Rethinking transport
27–30 April 2020

TRA 2020 HELSINKI

Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland

Infrastructure modifications to support the introduction of the automated driving *(full paper)*

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Abstract

The foreseeable introduction of highly Automated Vehicles raises the question which infrastructure measures could support the exploitation of the potential benefits of this new technology for the traffic sector. While the legal framework has been implemented in Germany for the market introduction of automated systems up to level 3 according to standard SAE J3016, generally accepted recommendations for the adaptation of the road infrastructure and the underlying technical regulations have not yet been established. As part of a basic research the needs for infrastructure measures were analysed in a scenario-based approach. The requirements Automated Vehicles bring about mostly arise on the layer of vehicle guidance, which is highly-relevant for safety and remains the ultimate challenge of environmental perception technology. These issues can be facilitated or settled by means of standardisation, real-time information, improved machine readability and reliability to name the essential core-requirements at abstract level. The evaluation of possible infrastructure measures shows that constructive or physical infrastructure modifications are in most cases costly and only feasible in the long- or middle term. Most issues, however, can be solved by provision of real-time data on upcoming infrastructure-status including road works, road traffic regulations, etc. This would be feasible e.g. via a backend-based digital HD reference map combining event localization with all relevant infrastructure-information as a reference-base for Automated and Connected Vehicles. The latter could be a core element of future strategies to develop the current infrastructure even further. Open questions remain concerning the concrete implementation of such a map in practice. Additionally, research needs have been identified concerning reliable machine readability of road markings.

Keywords: automated and connected driving; road infrastructure; digital infrastructure, high definition reference map, road markings

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1. Introduction

Vehicle automation-technology is progressing rapidly. Already today, Advanced Driver Assistance Systems (ADAS) are available on the market, for example Lane Keeping Systems in combination with longitudinal control (e. g. Adaptive Cruise Control (ACC)). These systems support the driver in various situations, whereby the driver remains permanently in control and responsible for the driving task. The next generation of systems shows a considerably extended range of functions: Unlike ADAS, automated systems classified as level 3 or 4 according to SAE J3016 are characterised by the capability to take over continuous vehicle motion control and allow the driver to turn to tasks unrelated to driving. Current technology road maps foresee the introduction of first Level 3 functions for passenger cars as soon as 2020 (VDA, 2019, ERTRAC, 2019). From a legal standpoint, in Germany, with the 8^{th} revision of the Road Traffic Act (2017) legal adjustments to the national legal framework have been implemented to allow for the use of Automation up to level 3 as defined by SAE J3016. In contrast, up to now it is largely unknown, which implications for the design of the road infrastructure result from the introduction of Automated Vehicles. With the human driver released from the driving task, these systems need to be able to operate in a self-dependent manner on the existing road infrastructure. A key question for road operators and political decision makers is what infrastructure measures are suitable and feasible to support the use and potential benefits of the Automated Vehicles e. g. in terms of traffic safety and efficiency (Farah et al. 2017, Lytrivis et al. 2018, C-ITS platform 2017).

2. Objective, Methodology

It is understood that the introduction of Level 3 vehicles on the road infrastructure induces reciprocal requirements on the vehicle and the infrastructure: The existing infrastructure puts up requirements on the capability of the Automated Vehicles, whereas the introduction of Automated Vehicles raises the question of adapting the infrastructure to benefit from the advantages automated driving promises in the road traffic sector. The latter question is the main objective of this paper. As basic research it depicts the results of an analysis of feasible measures for infrastructure needs for the Automated Vehicles on German federal highways. The analysis takes into account the results of the research project “Grundlagenprojekt: Infrastrukturbedarf automatisierten Fahrens” (Dierkes et al.) and the findings of a working group which originally developed the first set of recommendations then taken further and integrated into the “Strategy for Automated and Connected Driving” of the Federal Government of Germany (BMVI 2017, Kollmus et al. 2019). Infrastructure measures are closely connected to the issue of connected driving (especially car-to-infrastructure communication) and ITS-applications the details of which are not yet integrated into this paper.

