Towards Automated Driving: Unmanned Protective Vehicle for Highway Hard Shoulder Road Works

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***Abstract*—Mobile road works on the hard shoulder of German highways bear an increased accident risk for the crew of the protective vehicle which safeguards road works against moving traffic. The project "Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works" aims at the unmanned operation of the protective vehicle in order to reduce this risk. Simultaneously, this means the very first unmanned operation of a vehicle on German roads in public traffic. This contribution introduces the project by pointing out the main objectives and demonstrates the current state of the system design regarding functionality, modes of operation, as well as the functional system architecture. Pivotal for the project, the scientific challenges raised by the unmanned operation – strongly related to the general challenges in the field of automated driving – are presented as well. The results of the project shall serve as a basis to stimulate an advanced discussion about ensuring safety for fully automated vehicles in public traffic operating at higher speeds and in less defined environments. Thus, this contribution aims at contacting the scientific community in an early state of the project.**

I. Motivation

In Germany, road works at the hard shoulder of a highway during moving traffic are a common operational scenario for employees of the road maintenance service. Despite extensive precautionary measures, road workers are still exposed to the risk of an accident with moving traffic. In particular, this risk applies to the crew of a protective vehicle safeguarding short-time and mobile road works to the rear against moving traffic [1]. If the crew of the protective vehicle would not have to operate the vehicle during road works, the risk could be reduced significantly. Consequently, an automated and unmanned protective vehicle would reduce the risk of injuries or even fatalities at least on the part of the road maintenance service.

The use case of unmanned protective vehicles for highway hard shoulders implies a structured operational environment, and the number of situations which have to be perceived and considered for driving decisions is limited. The planned operating speed of the unmanned vehicle depends on the speed of the road works, which is at most 10 kph. This results in lower functional requirements compared to use cases on driving lanes or with higher speeds. Thus, the use case provides great potential for a first introduction of unmanned vehicles to public traffic. Moreover, project results can be used as a basis for future projects with more complex driving functions in more complex operational environments.

A consortium consisting of industrial partners, German road authorities as well as academic institutions was founded in order to develop and implement such a vehicle in the framework of the publicly funded project *Automatisch fahrerlos fahrendes Absicherungsfahrzeug für Arbeitsstellen auf Autobahnen*[1], abbreviated with *aFAS* (German for *Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works*).

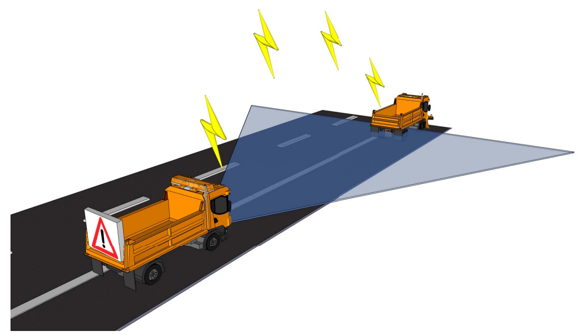

Fig. 1. Principle System Set-up of a Unmanned Protective Vehicle with a Road Maintenance Vehicle in Front

II. Objectives

Of course, one apparent objective of the project *aFAS* is to build a vehicle that is able to follow mobile road works automatically on the hard shoulder of a German highway.

The principle target set-up of such a system is depicted in Fig. 1. The leading vehicle serves as a road maintenance vehicle and carries out the actual task of the roadwork, e.g. mowing the roadside. The rear vehicle is the automated and unmanned protective vehicle equipped with a warning board to warn approaching traffic. The vehicles communicate via a wireless connection.

Due to the unmanned operation, the planned system has to be distinguished from recent advanced driver assistance systems. In recent advanced driver assistance systems, such as adaptive cruise control, lane keeping support, or automated parking, the driver serves as a fallback layer for system failures

[1]The project consortium consists of MAN Truck & Bus AG (consortium leader), TRW Automotive GmbH, WABCO Development GmbH, ZF-Lenksysteme GmbH, Hochschule Karlsruhe, Technische Universität Braunschweig, Hessen Mobil - Road and Traffic Management, and BASt - Federal Highway Research Institute.

An early version of this contribution was published in German to address the German speaking community [2].

978-1-4673-6596-3/15 $31.00 © 2015 IEEE
DOI 10.1109/ITSC.2015.115

and functional shortfalls. He or she supervises the operation of the system and can take over control in case of critical situations, as for instance in the Mercedes-Benz S-Class W222 with the DISTRONIC Plus with Steering Assist system [3].

