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Managed Automated Driving (MAD) – a Concept for Empowering Road Infrastructure

Julian Schindler[1*], Philipp Klein[2], Tobias Fleck[3], Albert Lee[4]

1. German Aerospace Center (DLR), Institute of Transportation Systems, Germany, julian.schindler@dlr.de

2. German Aerospace Center (DLR), Institute of Vehicle Concepts, Germany, philipp.klein@dlr.de

3. Forschungszentrum Informatik (FZI), Germany, tobias.fleck@fzi.de

4. Forschungszentrum Informatik (FZI), Germany, lee@fzi.de

Abstract

Current automated vehicles, even when appended with C-ITS support, require a vast number of sensors of various types per vehicle to empower them to cope with the variety of possible situations. However, most of these sensors are not required on large parts of the route while in addition, the horizon of vehicle-based sensors is very limited. On the other hand, roadside infrastructure can be placed fully matching specific local requirements and therefore ensuring optimal sensor performance, while communication can provide basically unlimited sensor ranges. Replacing vehicle-based sensors by infrastructure-mounted ones can therefore be a solution. Using this approach on dedicated routes (e.g. for public or freight transport) with fleet vehicles can be a starting point to make automated driving safer and economically beneficial. The German national project "MAD Urban" is investigating means of additional roadside support, including localization, object detection, and even vehicle control by infrastructure.

Keywords:

Infrastructure-based automated driving; Collective Perception

Introduction

In the past, the development of automated driving functionalities was very vehicle centered. The biggest research questions where about how automated driving systems could manage to take over the driving task from humans. While the situations the vehicles should be able to pass became more and more complex, the idea was that vehicles need to be able to understand the environment and make decisions on their own, as a sole entity – similar to human drivers. The rising complexity was visible e.g. at the DARPA Grand Challenge [1] and later the DARPA Urban Challenge [2], which both initiated the idea that automated driving will be the next big step. The introduction of the SAE J3016 [3] automation levels provided a very robust way for defining a spectrum of vehicle system capabilities and responsibilities, offering e.g. vehicle manufacturers to build systems which still require human supervision (up to level 2), or systems with redundant components offering autarkic behavior in defined areas (level 4). Esp. the complex system design with redundant sensor, partaker and network components required for higher automation levels revealed that vehicle automation systems require a large set of sensors, of various types to allow driving in any condition which can possibly occur, even when the Operational Design Domain (ODD) [4] of the system is limited to a narrow set. E.g. a system which is only able to drive automated on level 4 under perfect road and weather conditions still has the requirement to cope with a vast number of situations, including e.g. traffic jams, vehicles approaching from behind with very high relative speeds, wrong-way drivers and approaching emergency vehicles. In addition, vehicle-based sensors have the downside that their range is limited and that the error-rate of the sensors is rising with the distance to the detected object.

It has been found that wireless communication and C-ITS can drastically improve the automated vehicles' capabilities, e.g. when surrounding vehicles share their position, orientation and speed in Cooperative Awareness Messages (CAM), or when emergency vehicles provide warnings using DENM. But since only very few vehicles provide such data, ITS-G5 based systems can only be seen as additional benefit, and not as full sensor able to replace any vehicle sensor in a functionally safe way, i.e. an automated vehicle can use such information for e.g. additional safety and comfort, but it still needs to have corresponding sensors for vehicle-based detection on-board.

The same is true for infrastructure-mounted sensors providing additional object detection performance, e.g. at complex intersections or junctions with a limited field of view. Infrastructure sensors have the benefit that they can be chosen perfectly matching the local situations, plus that they have a better and wider field-of-view when placed at a higher location compared to the low-hanging vehicle-based sensors. Having such infrastructure support, e.g. in terms of Collective Perception Services (CPS) [5], is highly beneficial, not only in terms of safety, but also in terms of traffic efficiency, as shown in several research projects such as EU-H2020-MAVEN [6], EU-H2020-TransAID [7, 8] or the German national project KoMo:Dnext [9]. But the downside again is that all the possibly available services can only fully support vehicle automation functions and even replace vehicle-based sensors, when they are placed everywhere, on each stretch of road which is about to be used by automated vehicles. Such fully equipped road networks are not yet aspired in Europe today. Vehicle manufacturers as key stakeholders in this automation sector do not have effective business models available for this roadside infrastructure and it often does not fit to car manufacturers' goals. They still try to keep the asset of selling vehicle-based systems (although with additional backend functionality) and not to enter the risky market of road-based equipment. For a large scale roll out of automated vehicles, it will be very difficult to reach a high portion of the C-ITS benefits.