With regard to methodology, the objective was to found the analysis on the principle of “mutual understanding”, meaning to take into account the needs of the vehicle technology (e. g. requirements of camera based environment perception of infrastructure elements) as well as the needs and constraints of the existing infrastructure (e. g. very limited possibilities for constructional modifications in the short- and middle-term). To meet this demand, a holistic, scenario-based approach was chosen to identify potential risks and suitable solutions. In the first step, a set of critical scenarios was developed on the assumption of Automated Vehicles on the current infrastructure. In the next step, to address safety-relevant issues in the aforementioned scenarios, infrastructure-based solutions were identified. Finally the proposed solutions were contrasted with the status quo of the existing infrastructure and limitations to identify feasibility, efficiency and affordability. Only measures for Automated Vehicles were considered that do not place human drivers (e.g. SAE-Level 0) at disadvantage.

The analysis is based on the following assumptions and constraints:

- Limitation to automated driving functions classified as level 3 according to standard SAE J3016, partially level 4 systems will also benefit. Driverless functions without any limitations to the Operational Design Domain (level 5) are not covered by this analysis.
- Limited scope on German federal highways and further roads designed similarly (e. g. segregated lanes etc.). Automated Vehicles are assumed to share the same infrastructure with conventional traffic (all SAE levels, “mixed traffic”).
- Automated driving has been considered a function that is not permanently available and not available under all conditions (driver based automation – a driver is either available as a fallback with lead time or is optionally available to execute the task of driving).
- The discussion of possible solutions was open to all types of technology.

- It is assumed that with further developments in the field of Automated Vehicles, the so far identified needs for the adaptation of the infrastructure might alter.

3. Road infrastructure

According to Gasser et al. (2015) the following classification of infrastructure elements in the context of automated driving was applied (see Fig. 1):

- The *physical infrastructure* comprises the road as the constructed body including standardised design-principles, for example the dimensioned road cross-sections.
- *Traffic engineering* is a subset of physical infrastructure and includes all elements imposing traffic rules or with an effect on traffic efficiency. Examples are static road signs, road markings, traffic lights and variable Message signs.
- An example for *digital infrastructure* is the information provided to the vehicle (and possibly vice-versa) e. g. by means of connectivity and a digital HD map (see chapter 4.2.1).

The specifications of the German Technical Regulations on infrastructure provide for a standardised and safe design of roads. They ensure a comprehensive design in view of constructional, design-related and traffic technical aspects.

For example in the area of the *physical infrastructure* the Guidelines for the Design of Federal Highways (RAA) define design classes depending on the relevant road category according to the Guidelines for Integrated Road Network Design (RIN), which result in the applicable standardised cross-sections. Examples of standardised cross-sections are depicted in Fig. 2.

