Test and Evaluation of Connected and Autonomous Vehicles in Real-world Scenarios

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***Abstract*— Connected and autonomous/automated vehicle (CAV) technologies are shaping the design and the new developments in the automotive industry and, in a wider perspective, in the mobility sector as well. Despite the recent advances and on-going developments, and the enthusiasm around autonomous mobility systems, real-world testing of CAVs is a crucial element to allow the next generation of intelligent vehicles to come to our daily-life. The importance of realistic testing is recognized by academia, industry, public sector and stakeholders, and is reflected in all projects involving pilots and advanced prototyping. AUTOCITS* is one of the projects where CAVs and interoperability tests have been conducted. This paper concentrates on the assessment and performance evaluation of tests carried out during the AUTOCITS's Lisbon Pilot, in real-world conditions, involving CAVs and C-ITS technologies. New specific quantitative indicators (key performance indicators - KPIs) are proposed to back the assessment and evaluation criteria presented in this work. The KPIs' expressions are provided, which demonstrated to be very difficult to find in the literature. Results are reported and discussed according to the scenarios and field-data recorded during the Pilot.**

Workshop paper on Connected, Cooperative and Autonomous Driving (CAD).

Fig. 1. RSUs' locations and map of the motorway where the Pilot was trialled (centre). Some of the cars equipped with OBUs and autonomous driving systems (ADS) are shown (left and right), and some traffic control vehicles are shown as well.

I. Introduction

The potential societal, economic and technological benefits of automated, autonomous and related technologies are recognized by most of the players, policy-makers, companies, academia, stakeholders and entities involved in the transport and mobility sectors [1]. Although a variety of new advances and technologies in connected and autonomous vehicles (CAVs) are expected to happen in the near-future [2],[3],[4] it is necessary to test and evaluate the current and ongoing developments under real-world conditions. This is particularly of interest for highly automated vehicles because of the complex conditions they have to cope on the roads [5].

The testing and evaluation, or assessment, of CAVs in real-world scenarios is a challenging task. In the project AUTOCITS [6], which has an activity devoted to Pilots assessment, the main challenges are related to the different V2X technologies and automated/autonomous systems involved. The main goal of this work is to present an approach that serves as evaluation guideline, supported by quantitative data, for CAVs in a C-ITS environment broadcasting ITS services via Decentralized Environmental Notification (DEN) messages. The key principle governing the assessment approach discussed here is that the CAVs, driving in autonomous mode, have to change their behavior (e.g., speed changing) according to the DEN messages (DENM) [7],[8] they received from the infrastructure (I2V).

This paper presents a representative part of the field-results achieved during the AUTOCITS Lisbon-Pilot, which took place on the motorway called A9-CREL (see Fig. 1 - centre), where CAVs equipped with on-board units (OBUs) have been tested and evaluated. The methodology for evaluating the CAVs performance in the motorway, the key performance indicators (KPIs) used to support quantitative analysis of the test-cases, and results are presented and discussed in the next sections. The approach used to evaluate CAVs depends on recorded data (field data-logging) containing the vehicles' position, speed, time-stamps, received and interpreted DENM messages. Data has been recorded in the OBUs onboarded the CAVs under evaluation. The DEN messages have been broadcasted by fixed road-side units (RSUs) installed along the motorway circuit i.e., we have concentrated our evaluation on I2V communications.

A brief description of the employed C-ITS and CAVs, the scenario, test-cases, ITS services and data logging are provided in Section II. Section III provides a detailed description of the KPIs and their formulation. Field results are presented and discussed in Section IV. Finally, Section V brings concluding remarks and points out future work.

