Hazard Analysis and Risk Assessment for an Automated Unmanned Protective Vehicle*

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Abstract—For future application of automated vehicles in public traffic, ensuring functional safety is essential. In this context, a hazard analysis and risk assessment is an important input for designing functionally vehicle automation systems. In this contribution, we present a detailed hazard analysis and risk assessment (HARA) according to the ISO 26262 standard for a specific Level 4 application, namely an unmanned protective vehicle operated without human supervision for motorway hard shoulder roadworks.

I. INTRODUCTION

The automation of the driving task is probably the most challenging field of research in the automotive context. Level 4 and Level 5 systems – according to the definition of SAE [1] – combine the unlimited set of operational scenarios encountered in public traffic with the absence of human supervision. This implies highest demands regarding functional safety throughout the development of these systems. Thus, the applicability of the ISO 26262 standard [2] – the most recent standard for designing safety-relevant electronic systems in the automotive context – must be examined.

Following the ISO 26262 standard, a hazard analysis and risk assessment (HARA) is required in order to determine the criticality of the system under consideration. The results of the HARA strongly influence the efforts to be undertaken in the subsequent development steps for ensuring functional safety. Normally, the results of HARAs are not published and thus cannot be discussed in the scientific community due to reasons of non-disclosure. This also applies to the field of vehicle automation.

However, exceptionally high demands regarding system implementation and its safety result from the missing human supervision. Hence, in-depth discussions about functional safety are crucial before deploying automated vehicles in public traffic. In this contribution, we present the complete results of a HARA conducted for a specific Level 4 application. The paper structures as follows: We introduce the project aFAS and the functionality to be implemented in the project in Section II. In Section III, we define relevant terms, describe the HARA approach, and highlight important results. Finally, Section IV contains the implications on designing vehicle automation systems. Complete results of the conducted HARA can be taken from the Appendix.

II. SYSTEM DESCRIPTION & PROJECT CONTEXT

The project aFAS aims at developing an unmanned operation of a protective vehicle (AF A) on the hard shoulder of highways in Germany, cf. [3]. The vehicle is operated without supervision on hard shoulders only and with low speed of up to 12 km/h. The automated operation consists of three operating modes complemented by the Manual Mode which comprises the normal operation of the AFA with a human driver. Safe Halt serves as initial operating mode as well as for switching between Follow Mode and Coupled Mode. Furthermore, Safe Halt is activated if the system leaves functional system boundaries. In Follow Mode, the AFA follows the leading vehicle, which conducts the actual work such as cleaning the hard shoulder, in a defined distance of about 90 m. To follow the leading vehicle and to stay on the hard shoulder, the AFA perceives the leading vehicle as well as lane markings of the hard shoulder by environment sensors. In Coupled Mode, the AFA follows the leading vehicle in close distance of about 10 m in order to pass acceleration and deceleration lanes. This is primarily realized through motion data of the leading vehicle. For transmitting system states and commands (e.g. changes of operating modes), the vehicles communicate via radio.

For the HARA presented in the following (cf. Section III), we concentrated on the parts that are specific for the automated operation in order to reduce the complexity that arises when considering the entire vehicle. The considered functionality is summarized in terms of the item called AFA Logic. However, for unmanned operation additional elements are required, namely drivetrain, brakes, steering and environment perception. These elements are connected with the AFA Logic as depicted in Fig. 1. Hence, safety requirements can be inherited between connected elements.

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Fig. 1. Dependence of AFA Logic and connected elements

2German abbreviation for “Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works”
3German abbreviation for “Automated Unmanned Protective Vehicle”
4Defined as “system or array of systems to implement a function at the vehicle level, to which ISO 26262 is applied” [2, 1.69]
III. HAZARD ANALYSIS AND RISK ASSESSMENT

A. Terminology

A major contribution of the ISO 26262 standard is the definition of more than 100 terms related to functional safety of automotive electric/electronic systems. Yet, some terms must be further clarified for automated driving. In the context of the HARA, the terms hazard, hazardous event, operational situation, and malfunctioning behavior are the most common terms encountered. The term hazard [2, 1.57] is defined as “potential source of harm”, which is consistent to other definitions in safety engineering, e.g. [4], [5]. The definition used in the ISO 26262 standard specifies that a hazard is caused by malfunctioning behavior. Malfunctioning behavior itself is either caused by failures or unintended behavior of the system [2, 1.73]. Hence, the definitions of hazard and malfunctioning behavior are applicable for automated driving.