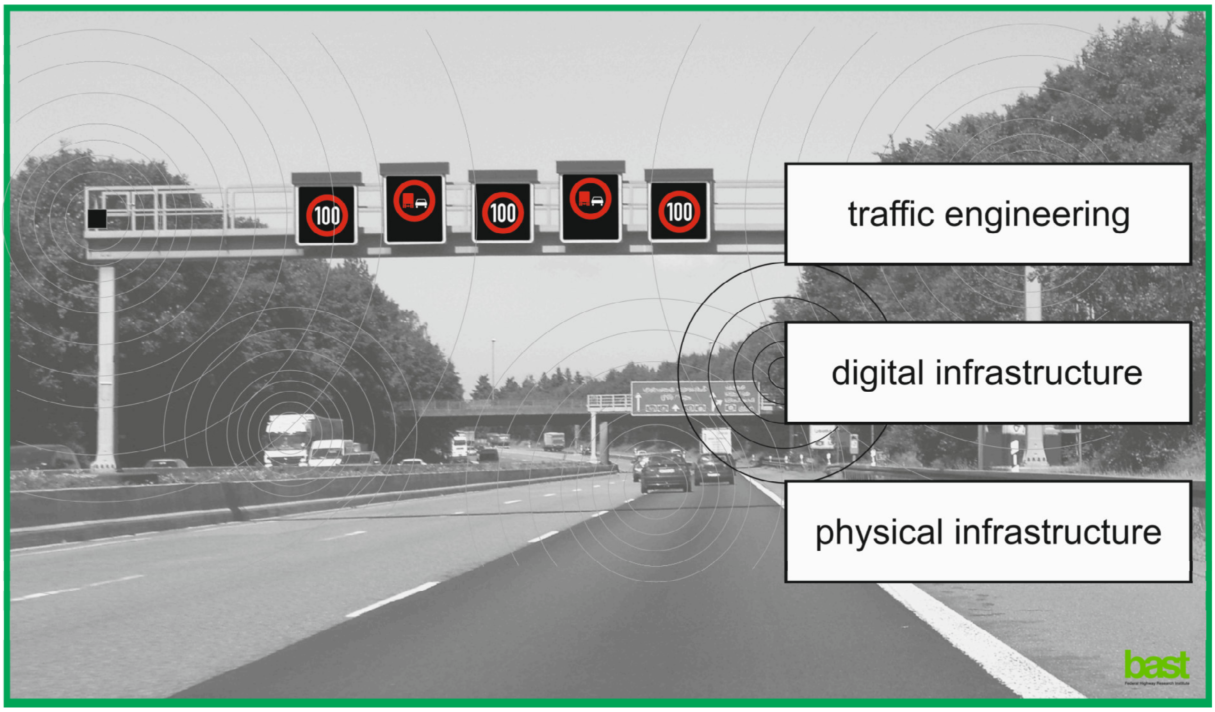

Fig. 1 Classification of infrastructure in the context of Automated Driving according to Gasser et al. (2015)

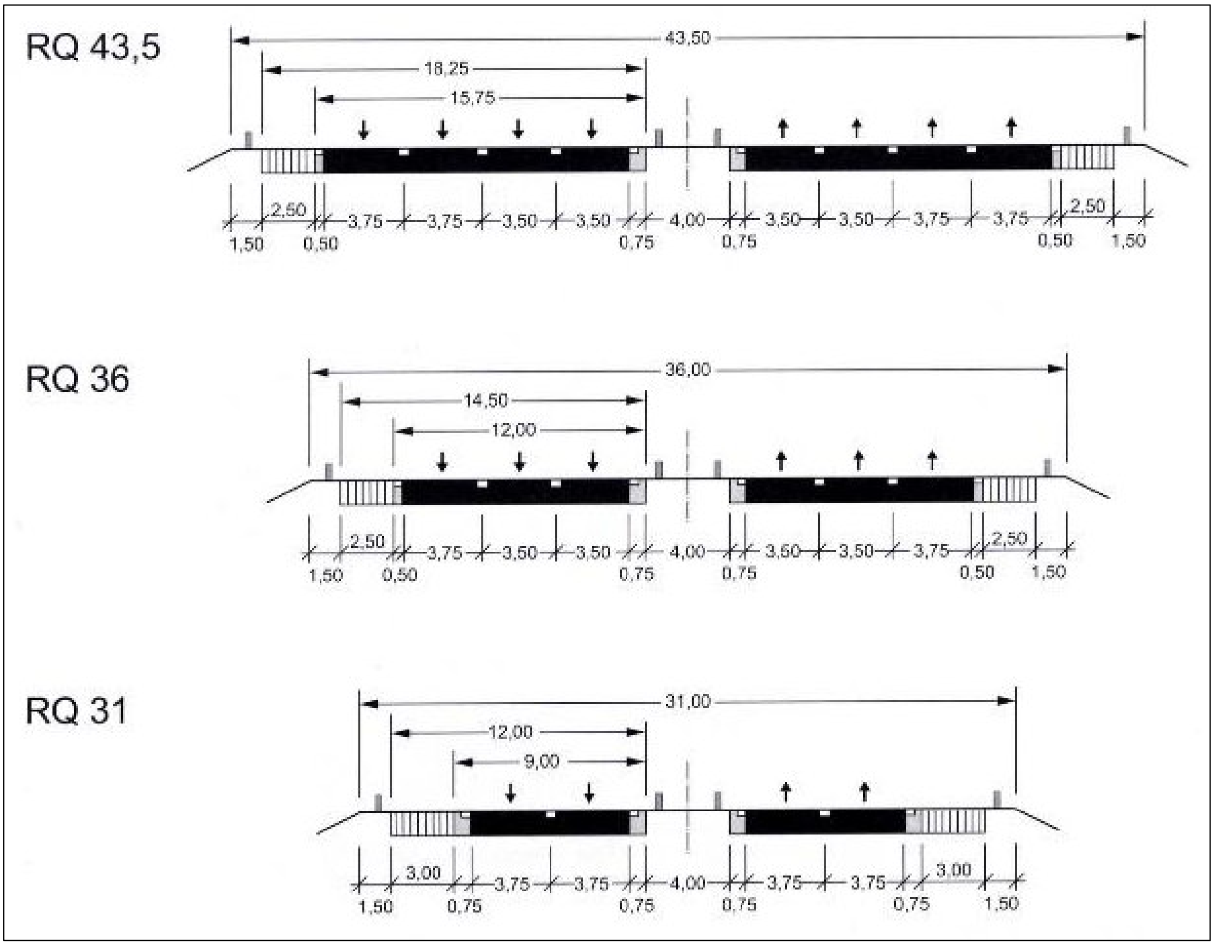

Fig. 2 Examples of standard cross-sections according to the German Guidelines for the Design of Federal Highways (RAA)

