Real-life implementation and Testing of Infrastructure-Assisted Routing Recommendations

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Abstract— **Advanced Driver Assistance Systems (ADAS) play a pivotal role in modern road vehicles, enhancing safety. However, persistent challenges in managing ADAS systems and automated vehicles during dynamic traffic scenarios hinder the widespread adoption of ADAS and Automated Driving (AD) systems. Recognizing the susceptibility of perception sensors to weather and road hazards, along with their typical operational limitations, V2X communication becomes critically important to achieve higher levels of autonomy and robustness. In the EU-funded project ESRIUM, safety improvement is attained by developing a digital map capable of accurately identifying road damage and offering real-time recommendations for connected vehicles. In this paper, we report the implementation and road testing results for the infrastructure-assisted automated driving system developed within the ESRIUM project. These tests were conducted on real-life public roads and under typical driving conditions on the Austrian highway A2, showcasing the effectiveness of infrastructure-assisted AD vehicles in diverse traffic scenarios. These findings represent a significant advancement in validating automated vehicles on operational highways, emphasizing the vital role of infrastructure and V2X communication in enhancing ADAS/AD road safety and efficiency.**

I. INTRODUCTION

ADAS, or advanced driver assistance systems, are increasingly prevalent in contemporary automobiles, offering the potential to decrease the cognitive effort required of drivers and enhance safety [1]. Nevertheless, there are still obstacles in managing and influencing the behavior of automated vehicles in dynamic traffic circumstances, particularly when transitioning from traditional to automated traffic. A hurdle in the process of commercializing ADAS or achieving higher levels of Automated Vehicles (AVs) is the need to effectively detect hazards, plan trajectories and make decisions in various scenarios [2], such as encountering lane closures or road damage. AVs encounter problems when it comes to avoiding maintenance zones on the road because their deployed sensors might be unable to detect small cones. The susceptibility of perception sensors to degradation in inclement weather is evident. The adverse space weather conditions are also detrimental to the Global Navigation Satellite System (GNSS) as well [3]. Therefore, V2X (Vehicle-to-Everything) communication is essential for achieving higher levels of autonomy (SAE Level-4 and Level-5 [4]) as it enables Connected and Automated Vehicles (CAVs) to receive real-time routing and driving recommendations.

Inspired by this, the EU-H2020-funded project ESRIUM [5] has the objective of enhancing the safety and resource efficiency of transportation on European roads. This will be achieved by developing a digital map that accurately identifies road surface damage and wear. The map will be utilized to minimize road works and related issues by effectively managing traffic and controlling road usage. Additionally, it will provide road operators with valuable information for planning maintenance activities. Furthermore, connected vehicles will receive route and driving recommendations to minimize road surface deterioration and the need for frequent maintenance actions.

The emergence of CAVs and infrastructure-supported automated driving functions has garnered significant interest in recent years, as outlined in [3]. The EU-funded project MAVEN in 2018 implemented V2X solutions that focus on guiding cooperative automated vehicles at signalized intersections, taking into account platoons, and providing information about the presence of non-cooperative road users, among other goals [6]. A fully connected and automated road environment was used to study infrastructure-assisted traffic management and cooperative driving around highway work zones in 2020. It simulates manual driving, mixed traffic, and infrastructure-assisted highly automated traffic using vehicle-driver models. The simulation results show that infrastructure-assisted traffic management and cooperative driving can improve traffic efficiency and safety, especially in high-traffic scenarios [7].

