated and forwarded to ES-PT_UE_03 as downlink traffic. MQTT messages are transported using the TCP protocol. Vehicles ES-PT_UE_01 and ES-PT_UE_02 send continuous messages at a rate of 10 Hz; hence, ES-PT_UE_03 receives messages at a rate of 20 Hz. Six trials were carried out in the scenario presented, involving an inter-operator handover (roaming) from the Portuguese to the Spanish network, using Telefonica SIMs for the OBUs. Each trial lasts around 60 seconds, each one involving an overtaking manoeuvre.

5.2. Measurements and data management

A variety of tools were selected and integrated into the vehicles to log CAM data at the different layers. At application layer, the software developed to exchange the messages was modified to dump CAM messages into a JSON file in the OBUs of both vehicles. At network layer, the traffic is dumped performing a filter on the network interfaces and ports involved in the connection. At access layer, a Qualcomm tool was used to gather RAN data. These raw logs are the basis to build the CDF files based on the flows between the PCOs (in this example, the three OBUs and the MEC server). All CDF files include positioning information coming from the GPS receiver. A Python script was developed to translate data from the Qualcomm tool and integrate all measurements taken at all levels. The script also matches the information between the vehicles and MEC, based on the payload of the messages, and calculates the aggregated measurements on the data flow between them to finally output the CDF files.

The CDF files are used as data logs to be uploaded to the CTS platform using the Data Builder application. After the data quality check is passed using the DQCT, both logs and meta data are uploaded by the software to the CTS, where it is checked for consistency. This process has been carried out successfully with the measurements used for this paper and, hence, test data have been

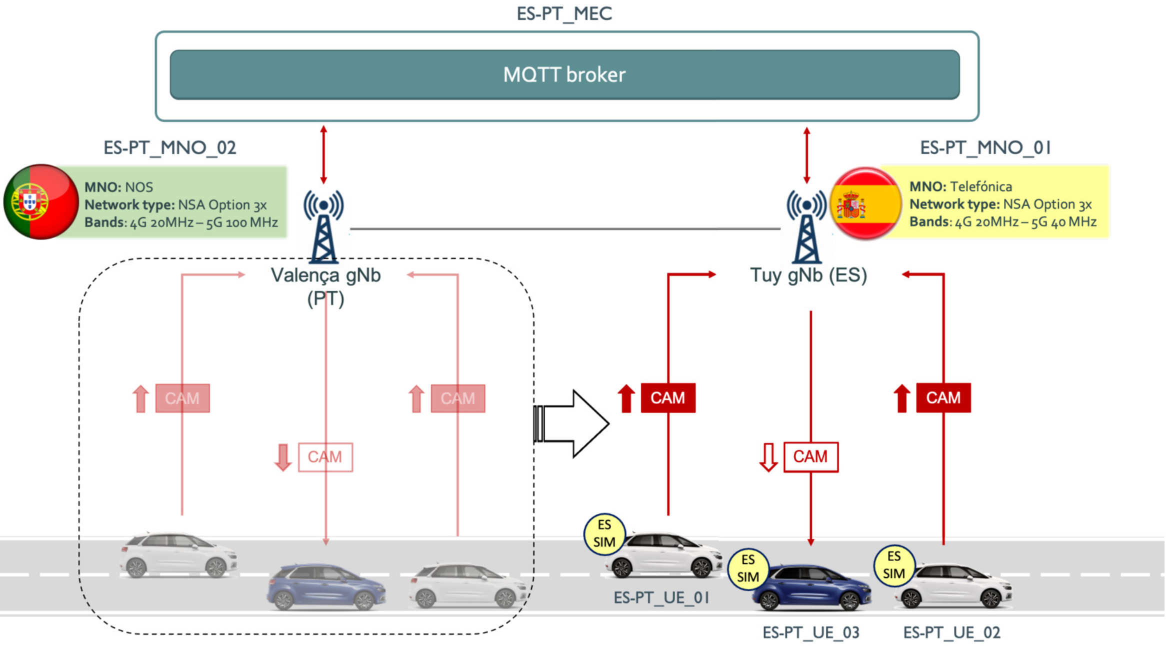


Fig. 4. Data flow in the overtaking use case.

finally inserted in the CTS database and statistics are calculated, without detecting any error. From these, the network latency and packet loss rate (PLR) between the vehicles and the MEC server are particularly evaluated, extracting these data from the source *e2elatency* and *packetlossrate* fields, respectively, from the CDF file that belongs to the network level (see Table 5). The statistics calculated by the CTS are used here as the *Network latency* (KPI #4) and *Network reliability* (KPI #7) in Table 2. The acceleration of the autonomous vehicle is also evaluated taking the data from the CTS, which comes from the source *speed* field from the CDF file of the application level (see Table 5). The acceleration is calculated in post-processing, accessing the data from the CTS database; hence, the CCAM KPI *Instantaneous accelerations* in Table 3 is computed.