The standardisation of *traffic engineering* is addressed by further guidelines. In particular the Guidelines for the Marking of Roads (RMS) and the Guidelines for Variable Message Signs (RWVZ) on federal trunk roads are to be mentioned, whereby the latter also comprise aspects of information technology.

4. Scenarios and measures

Scenarios considered for the analysis include a basic scenario and scenarios covering deviations from the basic scenario critical for Automated Vehicles.

4.1. Basic scenario

As described above, the construction and operation of roads in Germany follows comprehensive technical regulations. In consequence, the already high degree of standardisation of the existing road infrastructure, especially concerning highways (German federal highways and federal roads designed alike), is already highly beneficial for Automated Vehicles. Thereof, a basic scenario has been developed. Amongst others, the basic scenario is characterised by roads having dual carriageways, at least two segregated lanes for each direction, permanent existence of a hard shoulder, visible signs and road markings, daylight and absence of adverse weather conditions, rule-consistent driving of all road users (automated, non-automated vehicles). It is assumed that this basic scenario already allows for automated driving but may result in critical behaviour in unexpected situations (e. g. hard braking in case of obstacles in the carriageway ahead). The unambiguous and good quality of road markings and signs already enables automated driving in compliance with traffic rules and lateral positioning solely based on machine vision via onboard sensors. However, a digital map with additional information layers can provide information with an additional benefit in terms of safety.

4.2. Critical scenarios and measures

In practice, the existing infrastructure does not always comply with the basic scenario respectively with the design principles ideally to be regarded in case of construction, maintenance etc. In case of deviations from the basic scenario, an error-free operation of automated driving functions cannot be guaranteed. If deviations from the basic scenario occur, automated driving solely may no longer be possible. A level 3 or 4 system requires extensive and far-reaching knowledge of upcoming critical scenarios to be able to plan driving manoeuvres at an early stage.

To embrace deviations from the basic scenario, which have an impact on the automated driving, a selection of critical scenarios was derived. These scenarios have been classified into three further categories.

4.2.1. Plannable scenarios

Missing hard shoulder

In the German federal highway network - deviating from current design regulations - some segments exist without a hard shoulder. On these segments, the Automated Vehicle cannot leave the carriageway to reach a minimal risk condition. If the driver does not respond to a takeover-request, a stopping in the carriageway will represent a high risk for the driver and the following vehicles. Conceivable possible measures might be infrastructure-based: Static, machine-readable vertical signs could be set up sufficiently ahead of the segment without a hard shoulder, so that the driving task can be transferred to the driver in time or a minimal risk condition can be reached by stopping on the hard shoulder beforehand (measure of *traffic engineering*). In the long term, a conceivable solution is the constructional upgrade of the highway segments concerned with a hard shoulder in accordance with the regulations (*physical infrastructure*).

As an alternative to the aforementioned solutions, a digital high definition reference map (HD digital map) could be implemented as a measure in the field of digital infrastructure (see Fig. 3). A HD digital map would contain geo-referenced information processed via cloud- or backend-based services. It would be structured in several layers, which contain not only road geometry but further traffic engineering elements at high resolution. In addition to static information, dynamic information (e. g. obstacles in the lane ahead) can be included in a further layer. The map is intended to function as a "prolonged sensor" for the Automated Vehicle by enabling anticipation of the road beyond the limited range of onboard sensors and would allow to adapt manoeuvres accordingly.