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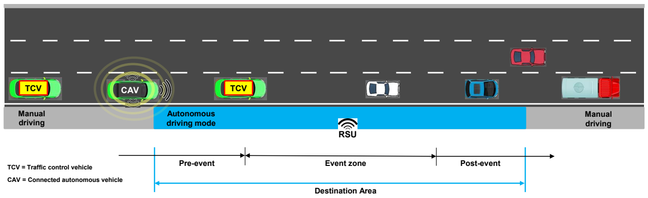

Fig. 2. Testing scenario: the CAV has to be in autonomous mode while driving in the destination area. The CAV's behavior changing is primary evaluated, at the event zone, as a reduction in the speed according to a event/sub-event received ITS message.

TABLE I

TESTED C-ITS SERVICES/EVENTS.

Cause (code)	Subcause (code)
adverseWeatherCondition-Adhesion (6)	iceOnRoad(5)
hazardousLocation-SurfaceCondition (9)	rockfalls(1)
adverseWeatherCondition-Visibility (18)	heavyRain(4)
accident (2)	unavailable(0)

II. TECHNOLOGY, SCENARIOS AND TEST-CASES

C-ITS and autonomous driving systems constitute the key technologies to enable CAV. C-ITS architecture, in the scope of this work, refers to a central ITS station (or traffic management centre - TMC), road-side units (RSU) and on-board units (OBU). In terms of ITS services, or facilities, DENM is particularly considered in the test-cases and results discussed hereafter. While CAM[1] supports periodic status data from vehicles (V2I) and RSUs to the TMC, the main goal of this paper is to provide evidences of real-world tests, performed during the AUTOCITS's Lisbon Pilot, where vehicles in autonomous mode received DENM data from RSUs (i.e., I2V) and changed their speed accordingly to the cause/sub-cause event. More details about the C-ITS infrastructure that supported the Pilot can be found in [9]. The scenario, the test-cases and the DENM events (services) considered are described in the next subsections.

A. Motorway scenario

The scenario where the tests involving CAVs were carried out is the motorway designated A9-CREL, or simply A9, in Portugal as shown in Fig. 1 (map in the centre). Three test-cases have been planned: dedicated lane, shared lane and non-restricted case [9]. However, due to safety reasons and risk mitigation, the 'non-restricted' testing scenario was decided to be out of the Pilot's scope. Another scenario, driving through a toll-system, is beyond the scope of this work. Figure 2 illustrates the motorway scenario which served as reference for the Pilot evaluation. A "moving corridor", with the CAV between two traffic control vehicles (TCV), was established to mitigate influence from other conventional vehicles driving on the road therefore, increasing safety of conventional road-users.

During the tests, complete coverage in the pre-event area(s) was guaranteed by RSU(s) installed alongside the road. The pre-event zone is where the CAV is expected

[1]CAM stands for Cooperative Awareness Messages.