The same applies to recent research projects. For example, the projects *Stadtpilot* of the Technische Universität Braunschweig [4], [5] or the Bertha Benz Challenge of the Karlsruhe Institute of Technology and the Daimler AG [6] still operate with a safety driver, who continuously supervises the automated driving functionality. Even in the Darpa Urban Challenge there was a supervisor who was able to halt the vehicles with a remote control [7]–[9]. Thus Ohl argues in [10] that these systems are classified as *Level 2 - Partial Automation* according to the definition of the SAE [11].

In the project *aFAS* – on the contrary – no supervision of the automated driving functionality is planned at all. This is for two reasons. First, it is the motivation to reduce risk for employees of the road maintenance service from being a part of accidents by removing the necessity for a human riding the protective vehicle. Second, in line with Bainbridge [12] it is assumed that a supervisor riding on the road maintenance vehicle is not able to permanently uphold the supervision task. Thus, the automated driving functionality fulfills the requirements for a classification as *Level 4 - High Automation* according to the definition of the SAE [11]: It is active in a limited operational scenario, whereby the automated driving functionality controls the actuators, monitors the driving environment and ensures the fallback performance of the system. A classification as *Level 5 - Full Automation*, the uppermost level, does not apply for the outlined scenario. This would involve the complete automation of the protective vehicle starting and ending at the depot.

The operational scenario of the project *aFAS* is well suited for the very first operation of an unmanned vehicle in public traffic in Germany. Compared to complex scenarios for automated vehicles such as urban environments, relatively simple constraints have to be considered due to the limitation of the target application to highway hard shoulders and low speeds. This particularly applies to the perception of the environment as well as to the behavior of the vehicle in case of a system failure. Moreover, a small user group will operate the vehicle.

Yet, the development and implementation of a suitable safety concept for the unmanned operation in moving traffic is the most crucial objective. In comparison to the aforementioned projects the driver cannot be regarded as a fallback layer in a safety concept. Most importantly, it has to be ensured in all situations that the vehicle will not change to the right lane of the highway, which is probably the most critical system failure.

In this context, the international ISO 26262 standard [13] represents the state-of-the-art for ensuring functional safety during the series development of electronic systems for vehicles up to a vehicle mass of $3.5\,\mathrm{t}$. Although the vehicle will have a total weight above $3.5\,\mathrm{t}$ and although the system is implemented prototypically, the ISO 26262 standard is applied for the development of the safety concept. This aims at two targets. First, the developed safety concept shall serve as basis for a later series development. Second, the principle applicability of the ISO 26262 standard for fully automated vehicle systems shall be examined.

In addition to normative, also legal boundaries must be identified as the unmanned operation of the protective vehicle requires an exceptional permission by German road authorities. It is expected that these considerations are very similar to legal considerations regarding automated driving in general.

Altogether, four overall objectives arise in the project *aFAS*:

- Development and implementation of an automated unmanned protective vehicle for road works on highway hard shoulders
- Development of a safety concept according to the ISO 26262 standard and its implementation for unmanned operation of the protective vehicle
- Consideration of legal aspects of automated driving as well as the identification of possible limits of relevant standards, in particular the ISO 26262 standard
- First operation of an unmanned vehicle in public traffic

III. System Description

In the following the current state of the system design is presented. This comprises a description of the planned functionality, the consequent modes of operation as well as the proposed functional system architecture.

A. Functional Description

A typical operational scenario looks as follows: In the beginning of the operation an employee of the road maintenance service manually drives the protective vehicle from the depot to the location of the road works. Having arrived at the location the employee stops the protective vehicle and switches to the road maintenance vehicle in front. There, the employee can activate the automated operation of the protective vehicle via a user interface. The vehicle guidance system then takes over the longitudinal and lateral control of the protective vehicle and follows the road maintenance vehicle in a defined distance at low speeds of about $10\,\mathrm{kph}$.

Also passing acceleration and deceleration lanes is within the range of functionality of the unmanned operation. To cover such situations, the protective vehicle follows the road maintenance vehicle very closely which is comparable to the approach realized in the project *KONVOI* [14]. This functionality has to be activated separately from the road maintenance vehicle, which triggers a close-up procedure. On the one hand, the resulting vehicle combination is a barrier as small as possible for road users leaving or entering the highway. On the other hand, it prevents traffic participants from driving between road maintenance vehicle and unmanned protective vehicle in order to avoid a potential hazard for these traffic participants.