Since each overtaking trial lasts around 60 seconds and the CDF files aggregate results in a per-second basis, each trial accessible in the CTS contains around 60 records. Each of these records contains cumulative, mean or most recent values for each parameter measured during tests. For the particular case of latency and network reliability, all packets transmitted and received within the one-second window are considered to get an averaged latency and packet loss rate during the second. Regarding, speed, since it is directly obtained from the GPS receiver, the last value obtained within the one-second time frame is reported in the CDF log file.

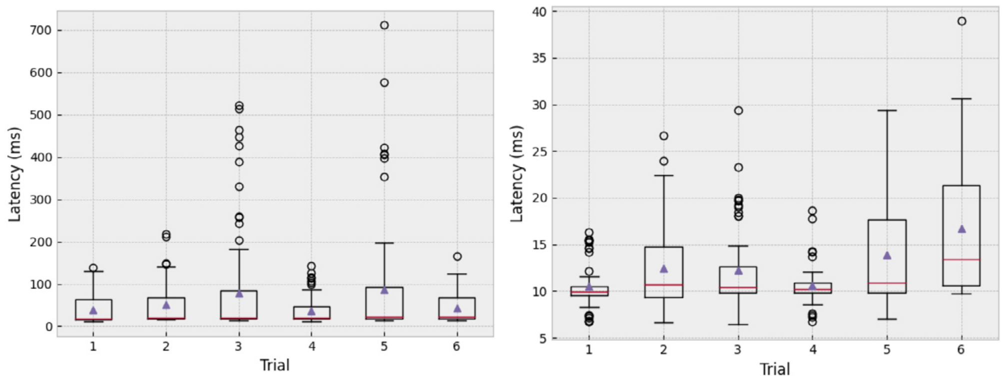
5.3. Results

The latency results obtained involve the network segments from the two surrounding vehicles to the MEC server (uplink), and from the MEC server to the autonomous vehicle (downlink). Results plotted in Fig. 5 indicate that network latency presents high asymmetry when comparing uplink and downlink. This is common in cellular networks prepared to support higher demands in the downlink. For uplink, most of the results are under 100 ms, observing median values of 20 ms and mean values around 50 ms. It is observed that results are highly variable from trial to trial, which is due to dynamic allocation of shared resources by the operator's core network and changing coverage conditions. Results obtained in the downlink traffic are significantly better, with mean values under 20 ms and median near 10 ms. The end-to-end latency (from vehicle to vehicle) is aggregated in the last plot in Fig. 5. The overtaking service is envisaged to support a maximum of 200 ms of end-to-end latency. As can be seen, most of the values for all the trials are under 200 ms, except for trial 5, in which the interval ranges from 20 to 250 ms. Some outliers for trials 2 and 3 also fall beyond 200 ms. It is expected that ongoing adjustments and advances in the network assure that 100% of cases fall within 200 ms of delay even under challenging handover conditions as considered here.

In order to further analyse the behaviour of the network during the tests, Fig. 6 shows the latency results obtained for a single uploading trial from one of the two surrounding vehicles in trial 4 (see Fig. 4). While latency values in the order of 20 ms are obtained as a regular basis when connected to the NOS network (Portugal), around 30 seconds after the start of the trial, the vehicle reaches the handover point configured in the project for the Spanish-Portuguese border at the International Bridge Tui-Valenca. The two base stations have been tuned with a transmission power to produce a handover at the bridge. This way, the signal strength perceived by the OBU around the middle of the bridge from the initial PT gNb is lower than the signal strength measured from ES gNb transmissions, and the handover is initiated. While the vehicles cross the bridge and the handover is carried out, the performance obtained is greatly affected, for about 20 seconds. Just after finishing the handover and when the car is near the Tuy gNodeB, the network performance improves.