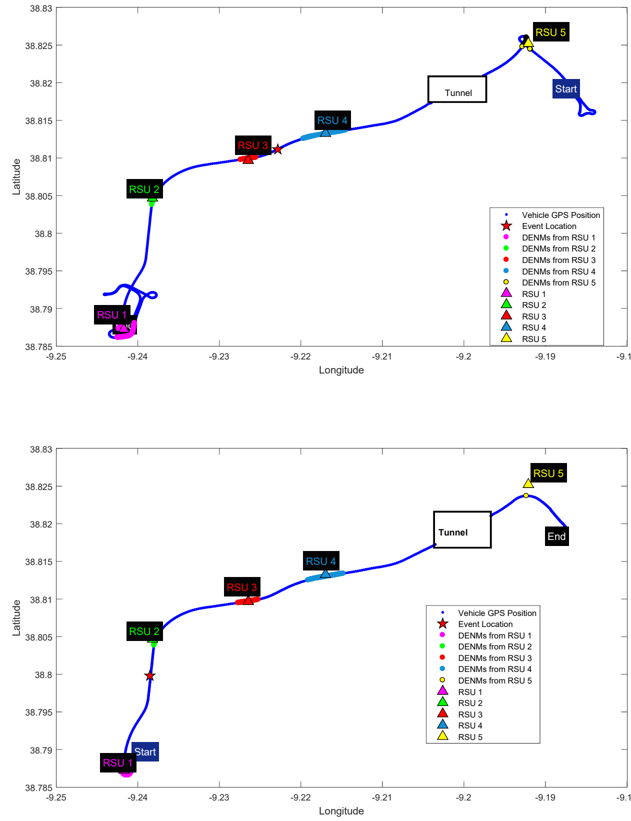

Fig. 3. GPS locations, latitude and longitude, as per data recorded by one of the OBU units equipping one of the CAVs that participated in the Pilot. The testing circuit/journey were carried out in both motorway directions, one at time. Events, defined by DEN-based services (see Table I) are indicated by a 'star' symbol. In terms of OBU's reception-coverage, the data shown in this figure indicates a middle-to-low coverage: as illustrated by coloured point centred on the RSUs.

to change its behaviors by reducing the speed to a pre-defined value V_{target} and to maintain this speed until the post-event zone is reached then, the CAV can increase the speed back to $V_{nominal}$. Both directions of the motorway were considered in the test-cases: one direction is called 'circuit-1' and conversely 'circuit-2' (the opposite direction). Figure 3 shows, using GPS coordinates, both testing-circuits on the A9 motorway. Starting and ending of journeys, the tunnel and the RSUs' locations are depicted as well. The 'coloured' points centred on RSU locations give us an idea of one of the OBU's reception-range capability used by one of the CAVs that participated in the trials; hence, Fig. 3 represents data collected by a particular CAV.

B. Test cases: C-ITS services

The tests were performed on 16, 17 and 18^{th} October 2018, and will be designated hereafter by Test_1, Test_2, Test_3 respectively. Four C-ITS messages, or data elements [7], have been considered in the tests. Each message has been associated to an event (a cause and sub-cause), making the messages unequivocal. Table I lists the cause and respective sub-cause implemented as DENMs.

The DENMs, broadcasted through the RSUs to the vehicles (i.e., I2V), were implemented having as reference the standard defined by the European Telecommunications Standards Institute Technical Committee Intelligent Transport System (ETSI TC ITS) and the Andreas Festag's work [8]. DEN basic service defines spontaneous events that may occur on the road, namely road hazard warning events as, for example, given in Table I.

C. Field data collection - data logging

The KPIs used to evaluate the Pilot use information from field-data (logging) recorded by the OBUs onboard the CAVs. Prior to the trials, a guidance document was created and shared with the CAVs' Teams (i.e., Pilot participants) containing the format/structure expected to be used to record field-data. Essentially, the messages should comprise three elements: GPS location of the CAV, a referenced timestamp, and the received DENMs. Although the importance of having a common internal data-format has been recognized, a lesson learned in this regard is that not all Teams implemented the data-logging format as desired.

The GPS positions, in decimal degrees format to enable an accuracy of centimetres, and the DENM based messages are pivotal data to allow a proper evaluation of CAVs. However, a geo-referenced timestamp is crucial to guarantee that a quantitative evaluation of the CAVs' behavior can be performed. In other words, a common timestamp between the received DENMs and vehicle's position/speed is key to make possible the calculations of CAVs' response time with respect to the moment an I2V message is received.

III. KEY PERFORMANCE INDICATORS

The KPIs calculation is based on vehicle's speed, its GPS positions, and received DEN messages. Threshold values have been used for assigning scores to the KPIs. A KPI has a 'positive' score if its value is within pre-defined threshold interval.

For the evaluation of the I2V communication (in this case, the interoperability between the RSUs and OBUs), 5 KPIs have been defined based on received DENMs and the GPS positions. The evaluation was performed on an event basis for the received DENMs related to the respective event.