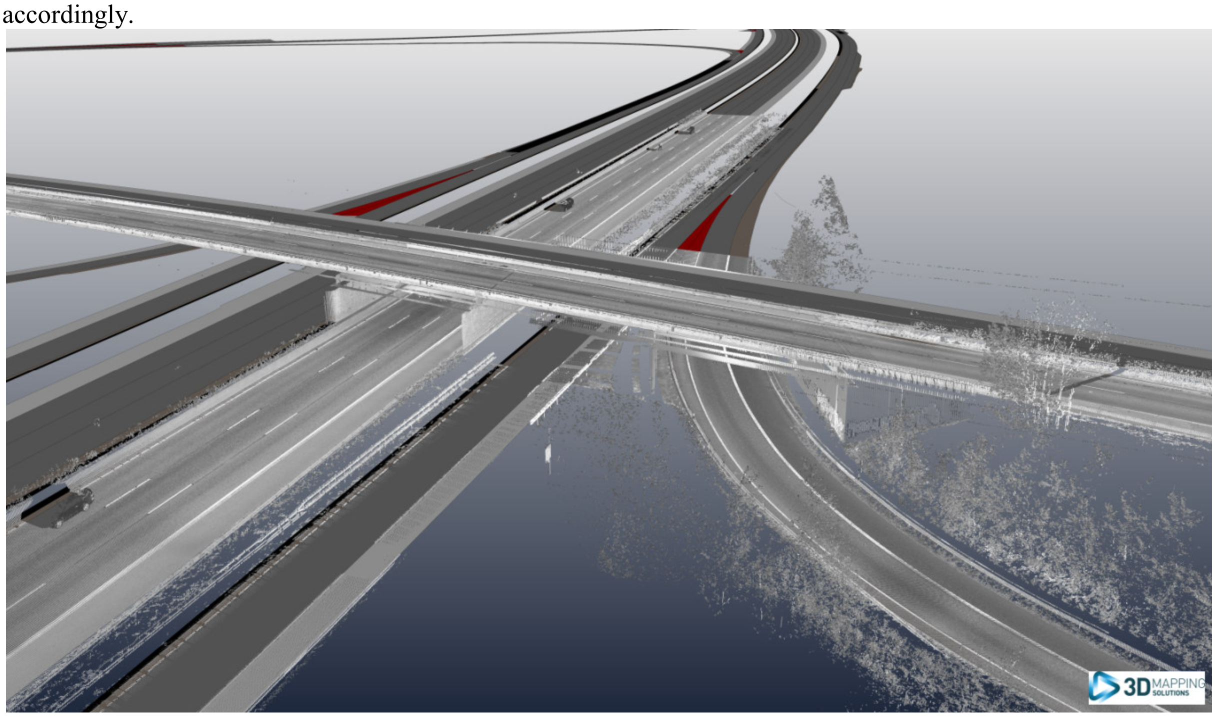

Fig. 3 Example for the result of a high-precision initial measurement of the road network in the Ko-HAF project (3D Mapping Solutions)

Temporary use of the hard shoulder as running lane under heavy traffic conditions (active traffic management)

As a means of active traffic management in Germany the temporary use of the hard shoulder for example under heavy traffic conditions can be allowed (see Fig. 4). According to German road traffic regulation (StVO) sign 223.1 is shown if the hard shoulder is to be used as a regular (additional) lane. For the signalling of traffic sign 223.1 a variable message sign is prescribed. Only the temporary use of traffic sign 223.1 is permitted. For the temporary use of the hard shoulder the construction of emergency stopping bays at regular intervals would be required from the perspective of Automated Vehicles in order to avoid Automated Vehicles stopping in the lane in case a takeover by the driver does not work. The existing Guidelines for the design of the temporary use of the hard shoulder already foresee the existence of emergency stopping bays.

Analogous to the scenario with a missing hard shoulder a critical situation can occur if the driver does not respond to a takeover-request since the hard shoulder is not available for a minimal risk manoeuvre by the Automated Vehicle. Therefore, as described in the previous scenario, the need for a machine-readable signage must be stressed (*traffic engineering*).

Fig. 4 a) sign 223.1 "use hard shoulder"; b) example of temporary use of hard shoulder (Picture: Autobahndirektion Südbayern, edited by BASt)

In the area of digital infrastructure measures the localisation of road-segments under temporary use of the hard shoulder as an additional lane could be included in a HD digital map. The same is possible for the exact location of the emergency bays as a redundancy for the sensor based detection. Furthermore, the current status of the temporary hard shoulder can additionally be communicated via "vehicle-to-infrastructure-communication" (V2I) and/or an HD digital map. This can serve as redundant information sources for this safety relevant information.