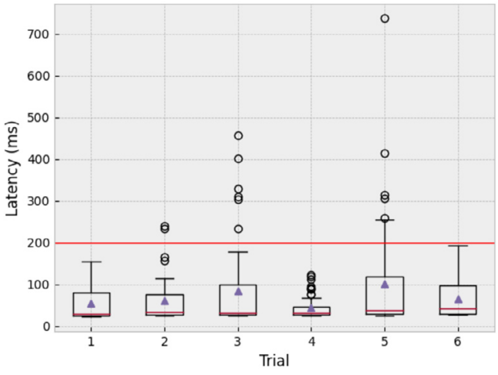
The network reliability results obtained for all the trials in both uplink and downlink are included in Table 6. They are provided in a table format, since most of the values are close to zero. It can be seen that for trials with higher delay results in Fig. 5, the PLR is generally bigger, which confirms that an unstable connection implies both high delays and low reliability. It is interesting that the downlink presents more losses than the uplink, which is attributed to lower sensibility of the radio equipment mounted on OBUs as compared with the gNB. In general, low PLR values are obtained for all the cases, given the error correction and retransmission mechanisms provided by 5G-NR technology, but also thanks to the connection-oriented network protocol used, i.e., TCP.

The downlink PLR reported during trial 4, the same trial considered in Fig. 6, is plotted in Fig. 7. As in the case of the delay study, problems are encountered in the time frame of the han-



(a) Aggregated latency for the uplink.

(b) Network latency for the downlink.



(c) Aggregated uplink and downlink (V2V) network latency.

Fig. 5. Network latency obtained in overtaking tests.

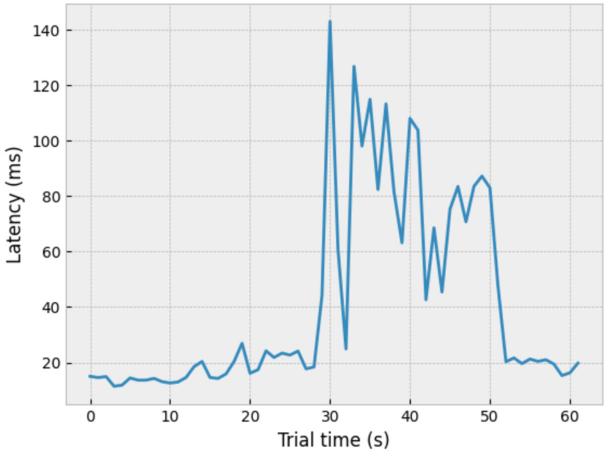


Fig. 6. Uplink latency results for one of the cars in trial 4.

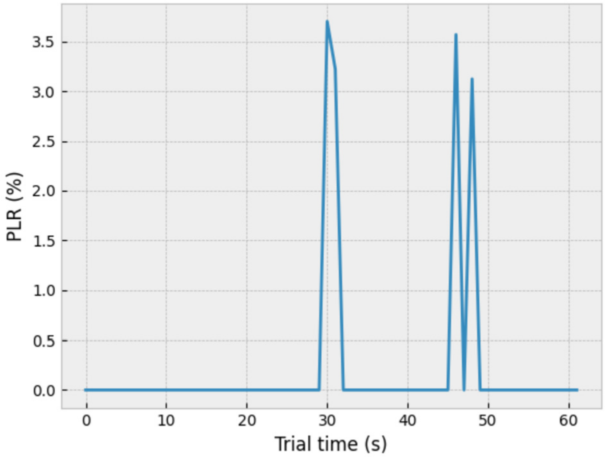


Fig. 7. Downlink PLR results in trial 4.

Table 6
Network reliability results obtained in overtaking tests.

Trial	Uplink PLR (%)	Downlink PLR (%)	V2V PLR (%)
1	0.0000	0.3831	0.3831
2	0.0000	0.3153	0.3153
3	0.1626	0.8703	1.0314
4	0.0000	0.2843	0.2843
5	0.2404	1.1513	1.3889
6	0.3436	0.2327	0.5756

dover period, with several packets losses. At the beginning and end of the test, all packets were delivered correctly. Considering that the initial target value marked for network reliability in the overtaking service is a PLR of 0.01%, none of the trials achieved the desired level, attending to the aggregated values in the last column of Table 6. Since most of the losses detected as due to handover, planned improvements in this line are expected to improve network reliability.

