# Infrastructure Supported Automated Driving in Transition Areas – a Prototypic Implementation

Julian Schindler
Institute of Transportation Systems
German Aerospace Center
Braunschweig, Germany
julian.schindler@dlr.de

Robert Markowski
Institute of Transportation Systems
German Aerospace Center
Berlin, Germany
robert.markowski@dlr.de

Daniel Wesemeyer
Institute of Transportation Systems
German Aerospace Center
Berlin, Germany
daniel.wesemeyer@dlr.de

Baldomero Coll-Perales
Department of Communications Engineering, UWICORE laboratory
Universidad Miguel Hernandez
Elche, Spain
bcoll@umh.es

Clarissa Böker
Institute of Transportation Systems
German Aerospace Center
Braunschweig, Germany
clarissa.boeker@dlr.de

Saifullah Khan
Institute of Transportation Systems
German Aerospace Center
Braunschweig, Germany
saifullah.khan@dlr.de

***Abstract*—When an automated vehicle (AV) of level 3 and above arrives at an area on the road which is not part of its operational design domain (ODD), it is forced to perform a transition of control (ToC) to the driver. If the driver is not responding, the ToC fails and a minimum risk maneuver (MRM) needs to be executed. When the penetration rate of such AVs on the roads is high, this will negatively impact traffic efficiency and safety. In EU H2020 TransAID, infrastructure supported traffic management measures have been investigated which reduce these negative impacts. The measures and their effects are tested intensively in simulation. To demonstrate that the measures could also be applied to the real world, feasibility assessments with real-world prototypes have been performed. This paper shows how the measures have been implemented in ITS-G5 communication, infrastructure and connected automated vehicles (CAV), and how the prototypes have been tested.**

***Keywords—cooperative automated driving, transition areas, transition of control, C-ITS, ODD***

## I. Introduction

Automated vehicles (AV) are not able to drive automated in all situations. Each vehicle has or is going to have its own operational design domain (ODD), which exactly specifies which situations can be handled, and which cannot. While vehicles designed for the lower levels 1 and 2 of automation according to SAE J3016 [1] will have (if properly used) a driver immediately responding in case the ODD is left and the system is malfunctioning, vehicles on levels 3 and above require more sophisticated measures to take the driver back into control. Starting latest in level 4, the vehicle automation also must be able to keep the vehicle in a safe state when a transition of control (ToC) is performed and even when the driver is not responding. Although the term "safe state" is discussable, the vehicle automation will most likely stop the vehicle with hazard warning lights switched on, a so called minimum risk maneuver (MRM). Being at the boundary of the ODD, the vehicle probably will avoid complex maneuvers, so the probability to just stop on the lane is high [2].

While research so far was focusing on the behavior of single AVs, the European Horizon 2020 project TransAID ("Transition Areas for Infrastructure-assisted Driving") focuses on the impact of ToCs and especially MRMs, when the penetration rate of AVs on the roads increases. Especially when looking at areas on the road where ODDs of several AVs end (so called "Transition Areas"), this has the potential of getting critical in terms of traffic safety, but also traffic efficiency. The more AVs are driving on the road, the more ToCs and MRMs will occur, leading to a larger impact [3]. TransAID is not only investigating the impact of Transition Areas, it is also elaborating possibilities of infrastructure support to reduce negative consequences. Here, new approaches in collective perception are in focus as well as ITS-G5 communication at vehicles and infrastructure, bundled to new traffic management measures. The effects of the new traffic management measures are on the one hand extensively investigated in simulation to cover large scale effects esp. at different AV penetration rates [3], but also the general feasibility of the approach in real world implementations is tested.

This paper summarizes these real-world implementations, on vehicle and infrastructure side. Therefore, the use cases that are covered by TransAID are introduced first. Based on the use cases, a communication message set has been defined, which is described in section III. Furthermore, infrastructure hard- and software as well as vehicle automation functionality had to be developed. Details are shown in chapter IV and V respectively. Chapter VI shows how the developments have been tested in feasibility assessments, before chapter VII concludes this paper.