The first two KPIs depend on DENMs data; concerning the other three KPIs, only the data in the time interval when the vehicle is moving in the same direction of the respective event is considered. The evaluation is performed by taking into account the RSU source and its received DENMs in a time interval when the distance of the vehicle wrt the RSU is equal to or less than the respective *dmrr*. The parameter *dmrr* represents the shortest distance between the first and the last received DENMs to the respective RSU under consideration.

The proposed KPIs are defined as follows:

1) Receiving the expected DENM (KPI-I1): For each RSU, this KPI assumes the value 1 whether any DENM is received or 0 otherwise (the threshold value is 1).

2) Suitable receiving time of the expected DENM (KPI-I2): Assumes the value 1 whether any DENM is received before the CAV reaches the event location, or 0 otherwise (threshold value is 1).

3) Percentage of received DENMs (KPI-I3): The ratio of the number of received DENMs over the expected number of received DENMs. The expected number of received DENMs is calculated by dividing the time interval considered in the evaluation, by the *transmissioninterval* present in the respective DENMs content (minimum and maximum threshold values are [25%,100%]).

4) Average time between received DENMs (KPI-I4): The average time between two consecutive DENMs subtracting the *transmissioninterval* (minimum and maximum threshold values are [0, *transmissioninterval*/0.25]).

5) Standard deviation time between received DENMs (KPI-I5): The standard deviation of the time between two consecutive DENMs. The minimum threshold value assumes 0 when the DENMs arrives at a fixed transmission rate. The maximum threshold value is defined considering the evaluation time interval, in which only the first and last 25% of the expected DENMs are received with a fixed time interval equal to the *transmissioninterval*.

To allow the CAVs speed behavior evaluation, 6 KPIs were defined based on the vehicle speed values recorded during the tests. The threshold values are dependent on the evaluation scenario i.e., dedicated lane (DL) or shared lane (SL). The first 3 KPIs, as in [10], are related to the vehicle speed; they are: 1) Maximum Speed; 2) Mean Speed; and 3) Minimum Speed. The other 3 KPIs are related to the vehicle's responsive-action (behavior) and consider changes on the vehicle speed and the arrival to the event zones. The KPIs are: 4) Response-time action as per the received DENM; 5) Response time after an event DENM; and 6) Response time to a detected event.

The first 3 KPIs are calculated per event zone, and represent the maximum, the arithmetic mean, and the minimum speed values recorded during the Pre-event, Event and Post Event zones. The threshold values for the KPIs are the same for the 3 event zones, with an exception for the event zone where the CAV is expected to maintain its speed. In that case, the threshold values of the KPIs "Maximum Speed" and "Mean Speed" are the same for the KPI "Minimum Speed". The calculations of KPIs threshold values, which depends on the testing scenario, are expressed by equation (1) - (7).

1) Maximum Speed (KPI-B1): the threshold values are

$$\begin{cases} [v_{nominal} - c_{min}, v_{nominal} + l_v] & \text{,if DL} \\ [v_{nominal} - c_{min} - \frac{v_r}{2}, v_{nominal} + l_v] & \text{,if SL} \end{cases} \tag{1}$$

where $v_{nominal}$ is the nominal speed in km/h that the autonomous vehicle can travel, c_{min} is the minimum variation of speed to define a behavior change of the vehicle, v_r is the expected speed reduction, in km/h, as per the DENM, and l_v is the limit calculated as ($l_v = 1.25 \times \frac{c_{min}}{2}$).

2) Mean Speed (KPI-B2): For the mean speed the threshold values are:

$$\begin{cases} [v_{nominal} - v_r - \frac{c_{min}}{2}, v_{nominal}] & \text{,if DL} \\ [v_{nominal} - \frac{3 \times v_r}{2} - \frac{c_{min}}{2}, v_{nominal}] & \text{,if SL} \end{cases} \tag{2}$$

3) Minimum Speed (KPI-B3): For the minimum speed the

threshold are defined as:

$$\begin{cases} [v_{nominal} - c_{min} - v_r, v_{nominal} - v_r + l_v] & \text{,if DL} \\ [v_{nominal} - c_{min} - \frac{3 \times v_r}{2}, v_{nominal} - v_r + l_v] & \text{,if SL} \end{cases} \tag{3}$$