Recently, Schulte-Tigges et al. proposed a software architecture and logic for CAVs that effectively utilizes hazard notification and road signage information from V2X messages [8]. This approach allows for the management of Operational Design Domain (ODD) decisions and reactions in a predictable manner. Their proposed software architecture incorporates a maneuver planner that utilizes separate state machines to respond to various types of V2X information. The system generates target objectives for a motion planner and path controller. The simulations illustrate the advantages of the presented CAV solution in comparison to a baseline autonomous vehicle (AV) model that solely depends on onboard sensors. Furthermore, they conducted real-world test-track experiments to confirm the usefulness of the proposed logic. However, the test track is only straight and without the presence of real traffic scenarios. This compromised the strength of their validation, but we successfully validated our infrastructure-assisted AV on busy and curvy highways, even in the presence of some trucks and adverse weather. Other state-of-the-art work about CAVs has a different focus,

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including decentralized protocol for CAVs' coordination [9], Vehicle-in-the-Loop (ViL) test environment with V2X communication [10], mechanisms to account for the special role of Infrastructure-assisted Collective Perception (ICP) [11], comparative analysis of EGNSS-based path tracking with and without open service navigation message authentication (OSNMA) [12], V2X communication accuracy [13] and delay [14]. However, none of those works implemented a validation with AVs on an operating highway.

As part of the ESRIUM project, a digital map was developed to detect and categorize road surface deterioration. This map assists in guiding traffic and reducing the need for road repairs. We have created and put into practice trajectory planners for AVs that utilize infrastructure to improve road safety and efficiency. The V2X message from the roadside unit (RSU) via the onboard unit (OBU) finally to our AV software bridges the gap between digital maps and AV maneuvers. In order to verify the effectiveness of our solutions under different traffic scenarios, we carried out practical experiments on the Austrian highway A2. As far as we know, there has not been a validation conducted on an operational highway that includes all working automated driving features along with OBU and RSU.

The rest of this paper is structured as follows: Section II describes two infrastructure-assisted scenarios: in-lane offset recommendation and lane change recommendation. Section III details the vehicle setup and control algorithms. Section IV discusses the real-world testing on the Austrian motorway A2, including the environmental conditions and test results. Section V summarizes this work and suggests our future directions.

II. SCENARIO DEFINITION

According to the deliverable [15] of the ESRIUM project [5], the implementation and results of the following two infrastructure-assisted scenarios are presented in this work:

1) In-lane offset recommendation (Fig. 1, cyan trajectory).
2) Lane change recommendation (Fig. 1, red trajectory).

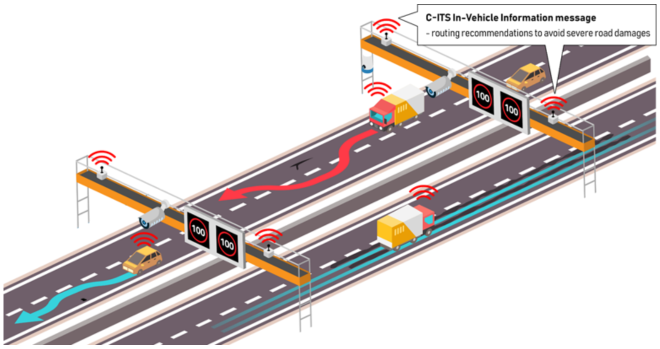

Fig. 1. Implemented scenarios: In-lane offset recommendation (cyan trajectory) and lane change recommendation (red trajectory).

In both scenarios, the automated vehicle receives C-ITS (Cooperative Intelligent Transport Systems and Services) messages of type IVIM (In-Vehicle Information Message, [16]) from the infrastructure via an onboard unit. For scenario 1, these messages contain a recommended lateral offset of $20\,\mathrm{cm}$, $30\,\mathrm{cm}$ and $40\,\mathrm{cm}$ to be executed by the automated vehicle to e. g. avoid potholes or delay the formation of lane grooves. Scenario 2 simulates the case of a blocked lane due to e. g. a construction site. Consequently, the vehicle receives the corresponding C-ITS message announcing a lane-change request to the left or right. This maneuver includes three so-called relevance zones: In zone 1, the vehicle is supposed to leave the corresponding lane to avoid an obstacle blocking this lane in zone 2. Then, in zone 3, the automated vehicle is again allowed to change lanes as needed.

The tests were conducted on an approximately $9\,\mathrm{km}$ long section of the Austrian motorway A2 between Graz and Lassnitzhöhe, as shown in Fig. 2, on the 27th of July, 2023.