After finishing the work task on the highway hard shoulder, the personnel deactivates the vehicle guidance system. The driver of the protective vehicle switches from the road maintenance vehicle back to the protective vehicle and manually returns it to the depot.

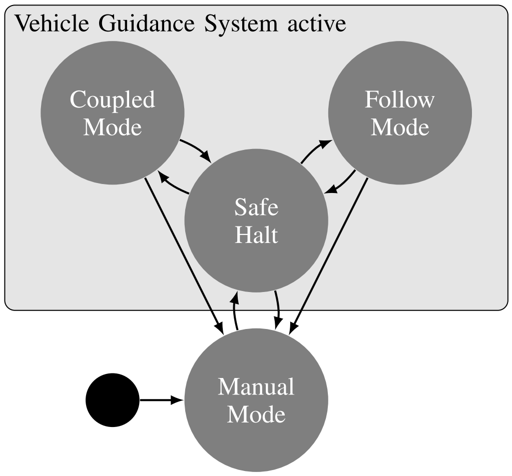

Fig. 2. Modes of Operation of the Planned System

B. Modes of Operation

Derived from the functional description, the four modes of operation of the protective vehicle shown in Fig. 2 are identified. Driven by a human driver, the vehicle is operating in the *Manual Mode*. The vehicle guidance system is not active. For the unmanned operation the vehicle guidance system must be activated from the road maintenance vehicle. The vehicle is then operating in one of the automated driving modes: *Follow Mode*, *Coupled Mode*, and *Safe Halt*.

Safe Halt serves as the initial mode of operation for the unmanned operation. The transition from *Manual Mode* to *Safe Halt* can only be realized if the vehicle is at a standstill. During the unmanned operation the *Safe Halt* can be reached from all modes of operation. After the transition into *Safe Halt* the vehicle is either already in standstill or is decelerated to a standstill as fast as possible. Finally, it is blocked by the parking brake or the operating brake. The vehicle also shall transition into *Safe Halt* in case the vehicle guidance system detects the violation of functional system boundaries. The latter are significantly influenced by the area of operation, environmental conditions and the detailed range of functionality. Eventually, *Safe Halt* must also be reached if any failures in the system's components are detected. Thus, there are three conditions for a transition to *Safe Halt*: By operator input, by reaching the functional system boundaries, or by a technical failure in the system.

Subsequently, different kinds of actions are necessary to reactivate the unmanned operation. If *Safe Halt* is reached on purpose by the operator, the operator has to choose the next mode of operation knowingly. If a functional system boundary is violated, the operator can try to reactivate *Follow* or *Coupled Mode*, provided that the system boundary violation has disappeared. If this is not possible, manual control of the vehicle is required. If a technical failure has occurred, it is not yet defined how the system should behave. It is imaginable that the operator would have to acknowledge the failure and restart the automated driving modes explicitly.

Starting from *Safe Halt* either *Follow Mode* or *Coupled Mode* can be activated. In the *Follow Mode* the actual task of the road works (e.g. mowing) is executed by the road maintenance vehicle. Concurrently, the protective vehicle follows automatically at a defined distance. Recent discussions aim at a system capable of keeping a distance of about $100\,\mathrm{m}$ at a velocity of $10\,\mathrm{kph}$.

In *Follow Mode*, the vehicle guidance system performs the longitudinal and lateral control based on environmental information. The environment perception extracts the lane boundaries, e.g. lane markings, of the highway hard shoulder, the road maintenance vehicle and other obstacles in front of the protective vehicle. If an obstacle is detected, for example an emergency halting car, the system automatically transitions into *Safe Halt*. The system also performs this transition in case it detects that it is not capable of maintaining unmanned operation. Potential reasons can be manifold, e.g. a low fuel level or functional limitations of the environment perception due to bad weather conditions.

In *Coupled Mode*, the protective vehicle is controlled by the vehicle guidance system, too. In contrast to the *Follow Mode*, the longitudinal and lateral control is purely based on control commands and state information of the road maintenance vehicle. To prevent other traffic participants from driving between guidance and protective vehicle, the protective vehicle follows the road maintenance vehicle at a very short distance. Currently, a distance of $5\,\mathrm{m}$ is discussed in the project. While lane boundaries are ignored in this mode of operation, obstacles in front of the protective vehicle are still detected. As in *Follow Mode*, the protective vehicle is able to detect functional system boundaries and to transfer itself to *Safe Halt*.

In reference to the required testing phase, a human driver (if present) can override the vehicle guidance system at any time by utilizing either the steering wheel, accelerator or brake pedal. Then, the system transitions to *Manual Mode* and the driver regains complete control of the vehicle.