4) Response-time action as per the received DENM (KPI-B4): it is the time difference between the timestamp when the vehicle starts reducing its speed - before it reaches the event location(ts_{svcp}) - and the receiving timestamp of the reference DENM (ts_d). The reference DENM is defined as the first DENM received before the event zone, with the associated timestamp (ts_{denm}), according to the following condition

$$ts_{re} - ts_{denm} \leq val_{dur} \tag{4}$$

where ts_{re} is the timestamp of reaching the event zone and val_{dur} is the *ValidityDuration* parameter present in the DENMs content. The thresholds are:

$$\begin{cases} [ts_{rp} - ts_d, ts_{re} - ts_d] & \text{,if DL} \\ [\max(ts_{fppe}, ts_{sam}, ts_d), ts_{re} - ts_d] & \text{,if SL} \end{cases} \tag{5}$$

where ts_{rp} is the timestamp of reaching the pre-event zone, ts_{fppe} is the timestamp of finishing the post-event zone in the prior event location, ts_{re} is the timestamp of reaching the event zone, and ts_{sam} is the timestamp of transitioning from manual to autonomous mode.

5) Response time after an event DENM (KPI-B5): this KPI is defined as the time difference between the timestamp when the vehicle starts to increase its speed - after leaving the event location - and the timestamp of the reference DENM (ts_d). The threshold's interval is

$$[ts_{fe} - ts_d, ts_{fpo} - ts_d] \tag{6}$$

where ts_{fe} is the timestamp of finishing the event zone and ts_{fpo} is the timestamp of finishing the post-event.

6) Response time to a detected event (KPI-B6): difference between the time-stamp when the vehicle's speed is steady (after the event location) and the timestamp when the vehicle starts to reduce its speed before reaching the event location. Values for the thresholds are:

$$\begin{cases} [ts_{fe} - ts_{svcp}, ts_{fpo} - ts_{svcp}] & \text{,if DL} \\ [ts_{fe} - ts_{svcp}, \min(ts_{spne}, ts_{eam}) - ts_{svcp}] & \text{,if SH} \end{cases} \tag{7}$$

where ts_{svcp} is the timestamp of starting the speed change (speed reduction) before the event zone, ts_{spne} is the timestamp of starting the pre-event zone for the next event location, and ts_{eam} is the timestamp of ending autonomous mode.

To compute the starting and ending moment of speed reduction or increasing (speed changes), these speed 'transitions' are calculated using the following two methods.

Method 1) Considering the speed values with associated timestamps, a local speed change is determined by finding the speed in which the value is above or below the mean speed, in a time window equal to or greater than 1s, having the standard deviation as threshold. A value above the mean plus standard deviation is associated to the increase of speed while a value below the mean minus standard deviation is associated to speed reduction. The speed change is characterized by a similar set of consecutive smaller speed changes (associated to a time window).

Method 2) Considering the received events and the aforementioned generated set of local speed changes (**Method 1**), the vehicle's response to the event is verified and if the speed variation is at least 75% of the expected speed reduction, a global speed change is considered. After the event, and in order to verify if the vehicle returns to the initial conditions, the maximum speed (in a speed change) is compared with the maximum speed before the event and if the difference is $\leq$ 25% of the expected speed reduction a positive speed change is considered.

IV. FIELD RESULTS

The Pilot had the participation of 2 CAVs, with distinct OBU and ADS technologies, and 1 CV (i.e., without ADS) equipped with its own OBU device. The vehicles have been involved in tests and trials during the three days period where vehicles performed different tests under specific conditions. Data logging, as described in sect. II-C, was collected through the OBUs in the vehicles. This section, however, gives emphasis to one of the CAVs field data; results are drawn from the KPIs, described before, and graphical/plot results support our discussions.