## II. Use cases

Although it is likely that the ODDs of AVs will expand in the future, meaning that vehicles will be able to cope with more and more situations, there will always be areas exceeding the ODD, e.g. roadworks, inconsistent lane markings, complex intersections, difficult weather conditions, etc. At the beginning of TransAID, several different limitations were investigated, and it was tried to categorize those. Since high level vehicle automation is currently just entering the market and therefore only available in research prototypes, it is a difficult task to foresee explicitly the ODD limitations and how AVs are going to implement ToCs and MRMs. In addition, it is very likely that vehicle manufacturers are dynamically working on their own AVs' limitations, as vehicles not able to cope with specific known situations will be less attractive for consumers than others. If AVs are not able to cope with quite common road situations, it will be tried to update the behavior until it gets possible, as long as the sensor equipment is able to allow this.

TransAID in general is not dealing with ToCs resulting from individual system or component malfunctioning, as those will happen anywhere on the road like vehicle breakdowns do today. Instead, the project focus is on specific areas on the road where it is likely that AVs' ODDs will reach their limits, and where those limitations are known, e.g. foggy areas at bridges, or roadworks. As TransAID is dealing with infrastructure-assisted measures, it has been decided to categorize the situations by the possible countermeasure of the infrastructure to avoid negative impacts. Therefore, a set of five services has been created, see Fig. 1 [4]. The first three services deal with the prevention of ToCs and MRMs by different measures. These are i) the provision of path information, ii) the provision of speed, headway and lane advice, iii) the separation of traffic to reduce complexity. When a prevention is not possible and ToCs and MRMs occur, infrastructure can reduce negative impacts by iv) managing the ToC/MRM. A different approach is chosen in v) the distribution of ToC/MRM. Here, ToCs are distributed on the road so that not all ToCs (and related MRMs) happen at the very same position, which else is at the spot where the AV discovers that it will not be able to cope with the upcoming situation automatically. This distribution will lead to a lower density of transition-related driving errors, and of MRMs.

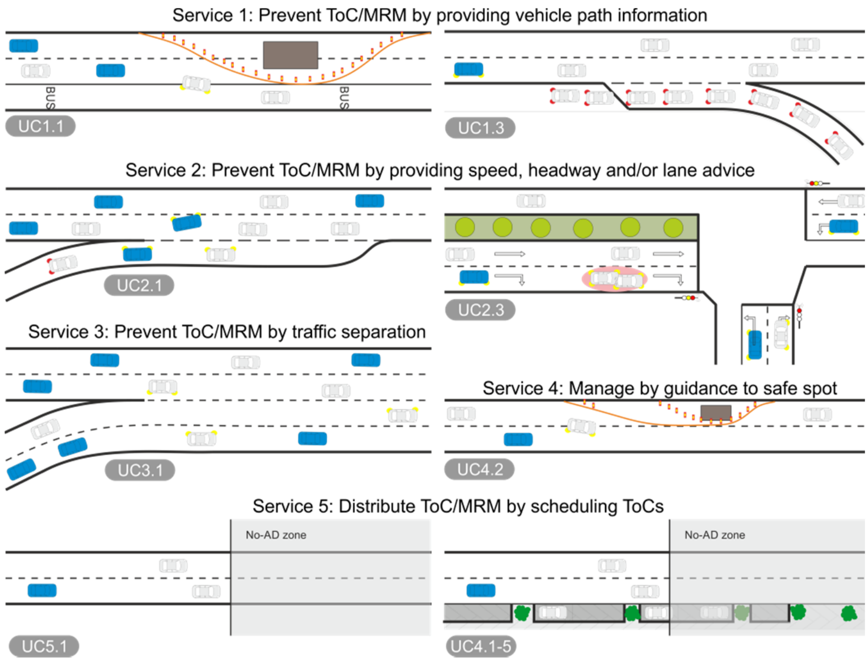

Fig. 1. Investigated TransAID services and scenarios. AVs are shown in blue.

After clustering into services, specific example driving use cases have been created which are able to demonstrate the countermeasure and the corresponding effects on traffic safety and efficiency, see Fig.1. These use cases cover:

- *Use case 1.1:* A closure of the complete road except a bus lane: Here, an AV is not allowed to use the bus lane when following existing traffic rules and will stop in front of the road closure. Infrastructure allows the usage of the bus lane temporarily by sending corresponding V2X messages.
- *Use case 1.3:* A traffic jam on the off-ramp. AVs can only use the off-ramp safely by changing to the emergency lane and queueing up, which is not allowed in several countries. Infrastructure can allow the usage in case of a traffic jam temporarily.
- *Use case 2.1:* Merging assistance on highway on-ramps by infrastructure support. Infrastructure gives early speed advice, fosters V2V cooperation and triggers early ToCs in case no gap is found.
- *Use case 2.3:* An accident on the right-turn lane of an intersection, requiring the AV to turn from the through-lane, which is not allowed when following traffic rules. Infrastructure dynamically supports by providing lane advice.
- *Use case 3.1:* Traffic separation to reduce complexity of a highway merging.
- *Use case 4.2:* Roadworks blocking all lanes except one, where dedicated areas for MRMs are provided (so called "safe spots"). Without the safe spots, AVs not able to pass roadworks will most likely stop on the free lane at the entrance of the roadworks, causing large negative impacts.
- *Use case 5.1:* Distributed ToCs in front of a zone where automated driving (AD) is not possible to avoid negative impacts of several transitions at one spot.
- *Use case 4.1-5:* Combinations of distributed ToCs and existing safe spots in urban areas.

Each use case is tested in several scenarios, i.e. showing different behaviors of the vehicles and successful as well as unsuccessful communication. On top, also baseline scenarios without any measure have been tested to demonstrate and analyze the impact of the measure. Simulations of all scenarios have been performed, and most of them showed a drastic improvement of the traffic efficiency and throughput [3]. Afterwards, all scenarios have been implemented in the real-world in a prototypic way, including communication, infrastructure sensors and action, and behavior of cooperative automated vehicles (CAV). All aspects are described in the following.

## III. Communication

In the implemented prototype, the road-side infrastructure and CAVs exchange standard V2X messages. Some of these messages have been extended to account for the TransAID's advanced support of automated driving [5]. These extensions ensure backwards compatibility and interoperability with the original V2X messages and maintain the logic and coherence of the original contents. The V2X messages exchanged in the implemented prototype include:

- *CAM (Cooperative Awareness Message)* [6]: provides information about position, dynamics and basic attributes of the transmitting station. 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. The CAM originated by a vehicle has been extended 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, e.g. for the infrastructure, to assess the actual traffic demands and compositions.

- *DENM (Decentralized Environmental Notification Message)* [7]: contains information related to a road hazard or abnormal traffic conditions including a description and its location. It alerts other road users about an unexpected event that has potential impact on road safety or traffic conditions.

- *CPM (Collective Perception Message*) [8]: contains data about objects (e.g. objects, vehicles, pedestrians, etc.) detected by the road side or CAVs using their built-in sensors. CPMs allow receivers to improve their perception of the driving environment.

- *MCM (Maneuver Coordination Message)* [9]: enables cooperative maneuvering or cooperative driving. CAVs use it (V2V) to exchange information about their planned and desired trajectories. TransAID has proposed extensions that the infrastructure can use (V2I) to support the CAVs' maneuver coordination with advisories and suggestions. These extensions allow the road side to send individual advisories to the CAVs on how to handle a ToC, create gaps, change lane, set a target speed and address a safe spot.

- *MAPEM (Map Message)* [10]: includes road and lane topology, and the corresponding lane attributes (e.g. bus or emergency lane), which can be changed dynamically in TransAID. The topology also includes the positions of safe spots in use cases 4.2 and 4.1-5.

- and *SPATEM (Signal Phase and Time Message*) [10]: for providing the status of traffic lights at signalized intersections.

The road-side infrastructure and CAVs are equipped with a V2X module that enables the exchange of the V2X messages. The V2X modules implemented at the road side and CAV are described below.

### *A. Road-side infrastructure communication implementation*

The road side unit (RSU) is composed of multiple modules used as sender or receiver for all the V2X messages used in TransAID. In order to transmit the messages, the V2X communication standards are used (e.g. IEEE 802.11p-ITS-G5-V2X). A Cohda Wireless MK5 RSU is mounted as the CCU (Communication Control Unit) which provides the ETSA software used to offer an UDP interface for sending and receiving BTP (Basic Transport Protocol) packets. Data requests and data indications are preceded by the Cohda header. The V2X messages are loaded with different content, as described before, according to the use cases. The process of encoding and decoding of the V2X messages is performed using their ASN.1 (Abstract Syntax Notation 1) representation, which is automatically converted into classes of a customized Java framework, the "V2X framework" created by DLR. This framework includes variable forwarding of V2X message content to other road side components per UDP on reception. At the same time, it is providing the CCU with actual information received from the road side components.