Therefore, a different strategy has to be chosen. The concept "Managed Automated Driving" (MAD) offers a different way of how C-ITS systems can enter the market by replacing vehicle-based with infrastructure-based sensors. The concept allows stepwise introduction of C-ITS systems benefitting safety and traffic efficiency from the very beginning, while at the same time reducing the sensor requirements and therefore the costs for each vehicle. Furthermore, MAD has the potential to include new functionalities in the infrastructure which are not part of current C-ITS developments, like full external vehicle control.

This paper summarizes the concept and introduces the steps that will be taken in the German national project "MAD Urban", which has recently started.

The Concept of Managed Automated Driving

The concept of Managed Automated Driving (MAD) has been developed during two small and short German national projects, called "U-Shift MAD" [10] and "U-Shift 33" [11]. During "U-Shift MAD", the general idea was to investigate the possibility of having highly sophisticated infrastructure components, including sensors for full monitoring of road segments, sensor processing, object detection, object classification, trajectory generation and communication capabilities for the individual automated vehicles monitored by the sensors. If the infrastructure has that high capabilities, the required sensor and computational power of the vehicles themselves can be remarkably low. During the project, business models have been developed and investigated for different use cases, starting from freight vehicles driving on a dedicated short stretch of road, e.g. between two companies or hubs, via longer stretches of roads, e.g. used for public transport lines, up to full urban districts covered with that technology. The study [12] showed promising results in several segments. On the one hand, it was found that such infrastructure-based technology can drastically improve safety, since sensors can be placed higher compared to vehicles and therefore have benefits in their field of view. On the other hand, the concept can be financially advantageous, as infrastructure-based sensor and processing units (in the project so called "Road Capturing Units" (RCU)) can be built using existing technology. By having numerous of those RCUs on the road, e.g. mounted on every lamp post, the costs will be significantly lower per unit, esp. as those units do not require rugged designs and are mounted at a fixed position. In the same time, equipping an area with RCUs will make vehicle sensors less required or even obsolete. Starting with the simplest use case between two companies or hubs, such sensor-less vehicles (so called "Managed Automated Vehicles" (MAV)) may be used to perform the required driving tasks. This in general allows a stepwise introduction of such technology from small dedicated road stretches to transport lines and finally to full urban districts over time. In addition, the RCUs may provide additional information to other automated vehicles using "standard" C-ITS messages such as CPM, also providing benefits in terms of safety for those vehicles in the area.

Driven by the promising results, the successor project U-Shift 33 dealt with the technical feasibility of the above sketched concept. Here, the concept was detailed. It was found that several RCUs may even be linked to put further processing capabilities in so called "Edge Processing Units" (EPU). Those EPUs could also be linked to backend services, which allows the flexible processing of e.g. sensor data either close to the detector or using sophisticated AI hardware further away. Or in offers scalability for trajectory generation, either directly on-side in the RCU for individual vehicles, in the roadside edge for full road stretches or fully harmonized for hundreds of vehicles in backends. Furthermore, the concept was adapted to cope with recent developments of automated driving, e.g. the necessity of having a technical assistance monitoring the behaviour of automated driving functions and the capability of providing remote assistance when automated driving reaches its limitations, as required by the German *Autonome-Fahrzeuge-Genehmigungs-und-Betriebs-Verordnung* (AFGBV) [13]. As consequence, the concept was enriched by corresponding "Remote Operation Centers" (ROC), which offer remote assistance, remote driving capabilities and backend logging mechanisms for infrastructure-based sensors and vehicle commands. Finally, since MAVs are initially intended to be fleet vehicles, the question of how such vehicles are handled in depots or workshops has been discussed in the project. The following Figure 1 gives an overview on the architecture.