Figures 4, 5 and 6 show the speed of the CAV, evolving in a time basis (in seconds), for six test-cases. The speed values in red denote that the CAV was on the "Event zone" of the circuit. The black-circles marks, in the speed curves, are points used as reference of speed (behavior) changing according to the event definition and the DENM associated to it. Tables II, III and IV show the results for interoperability KPIs. Table V shows the thresholds values related to the CAV's speed change.

Different testing scenarios were performed in Dedicated Lane (Test$_1$) and in Shared Lane (Test$_2$ and Test$_3$). These scenarios allowed the assessment of the CAV's behavior to the received DENMs. For the tests, the expected speed reduction (v_r) was 20 km/h. The values for the *ValidityDuration* and *transmissioninterval* parameters in the DENMs were set to 86400 seconds and 36 milliseconds respectively. The value of c_{min} was equal to 10 km/h.

In terms of recorded data both GPS coordinates and DENMs data, as shown in Fig. 3, have been correctly recorded along the entire route in the two directions. In particular, the DENMs recorded by the OBUs were received correctly (KPI-I1). The results of the KPIs related to the interoperability are shown in Tables II and IV (KPI-I4 and KPI-I3). As the threshold values of the KPI-I5 are different for each KPI, the values present in Table III are actually the ratio between the KPI values over the respective maximum threshold value. Missing values in Tables II, III and IV represent a negative score of KPI-I1 (i.e., no DENM has been received). KPI-I2 obtained a positive score for all use-case tests, which means that at least one DENM was received before reaching an event zone. Finally, the reliability of the

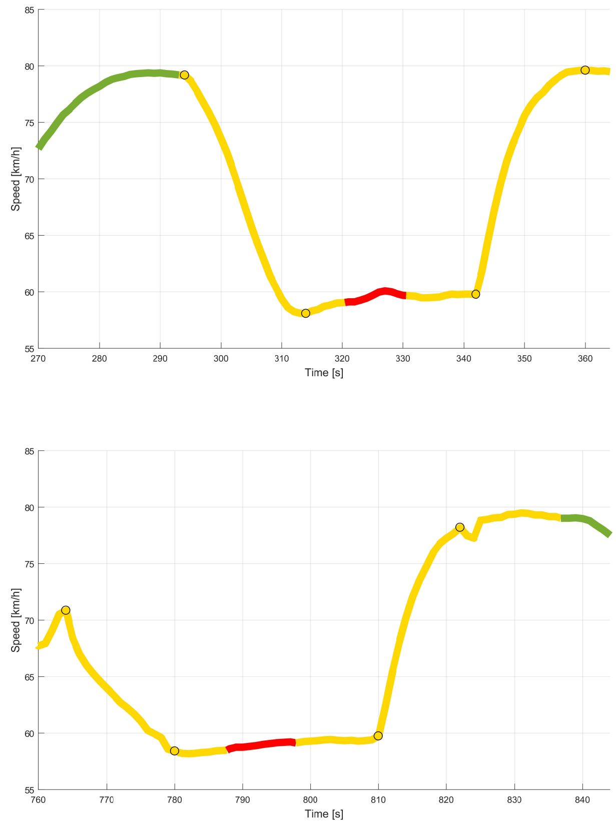

Fig. 4. $Test_1$'s speed profile, representing one of the CAV's tests, emphasizing the event zone (in red), the pre and post-event (yellow, from left to right), and the reference points (black circles). The first curve, on the top, represent the event in one of the motorway's direction (circuit-1) and below we have the speed profile for circuit-2.