### *B. CAV communication implementation*

At the CAV side, the V2X module is implemented using a Cohda Wireless MK5 OBU (On Board Unit). The CAV's V2X module includes an application layer that has been developed to manage the transmission and reception of all V2X messages.

On the reception chain, the V2X module's application processes the V2X messages through a callback function that is invoked whenever any packet is received at the lower layers. V2X messages are classified at the application layer based on their unique BTP ID. For example, DENM and CAM messages use the standard ETSI BTP port 2001 and 2002, respectively. The content of the V2X messages is UPER (Unsigned Packet Encoded Rules) encoded and they have to be decoded in order to access their content. The decoding of the V2X messages is performed using their ASN.1 representation. The information of the V2X messages is then made available to the rest of the modules at the CAV through specific UDP interfaces. These interfaces are made of data structures which are populated using the content of the V2X messages. This includes, for example, the advisories transmitted by the RSU to the CAV that need to be forwarded to the CAV's automated driving software (AD SW) to plan the future trajectories.

On the transmission chain, the V2X module's application utilizes the data structures of the UDP interfaces received from the AD SW to create the V2X messages. For example, the V2X module receives the planned trajectory from the AD SW. This information is included in the MCM message to be transmitted by the CAV's V2X module. Before the V2X messages are transmitted, they are UPER encoded following their ASN.1 representation, and a BTP header is added for their classification when they are received.

## IV. INFRASTRUCTURE

The infrastructure part of the tests consists of three components (Fig. 2): i) a mobile traffic light that provides SPATEM and MAPEM information, ii) a mobile RSU that runs all infrastructure services that are not using a traffic light (CPM, MCM, DENM, MAPEM), e.g. for informing the automated vehicles about obstacles or lane driving statuses, and iii) a variable message sign.

The mobile traffic light is connected to a Beckhoff industrial PC which runs a SUMO simulation of the test track (see Fig. 3). Based on the current and the forecasted state of the simulated traffic light, a SPATEM message is generated and sent to the mobile traffic light. The signals of the traffic light are switched according to the contained information. Also, a port on the Beckhoff PC listens for incoming CAM messages of connected vehicles (CV) and CAVs. Based on the position information, a vehicle is inserted into the simulation and moved inside the scenario through the position updates every second. Thus, the CAM information could be further used for debugging purposes, i.e. validating the vehicle's position, or for incorporating dynamic traffic light control as done in the project MAVEN [11]. In TransAID, the mobile traffic light operates with a fixed time control.

The mobile RSU consists of a mobile retractable pole with a pan tilt zoom (PTZ) camera of type ACTi B94 mounted at the top and the described Cohda hardware. The ACTi B94 is a 1.3 megapixel mono camera that is powered by PoE (Power over Ethernet), suitable for outdoor usage

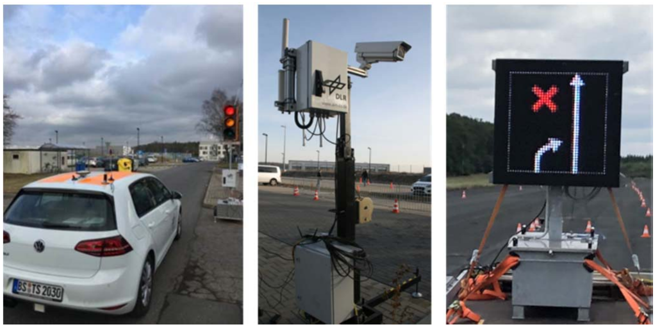

Fig. 2. DLR's FASCarE in front of the mobile traffic light (left), the mobile RSU (middle) and the used VMS (right).

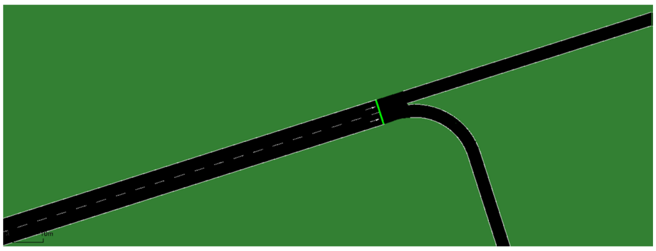

Fig. 3. SUMO map of the use case 2.3 intersection.

and can record videos at 30 fps with a resolution up to 1280x960 pixels. The recorded images are further processed through object detection performed by a neural network, specifically a tensorflow implementation of a Faster-R-CNN trained on a manually labelled dataset acquired at the DLR reference track [11]. To allow for fast inference time, the data is processed on an ECX 1200 computer with an integrated NVIDIA GeForce GTX 1050 Ti graphics card. In a second processing step, detected objects are tracked over time with an adapted version of the Kalman filter based approach presented in [12]. These tracks in image coordinates are then transformed into the UTM coordinate system based on the calibrated inner and outer orientation of the camera. The tracks in the CPM format are subsequently used for road side traffic management algorithms and are also sent to the Cohda RSU as described before.