C. Proposed Functional System Architecture

Within the context of the project *aFAS* several functionalities will contribute to realize unmanned operation. In order to obtain an overall system understanding, a functional system architecture following the general approach of Matthaei and Maurer [15] is developed. The authors propose a three level architecture whereby the vehicle is embedded into a superordinate system. The levels are

- strategical level: planning, macro-scale resolution,
- tactical level: decision making, meso-scale resolution,
- operational level: reactive stabilization, micro-scale resolution.

Fig. 3 illustrates the actual state of the system architecture containing the major parts of the overall system. Starting from the approach of Matthaei and Maurer, parts of the general functional system architecture are left out. In the context of the project *aFAS*, neither external a priori data nor absolute global localization data are utilized. Due to the limited use case there are no functional components on the strategical level. Strategic decisions are the task of the employees of the road maintenance service. Consequently, the scope of the project *aFAS* is on the operational and tactical level.

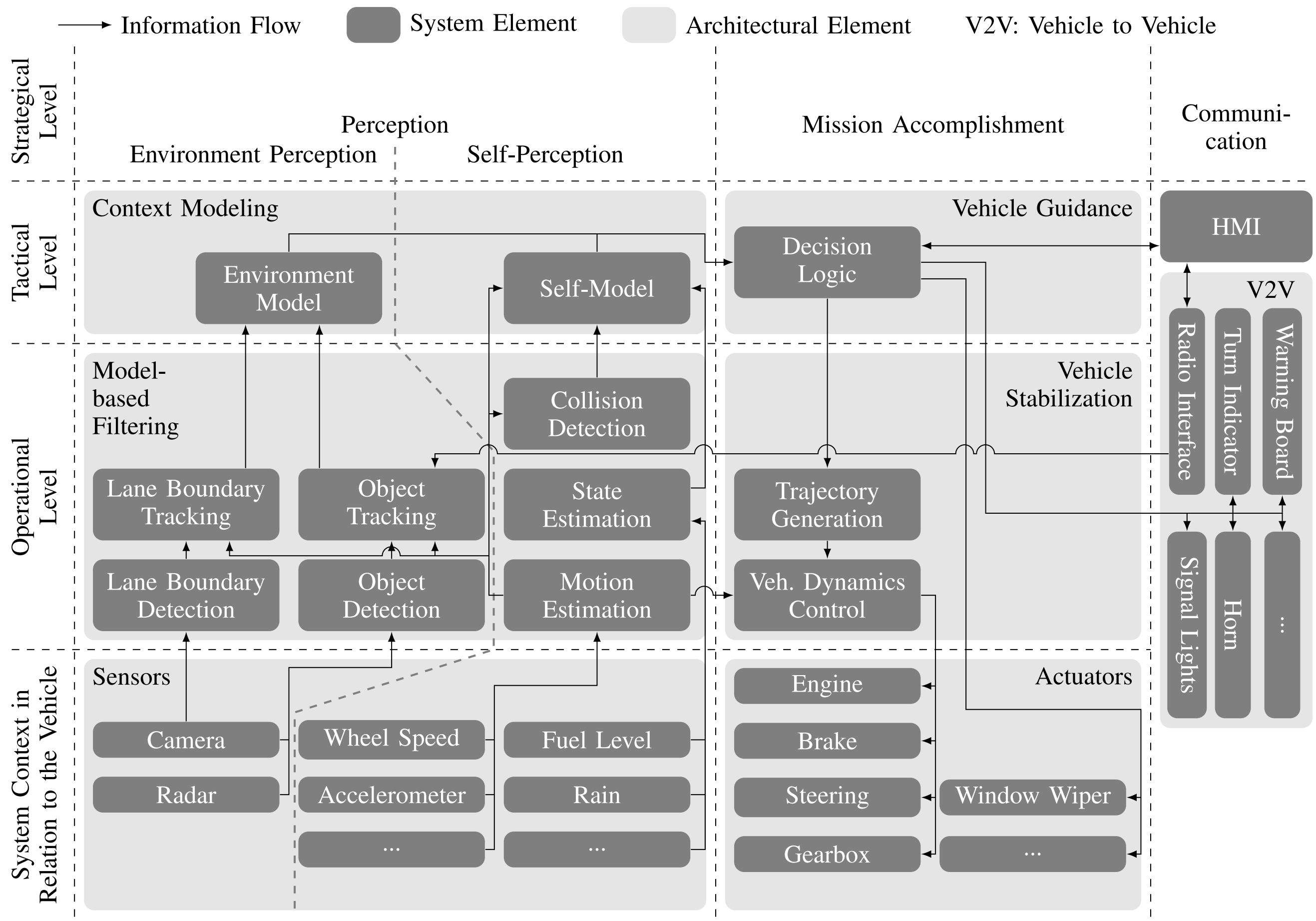

Fig. 3. Functional System Architecture of the Planned System with Information Flow

