Infrastructure-Supported Cooperative Automated Driving in Transition Areas

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***Abstract*—Automated driving is not possible everywhere. Limited by the Operational Design Domain (ODD) of vehicle automation functions, Transitions of Control (ToC) are required. If the ToCs fail, Minimum Risk Maneuvers (MRM) are executed, resulting in stopped vehicles on the road. As a result, traffic is negatively impacted, esp. when the number of automated vehicles (AVs) rises. To reduce such negative impacts, the EU-H2020 TransAID project has designed novel infrastructure-assisted traffic management measures using V2X communications, and evaluated them via simulations and field trials. This paper shows how prototypic real-world tests were performed to validate feasibility of the TransAID measures on public road and test track trials. The obtained results show that infrastructure support and V2X communication can contribute to drastically reduce the need to perform ToCs, MRMs, and hence the risk of blocked roads.**

Keywords—Connected Automated Driving, Transition of Control, Minimum Risk Maneuver, Transition Area, Feasibility Assessment, V2X.

I. INTRODUCTION

Mobility is about to change due to climate protection, individual transportation needs and the trend to a network society. One key enabler for future mobility is automated driving (AD). While early research focused on driving automated in different kinds of environments [1][2], vehicles with more and more automation capabilities are now entering the market. Here, the major selling point is on specific features such as relaxed and safe travel on a growing number of roads, from highways to inter-urban and urban ones. One fact known by vehicle manufacturers, but not well understood by drivers (e.g. current prominent Tesla crashes), is that all automation systems have limitations. In fact, AD is restricted to the operating conditions specified in the Operational Design Domain (ODD) of the automation systems. Although the frontier of AD capabilities is pushed further away year by year, it should be clearly stated that there will be limitations independent of the targeted level of automation, and that even SAE level 5 vehicles will not be able to overcome all situations. Whenever automated vehicles (AVs) cannot handle a situation on the road, they shall keep guaranteeing safe operation. While vehicles up to SAE level 4 will try to bring the driver back into the loop by issuing a Take Over Request (TOR) and performing Transitions of Control (ToC), vehicles of SAE level 3 and above will also perform Minimum Risk Maneuvers (MRM). According to current research, AVs will mostly decelerate and stop when encountering a situation beyond their ODD.

Putting together a rising number of such AVs on the roads and the issue that vehicles will not be able to cope with all situations and consequently will perform braking maneuvers as MRMs directly leads to the assumption that negative effects on traffic efficiency and safety will occur. Assuming that most of the situations will not arise from sensor failures, but from environmental conditions in a given area ("Transition Area"), will aggravate the negative impacts. Traffic management (TM) centers and the road infrastructure can play a key role in attenuating the negative effects of ToCs/MRMs in Transition Areas. To this aim, they can exploit C-ITS and connectivity to communicate with vehicles via V2X (Vehicle-to-Everything) and manage the execution of ToCs.

Using this approach, the EU-H2020 TransAID project has, besides others, the following main objectives:

- Estimate the impact of ToCs and MRMs on different penetration rates of automated vehicles.
- Develop novel TM measures to reduce negative impacts on traffic efficiency and safety. These measures exploit the support of the infrastructure including sensing and ITS-G5 based communication capabilities.
- Define and study V2X message sets to allow cooperation between infrastructure and vehicles and between vehicles.
- Estimate the impact on traffic efficiency and safety of the TM measures.
- Show that the developed approaches are feasible in terms of prototypic real-world implementations.
- Develop guidelines and a roadmap to stakeholders.

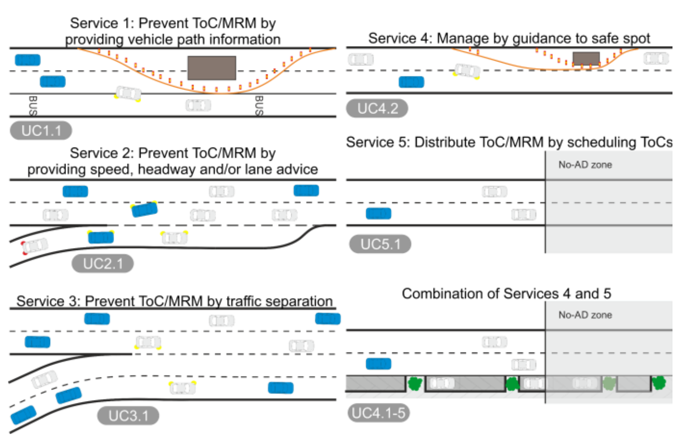

Fig. 1. Excerpt of investigated TransAID services and use cases. Blue vehicles are CAVs.