This scenario comprises a requirement on the capability of Automated Vehicles resulting from existing infrastructure: the Automated Vehicle must be able to interpret the meaning of the continuous road marking lines between the right carriage way and the hard shoulder correctly. According to StVO the crossing of a continuous road marking (sign 295) is prohibited. In combination with sign 223.1 "use hard shoulder" the continuous marking (sign 295) would be interpreted as a dashed road marking (sign 340) permitting to cross in both directions. The capability of Automated Vehicles to follow traffic rules correctly, especially in complex cases as described above, needs to be ensured.

Construction site on one carriageway

Construction sites involve a variety of deviations from the basic scenario. Examples are the reduced number and width of lanes, the existence of white and yellow road markings in parallel, the use of hard shoulders as regular lanes and the use of the opposite lane. The requirements concerning the compliant and machine-readable use of road signs and markings described in the scenarios before also apply to construction sites. This particularly concerns traffic sign 123 StVO "construction site" (*traffic engineering*). Further the localization of traffic sites in a HD digital map could ensure that the driver can take over the driving task in time before reaching the construction site *(digital infrastructure)*.

In case of an unsuccessful takeover by the driver (in spite of this belonging to the driver's duty, see § 1b StVG), this measure would allow for minimal risk manoeuvres before entering the construction site.

4.2.2. Changes occurring short-term; wear and dirt on traffic signs and markings

This category includes insufficient visibility respectively comprehensibility of traffic law regulations resulting from an improper condition of road signs, markings and traffic engineering equipment.

Insufficient machine readability of road markings and signs

An infrastructure solution for this scenario could be the implementation of a standardised quality management system which ensures that gradual deteriorations are detected and maintenance-measures are detected in time. This would require the development of methods and measurement systems for the network-wide monitoring of road markings and signage quality.

Open questions remain regarding the requirements on the visibility of road markings for the detection by Automated Vehicles (see also EC 2018). There is no evidence at present for additional requirements on the quality and availability of road markings for automated driving. However, road markings are of great relevance for the lateral positioning of Automated Vehicles in the foreseeable future. Assuring a defined minimum quality could increase the steering safety of Automated Vehicles (and is beneficial for drivers too). So far basic knowledge is missing concerning the properties of road markings relevant for machine detection and minimum requirements taking into account adverse weather and light conditions. Also road segments with complete absence of road markings on one or both side(s) of the running lane e. g. due to the renewal of the adjacent road surface occur (see Fig. 5). So far it is not known up to which length missing markings can be considered to be compensated safely by the Automated Vehicle.
In the aforementioned way an urgent need for research in the area of machine detection of road markings becomes apparent.

Fig. 5 Segment with missing road markings on one side of the lane

Suddenly occurring damages could be detected and communicated via V2I based on data from the vehicle fleet equipped with suitable sensors. For this purpose, the development of appropriate concepts for the automated detection of such defects is necessary. Here too, the communication of no longer or only poorly visible road signs and markings e.g. via a HD digital map, updated in high frequency, is conceivable.

Signs and instructions by police officers, right of way of emergency vehicles

This scenario includes signs and instructions from police officers as a short-term traffic law measure. According to § 36 StVO signalling and instructions by police officers are to be followed. They take precedence over all other orders and other rules. Police officers may also stop road users e.g. in case of general traffic controls. The stop sign would need to be given by means of suitable technical equipment on the emergency vehicle, a traffic paddle or a red light machine-readable by an Automated Vehicle.

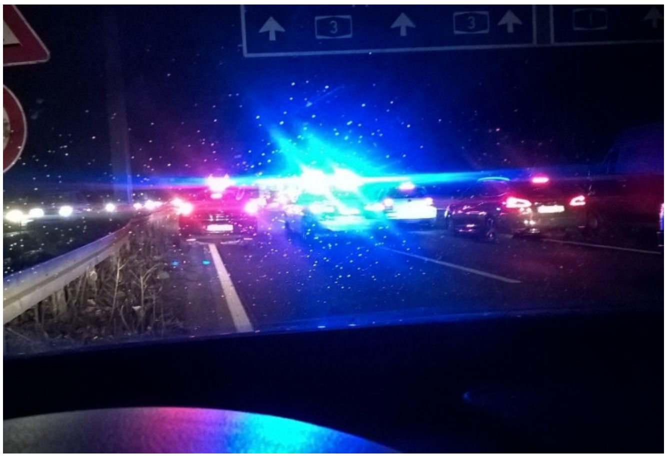

Fig. 6 Emergency forces (picture: BASt)

For the recognition of instructions by police officers based on vehicle sensors or V2I, further considerations are necessary in view of upgrading traffic paddles and traffic sticks by means of communication technology for machine readability (thus replacing instructions by hand signs only).