The acceleration obtained for the trials is plotted in Fig. 8. This shows the dynamics of the autonomous car when performing an overtaking manoeuvre. Initially, the car accelerates within the right lane until reaching another vehicle (first green period). At this moment a deceleration is reported to adjust the speed and prepare the overtaking (first red period). When the left lane is free, the vehicle starts the manoeuvre and accelerates (second green period, in the middle of the plot), until the overtaking is performed, and then it comes back to the original lane, by adjusting speed to in-

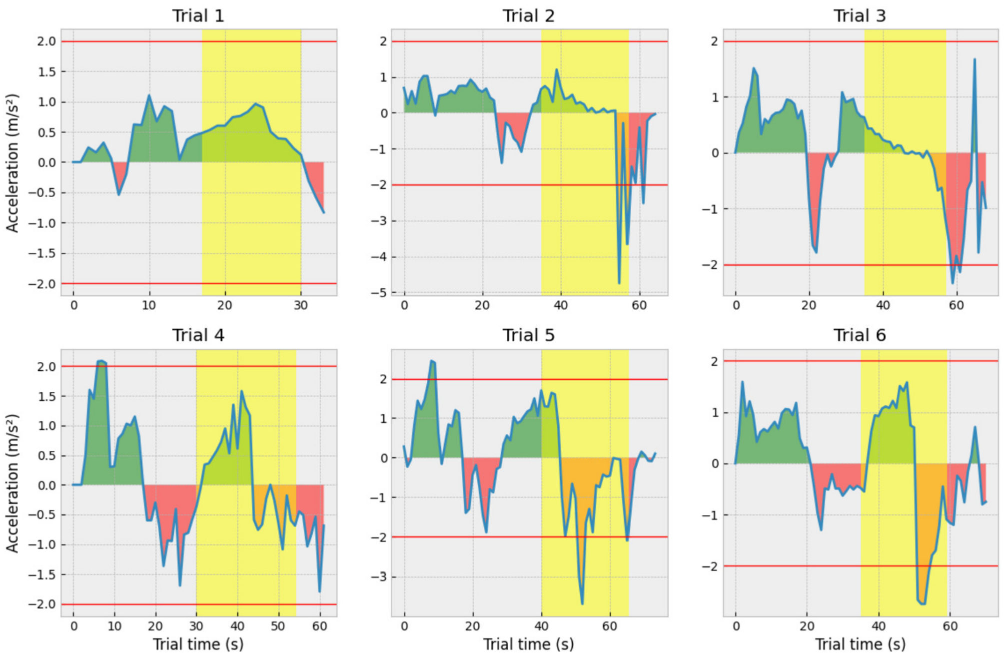


Fig. 8. Acceleration results obtained in overtaking tests for the autonomous vehicle.

Table 7
Instantaneous accelerations and jerks out of limits.

Trial	$\lvert Acc\rvert > 2$ m/s^2 (#)	Relative (%)	$\lvert Jerk\rvert > 0.9$ m/s^3	Relative (%)
1	0	0	0	0
2	3	4.62	9	13.85
3	2	2.90	7	10.14
4	5	6.76	12	16.22
5	3	4.62	9	13.85
6	4	5.63	3	4.22

corporate to the traffic flow (last red period). Indicative lines are used to identify acceleration periods with absolute values over 2 m/s^2, since this is the limit established to identify anomalous instantaneous accelerations. Most of them are obtained during the overtaking or when adjusting the speed (by breaking) after that. It is more frequent to report negative acceleration peaks, given that for the vehicle it is easier to decrease speed by breaking, than increasing it by accelerating. Further work is pending in this line, but it is interesting to see that more noise in vehicle dynamics is observed in the second half of each trial, which is attributed to the unstable network conditions due to handover (shadowed area). The jitter in E2E network delay slightly affects vehicle control, since perception of speed and position about the rest of the vehicles is diverted.

Table 7 includes the number of anomalous instantaneous accelerations over 2 m/s^2, as the CCAM KPI to be calculated. A maximum of 10% of these measurements is considered as target value, given that overtaking tests involve continuous manoeuvres; hence, satisfactory results are obtained here. According to [32], comfortable driving schemes involve jerk values between 0.3 and 0.9 m/s^3. Considering a jerk limit of 0.9 m/s^3, the number of times this threshold is exceeded is included in the second half of Table 7. Around 10% of the total records are considered uncomfortable, mostly attributed to the second half of each trial, when the overtaking is carried out and the vehicle speed is adjusted to come back to the original lane. These periods also match with the network handover, as indicated above; hence, it is expected that improvements in the network, together with updates in the vehicle control algorithm to smooth manoeuvres, help to obtain better user experience.