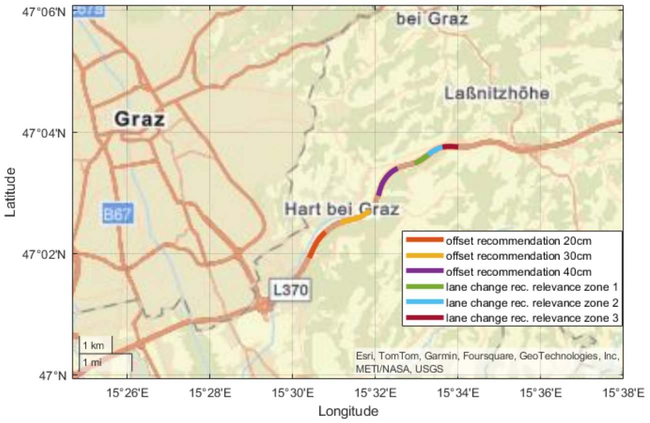

Fig. 2. Tests were done on a section of the Austrian motorway A2 between Graz and Lassnitzhöhe.

III. VEHICLE SETUP AND CONTROL ALGORITHMS

The test vehicle is a Ford Mondeo Hybrid equipped with additional hardware for environment perception, communication with road infrastructure, and execution of the developed algorithms, see Fig. 3. Drive-by-wire is possible in terms of throttle, brake, and steering commands as well as access to on-board sensors such as acceleration, yaw rate, and speed, both accomplished via CAN. For localisation, a Septentrio Mosaic-H5 EGNSS receiver with EPOSA-RTK (Echtzeit Positionierung Austria [17], which translates to

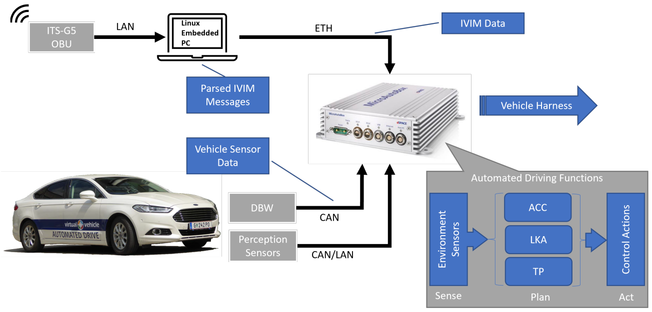

Fig. 3. Test vehicle setup and architecture.

"real time positioning Austria", Real Time Kinematic) was installed. The overall hardware setup for the implementation of the routing recommendations on the vehicle side and the corresponding interfaces are shown in Fig. 3. A self-developed OBU receives C-ITS messages and transmits them to a Linux embedded PC, where they are parsed and decoded by a Python program. Finally, the lane offset and lane change recommendation extracted from the IVIM data is delivered to a dSPACE MicroAutoBox II, which is a real-time platform used to run all control algorithms.

For the demonstrated scenarios, decoupled handling of longitudinal and lateral vehicle motion control was sufficient. Therefore, an ACC (adaptive cruise control) module combined with a PI controller was used to either maintain a desired speed or a constant time gap to the vehicle in front. For lateral motion control, a rule-based trajectory planner was implemented to compute Bézier-based reference paths in a Frenet frame w.r.t. the centerline of the current lane. Following this reference path was then handled by an LQR-based state feedback controller. For more details regarding the control algorithms, the interested reader is referred to [18]–[20]. The lateral position of the vehicle was controlled based on the lane markings detected by a commercial camera system from Mobileye.