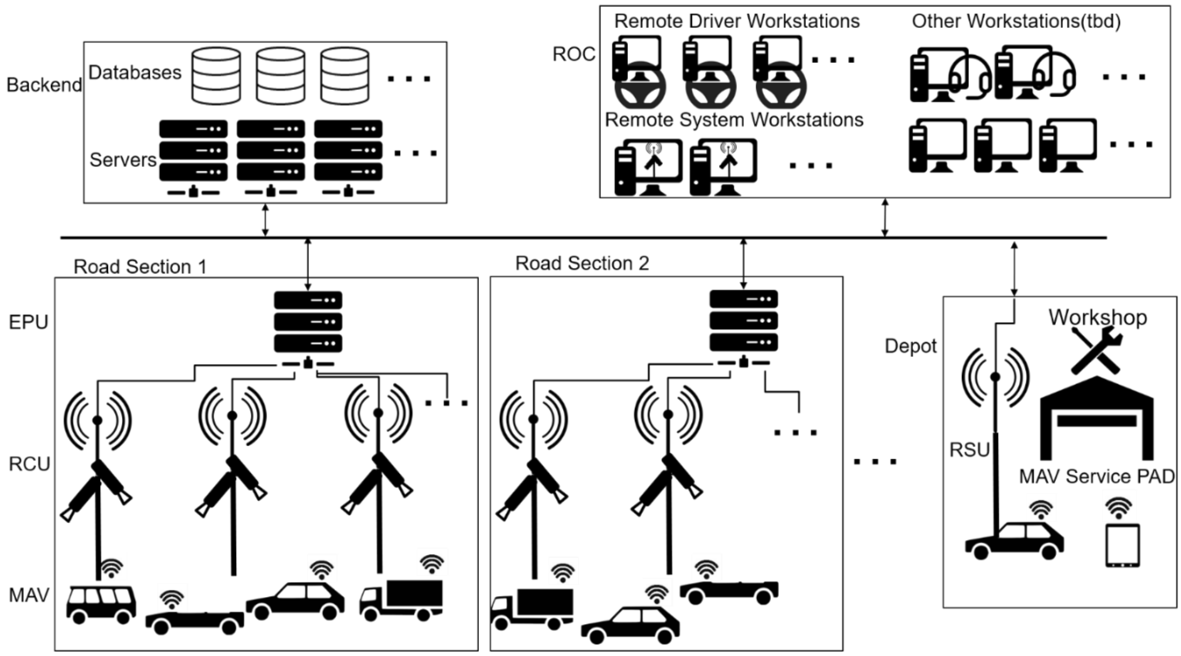

Figure 1: MAD Architecture overview created in the U-Shift 33 project.

As project outcome, the technical feasibility on a small scale could be shown. The general architecture has been set-up, including the backend, EPU and RCU system as well as the local communication using mesh-Wi-Fi, but without any vehicle automation functionality due to the short runtime of the project of only 6 months. Instead, the processing of infrastructure-based sensor data, the logging of data, the manual control in depots using an external control device and the capabilities of remote driving using the system could be shown. It also reveals several requirements in terms of bandwidths, latency and quality of service between the different entities.

The recently started 3-year-project "MAD Urban" is now going to continue the developments. The project is testing the MAD concept on public roads using fully equipped test vehicles and multiple types of infrastructure sensors in different places. The major goal of MAD Urban therefore is to test which functions can be placed in the infrastructure safely. It is going to reveal the real capabilities of remote sensing as well as the limits of infrastructure-based trajectory planning or even control of automated vehicles.

Cooperation Levels

When talking about empowering infrastructure to take over functions that were fulfilled by vehicle automation functions inside the vehicles, it is first of all important to clarify the different roles and the related responsibilities of the different entities. In the past, this problem was investigated mostly in terms of role distribution of the driver and the automated vehicle, which resulted in a spectrum of vehicle control and finally leading to the different levels of vehicle automation as specified e.g. in SAE J3016 [3]. There are many roles in relation to highly automated driving, esp. driver, vehicle automation function, remote operator (remote driver or remote assistant), technical assistance and infrastructure.

Therefore, a more general scheme of the different ways of cooperation between the entities, their role definition and responsibility distribution needs to be defined. An approach is provided in [14], where seven so called Cooperation Levels (CL) are described, shown in Figure 2.