Furthermore, combining operational situation and hazard yields a hazardous event [2, 1.59]. In contrast to hazard and malfunctioning behavior, the ISO 26262 standard’s definitions of the terms operational situation and hazardous event are vague with respect to automated driving. A similar vagueness can be found in [4] and [5]. An operational situation is defined as “scenario that can occur during a vehicle’s life” [2, 1.83], equaling the terms situation and scenario. However, both terms – together with the term scene – are widely used in the context of automated driving and must be distinguished from each other according to Ulbrich et al. [6], who present a comprehensive literature review regarding these terms. Ulbrich et al. define and substantiate a scene as an all-encompassing snapshot of an environment together with the self-representation of all actors and observers contained (objective scene). In the real world, a scene is always subjective for each observer. A situation is derived from the subjective scene perceived by a traffic participant. It contains all necessary premises to derive suitable driving decisions. A scenario is the temporal concatenation of related scenes. Hence, we utilize the term operational scenario in preference to operational situation in the following since an objective exterior view is what is required for conducting a HARA.

The vagueness of the term hazardous event results from the linguistic ambiguity of the term event. This ambiguity is not resolved in the ISO 26262 standard. Event either addresses a period of time or – in a physical/technical sense – a point of time [7]. In engineering, one would consider the latter as intended meaning, yet the temporal interpretation is meant by the ISO 26262 standard in our understanding. What is actually required for obtaining a classification of safety criticality, is an operational scenario combined with a hazard. Thus, we utilize the term hazardous scenario in preference to hazardous event in the following.

B. Approach

For conducting a HARA, a linear reference process is illustrated in the ISO 26262 standard [2, Part 3], which rather addresses the interdependencies of single steps than necessary iterations to reach completeness. Warg et al. [8] describe an iterative process for developing HARAs in the context of automated driving. The process we applied in regard to the AFA Logic is similar to the approach proposed by Warg et al. and is depicted in Fig. 2. Yet, our approach differs from the approach of Warg et al. in certain aspects and extends it as well: While Warg et al. take a preliminary feature description as initial input resulting in an item definition during the process, our process input is a well advanced item definition.

Furthermore, we introduce two loops instead of one for refining the work products. Effects of both loops on the AFA Logic are described in the following subsection. The item refinement – comparable to the function refinement of Warg et al. [8] – describes extending or (in most cases) narrowing the functional range of the item under consideration. By this means, the merely functional consideration of the item according to the ISO 26262 standard is supplemented by considering technical feasibility, e.g. due to limited project resources or not yet available technology. In contrast, the safety refinement does not affect the functional range. Rather, it aims at refining the determined hazardous scenarios in order to enable technically realizable safety concepts through reaching more precise and definite safety goals. The safety refinement is comparable to the procedure to reach completeness of HARAs of Johansson [9].

Apart from refinement, each iteration loop consists of six steps. In the first step, functionalities are extracted from the item definition. Subsequently, potential malfunctioning behavior and related hazards are derived in the second and third step, respectively. The combination of hazards and operational scenarios derived from the item definition then yields the hazardous scenarios in the fourth step. Determining Automotive Safety Integrity Levels (ASILs) and safety goals are the fifth and the sixth step in Fig. 2 which are strongly linked.

C. Results

We developed the HARA together with experts from the industrial members of the aFAS consortium3, in iterative group meetings. As mentioned, the complete results can be found in the Appendix. In the following, we highlight selected results that affect functional range, environment perception, human machine interface (HMI), and user interaction, as well as central control logic. Table 1 presents the identified safety goals. Its order – as the HARA’s numbering

![Fig. 2. Process of HARA generation and refinement](image-url)
in the Appendix – illustrates the several iterations necessary to obtain a result commonly accepted among the contributors. For instance, safety goal SG16 was added in a later iteration, although strongly connected to safety goal SG04.

Initially, the functional range was supposed to include automated unmanned operation on the motorway’s right lane as well, in order to be capable of driving around obstacles on the hard shoulder. During *item refinement*, however, the functional range was reduced, as this feature was technically too challenging due to limited project resources. Accordingly, the unmanned operation was restricted to hard shoulders as well as acceleration and deceleration lanes, both with a limited velocity of 10 km/h (plus 2 km/h tolerance).

An example for the above mentioned *safety refinement* loop are safety goals SG03 and SG12. Safety goal SG12 was established in one of the first iterations effecting high ASIL ratings on all involved components, namely environment perception, AFA Logic, and actuators. In subsequent iterations, we differentiated between unintended steering actuation beyond the specification of the item definition (up to full steering actuation) and unintended steering actuation within the specification. This results in different hazardous scenarios which were rated separately. Consequently, safety goal SG03 was introduced, which targets at limiting the maximum steering angle and thereby reduces the effects of malfunctioning behavior of other system elements. Due to the limited steering angle, the AFA will intrude the right lane of the motorway with less lateral velocity. Thus, the controllability rating can be reduced as other traffic participants can react more appropriately. By this means, the limitation of the steering angle in automated operation gains the former high ASIL rating (ASIL D) of safety goal SG12 while the rating of safety goal SG12 is reduced (ASIL B).