As a starting point, a use case (UC) catalogue was developed in the project. As the number of possible reasons for vehicle automations unable to cope with upcoming situations is endless, it has been decided to cluster the UCs by the developed TM measures. As described in [3] and shown in Fig. 1, a set of five different services was established:

- *Service 1 – Prevent ToC/MRM by providing vehicle path information*: Here, a path is provided by the infrastructure which allows connected automated vehicles (CAV) to overcome a given situation.
- *Service 2 – Prevent ToC/MRM by providing speed, headway and/or lane advice*: Sometimes, parametrizing automation capabilities can avoid critical situations and reduce ToCs/MRMs.
- *Service 3 – Prevent ToC/MRM by traffic separation*: Separation of traffic is the most drastic way of coping with different capabilities.
- *Service 4 – Manage by guidance to safe spot*: In case a ToC/MRM is not avoidable, infrastructure can help to find a place where the vehicle can stop safely without being an obstacle for others.
- *Service 5 – Distribute ToC/MRM by scheduling ToCs*: Having all ToCs close to the critical area has larger impacts than distributing them along the road.

For all the services, example UCs have been created. A subset is shown in Fig. 1. Some of them also combine different services. A detailed description of all UCs can be found in [3] and [4].

As a first step, all UCs have been simulated with SUMO to get insights on the impacts at different penetration rates of CAVs and AVs [5]. As communication between the Road-Side Infrastructure (RSI) and vehicles is crucial for the effectiveness of the TM measures, more detailed simulations coupling SUMO with ns-3 in the iTETRIS framework have been performed. Results of these simulations [6] confirmed that infrastructure support benefits CAVs' behavior at Transition Areas. In order to reach a higher Technology Readiness Level (TRL), the developed infrastructure-assisted TM measures, protocols and cooperation techniques have also been implemented in prototypes by project partners. Feasibility assessments have been performed to analyze whether the used approaches are sufficient to implement the infrastructure-assisted TM measures in real-world.

This paper summarizes the work done to assess the benefits of the infrastructure support on AD in Transition Areas in the real world. First, the process of the assessment is shown in Section II. Section III describes the used setup, including RSI hardware, implemented V2X messages and briefly the used CAVs. Since not all UCs can be described in detail in this paper, Sections IV and V show the results of two example UCs. While Section IV focusses on UC 2.1 implementing *Service 2*, Section V shows UC 4.1-5, a combination of *Service 4* and *Service 5*. Finally, Section VI concludes this paper.

II. Feasibility Assessment

Despite TransAID main focus on simulations, real-world prototypes have been implemented to get a closer view on the chosen V2X messages, protocols, TM measures and CAVs' behavior. This is very relevant, as it may reveal possible shortcomings of systems, which cannot be found in simulations easily. Especially in cooperative systems, where the behavior of one entity influences others, real-world implementations may result in jittering when signal propagation times are varying and the systems are not accurately parametrized to cope with this.

In the project, feasibility assessments have been performed in two iterations to allow refining of V2X message sets and TM measures. In each iteration, a list of requirements has been set up as a first step. The requirements have been used to create and implement the system architecture of the infrastructure, and of additional vehicle automation components and their interfacing to the existing vehicle automation frameworks.

After agreeing on a common architecture, the hardware has been set up at different partners and the software has been implemented. This included mobile infrastructure hardware used on test tracks as well as at the A13 motorway in the Netherlands. Besides, the V2X message sets have been set up with their interfacing to the existing vehicle automation functions. The complete setup is described in Section III.

During the first project iteration, one large feasibility assessment has been performed on the test track of Peine-Eddesse, Germany. Here, a first version of the implementations (TRL 3) has been tested in all UCs. As the UCs were tested in different ways, e.g. with and without RSI interaction, a sum of 15 scenarios was showcased. Partners and experts had the chance to rate the CAVs' behavior and their interactions with RSI and other vehicles. The main focus at this stage was to fulfill the requirements. Additional opinions on e.g. smoothness of the behavior, look-and-feel of the provisional HMI, or traceability of automation parameters were also noted down. Results of the first iteration are presented in [7].

The first feasibility assessment already showed a good coverage of requirements, but also revealed some shortcomings, as some simplifications had to be made at that stage of the project, e.g. in the detection of objects and online calculation of measures. After refining some protocols and detailing the behavior, the second feasibility assessment took place about one year later. This time, a set of more than 30 scenarios was tested. The goal of this second iteration was to enhance the TRL of the functions to level 6, so that a proof-of-concept could be shown partially even on public roads. This assessment was clustered into three parts: (a) detailed testing of all UCs on the test track of Peine-Eddesse, Germany; (b) public road tests of UC 2.1 through an infrastructure-assisted merging assistant on the Dutch motorway A13; (c) detailed analysis of the UC 4.1-5 showcased on the test track of Griesheim, Germany, that focuses on distribution of ToCs and safe guidance of CAVs to stop. The results of (b) and (c) are shown in Sections IV and V, respectively, enhanced by some findings of (a) in the appropriate UCs.