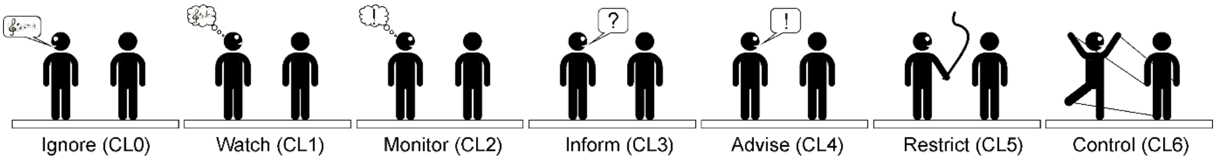

Figure 2. Role definition according to [14]

Here, each entity can have a specific relation to each other entity, from full ignorance to full control. While current C-ITS deployments like CAM or DENM provisions are not going beyond a pure information (CL3) from the entity infrastructure or vehicle to the entity vehicle, some research projects also strive higher levels, e.g. by providing lane or speed advise, corresponding to CL4. In MAD Urban, also the full control of vehicles by the infrastructure is planned, which implies CL6. As the vehicle/MAV is passing different RCUs while driving, the entity which is controlling the vehicle is changing over time. Figure 3 is giving an example where a vehicle first passes four RCUs (A-D). When an RCU comes into range, it is first of all just providing additional information to the vehicle (CL3). When the vehicle is close enough, the RCU switches to CL6 until the vehicle has passed. In the figure, there is an area where neither RCU D nor RCU E can take over full control, possibly as the situation cannot be fully interpreted. Therefore, both RCUs can only restrict the movement of the vehicle by using the available information (CL5), i.e. the known obstacles can be defined as no-go-areas for the vehicle. Since the vehicle cannot be without any entity in control (CL6), it is required that a remote operator is taking over in this segment.

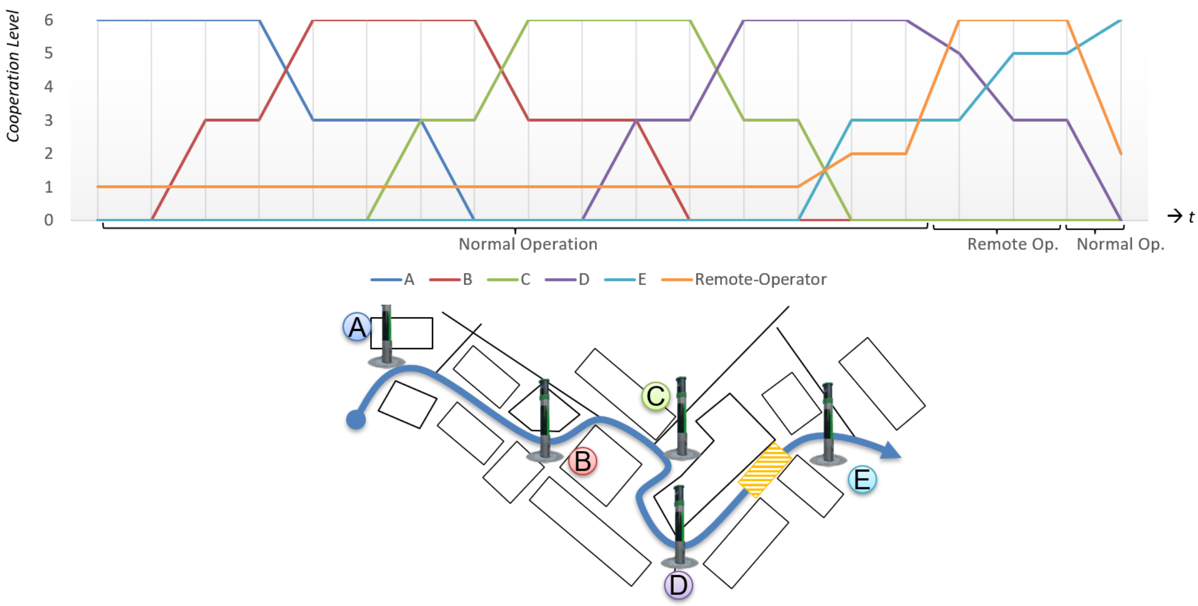

Figure 3: Cooperation Levels for Managed Automated Driving. While an MAV is passing several poles, the control is shifting between different entities. In case of an issue on the road a remote-operator needs to take over. Adapted from [14]

Planned Implementations

In the project MAD Urban, implementations of several sub components are planned. In general, MAD is researched in the project by using vehicles which also have a full sensor or even vehicle automation stack on board to allow gradual testing of all sub components and comparison to vehicle-only solutions. This section gives a broad overview on the planned implementations.