The previous reduction of the ASIL rating of safety goal SG12 also affects the functional block of the AFA Logic, which must be implemented with ASIL B as well. In discussions prior to the project start, a group of experts from the consortium underestimated the efforts to be undertaken for implementing the AFA Logic as well as of the human machine interaction. If the operating mode is wrongly displayed, the AFA could intrude the right lane of the motorway and cause severe accidents, cf. HARA IDs 37 and 37a in the Appendix. Consequently, the correct display of the actual operating mode must be ensured (safety goal SG07, ASIL A). Both aspects illustrate the high demands on all system parts which originate from the missing human supervision.

The HARA’s results concerning the environment perception are of particular interest, since automated vehicles are operated in an open environment where they encounter an infinite set of operational scenarios. For the AFA, safety goals SG12 and SG13 address environment perception. While safety goal SG12 obtained an ASIL B rating, the detection and reaction to obstacles on the path are rated with QM since persons involved in the scenarios can generally control the scenarios due to the low velocity of the AFA.

As already depicted in Fig. 11 the AFA Logic is connected to further items. Although a HARA is a top-down procedure, at some points technical aspects must be considered. In the planned system implementation of the unmanned operation, the AFA Logic has access to steering and brakes. In particular, the technical implementation of the brake system creates potential for malfunctioning behavior. Therefore, the manual operation must be considered in the HARA as well. As the malfunctioning behavior can create critical outcome in several scenarios, the related safety goals obtain highest ASIL ratings. This means that elements connected to the AFA Logic inherit according safety requirements.

### IV. Discussion and Related Work

Although the functional range considered in the aFAS project is small compared to functional ranges of future automated vehicles, several implications can be derived from our experiences made. The presented HARA is primarily based on the experience and knowledge of the involved contributors from industry and academia with a range of experience from one to more than ten years. Despite the small functional range, the contributors agree on that it was challenging to take all relevant aspects into account in order to reach consistency between item definition and HARA. This reflects in the several iterations necessary to reach a common result. Using only expert knowledge might lead to missed scenarios and thus to building unsafe systems. Consequently, we expect that HARAs for systems featuring more comprehensive functional ranges must be supported by methods and tools. The approach for refining item and safety aspects described in subsection III.B appears suitable in general. However, more distinguished methods must be developed for single steps in order to gain appropriate results.

As input to the HARA process, the AFA Logic’s item definition is written in natural language, supported by some tables and figures. All functionalities considered in the

| TABLE I | PROTECTIVE VEHICLE’S SAFETY GOALS FOR UNMANNED OPERATION |
|---------|----------------------------------------------------------|
| ID      | Safety Goal                                              |
|---------|----------------------------------------------------------|
| SG01    | Unintended and not permitted operating mode change must be prevented. |
| SG02    | Intended and permitted operating mode change must be ensured. |
| SG04    | Display of actual operating mode in HMI must be ensured. |
| SG07    | Manual Mode                                             |
| SG08    | Unintended anti-lock brake actuation must be prevented. |
| SG09    | Unintended acceleration must be prevented.               |
| SG10    | Anti-lock functionality must be ensured.                 |
| SG11    | Steering actuation beyond specification must be prevented. |
| SG12    | Deceleration to standstill must be ensured.              |
| SG13    | Leaving tolerance ranges must trigger operating mode change to Safe Halt. |
| SG14    | Maximum velocity must not be exceeded.                   |
| SG15    | Overturning hard shoulder markings must be prevented.    |
| SG16    | Detection of and reaction to (deceleration to standstill) relevant obstacles (humans, vehicles, etc.) must be ensured. |
| SG17    | Identification of leading vehicle must be ensured.       |
| SG18    | Detection of missing leading vehicle and operating mode change to safe halt must be ensured. |
HARA were extracted manually. This was a process taking several iterations since functionalities had not been considered or had initially been defined contradictory. For items with a wider functional range, item definitions with a more extensive utilization of semi-formal or even formal notations are necessary for ensuring proper identification of all relevant functions and related malfunctioning behavior. Moreover, this eases traceability between item definition and HARA.