III. General Description of the Test Platform

The test platform developed to validate the benefits of the infrastructure support to CAVs in Transition Areas includes RSI and CAVs. Fig. 2 shows the logical architecture of the platform. The RSI and CAVs communicate using commercial ITS-G5 enabled V2X devices. The RSI fuses the information received through the V2X communication together with the data gathered by other infrastructure sensors like video and radar cameras. At

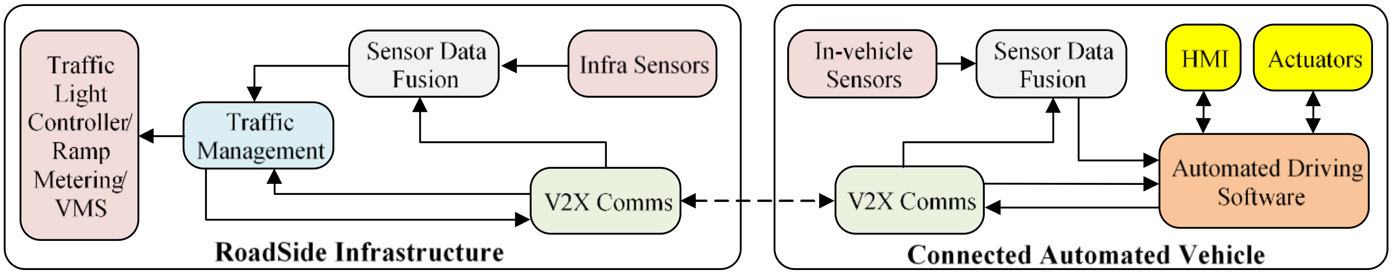

Fig. 2. Architecture of the test platform

the TM module, the RSI implements the TM measures using the processed information received from RSI's Sensor Data Fusion module and direct information received from the V2X Communication module. The derived TM measures might result in commands over the traffic lights' controller, ramp metering and variable message sign (VMS). In addition, the TM module interfaces with the V2X Communication module. Through this interface, the TM module sends information (e.g. suggestions or advisories about how to handle a ToC) to create the V2X messages that are used to support the CAVs.

The CAVs, and also connected non-automated vehicles (CV), combine the V2X messages received from the RSI with the data collected from built-in sensors. This combination is performed at the Sensor Data Fusion module that provides the processed data to the Automated Driving Software (AD SW) module. The AD SW uses this input information as well as direct V2X information to interpret the environment and to plan the behavior of the automation, including the planning of the CAV's trajectories and their conversion to driving commands. These driving commands are implemented in the Actuators module that interfaces with the AD SW module. The developed platform includes also an interface between the driver and the AD SW. This is implemented through the Human-Machine-Interface (HMI) module that offers output of visual, acoustic and haptic feedback as well as input of manual control commands including the enabling and disabling of vehicle automation functions. Finally, the AD SW includes also an interface to the V2X Communications module. This interface is used to pass information that is used to create the V2X messages that the CAV will transmit.

A. V2X messages

The implemented platform allows the RSI and CAVs to extend their perception and knowledge of the driving environment through the continuous exchange of ETSI ITS standard V2X messages. V2X messages are also used to implement advanced infrastructure-assisted TM measures that exploit V2X to manage the execution of ToCs. In particular, the V2X messages implemented include: Map Message (MAPEM), Signal Phase and Time Message (SPATEM), Cooperative Awareness Message (CAM), Decentralized Environmental Notification Message (DENM), Collective Perception Message (CPM) and Maneuver Coordination Message (MCM). The increased support for AD proposed in TransAID has requested extending some of these standard messages. The proposed extensions follow the original V2X messages' content and ensure backward compatibility for guaranteeing interoperability with legacy/original V2X systems. Details can be found in [9] with respective ASN.1 definitions in [7].

1) MAPEM

The MAPEM message describes intersections and/or road segment topologies, and the corresponding lane attributes (e.g. bus or emergency lane). TransAID uses MAPEM to prevent or mitigate possible negative effects of ToC. This includes, for instance, special permissions to temporarily drive automated on bus or emergency lanes, and the presence of safe spots where MRM stops can be performed.

2) SPATEM

In combination with MAPEM, SPATEM messages define the status and timing conditions of traffic lights at signalized intersections.

3) CAM

The CAM message includes information about position, dynamics and basic attributes of the transmitting vehicle. The structure of CAM messages is made of different containers that are transmitted with high or low frequency depending on how essential the information they include is for the surrounding road users. TransAID has extended the CAM to include an *AutomatedVehicle* container that CAVs use to notify their current SAE automation level and if the vehicle is currently performing an MRM. This information is useful for the infrastructure to assess the actual traffic demands and compositions, and for the surrounding CAVs/CVs to be informed of a risky maneuver.

4) DENM

The DENM message contains information related to a road hazard or abnormal traffic conditions including description and location. It alerts other road users about an unexpected event that has potential impact on road safety or traffic conditions.