In addition, the mobile RSU provides all further infrastructure message types that need to be sent in the TransAID use cases, i.e. MCM and DENM. The software installed on the RSU has been programmed in Java and uses the introduced "V2X framework" for sending and receiving. By using the classes of the framework, a script for each TransAID scenario was written, defining:

- The types of messages to send,
- the content of the messages,
- initial delays before sending messages and
- the time gap between sending the messages.

The use cases can be easily adapted before running them by using the corresponding .conf files. An example of such a .conf file defining the content of an MCM with a lane change maneuver advisory by the infrastructure is depicted in Table I. The first entry `scenario.id` defines the name of the scenario, which is just an internal identifier. `station.id` refers to the sending station (i.e. the RSU), `target.station.id` to the receiving station (the vehicle that should perform the lane change). The next entries are defining the lane change, namely the target lane (`target.lane.id`) and the starting position of the lane change maneuver (`target.lane.startpos`). The entries `leading.id` and `chase.id` are at the moment placeholders, in case a leading and a chasing vehicle should be used in the future.

Based on the information defined in the .conf file, the corresponding message fields are filled and then the message is sent to the target station. The message is sent as soon as a certain trigger condition is met and will be sent as long as the scenario runs or until an updated message needs to be sent. In order to perform more complex maneuvers, e.g. sending speed advice to on-ramp vehicles to allow merging, receiving messages is essential. Therefore, the V2X framework provides methods to receive common message types.

In case of a speed advice, CAMs of C(A)Vs are received in order to first calculate the point of collision where the vehicles would meet and then calculating speed advice in order to allow the on-ramp vehicles to merge in appropriate gaps. Also the CPMs generated by the ACTi camera as well as received CPMs (e.g. from CAVs) can be used for the generation of speed advisories in order to include not only C(A)Vs' positions, but positions of all vehicles.

In addition, CPM data is used in use cases 4.2 and 4.1-5. Here, the camera is monitoring the road, but also the safe spots. In this way, the camera can support cooperative lane changes in the vicinity of bottlenecks or transition areas by providing CPMs including the detected objects plus MCMs with lane change advisories. In addition, the camera also detects if a safe spot on the road is currently occupied or not. Besides continuously sending the positions of all available safe spots in the MAPEM, the infrastructure can provide different ToC advisories depending on the availability of safe spots, matching the ToC endpoint on the road with an available safe spot (see Fig. 4). In case the CAV indicates in its CAM that it is performing a ToC or MRM, the infrastructure immediately provides a lane advice to the corresponding safe spot.

The third component of the infrastructure is a Niechoj electronics LUMEX full matrix variable message sign (VMS) compliant with EN 12966. It is a full color display with a resolution of 39x40 pixels. This device is used to

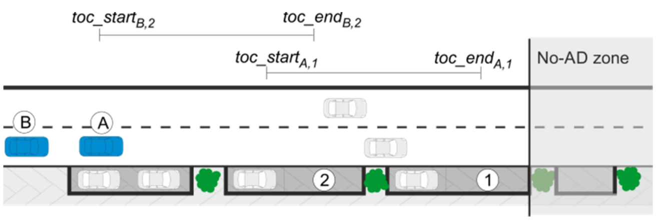


Fig. 4. Use case 4.1-5 with ToC distribution (schematic). CAV A is getting a late ToC advice as it should use safe spot 1. CAV B is getting the advice earlier, since it needs to target safe spot 2.

TABLE I. EXAMPLE .CONF FILE

| | | |
|---|---|---|
| scenario.id | = | 213 |
| station.id | = | 254 |
| target.station.id | = | 1002 |
| target.lane.id | = | 3 |
| target.lane.startpos | = | 250 |
| leading.id | = | 0 |
| chase.id | = | 0 |

provide information about upcoming situations also to vehicles not able to receive V2X messages.