For the environment perception, a sensor set is deployed consisting of long- and mid-range radar as well as a camera system. The raw data are fed into the model based filtering processes which in parallel detect and track the lane boundaries and objects. Following, this information is used to generate and update the environment model containing the boundaries of the drivable area and the objects in front of the protective vehicle.

Simultaneously to the environment model, a self-model of the system is generated. The self-model is the result of self-perception, which combines sensor values to a model based representation of the vehicle guidance system. All kinds of available vehicle sensors are utilized to improve the self-representation. Among others, this includes gyroscopes and accelerometers but also fuel level or tire pressure sensors. Derived from the sensor raw data, the motion estimation and generation of additional state variables are conducted. The motion estimation is additionally utilized for the detection of other vehicles colliding with the protective vehicle from behind. Connecting the self-perception with the environment perception, the motion estimation is also relevant for tracking lane boundaries and objects.

Based on both types of perception, the current mission is accomplished. On the tactical level a decision logic determines which discrete action shall be performed. Besides the information gained by both types of perception, commands stemming from the human-machine interface in the road maintenance vehicle are considered. In particular, this affects state changes triggered by the human operator and the change of parameters of the operating modes, like distances or maximum speeds. The discrete action comprises the motion of the vehicle on the one hand, but also the usage of turn signals, window wiper etc. on the other hand.

Next, the discrete action is transferred to the stabilization level, where a target trajectory is generated. The target trajectory is then fed into the vehicle dynamic controller which finally controls the vehicle's actuators.

IV. Scientific Challenges

Different scientific challenges result from the very first operation of an unmanned vehicle on (at least) German roads. These can be classified in technical, normative, and legal challenges which also affect each other.

A. *Technical Challenges*

From a technical point of view, the major challenges are the development and validation of the safety concept. The development involves consideration of the whole processing chain starting with environment perception sensor data fusion through the vehicle guidance system to the actuators. All these tasks that are executed by a human being in a manned vehicle are now performed by an electric/electronic system. Furthermore, the human driver also perceives the actual performance and capability of himself as well as of the system and can react accordingly.

Regarding the environment perception, different sensor technologies offer different strengths and weaknesses [16, Part IV]. This strongly relates to the actual environmental conditions and the specific application. To respond to this challenge, at least a dual redundant sensor set-up seems necessary. Yet, it is not obvious how a safe detection of objects on the hard shoulder can be realized under prevention of false negative results. This requirement differs from the development of current driver assistance systems where one of the main goals is to achieve a very low false positive rate due to user acceptance [16, Part IX]. The same applies to the detection of the lane boundaries of the highway's right lane and the detection of the road maintenance vehicle in front. Consequently, a permanent estimation of the perception performance must be guaranteed during the unmanned operation.

Based on a safe environment perception, the generated information are utilized for the planning of the trajectory. In this context, the safety concept must address the correct generation of control commands for the actuators. This leads to the sophisticated task of so called *planning under uncertainty* [17]. Here, trajectories are prohibited that either will leave the valid operational environment or that will leave system boundaries such as maximum acceleration or maximum steering angles.

Finally, also the correct realization of the generated control commands by the actuators must be ensured. Therefore, strategies must be brought up in order to deal with failures of one of the actuators.

As the project *aFAS* has a unique character, no similar approaches and underlying safety concepts are known to the authors. Thus, a short overview of safety concepts for advanced driver assistance systems follows. Hörwick and Siedersberger [18] present a safety concept for automated vehicles based on *action plans*. The safety concept was developed for a traffic jam assist and was further detailed in [19]. A key aspect of the safety concept is system monitoring to detect malfunctions and failures. The detected events result in the execution of action plans, which transfer the vehicle into a safe driving state. According to a system wide safety concept for unmanned operation, the vehicle must permanently operate in a safe state. As the traffic jam assist is operating in situations with speeds below $60\,\mathrm{kph}$, a safe driving state is a standstill of the vehicle. As research in the project *aFAS* shows, a standstill of the vehicle is an appropriate safe driving state for the unmanned protective vehicle as well. Results from [18] and [19] will be further investigated in the project *aFAS*.