5) CPM

The CPM message contains data about objects (e.g. obstacles, vehicles, pedestrians, etc.) detected by the RSI or CAVs using their built-in sensors. Since sensors range is reduced and its view is limited to line-of-sight conditions, CPMs received via V2X allow receivers to improve their perception of the driving environment.

6) MCM

The MCM is a newly defined message that enables cooperative maneuvering or cooperative driving. It is currently under standardization at the ETSI Technical Committee on ITS [8]. MCM is being defined to include the vehicle's planned and desired trajectories (V2V). CAVs can exploit this information, together with the right-of-way driving rules, to coordinate their maneuvers. Encouraged in part by TransAID, it is being also considered that MCM messages can be extended to include advisories and suggestions from the RSI to the CAVs to support the maneuver coordination. In particular, after the RSI has performed a risk analysis of the local situation, these extensions would allow the RSI to send individual advisories to the CAVs on how to handle a ToC, set a target speed, change lane, create gaps, and head towards a safe spot. TransAID has proposed the following containers to the MCM (detailed information in [9]): 1) *LaneAdvice*: suggests to an individual CAV the target lane, the leading and following vehicles after the merging, and where/when the lane change should be performed; 2) *CarFollowingAdvice*: indicates to a CAV a target gap or speed and the distance range where this applies; 3) *ToCAdvice*: informs how to handle the ToC by indicating when/where the CAV should perform the ToC, and what automation level it should adopt after the ToC; and 4) *SafeSpot*: indicates the range of locations where the CAV can perform a safe spot.

B. Road Side Infrastructure (RSI)

Two different mobile RSI platforms have been used in the project (see Fig. 3). The first, a mobile retractable pole is equipped with an ACTi camera (type B94), and a Cohda Wireless's MK5 Road-Side Unit (RSU) that acts as the V2X communications (comms) module at the RSI side (see Fig. 2). Both devices are powered over ethernet, and mounted on a Robot Operative System (ROS) platform. The camera's 1.3 Megapixel images, recorded at 30 fps with a resolution of 1280x960 pixels, are processed on an NVIDIA GeForce GTX 1050 powered EXC-1200 computer. Through a trained neuronal network, a ROS node performs the object detection of the recorded images. The detected objects are subsequently tracked over time in order to determine object velocities, reduce uncertainties and also provide object histories. The tracking is based on a Kalman filter that performs the prediction step based on a constant velocity model. The tracked objects are formatted into ROS messages following the format of V2X CPM messages, e.g. to ensure the correct value ranges and units. The CPM-related information is forwarded to the RSI's TM Module to create the CPM before transmitting through the MK5 RSU.

The second mobile RSI platform (research version of Dynniq's RSU Wifi-11p Mk2 in the mobile RSI and research version OBU V2X-M200 in the CV) shares similar features to the one described above. The main difference lies in the utilization of a radar camera and additional infrastructure sensors like inductive loops (data retrieved via MTM outstation) that provide accurate data, e.g. speed, lane occupied, position, heading and headway about vehicles passing nearby. This information is of particular importance for the infrastructure-assisted merging assistant (UC2.1).

C. Connected Automated Vehicle

The CAVs are equipped with multiple sensors that are connected via Ethernet and integrated with the ROS system. Following a similar procedure as in the RSI, the objects detected by the sensors are forwarded to the Sensor Fusion module to be combined with the information received through the V2X module (see Fig. 2). The CAV uses this information to implement planning and decision making at the AD SW. Planning and decision making is based on these four steps: 1) environmental data aggregation; 2) goal-oriented data abstraction in so called views; 3) maneuver planning; and 4)

Fig. 3. Used mobile poles, equipped with cameras, RSUs and workstations on the test track (right) and on the highway (left)

maneuver selection. To this aim, in addition to the environmental data received from the Sensor Data Fusion module, the AD SW utilizes road geometric and topological data from an HD map and a navigation component. The decision making is made over a set of cost-rated planning maneuvers that seeks selecting an appropriate, feasible and low-cost maneuver.

With regards to connectivity of CAVs, the V2X communication module receives information from the AD SW to create V2X messages. Specific UDP interfaces are defined to communicate them. The UDP interfaces use data structures matching the content of V2X messages. The V2X messages are UPER encoded using their ASN.1 representation, and appended with their unique BTP header, before they are transmitted. On the reception path, the V2X module processes the received V2X messages and forwards the relevant information to the Sensor Fusion module or to the AD SW directly through specific UDP interfaces. The same process is followed at the RSI side.

IV. Example: Merging Assist

A. Overview

This section details the tests conducted to demonstrate the feasibility of the TransAID *Service 2 – Prevent ToC/MRM by providing speed, headway and/or lane advice*. The tests are conducted following the UC 2.1 that focuses on motorway merge segments. Fig. 1 shows the schematic layout of this UC. The scenario includes a one-lane on-ramp which directs traffic to a one-lane acceleration lane. This lane merges into the two-lane mainline motorway.