## V. VEHICLES

At DLR-ITS, two research vehicles able to drive automated are used: the FASCarE, a fully electric Volkswagen eGolf, and the ViewCar2, a Volkswagen Passat GTE. Both vehicles are equipped with differential GPS receivers, a localization platform, several sensors such as lidar, camera and radar, and Cohda Wireless OBUs as described. The software of the vehicle automation in both CAVs consists of several components [13].

Static environmental information is published by the so called map provider. Given a high definition map, it transforms its data into the internal environment representation of the vehicle automation and provides other modules with the static data of the surroundings of the automated vehicle. The internal environment representation follows a lane based approach, i.e. coordinates combined to right and left borders of a lane on which the automated vehicle can drive. The navigation module evaluates the map and publishes the cost of each lane to reach a given navigation target. That cost is used for trajectory evaluation in the trajectory planning module. For trajectory planning itself, a model predictive control approach is used [14]. The results are multiple trajectories that fulfill different purposes, e.g. breaking to a stop, lane change to the left lane, keeping the current lane or lane change to the right lane.

Furthermore, costs functions for each trajectory are evaluated, forwarding only the trajectory with the lowest cost to be executed by the vehicle. The cost for a given trajectory includes several components such as a deceleration cost, i.e. the vehicle prefers trajectories with lower deceleration, the aforementioned navigation cost, a basic lane change cost and costs introduced through V2X communication. Generally, V2X communication in TransAID can impact the automation in the following ways: MAPEM and DENM can lead to changes in the environment representation and MCM can both impact the planning constraints of the planner directly and the cost functions for the different maneuvers.

A MAPEM message can have different lane types than the original high definition map available to the automation. In that case, the coordinates within the lane definitions of the MAPEM are matched to the lanes in the environment representation and the lane types in the environment representation of the automation are adjusted accordingly. This method can be used to open a former emergency lane or bus lane for driving for the automated vehicle. The DENM including event location is also mapped to lanes within the environment representation, allowing the positioning of dangerous events when planning the vehicle movement.

However, in contrast to the usage of the MAPEM, the roadworks container of the DENM is used to close certain lanes, i.e. they are not drivable anymore for the automation (see Fig. 5). Any change in the environment also triggers a re-planning of the navigation, so the optimal route to the target is always available.

SPATEMs are interpreted in combination with MAPEMs, as MAPEMs indicate the position of stop lines mapped to the internal environment representation, while the state of the stop lines is received by the SPATEM, together with a speed advice. Both messages are interpreted by the trajectory planner.

CPMs and CAMs are interpreted in the sensor data fusion of the CAV to extend the field of view and the range of the on-board sensors. This information is for example used when the vehicle enters the highway in use case 2.1.

Exchange of MCM via direct V2V communication between vehicles enables cooperative maneuvers like opening gaps for another vehicle by braking or by changing the lane. Therefore, vehicles always send their planned trajectory, but in case of e.g. lane closings or desired lane changes also a desired trajectory. This trajectory is received by the other vehicles. If a CAV's planned trajectory is conflicting with a desired trajectory of another vehicle, it is calculating the costs for changing the own trajectory so that it does not overlap anymore. This can result in a lane change or speed adaptation depending on the current situation, and therefore is key to cooperative behavior of CAVs.

Besides the V2V communication, MCMs are also received from the infrastructure. For example, an MCM can contain a speed advice. When received, the planner tries to respect this speed whenever possible, or slower in case of other constraints like vehicles driving ahead.

A lane advice through the MCM is represented by additional costs for all other lanes according to their distance to the advised lane. The distance between two lanes hereby is defined by the number of lane changes necessary to reach that lane. The amount of the additional costs is fine-tuned depending on how much the vehicle should follow infrastructure advice.