IV. TEST RESULTS AND DISCUSSION

In total, nine individual test runs with three runs per desired speed of $90\,\mathrm{km/h}$, $110\,\mathrm{km/h}$ and $130\,\mathrm{km/h}$ were performed (Table I). Environmental conditions such as weather conditions and traffic density varied naturally during the tests. For the analysis of the driving function performance, the following data was logged:

TABLE I

TEST RUN AND DESIRED VELOCITY

Test run	Desired velocity (kph)
1-3	90
4-6	110
7-9	130

- Relevant vehicle CAN data (drive-by-wire status, speed, acceleration, angular rates, wheel speeds, . . .)
- Lane boundaries
- Detected objects
- EGNSS positions
- Parsed C-ITS messages
- AD function internals, e.g. lateral position of the vehicle w.r.t. the center of the current lane to easily assess the in-lane offset

For the analysis of the results, we present a plot of (1) the actual versus the desired velocity and (2) the actual as well as the recommended lateral offset via C-ITS. The interpretation of the lateral offset is w.r.t. the center of the current lane (centerline) and the offset is positive when the look-ahead point is to the right of the centerline. Therefore, during a lane change the point of reference changes from the center of the initial to the center of the target lane and results in a double-peak spark (see e. g. Fig. 5). Additionally, grey shaded areas highlight the relevance zones 1-3 of the vehicle location w.r.t. the lane change recommendation. In zone 1, the vehicle should leave the rightmost lane to avoid e. g. a virtual road damage in zone 2. Eventually, in zone 3, the vehicle is allowed to change back to the rightmost lane.

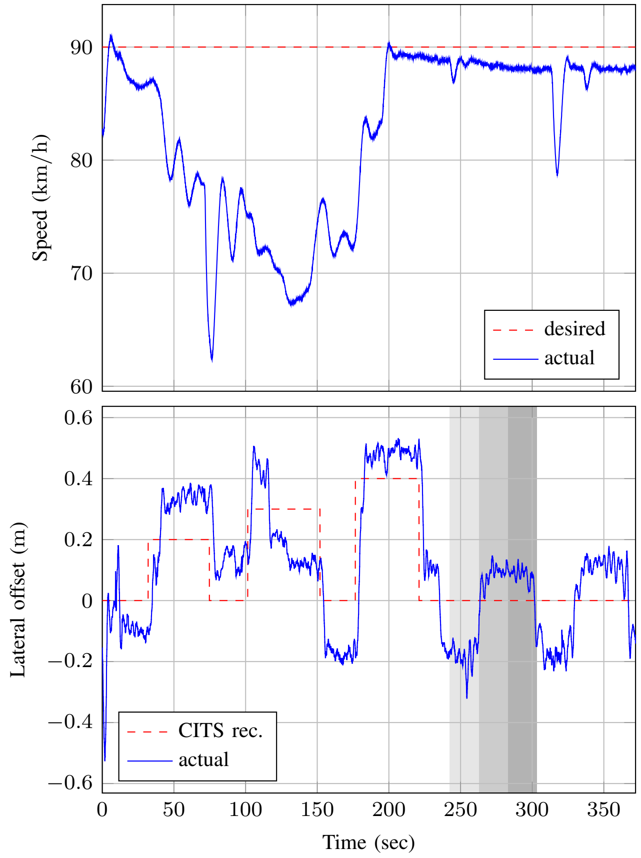

Fig. 4. Test results for a desired speed of $90\,\mathrm{km/h}$. Velocity (top) and lateral offset (bottom).

The individual results of all test runs were reported in the deliverable [21] of the ESRIUM project [5]. In this work, the results of one test per desired velocity are presented. Data and a visualization have been deposited to the Zenodo database [22] and are accessible for download and viewing by the public.