In this UC, it is considered that due to the limited perception and possibly obscured field-of-view, e.g. sloping on-ramp topography, road curvature, greenbelt, shades and extreme weather, etc., (C)AVs could not timely plan to accelerate to catch the future merging possibilities downstream, nor decelerate to fit in an approaching gap from upstream. In case of insufficient situational awareness, (C)AVs cannot perform the high-speed merging task in automation mode anymore. Then, it is assumed that a ToC will be requested and the driver should take over. If the ToC was not successful, the (C)AV would perform an MRM. This would result in that the (C)AV would decelerate and stop before the end of the acceleration lane, and would generate significant traffic risks.

To address this situation, TransAID has developed a merging assistant system that leverages the support of the infrastructure. In particular, the merging assistant system implemented at the RSI provides speed and lane advisories to the CAVs on the on-ramp. This information allows the CAVs to prevent the ToC/MRM and serves for a smooth high-speed merging into the motorway. The core algorithm of the merging assistant is described in [5]. The main function of the merging assistant algorithm is to follow the driving behaviors (acceleration/deceleration pattern) of on-ramp CAVs and then predict future merging gaps and calculate lane change (merging) position and merging speed. To this aim, it is of key importance to get accurate data of the surrounding traffic conditions including vehicles' position, speed, headway, etc. As detailed in Section III.B this information is obtained using the inductive loops and radars camera available at the RSI. With these input traffic data, the merging assistant algorithm calculates the speed advice at run-time. The RSI transmits the derived speed advices to the on-ramp CAVs utilizing the MCM messages. The merging assistant algorithm continuously checks whether the maneuver is executed safely until the CAVs merge into the mainline motorway. If adjustments are needed, the merging assistant algorithm sends updated MCM messages with the new speed advisories.

B. *Use case setup*

Fig. 2 depicts the logical architecture of the implemented prototype platform. General details about the utilized equipment and their setup are presented in Section III.

The prototype was deployed as a proof-of-concept field trial on the A13 motorway (51°57'01.7"N 4°24'54.5"E) in the Randstad region, the Netherlands. The trial is performed on a fairly busy motorway close to Rotterdam The Hague Airport. On the test site, a one-lane, half-circle shaped on-ramp of approximately 200m is followed by a straight one-lane acceleration lane of 465m. This lane merges into a three-lane motorway (A13) with a speed limit of 100Km/h. Considering the complexity of high-speed merging maneuver on this stretch of daily commute motorway, we assume the CAVs cannot perform the task in automation mode without noticeable disturbance to the real traffic on the acceleration lane. Note that if the CAV cannot autonomously perform the merging maneuver, it will issue a ToC that after a lead time of 10s will result in an MRM if the human driver does not take over control. In addition, the proving ground is a public road with live traffic, which currently does not allow AVs in automation mode. Therefore, we carried out the tests disabling the vehicle automation functions. Two expert human drivers mimic this behavior and exploit the vehicle connectivity to perform the merging maneuver.

In the scenario, two sets of inductive loops are deployed in the motorway that are used to collect information about the mainline vehicles. One of the inductive loops is 515m away to the merging point (upstream), and the second one is 50m away from the merging point (downstream). Additional data about the mainline motorway is also detected using a radar camera. These two input data are fused in the implemented RSI (see Fig. 2) and utilized by the implemented merging assistant system to identify potential gaps in the right-most lane of the mainline motorway. The merging assistant also calculates the speed advice, time-to-merge and distance-to-merge for the test vehicle.

The RSI continuously transmits the processed data obtained from the inductive loops and radar camera using CPM messages. Both the RSI and the CAV (CV in these tests) display the transmitted and received information in their HMI. Fig. 4 and Fig. 5 show an example of the information that is displayed in the HMI. For example, at the RSI side (Fig. 4), it shows information about the advice that is transmitted to the vehicle on the on-ramp: time to merge and speed advice. A check box also shows whether the vehicle accepted or rejected the advice. In addition, the RSI's HMI shows status information about the vehicle approaching the merging point such as the distance to merge, and its current speed. A live video is also displayed. At the CV side (Fig. 5), the merging assistant information is also displayed (time to merge, speed advice, and distance to merge). The driver can manually accept or reject the advice and this ACK/NACK is reported to the RSI via V2X messages. In addition, the HMI shows, using a vertical red bar, the current speed of the vehicle (yellow arrow) and whether it is within the suggested speed (green bar). Besides, a graphical representation of the merging segment is displayed.

C. *Real-world results*

As a first step before deploying the prototype platform on site, an emulation platform was created that integrates the hardware and software components into a virtual radio network. The objective is to test the integrated platform and modulated components' functionalities before setting up the field trial on site. With live traffic data from inductive loops on the motorway, a key indicator is whether MCM-based speed advice is accurate. Empirical results of the emulation showed the test vehicle was able to merge smoothly into the mainline motorway without ToC/MRM, if it follows the speed advice. The emulation platform also allows testing whether the merging maneuver is executed or not when the CAV does not receive the information from the merging assistant system. This option will be used for comparison purposes.