The ISO 26262 standard is structured along a reference development process. At its end comes the validation of the safety concept. The major challenge here is to validate a system operating in an open set of situations. An open set of situations addresses the non-quantifiable number of situations that can occur during the unmanned operation in moving traffic in combination with environment perception. The dimension of the challenge is underlined by Winner as he estimates a 100 million kilometers of test drives for an automated vehicle [20].

The amount of possible situations in the project *aFAS* may be small compared to, e.g., a fully automated system driving in urban environments. However, also in the limited operational scenario of the automated protective vehicle the set of operational situations is too huge to be collected with reasonable efforts. Thus, methods must be established that determine a necessary validation depth. For example, Schuldt et al. [21] and Nentwig and Stamminger [22] propose potential approaches.

B. Normative Challenges

So far, the partners agree on the ISO 26262 standard being not sufficiently designed as a guideline for designing safe systems operating in an open set of situations. For this reason, the suitability of the standard for the development of unmanned vehicles operating in public traffic is challenged throughout the project. By means of this, outstanding issues of the standard regarding the development of unmanned vehicles shall be identified and documented for discussions with the scientific community.

One central aspect considered during the project *aFAS* is the question of when such a system can be defined *safe* and whether state-of-the-art methodology is sufficient for system validation.

Another normative aspect recently discussed is the interpretation of the term *item* according to the definition in part 1 of the ISO 26262 standard [13, part 1]. There, in section 1.69 an *item* is defined as a

> *System or array of systems to implement a function at the vehicle level, to which ISO 26262 is applied.*

while in section 1.129 the term *system* is defined as a

> *Set of elements that relates at least a sensor, a controller and an actuator with one another.*

Hence, it is possible to describe the item and its system boundaries considered in the project *aFAS* in two different ways as Kriso et al. [23] argue. First, one can consider all necessary components as the item. So the item would consist of all perception components, the decision logic as well as all actuators. Second, the item consists of the additional components for the automated driving functionality, namely environment perception, decision logic and human machine interface. In this case, the actuators are considered as a single item each. From a functional perspective, this would not make any difference. Yet, the selection of the system boundaries significantly effects the metrics for probabilistic hardware failures to be fulfilled according to part 5 of the ISO 26262 standard. The discussion here turns on the topic whether stricter target values for hardware failure metrics – as they would result from the first approach – are necessary for unmanned vehicles.

C. Legal Challenges

Besides technical and normative challenges, another focus of the project *aFAS* is the comprehensive consideration of legal aspects of the unmanned operation of vehicles in moving traffic. Thereby, results are expected that can be applied to future unmanned vehicles with a functional scope far beyond the unmanned protective vehicle.

Conflicts arising from the current jurisdiction in Germany are expected on account of the fact that exclusive machine driving without human involvement is not provided for by law. This leads to inconsistencies in different legal fields. In absence of the human driver, demands on technology rise tremendously. Moreover, liabilities for products and the manufacturer's responsibility are likewise affected.

From a legal point of view, influencing and relevant legal aspects for the realization of the project *aFAS* can result from legal classification of different parts of roads (lanes, hard shoulders, on- and off-ramps, etc.) as consequences may vary accordingly (e.g. in respect of the Vienna Convention [24], [25] or liabilities). This will be assessed over the project's duration.

Finally, generalizable aspects of the legal insights gained in the project *aFAS* will be summed up for the employment on future unmanned vehicles operating in less constricted operational scenarios.

V. CONCLUSION

On the road to fully automated driving in public traffic, several challenges regarding technical, normative and legal aspects have to be solved. In this context, the project *aFAS* aims at the very first operation of an unmanned vehicle in public traffic by automating a protective vehicle for highway hard shoulder road works.

Despite the low speeds and comparably simple environmental conditions at hard shoulder road works, challenges regarding technical, normative and legal aspects result in the project *aFAS*. Beyond the scope of the project, these aspects are highly relevant for the recent discussions on automated driving in general. Some aspects already identified were presented in this contribution and shall serve as basis for in-depth discussions with the scientific but also industrial community.

Eventually, the results gained in the project *aFAS* shall be generalized in terms of guidelines for ensuring safety of unmanned vehicles with a more comprehensive range of functionality. In parallel, additional need for research is revealed.

ACKNOWLEDGMENT

The project *aFAS* is partially funded by the German Federal Ministry of Economics and Technology (BMWi). We would like to thank our project partners and colleagues for their support of our work.

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