Backend services

The backbone of the overall system which is going to be set up in the project are several backend services. They play a major role for the system, although the major data processing of sensor data and the vehicle control itself is done at the edges/EPUs, due to scalability, latency and bandwidth requirements. Nevertheless, the backend services are required for logging, e.g. in case a remote operator needs to take over. In this case, video, object and command data is logged in the central system for e.g. forensic accounting. The backend service is establishing and monitoring the different communication channels between remote operators, EPUs, RCUs and MAVs, as the communication itself is not done via the backend due to latency requirements and scalability reasons. Further tasks are the provision of additional services for the remote operators, such as the provision of road and weather conditions, as well as services for dispatching of fleet vehicles, fleet vehicle coordination and user management (e.g. of remote operators).

Sensors

While real-time detection, classification and communication are basic requirements for roadside infrastructure assisted driving, current suggested solutions on the market do not meet the expected precision, real-time performance and cost-effectiveness for infrastructure-based highly automated driving use cases. Furthermore, partial or complete occlusion of traffic objects from roadside field of view, especially in a complex urban area, is often not considered enough to ensure continuous safety and security.

In the project "MAD Urban" various perception strategies based on stereo-cameras as well as the combination of LiDAR and visual camera are to be implemented and evaluated with the focus on their suitability and limitations. On the one hand, the rapid development of AI methods last years in the field of LiDAR and camera perception has immensely improved the performance of detection and classification algorithms on the sensor levels, but on the other hand, these often require extremely high computing hardware specifications and do not fulfill the real-time requirement of low latency to be deployed on roadside infrastructure. "MAD Urban" researches how innovative AI methods fit to the roadside LiDAR-camera to enhance the stereoscopic data and how classic approaches of stereo camera environment perception systems could enable steady and generalized detection and tracking of traffic objects without relying on pretrained networks.

As the infrastructure-detected objects also include the vehicles in sight, the object data can also be used for localization of automated vehicles. Finally, it is planned to fuse sensor data from roadside infrastructure and the existing vehicle sensor data in terms of collaborative and collective perception.

Automation function

As described, one of the final goals of MAD Urban is also to test which parts of vehicle automation functions can be placed in the infrastructure. While the sensing part is the first step, also planning and acting components can be placed in the infrastructure, including cooperative trajectory planning and possibly even direct control of the MAVs. Therefore, it is first of all very important that the vehicles which are going to be controlled are localized precisely by using the above mentioned infrastructure-based sensor approach. As a next step, similarly to vehicle-based automation functions, an interpretation and forecast of the movements of the road users is calculated, taking into account that the behaviour of MAVs can be fully controlled, while the behaviour of "standard" automated vehicles may be at least influenced, if corresponding protocols (which are to be developed) are followed. Depending on the provided information, the progression of automated vehicles can be taken into account when calculating the forecast, esp. if such vehicles are sending information about currently executed maneuvers, such as planned trajectories being distributed using e.g. Maneuver Coordination Messages (MCM) [15]. In contrast, the progression of manually driven or "unconnected" vehicles can only be guessed. Using the current obstacle positions and the forecast of the obstacle movements, trajectories can be calculated for each of the controllable vehicles. Depending on the number of cooperative entities in the area, the trajectory calculation can also be done cooperatively, by e.g. taking into account additional information like e.g. current fuel levels of the vehicles or vehicle priorities, which are available in the backend. Depending on the finally achieved latency of the complete cycle of object detection, localization, situation interpretation, object movement forecast, trajectory planning, provision of the trajectories to the vehicles and vehicle-based execution, it may even be possible to go closer to the actual vehicle controls in the infrastructure. It will be one of the optional project goals to check if also direct vehicle control by sending just acceleration and steering commands to the vehicles is a feasible option.

Depending on the level of infrastructure-based control, being trajectories or direct control commands, also the vehicle side of the automation function is part of the research. Major research questions here will cope with discrepancies between vehicle-based and infrastructure-based trajectories/commands. These can be calculated as it is planned to use the Open Source vehicle automation software stack ADORe [16] in the vehicle as well as in the infrastructure. Also, the merging of self-planned and received trajectories/commands will be investigated in the vehicle software stack. The final goal is to dynamically switch between vehicle-based and infrastructure-based trajectory planning and control while driving.