Once the accuracy of the system was validated in the emulation platform, the field trial was performed around 11:00 (CET) on Thursday 25th June 2020 with a traffic count of 1200 veh/h/l, which indicated the traffic volume is closest to Level of Service (LOS) B [10]. The feasibility of TransAID merging assistant with MCM-based speed advice are shown using the following performance indicators:

- ToC rate: percentage of ToC. This shows when the vehicle cannot perform the merging task. With a non-automated CV, the merging task fails because:
  - Speed advice was not received successfully.
  - Gap is not available due to very dense traffic, such as congestion forming on the motorway.
  - Insufficient confidence (malfunctioning/inaccurate speed advice suspicion) to follow the speed advice.
- Disturbance to traffic: successful merge without perturbation to real traffic.
- Stable trajectory: informative trajectory with stability and comfortable acceleration.

The obtained empirical data are reported in Table I with average ToC rate over nine test runs. Table I compares the results obtained in the emulation platform and field trials. For the case of the emulation platform it assumed that the CV is not supported by the developed merging assistant (i.e. speed advice to the on-ramp vehicle). This allows to give a first estimation of the benefits of this system that is utilized in the field trials. The emulation results show that the emulated on-ramp CAV requests a ToC to the driver in 67% of nine runs. On the same road stretch during field trials, the on-ramp CV requests a ToC in 0% of nine runs, i.e. speed advice was received correctly, gap was correctly found and the human driver finds the advice appropriate. In addition, the field trial showed the speed advice was calculated, sent and received successfully. With the on-ramp human-driven CV mimicking conservative CAV behaviors, the result of 0% ToC rate is optimistic to identify the feasibility and accuracy of speed advice to realize merging maneuvers. In addition, minimum disturbance to the other live traffic was observed. Therefore, the potential perturbation caused by CVs accepting speed advice was not obvious. On the user application level, the received speed advice was relatively stable and therefore the planned trajectory was accurate with comfortable acceleration/deceleration.

D. CAV additions

Besides the original public road implementation using CVs, further research has been performed to investigate how the UC can be enhanced when CAVs use their full potential, including an online maneuver coordination using V2V communication. As described in section III, the original purpose of the MCM is the coordination of driving maneuvers. Here, each CAV constantly transmits its currently planned and desired trajectory. In case of merging, the desired trajectory constitutes the lane change from the on-ramp to the highway, see Fig. 6. A CAV driving on the highway can acknowledge the lane change desire by adapting its own planned trajectory accordingly. It may create a gap by braking or by changing the lane, if possible. It may also negotiate its behavior with other CAVs on the road, if necessary, by using the same approach.

In TransAID, corresponding scenarios have been implemented on the test track of Peine-Eddesse (Fig. 7). Two research vehicles have been equipped with the appropriate communication and vehicle automation features and have been tested with additional surrounding traffic on the site. On top of the plain V2V scenarios, also combinations of V2V and I2V infrastructure advisories are tested. Here, the RSI is monitoring the highway with a camera and RSU as described in Section III. Having an overview of the situation by fusing camera, CPM and CAM data, the RSI is able to give speed advice to the CAVs on the highway and on the on-ramp individually. In addition, the RSI is able to suggest an early ToC advice via MCM to the vehicle heading for the on-ramp in case the highway is too crowded and no other cooperative CAV is driving there. By doing this, late ToCs and even dangerous MRMs occurring on the on-ramp itself can be avoided.

The experiments on the test track showed that cooperation between vehicles, but also between RSI and vehicles is technically feasible and offers several positive effects, even with a rising number of CAVs on the road. The concept of MCMs has been found very valuable since it is scalable while also offering individual advice. On the other hand, a good definition of when a maneuver is desired is important. In some cases, it may also be helpful if more than one desired trajectory could be shared, as CAVs often have different options. Future research should also compare the flexible V2V-MCM approach with other protocols, e.g. the Space-Time Reservation Procedure (STRP), where an explicit and guaranteed reservation of space is negotiated instead of trajectories [11].

V. EXAMPLE: SAFESPOT ADVICE

A. Overview

In this prototype implementation, the feasibility of the TransAID combined services 4 and 5 (UC4.1-5) is validated. The evaluation scenario selected is a road section with a no-AD zone at the end (Fig. 1, see UC4.1-5). The prototype aims at showing the advantages of the TransAID's ToC management scheme compared to a baseline approach where CAVs receive DENMs from the infrastructure and are only informed about the presence and location of the no-AD zone downstream. In this baseline approach a CAV issues a TOR when in the DENM relevance zone, that is at a distance to the no-AD zone equal to a 'relevance distance' indicated in the DENM. As the relevance distance is a fixed value for all the vehicles, nearby-driving vehicles approaching the no-AD zone would execute the ToCs at approximately the same location. Executing ToCs at close locations implies risks, since drivers need some time to control