A. Results

The results for the test case with a desired velocity of $90\,\mathrm{km/h}$ are presented in Fig. 4. The automated vehicle adapted its speed according to the surrounding traffic and shows acceptable overshoots which stayed below $1\,\mathrm{km/h}$. Unfortunately, due to dense traffic it was not possible to perform the recommended lane changes, as can be seen from the highlighted relevance zones (grey shaded ares). From the lateral offset, we can make the following observations: Although there are obvious deviations of about $10\,\mathrm{cm}$ to $20\,\mathrm{cm}$, the actual offset in general follows the CITS-reference. The main cause for these deviations can be traced back to road curvature combined with the look-ahead of the

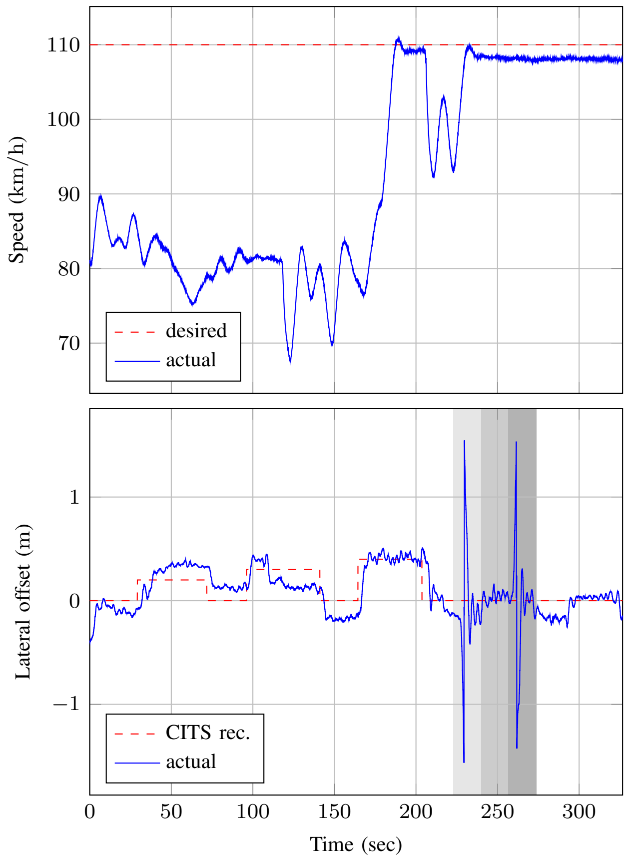

Fig. 5. Test results for a desired speed of 110 km/h. Velocity (top) and lateral offset (bottom).

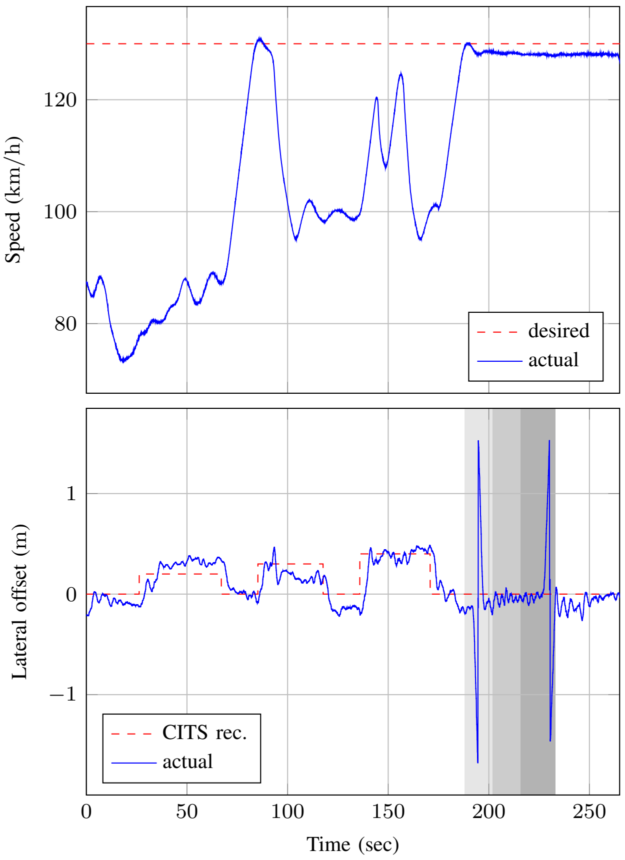

Fig. 6. Test results for a desired speed of 130 km/h. Velocity (top) and lateral offset (bottom).

steering controller, road slope, and missing integral action of the steering controller and is elaborated in more detail in section IV-B.