Remote Assistance and Operation

As said, automated driving on level 4 requires the support of a remote assistance in case an issue has been detected on the road or with the vehicle itself. In Managed Automated Driving, also infrastructure and edge components play a significant role. On the one hand, not only vehicle functions need to be monitored, but also the infrastructure-based functions. It is required to check the performance of the overall system all the time. On the other hand, the additional sensors of the infrastructure can drastically improve the capabilities of a remote assistant, as camera streams not only from vehicles but also from infrastructure-based cameras can be accessed, which extends the field of view. In the project, it is planned to also set up all required components for remote assistance. It will also be matter of research if remote driving of MAVs is possible, and what is needed to achieve this goal.

Communication

Since a lot of communication will be done locally between the RCUs/EPUs and MAVs, the use of local area networks with low latencies are beneficial. It will be part of the project to investigate if ITS-G5 technology will be sufficient for this purpose, which would be most favourable as protocols such as MCM may be used for large parts. If this is not sufficient, also standard mesh Wi-Fi systems will be rolled out additionally to explore if those systems can be used for MAD services.

Since esp. in case of remote assistance both bandwidth and latency play an important role, as not only object and command but also video data has to be provided, and as remote operation centers are normally not located close to the place of driving, also 4G and 5G communication will be part of the tests, complementing optical fibre connections between different EPUs, RCUs, the backend and the remote operation centers.

Safety

As large parts of the automation functionality are processed within the infrastructure, being on the level of sensors or on the level of planning and control, another research aspect is the distribution of the safety layer between the infrastructure and the test vehicles. The safety layer within the infrastructure is going to monitor the performance of the used object detection and fusion as well as the trajectory planning algorithms and will provide an appropriate response for the MAVs in case of a dangerous situation. By using additional sensor information from a 3D LiDAR or other depth data, the vehicle-based safety layer will then cross-check the infrastructure safety layer results locally and trigger an intervention if required. The safety investigations are contributing to the operational safety domain of MAD for deployment of the system on the road.

Planned Integrations and Demonstrations

During the project MAD Urban, selected hardware and software components and systems will be integrated, tested and evaluated in two German test areas for autonomous driving, the Testbed Lower Saxony (TFNDS) and the Test Area Autonomous Driving Baden-Württemberg (TAF-BW).

Testbed Lower Saxony, Germany

The Testbed Lower Saxony (TFNDS) is including 280 km of highway, rural and urban roads, equipped with different road side technologies, including ITS-G5 communication or full stereoscopic camera coverage for object detection and tracking of road users in some parts. For MAD Urban, an urban area in the northern part of the city of Braunschweig, Germany, is used: the Tostmannplatz intersection, being part of the public road network. This intersection is already equipped with several sensors and communication hardware and also has the capability to dynamically adapt traffic light phases, all shown in former research projects [17, 18]. During MAD Urban, the intersection is going to be equipped with at least two additional RCUs developed in the project, as well as an EPU at the intersection which is linked to the backend using fibre optic connections. Also part of the tests at the TFNDS are DLR's research vehicles which are fully equipped automated vehicles using the ADORe automated driving software stack. Furthermore, a remote operation center is located at the premises of DLR in Braunschweig, approx. 2.5 km away of the Tostmannplatz, which will be used for remote assistance of the test vehicles.

Although the final positions and field-of-views of the RCUs is not finally set, probable test scenarios are already under development, as shown in Figure 4. It is planned that a fully automated test vehicle (v1) is approaching the Tostmannplatz while using the vehicle-based automation software. When approaching the intersection, additional information (e.g. object data) is received and the connection to the local Wi-Fi is established. When coming into the field-of-view of the stereoscopic cameras and when the vehicle is tracked correctly, the control of the vehicle is handed over to the local infrastructure, here to RCU A in point 1. On the intersection, the control is shifted from one RCU to another, here more than once (2-4) due to the field-of-views and the strength of the communication signal of the specific RCUs. When leaving the appropriate area, control is handed back to the vehicle-based automation software (at point 5). The full dynamic process of handing over control is therefore under test.