TABLE I. AVERAGE TOC RATE OF EMULATION (W/O MERGING ASSISSTANT) AND FIELD TRIAL (W/- MERGING ASSISSTANT)

Emulation	Field Trial
67%	0%

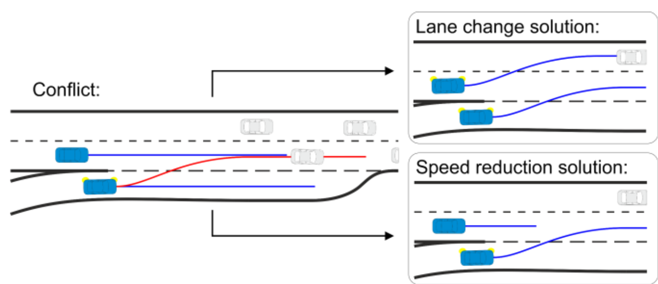

Fig. 6. Cooperative lane change using the MCM-V2V approach. Each CAV has its own planned trajectory (blue). The merging vehicle also has a desired trajectory (red). The highway vehicle has different options to react cooperatively.

Fig. 7. Cooperative lane change of the highway CAV (middle) driving on the virtual highway in UC 2.1., when the merging CAV (left) tries to change lane. Infrastructure gives an early speed advice to the on-ramp vehicle. Then, both vehicles coordinate the lane changes by using the MCM-V2V cooperation.

adequately the vehicle after a period of inactivity [12]. In case of an MRM, CAVs shall decelerate and stop. In some situations, it might happen that a CAV performing an MRM has no other option than stopping on the driving lane since there are no parking spots available. However, this can block traffic and generate significant traffic risks.

The TransAID approach implements a more advanced infrastructure-assisted ToC management scheme to solve the above-mentioned inefficiencies. It relies on MCM extensions that allow the infrastructure to support cooperative maneuvers (see Section III). With these extensions, individual advisories can be sent by the infrastructure to the CAVs to inform them how to manage ToCs and safe spots (among others) in a safer and traffic efficient way. In the TransAID MCM-based ToC management scheme, the infrastructure not only notifies about an upcoming ToC but also suggests a spatial distribution of ToCs over a wider Transition Area: in the example of Fig. 1, it would suggest close-by driving CAVs to trigger the ToC at two different locations. This minimizes the risks that drivers recover control of their vehicles at close distances when they have still not recovered full attention and their driving performance is lower. The MCM-based ToC management scheme also implements a procedure to handle efficiently MRMs. It constantly suggests CAVs road sections with safe spots where to stop if drivers fail to take over. With this information, the CAV implements an MRM guiding to a free section of the parking lane. This prevents risks and blockage of the driving lanes.

B. Use case setup

The implemented prototype platform and its logical architecture are depicted in Fig. 2. The RSI and CAV use the setup described in Section III.

Field trials have been conducted at the Griesheim airport on a virtual two-lane road of a length of approximately 1 km. The last 300m of the road is where AD is not allowed (no- AD zone in Fig 1). The RSI is located at the start of the no AD zone. An emergency lane where the stop the CAV is available next to the two-lane road. When the tests start, the CAV reaches a target speed of 60 km/h when it is 700m away from the no-AD zone. The RSI informs the CAV that it should perform a ToC before reaching the no-AD zone via DENM or MCM messages. Safe spots to safely stop the CAV in case of MRM are obtained as randomly selected 25m-length sections of the emergency lane. For each test run, at least one safe spot is available in the scenario.

We consider that from the moment a ToC is requested, the driver has a lead time of 10s to take over control before an MRM is executed [13]. To better compare DENM-based with MCM-based ToC management schemes, it is assumed that the driver does not intervene in time and the CAV always executes an MRM. When the TOR's lead time expires and the MRM starts, the CAV must slow down to a $Speed_{MRM}$=20Km/h before it can smoothly change to the emergency lane and park.

The RSI transmits DENMs periodically at 1Hz. A TOR is triggered at the receiving CAV upon entering the DENM relevance area (i.e. when reaching the 500m relevance distance). As the DENM does not indicate safe spot locations, this implementation assumes that the CAVs park on the emergency lane only if a safe spot is available when reaching the $Speed_{MRM}$. Otherwise, it stops on the driving lane.

Besides DENMs, the RSI transmits MCMs including individual *ToCAdvice* and *SafeSpot* advisories to incoming CAVs to operate the MCM-based ToC management scheme. The RSI suggests a CAV to schedule the TOR execution so that it reaches the assigned safe spot driving the minimum possible distance at $Speed_{MRM}$. For doing this, the RSI first selects a safe spot for the CAV and considers its current location and driving speed (available through the CAMs) to identify the location where the TOR should be issued. When receiving the advisories, the CAV keeps its driving speed and triggers the TOR only at the advised ToC location. When the TOR's lead time expires the CAV would slow down to $Speed_{MRM}$ and drive a short distance before finding the suggested safe spot and smoothly executing the forward parking maneuver. Here, it is important to stress out that the RSI makes conservative calculations when selecting the locations where the TORs should be executed. It assumes an adequately large distance from the safe spot to account for the vehicle's TOR lead time and deceleration profile.