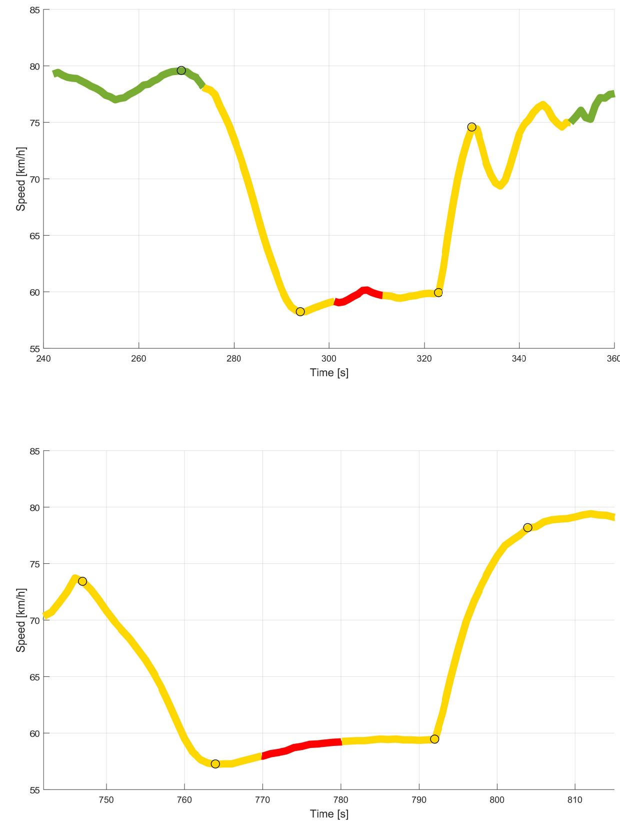

Fig. 5. $Test_3$'s speed data relative to a test-case in the shared-lane (SL) scenario. The results shown in the top figure (during circuit-1), were recorded having another vehicle (a CAV as well) sharing the same lane and driving in front of of the testing CAV. This explains, in part, the behavior evidenced in the post-event zone.

data can be verified through the low value of KPI-I5 (see Table III). Only one case in Table IV ($Test_2$ - Event 1, RSU 5) fails the threshold value, because there was a 'gap' in the reception of DENMs in the time interval.

The evaluation of KPI-B1, KPI-B2 and KPI-B3 dependeds on the vehicle nominal speed $v_{nominal}$ (80 km/h during the tests reported here) and the testing scenario (DL or SH). The threshold values for each testing scenario are presented in the Table V. The vehicle speed values along all the event zones situate between the defined threshold values; this indicates the expected vehicle's behavior performance which is necessary to accomplish the test-scenarios (as planned).

The reference points (black circles) in the Figs. 4, 5 and 6 show that the behavior changes (speed changes as calculated using Method 1 and Method 2) were performed as expected - within the event zones. During the tests, the behavior changes were performed correctly; therefore KPI-B4, KPI-B5 and KPI-B6 have positive scores.

TABLE II

RESULTS FOR KPI-I4 (AVERAGE TIME IN MS OF RECEIVED DENMS).

Test	Event	RSU 1	RSU 2	RSU 3	RSU 4	RSU 5
$Test_1$	1	33	11	13	30	0
$Test_1$	2	7	3	20	—	—
$Test_2$	1	37	—	11	27	102
$Test_2$	2	6	—	9	25	26
$Test_3$	1	30	—	20	17	—
$Test_3$	2	5	—	8	27	—

V. REMARKS AND CONCLUSION

This paper contributes on quantitative evaluation 'metrics', referred as KPIs, to support assessment/evaluation of CAVs in motorway scenarios. The key technologies briefly discussed in this work, which allow CAVs trials/tests in real-world scenarios, are: C-ITS system, RSU, OBU and ADS technologies. In particular, this work concentrates on the test-cases implemented and tested as part of the AUTOCITS Lisbon Pilot. CAVs, CVs and vehicles with more or less automated functionalities participated in the Pilot. A list of C-ITS services/facilities were implemented and broadcasted via the RSUs installed on a motorway.