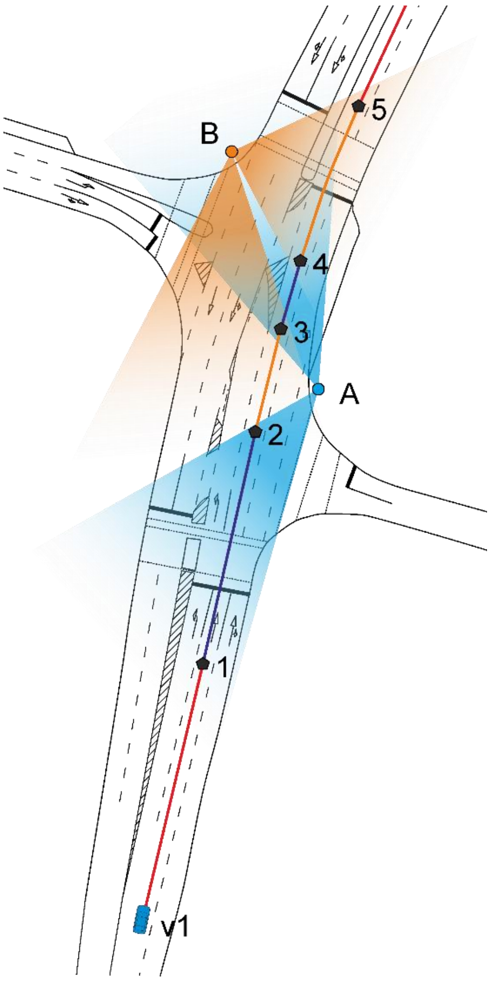

Figure 4: A possible scenario on the Tostmannplatz, with preliminary positions of two RCUs (A, B), their sensor field of views, and the positions of shifts of control between the entities at points (1-5)

Test Area Autonomous Driving Baden-Wuerttemberg, Germany

The Test Area Autonomous Driving Baden-Wuerttemberg (TAF-BW) is designed to support the deployment, testing and evaluation of new mobility concepts under real world conditions with a focus of testing on open roads. For this purpose, the test area provides stationary roadside infrastructure [19] with roadside communication units and a suitable roadside perception infrastructure as well as mobile sensor platforms [20] that can be used to test collaborative algorithms under real world conditions and to collect validation data from the tests.

Within the MAD Urban project, the test area will be used to test different aspects of the managed automated driving concept, including vehicle connectivity and communication protocols (vehicle-to-infrastructure communication, V2I), collaborative environment perception algorithms between roadside infrastructure and concepts for dynamic safety modules that allow to dynamically assess the safety properties of the system at operation time. For this purpose, selected systems will be deployed to research vehicle platforms for connected automated driving and will be tested within the test area.

Cross-validation

In order to ensure the generalizability of the developed components, methods and especially V2I communication protocols, cross-validation will be performed between the two test areas. This includes that selected components will be evaluated with research vehicles in both test areas. Cross-validation in the Test Area Autonomous Driving Baden-Wuerttemberg focuses on collaborative, infrastructure based realtime environment perception systems and the Testbed Lower Saxony focuses on collaborative maneuver-, path- and trajectory-planning methods that will be tested within the testbed. The developed safety model will be deployed and evaluated in both testbeds.

Demonstrations

Parts of the implementations will be demonstrated in open events. The first event displaying sensor and remote operation parts of the project (among related aspects of side projects) will be the German National Garden Show in Mannheim, Germany (BuGa'23) [21]. It will be opened from April to October 2023.

A second demonstration is going to take place Spring 2025. Here, it is planned to showcase the full stack of possibilities, from collective perception to full MAD.

Conclusions

This paper showed the need of rethinking automated driving. By removing sensor and computing components from fleet vehicles and bringing them into the infrastructure, new services can be developed, up to the enabling of fully cooperative vehicle control by roadside infrastructure. While the corresponding business models have been discussed in prior projects, this paper focusses on the developments in the new German national project MAD Urban, which is bringing the concept of Managed Automated Driving to public roads. As the project has just started, only the very first results in terms of the need for describing the role definition and the capabilities could be shown. This is accompanied by a description of the general setup of the project, its planned implementations as well as integration and demonstration activities. This paper therefore serves as an introduction for upcoming research results, as the project is going to run until mid of 2025.

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