C. Results

The advantages of the MCM-based ToC management scheme are proven using the following indicators:

- Successful MRM: percentage of times the CAV executes a safe MRM (the CAV is able to stop at a safe spot).
- ToC Distribution: range of distances where the ToC is triggered.

The empirical results reported below are average values measured over 50 field tests under 8 different scenario configurations obtained by changing the location of the safe spots (the emergency lane is divided into 25m-long sections - or spots- that can be free or occupied with the same probability. Testable scenarios are chosen among those where at least one safe spot is available). Table II compares the performance of the two infrastructure-assisted ToC management schemes in terms of successful MRM. The empirical results show that when the CAV follows the DENM-based ToC management scheme, it does not always successfully implement a safe MRM. It is important to recall that the DENM's relevant information is only available at the CAV once it is within the relevance distance (i.e. 500m away from the no-AD zone). At this point in time, the AD SW triggers the TOR and the CAV slows down from its driving speed to $Speed_{MRM}$. Therefore, the CAV misses any safe spot available from the start of the DENM's relevance area to the point at which it reaches $Speed_{MRM}$. In addition, the CAV is only allowed to park at the location where it reaches $Speed_{MRM}$ since it does not have further information about the availability of safe spots downstream. In particular, CAVs using the DENM-based approach only find a safe spot 12.5% of the times. In turn, CAVs must stop on the driving lane in 87.5% of the tests. Table II shows that the MCM-based ToC management scheme always allows the CAV to perform a successful MRM. This is thanks to the MCM's *ToCAdvice* and *SafeSpot* advisories received from the RSI that inform when/where to execute the ToC for reaching the assigned safe spot and park in case of MRM.

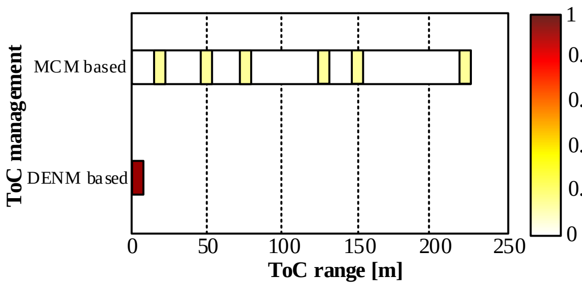

Fig. 8. ToC distribution

TABLE II: SUCCESSFUL MRM COMPARISON

DENM-based ToC Management	**MCM-based ToC Management**
12.5%	100%

The study in [5] showed through simulations that traffic safety and efficiency is undermined when ToCs at multiple CAVs are concentrated at close locations. From this point of view, having a management scheme that spatially distributes the ToC points at multiple CAVs is preferable. To see how the compared schemes have performed in this regard, Fig. 8 shows the empirical distribution of the ToC points. In the case of the DENM-based scheme, CAVs issue the ToC as soon as they enter the DENM's relevance area at the exact same location that is 500m away from the no AD zone. Then, Fig. 8 shows that the ToC range is of approximately 0m for all cases. The MCM-based ToC management scheme seeks minimizing the distance that the CAVs travel at $Speed_{MRM}$ and at the same time distributing the ToC points. To this aim, it links each possible safe spot with a location where to issue the ToC. Considering that all potential safe spots are independent and equally usable, the distribution of the ToCs in this case depends on the length of the sections considered free on the emergency lane and the distance traveled by the CAV during the TOR's lead time and deceleration from driving speed to $Speed_{MRM}$. Since the emergency lane is divided in 25m-length sections where vehicles could stop, the distribution of ToC points is discrete and equally spaced as shown in Fig. 8. Even if field tests were not conducted for all possible locations where safe spots could be, Fig. 8 demonstrates that the MCM-based approach achieves a much better spatial distribution of ToC points.

VI. CONCLUSIONS

This paper has demonstrated through an implemented prototype platform and field trials that the combination of infrastructure, vehicle logic and V2X communication offers a great potential for diminishing negative impacts of automated driving at Transition Areas. As the infrastructure has a better overview of the overall traffic situation and specific local environmental conditions for transitions, it can optimize traffic flow and reduce the number of ToCs/MRMs by providing specific, and sometimes even individual advice (e.g. speed, lane, headway…) to the CAVs. When transitions of control are unavoidable, it can provide optimal positions for ToCs and consecutive MRMs, reducing the risk of CAVs blocking the road. By combining infrastructure advice with V2V cooperation strategies, CAVs are also able to negotiate their behaviors, leading to a smoother interaction e.g. at lane changes.

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