Fig. 5 shows the results for the test case with a desired velocity of 110 km/h. The lateral offset shows to successfully performed lane changes in the relevance zones 1 and 3 at about 230 s and 260 s. The speed signal only shows minor overshoots again.

No major differences were observed during the test case with a desired velocity of 130 km/h, which is shown in Fig. 6. Again, the traffic situation caused the automated vehicle to stay mostly below the desired velocity. The maximum overshoot was less than 1 km/h. Lane changes were performed at about 195 s and 230 s in the recommended zones as received via C-ITS.

An evaluation regarding successfully performed lane changes of all test runs is summarized in Table II.

B. Road curvature analysis

The role of road curvature as a disturbance which deteriorates path tracking performance is well known from literature (e. g. [23], [24]). Therefore, imperfect tracking of the reference path was expected, even though the actual amount of the deviation due to superimposition of all present perturbations in a real-world scenario was unknown. In particular the curvature of a reference path can be treated as a known disturbance during controller design, since it is provided from today's available sensors. But still, there are other disturbances like side wind and road slope. As a conclusion, integral action in the steering controller to compensate for such unknown disturbances seems mandatory for a use-case like in-lane offset, which requires path tracking accuracy within a few centimeter.

To underline the effect of road curvature on the lateral offset, we further analyze the trajectory from test run as shown in Fig. 4. For this, the results from this test run are beneficial, as there was no lane change performed. It is worth noting, that in addition to the curvature, also the look-ahead distance of the steering controller adds to the error of the lateral offset but is also a result of the road curvature.

C. Rise time analysis

Fig. 8 shows the closed-loop vehicle response for a step in the lateral offset reference (obtained via C-ITS) from 20 cm to 0 cm (green line). The trajectory planner uses a fifth order polynomial with a fixed length of 4.5 s to compute a smooth transition (cyan line) for the underlying steering controller. The offset-compensated lateral offset (yellow) is used to discuss the rise time of the control loop. As a definition for the rise time we use the duration until the lateral offset settles within 90 % of the reference value. From Fig. 8 it can be seen, that the rise time essentially matches the duration of the

TABLE II

EVALUATION OF SUCCESSFULLY PERFORMED LANE CHANGES AS RECEIVED VIA C-ITS MESSAGE.

Test run	Relevance zone 1	Relevance zone 3
1	✓	✓
2	no lane change[1]	no lane change[1]
3	✓	✓
4	✓	✓
5	no lane change[1]	no lane change
6	✓	✓
7	✓	✓[2]
8	no lane change[3]	✓
9	✓	✓
Total	6/9	7/9

[1] Traffic prohibited lane changes

[2] The lane change was started but not finished in relevance zone 3.

[3] The traffic situation required a lane change to the left lane before entering relevance zone 1. Therefore, no lane change was done in relevance zone 1.

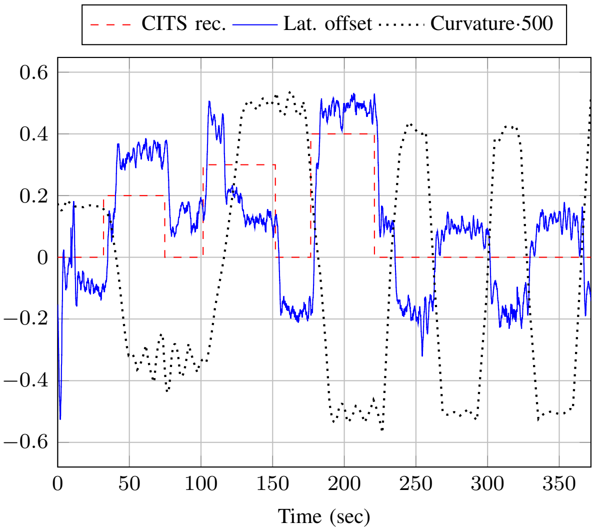

Fig. 7. Relation of road curvature and lateral offset. A positive curvature causes a negative offset error and vice versa. Notice that the curvature is scaled for improved readability.

planned offset, making this a viable approach for tuning of driving comfort. Table III displays the rise times associated with all implemented in-lane offset recommendations. There were two instances where no rise time could be recorded: In test run 1, the step in the offset recommendation 0 to 20 cm was not logged, and in test run 4, offset recommendation 40 to 0 cm was disrupted by a lane change, preventing the determination of the reaction time. The average value of all measured rise times is 3.59 s. In contrast, the rise time of the planned curve is 3.35 s.