An indicative visualisation of the combined effect of the network performance and operation of the autonomous overtaking manoeuvre can be see in Fig. 9. Here, the results of network latency, PLR and acceleration for trial 4 are plotted together. The range for the plots have been modified for the sake of clarity. The degradation of network performance is clear during the handover (shadowed area), with the mentioned increase of network latency and PLR. Several acceleration adjustments appear even after finishing the manoeuvre after 45 seconds of test, which can be attributed to network instability. Progress on handover operation is out of the scope of the current paper, but it is in the work plan of 5G-MOBIX, which is now working on implementing a local breakout solution to speed-up handovers and data sharing among NOS and Telefonica networks. Nonetheless, it is important to bear in mind that these trials consider a highly unfavourable scenario particularly set for evaluating a worst case situation when using an advanced driving service.

As can be extracted from the results, the operation of the evaluation platform has been validated through a set of tests to compute network and CCAM KPIs. It is now ready to collect, process and make available measurements and results coming from different network setups and involving varied scenarios implementing different CCAM services.

6. Conclusion

The present work has described the path towards creating an evaluation platform ready to measure both operational and performance metrics of 5G-NR networks in the context of CCAM services. This has been carried out within the EU 5G-MOBIX project, which particularly study network implications in cross-border scenarios through real evaluation. A set of KPIs has been presented, to measure 5G network performance and the operation of final services under test (CCAM KPIs). Different perspectives for evaluation are considered, such as attending to the type of traffic and involved network segments, or regarding the abstraction layer under observation, from access to application layer. A wide set of measurement fields have been considered across network layers, all of them normalised by a common measurement methodology and data format. A data processing infrastructure has been deployed to

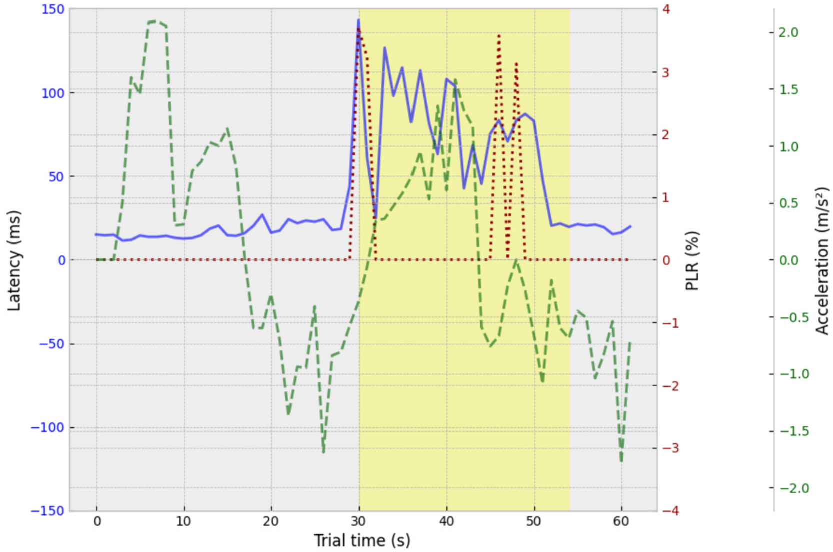


Fig. 9. Uplink latency, downlink PLR and acceleration results in trial 4.

make easier data management through a common platform that automatises data quality assurance, management of test reports, calculation of statistics for overall comparison, and calculation of final KPIs.

A reference test case is described in detail, which validate the evaluation platform under a real scenario about autonomous overtaking, presenting an innovative experimental campaign with a 5G-NR network deployment with autonomous vehicles in an European border. Results are gathered from the evaluation platform, after covering the stages of measurements, logging, aggregation of data, storage in database, and calculation of statistics. An analysis of the network performance in terms of latency and PLR has been carried out, highlighting the effect of handovers and their potential impact on final services. For this, the vehicle dynamics is analysed considering acceleration during the overtaking manoeuvre. These tests are only the first ones within a huge set of trial runs to be done for each of the use cases considered in 5G-MOBIX. The platform and tests presented here present a reference for future experimental evaluation works using 5G or beyond 5G networks in the field of CCAM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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