The lessons learned from the Lisbon Pilot and the assessment/evaluation results have helped and supported the AUTOCITS' Pilots in France and Spain. In a wider perspective, the detailed description of the KPIs presented in this work and the reported results can, to some extent, facilitate further CAVs trials and tests in other countries.

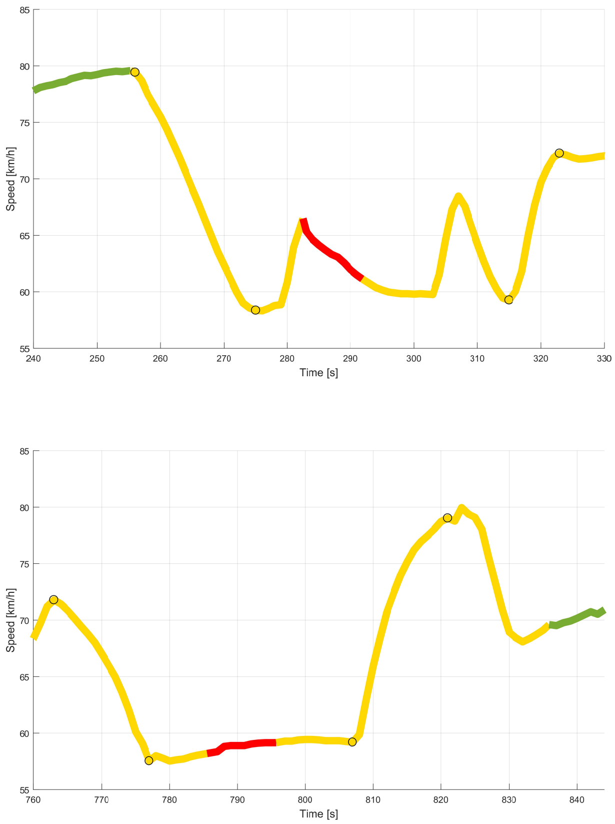

Fig. 6. The result on the first curve, obtained from circuit-1, indicates that the CAV behavior whist driving autonomously in the event zone was not uniform. Probable reasons are related to the TCV vehicle driving ahead of the CAV and/or the CAV's ADS system itself. These curves were obtained from data collected during Test_2.

TABLE III

RESULTS FOR KPI-I5 (STD TIME OF RECEIVED DENMS).

Test	Event	RSU 1	RSU 2	RSU 3	RSU 4	RSU 5
Test_1	1	0.13	0.09	0.11	0.12	0.05
Test_1	2	0.06	0.04	0.18	—	—
Test_2	1	0.00	—	0.05	0.14	0.67
Test_2	2	0.03	—	0.04	0.11	0.30
Test_3	1	0.00	—	0.09	0.08	—
Test_3	2	0.03	—	0.05	0.15	—

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TABLE IV

RESULTS FOR KPI-I3 (PERCENTAGE OF RECEIVED DENMS).

Test	Event	RSU 1	RSU 2	RSU 3	RSU 4	RSU 5
Test_1	1	52%	73%	72%	51%	46%
Test_1	2	83%	92%	59%	—	—
Test_2	1	45%	—	77%	43%	20%
Test_2	2	69%	—	76%	58%	28%
Test_3	1	52%	—	59%	66%	—
Test_3	2	88%	—	79%	56%	—

TABLE V

THRESHOLD VALUES [KM/H]: (KPI-B1, KPI-B2 AND KPI-B3)

KPI	Pre Event 1	Event	Post Event
Dedicated Lane			
KPI-B1	[70,86.25]	[50,66.25]	[70,86.25]
KPI-B2	[55,80]	[50,66.25]	[55;80]
KPI-B3	[50,66.25]	[50,66.25]	[50,66.25]
Shared Lane			
KPI-B1	[60,86.25]	[40,66.25]	[60,86.25]
KPI-B2	[45,80]	[40,66.25]	[45,80]
KPI-B3	[40,66.25]	[40,66.25]	[40,66.25]

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