This assessment indicates a favorable correlation between the rise time of the planned offset and the executed offset.

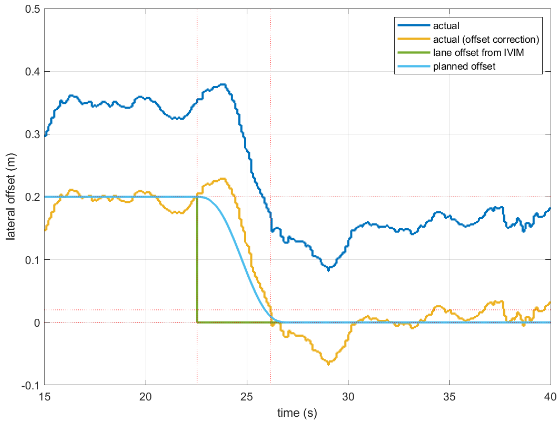

Fig. 8. Rise time estimation based on the lateral offset w.r.t. the in-lane offset recommendation via C-ITS.

TABLE III

RISE TIME EVALUATION FOR THE IMPLEMENTED IN-LANE OFFSETS.

Test run	0 to 20 cm	20 to 0 cm	0 to 30 cm	30 to 0 cm	0 to 40 cm	40 to to 0 cm
1	-	3.60	3.40	3.40	4.50	3.40
3	3.45	3.50	3.10	3.55	2.80	3.30
4	3.30	3.20	2.70	3.50	3.30	-
5	3.40	3.70	3.05	3.40	3.55	4.90
6	3.50	3.60	2.95	4.30	3.40	2.60
7	3.10	2.40	3.10	3.50	5.20	4.60
8	3.40	3.40	3.15	3.95	4.30	3.30
9	3.35	4.50	3.70	3.20	4.20	6.40
10	3.30	3.10	4.90	3.40	4.45	2.30

V. CONCLUSION AND OUTLOOK

In this paper we implemented and analyzed infrastructure-assisted automated driving functions in a novel manner, focusing on utilizing specific infrastructure routing recommendations to adapt and enhance their behaviour in a context-aware manner. The infrastructure routing recommendations conveyed through typical C-ITS messages like IVIM, include specific lane-change and in-lane offset suggestions. This study anticipates that connected automated vehicles, capable of adjusting their behaviour based on routing recommendations, will offer advantages to both road operators and vehicle owners.

The gradual degradation of the road surface benefits road operators, while vehicles benefit from a safer and more comfortable ride by avoiding rutted or damaged road sections and blocked lanes, thanks to the provided routing recommendations. This concept is part of the recently completed EU-H2020 funded project ESRIUM, which aims to develop the complete value chain for implementing this idea and assess its feasibility. Building upon previous work [12], [19], [20], this study extends the testing and validation of the planning and control algorithms developed in a simulation framework to a real-life demonstration and analysis of the collected data.

In this context, ESRIUM Project's infrastructure-assisted trajectory planning and tracking solutions for AVs, enhance road safety and efficiency. Our real-world tests confirmed the system's ability to handle in-lane offsets and lane change scenarios effectively. Despite challenges like heavy rain affecting sensor performance, our system showed resilience in varied environmental conditions.

Future work will focus on refining the control algorithms and expanding the system's capabilities to handle more complex driving scenarios, by combining V2X communication with our developed safe trajectory planners for Minimal Risk Maneuver [25] and Evasive Maneuver [26].

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