4.2.3. Upcoming, unforeseeable scenarios

The scenario covers, according to today's state of knowledge, unforeseeable situations. These situations occur suddenly and in some cases will appear for the first time. The following scenarios were analysed:

Suddenly occurring damages to the road surface e. g. “blow-ups” affecting safe vehicle control significantly

Suddenly occurring obstacles on the carriageway, accidents, end of traffic jams

Adverse weather or light conditions (e. g. insufficient visibility of road signs and markings, insufficient skid resistance due to weather conditions)

Due to the abrupt and unexpected occurrence of these scenarios constructional measures are inconceivable when appearing for the first time. However, traffic engineering could be applied in such a way that existing detection-systems (including those in vehicles ahead) could be applied to capture these sudden deviations from the normal state. It must, however, be considered that only a very small percentage of the existing road network is currently equipped with such systems. Equipping the full highway network with such *traffic engineering* detection systems is not considered feasible. In addition, suitable automated detection systems as infrastructure based solutions, sufficiently sensitive to the aforementioned conditions are not known so far.
Here only the availability of data from the vehicle fleet would presumably improve safety: Information on obstacles already detected could be integrated in the HD digital map as a temporary feature (*digital infrastructure*). Alternatively this information could likewise be transferred by means of V2V-communication to the Automated Vehicle. The issue of the first-time appearance still remains to be dealt with.

5. Conclusions and open questions

The evaluation of the feasibility of the proposed solutions shows that the implementation of measures in the field of the physical infrastructure and traffic engineering can only be realized in the middle or long term due to the significant need for financial and personnel resources. In other cases, critical situations like suddenly occurring obstacles cannot be solved by modifications of the physical infrastructure and/or traffic engineering in the first place. Thus it becomes ever more apparent that a HD digital map as a backend-based solution for infrastructure-relevant information would be a core element of most measures discussed here or has the potential to bring alternative solutions together in one. Such an instrument could - as a superordinate reference - enable the localisation of the vehicle, relevant elements of the infrastructure as well as disruptions to traffic flow. At the same time the HD digital map has the potential to inform vehicles about (temporary) conditions or incidents far beyond the limited range of vehicle sensors. Thereby infrastructure related information can be made available for the vehicle control system, for example as a basis for deciding to return the driving task to the driver. Here the aspect of bidirectionality is decisive: On the one hand the HD digital map should provide information to the vehicle; on the other hand the HD digital map should show the capability to receive information from the vehicle fleet about suddenly occurring incidents. This set of information would be available to other vehicles as relevant with the highest possible actuality. This is also relevant for information from the vehicle fleet e. g. on insufficiently visible road markings and signs. For this purpose, standardised data formats and interfaces are essential as well as the availability of a high-performing communication technology.

Road authorities and the road maintenance services would play a complementary role in updating the HD digital map. For example changes in the arrangement of traffic signs and short-term construction sites could be likewise be included into the HD digital map. For this purpose standardised procedures would need to be developed and established.

Nevertheless, it must be stated that such a HD digital map so far does not exist in practice. The technical feasibility of a HD digital map has, however, been demonstrated within research projects e. g. “Ko-HAF”. There are open questions concerning the operator model, standards and interfaces (e. g. to road operators), the update of map data and the involvement of road operators. Particular attention must be given to the aspect of functional safety of the connectivity required as the HD digital map will be applied in the safety relevant area of Automated Vehicle control. There would be high requirements on availability, quality and technical security to be met. It further seems recommendable to evaluate the role of existing platforms such as the National Access Points (e.g. in Germany the Mobility Data Marketplace (MDM)).

Furthermore, the interaction between emergency vehicles and Automated Vehicles (potentially realised by car-to-car communication) as well as the implementation of short-term instructions by police officers remains a challenge.

Research need is also apparent in the analysis of further critical scenarios that take into account a wider range of boundary conditions (e. g. automated driving at night, under rainy conditions) and in this case especially relevant within the area of machine readability of road markings and road signs.

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