A ToC advice by the infrastructure serves as input to the vehicle automation. It is used in the planner's ODD guard. Here, distances or times for ToCs are received, as well as a reason. Depending on the preferred infrastructure measure, the best parameters can be chosen by the infrastructure. On the receiver side, the restriction is also only treated as advice, although in TransAID's prototype feasibility tests the advice is always followed. During the first phase of the infrastructure-initiated ToC, the automation stays in control of the vehicle and keeps driving while waiting for the driver to take over. Only if the driver does not respond in time or distance, the automation will bring the vehicle to a stop by executing an MRM, i.e. braking to a standstill in the current lane. The safe spot advice of use cases 4.2 and 4.1-5 extends that concept by also leading the automated vehicle to a space where it can safely stop when executing an MRM without disturbing the traffic around it. In case of a safe spot advice, the generally available safe spot positions are indicated in received MAPEMs. The guidance to a specific free safe spot, detected by the infrastructure camera, is accomplished by reception of a dedicated safe spot area for this CAV

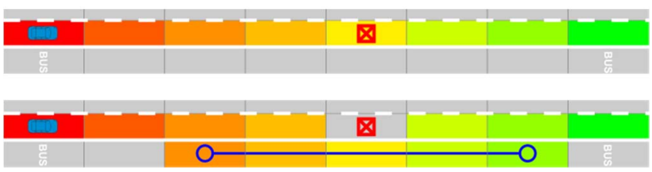


Fig. 5. Lane type change in use case 1.1. Above: the right lane is the not usable bus lane. The red dot represents the DENM event position of the road works. Below: the bus lane gets the attribute "drivable" after MAPEM reception for a few sections.

combined with the ToC advice in MCMs.

The vehicle automation is accompanied by a prototypic HMI showing the current state of the automation and information received by V2X for debugging.

## VI. Feasibility Assessments

In TransAID, the complete system of infrastructure, vehicles and communication is tested in several feasibility assessments. The feasibility assessments have the goal to demonstrate that the TransAID approach can be implemented in real prototypes, allowing the measures to be further investigated for a potential standardization and market introduction. To test the full stack of use cases in a flexible way, all tests have been performed on a local testbed (see Fig. 6). Here, a digital map of the use case was virtually placed on the road, allowing the vehicles to perform their driving tasks. To produce realistic scenarios, the CAVs have been accompanied by manually driven vehicles on the road.

During the first DLR feasibility assessment performed in summer 2019, five use cases have been investigated with reduced infrastructure and vehicle automation capabilities in a set of 15 scenarios. Here, it has been shown that the communication is well suitable for performing the required functionality (see Fig. 7). Only a few issues were found, mostly related to V2V-MCM communication in cooperative lane changes and some properties of the defined messages which resulted in partly unstable or oscillating behavior of the vehicles, e.g. when lane changes are performed (see [15] for details). As result of the first iteration trials, parts of the messages, the vehicle reaction and infrastructure behavior have been improved, and the full set of required functionality has been developed, so that all use cases are now tested in another set of 26 scenarios in a second DLR feasibility assessment. Due to the Covid-19 outbreak, not all scenarios could be tested on the test track until now (June 2020), so that some of them could only be tested with the real cars, infrastructure and communication in realistic Hardware-in-the-Loop tests where only the sensor parts of infrastructure and vehicles have been simulated. Nevertheless, it could already be shown that all developed messages are working as intended, and that the vehicle automation is responding correctly to all advisories. This includes all I2V advisories as well as V2V-MCM vehicle cooperation tested e.g. in highway merging use case 2.3.

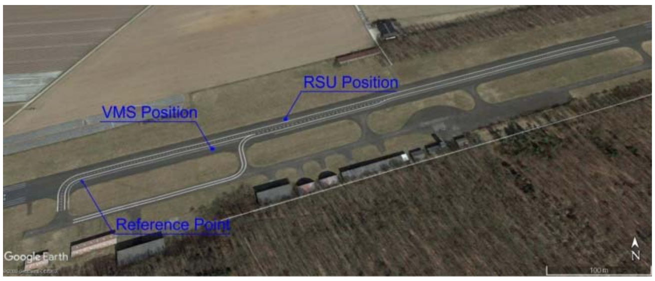


Fig. 6. The virtual road layout of use case 2.3 on the testbed in Peine-Eddesse, Germany.

Fig. 7. Cooperative lane change of the FASCarE (middle) driving on the virtual highway in use case 2.3., when the ViewCar2 tries to merge. Infrastructure gives an early speed advice to the on-ramp vehicle. Then, both vehicles coordinate the lane changes by using the V2V-MCM-cooperation.

## VII. Conclusions

This paper has shown how traffic management measures dealing with transition areas have been implemented in real-world hard- and software. The developed message sets are suitable for the provision of advisories to CAVs, enabling infrastructure to reduce negative impacts on traffic efficiency and safety. Therefore, if the TransAID technology is standardized and brought to series production, this will benefit the smooth introduction of high-level automation functions.

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