For targeting completeness of hazardous scenarios, different approaches for identifying hazards and operational scenarios can be found in literature. Comparable to the approach in the aFAS project, Johansson [9] suggests experts to challenge each single hazardous scenario. If they do not find additional scenarios that lead to new safety goals, the list is likely to be complete states Johansson. However, correct ASIL ratings are required besides completeness of safety goals. Thus, the aFAS consortium also considered ASIL ratings of hazardous scenarios with the same safety goals. Warg et al. [8] propose an identification of both hazards as well as operational scenarios based on tree structures. Out of the aFAS consortium, Bagschik et al. [10] propose an approach for deriving all relevant hazardous scenarios systematically by combining operating modes, functions (derived by skill graphs), malfunctions (derived by a HAZOP analysis), and scene discretization. However, suitability of these approaches still needs to be proven for systems of future automated vehicles in terms of considering all relevant scenarios. The first two approaches need to prove their suitability for automated vehicles with a wider functional range. In contrast, the approach of Bagschik et al. creates automatically an extensive list of scenarios. However, each scenario must be assessed manually regarding safety criticality.

Once hazardous scenarios are identified, the next challenge is determining the ASIL classification. As already mentioned, the classification for the unmanned operation of the AFA is based on expert knowledge. A few aspects of the exposure – such as the rate of emergency stopping vehicles – are justified by investigations of the aFAS consortium. Severity and controllability are purely based on experts’ contribution. Furthermore, standards such as the SAE J2980 standard [11] are of limited contribution for the project aFAS since they do not consider operations on the hard shoulder and focus on vehicle motion control systems. In general, controllability of hazardous scenarios is very low for Level 4 or Level 5 applications with passengers. The controllability of hazardous scenarios without passengers – as in the project aFAS – is determined by surrounding traffic participants. For future application of automated vehicles, methods for objectification of the parameters must be discussed. At least, evolving standards such as the SAE J2980 standard [11] towards automated driving can support a common understanding.

So far, we conclude that methods for a systematic consideration of each HARA step can be found in literature. Consequently, one can argue that a holistic systematic HARA process is beneficial, as i.a. presented by Kemmann and Trapp [12] as well as by Beckers et al. [13]. Kemmann and Trapp [12] introduce A Structured Approach for Hazard Analysis and Risk Assessments (SAHARA), which systematically considers each HARA step. The authors consequently use model based approaches for item definition, hazard identification, as well as for classification of controllability, severity, and exposure. Beckers et al. [13] emphasize utilization of UML based notation. This ensures the traceability throughout the HARA process and enables potential for formal verification. Still, single HARA steps in the approach of Becker et al. strongly depend on expert knowledge. For both approaches, proof of applicability to automated vehicles must be furnished.

V. Conclusion

The example of the unmanned protective vehicle reveals challenges during a HARA for automated vehicles operated without human supervision. It was demonstrated that conventional HARA approaches are of limited suitability, especially for future applications with a wider functional range. Consequently, already existing systematic approaches must be evolved towards automated driving functionalities without human supervision. For this, an in-depth consideration of each single HARA step is required. Furthermore, for merging the two worlds of automated driving and functional safety, clarification of used terminology is crucial to reach a common understanding.

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### APPENDIX

Table III displays the HARA developed in the project aFAS. Omitted and alphanumeric IDs reflect the iterative process of HARA development during item and safety refinement, cf. subsection [II.B] Several IDs were discarded while the ID numbering was not adjusted, in order to preserve traceability between different HARA versions.

#### TABLE II
RESULTS OF HAZARD ANALYSIS AND RISK ASSESSMENT OF THE AUTOMATED OPERATION OF THE UNMANNED PROTECTIVE VEHICLE

| ID | Operating Mode | Function | Malfunction | Hazardous Scenario and Consequence | S | Rationale | E | Rationale | C | Rationale | A | SG |
|---|----------------|----------|-------------|-----------------------------------|---|-----------|---|-----------|---|-----------|---|-----|
| 1 | Manual Mode | Operating mode change | Unintended or not permitted transition to other operating mode | Drive on road in convoy (up to 90 km/h, depending on speed limit). Operating mode change to Safe Halt leads to unpredictable deceleration (4 m/s² in Safe Halt according to item Definitions) to standstill. The same applies when changing to Coupled Mode or Follow Mode, as these operating modes then will be operated beyond accepted parameters, which cannot be an operating mode change to Safe Halt. Deceleration leads to rear-end collision of succeeding vehicle. | S2 | Assuming succeeding traffic participants use seat belts and brakes intuitively, the collision will happen with medium velocity which leads to severe injuries. | E4 | Drive to and from location of road works via roads and motorways occurs for each road work. | C2 | Traffic participants not complying with traffic rules is commonly observable on German motorways (accorded velocities, tailgating, etc.). Reaction time 1.5 s, distance 35 m, deceleration 4 m/s². | B | SG01 |
| 2 | Manual Mode | Steer | Unintended steering | Drive on road or motorway. Unpredictable oversteering from lane leads to collision with other traffic participants. | S3 | Road: Head-on collision with oncoming traffic, true etc. motorway: Collision with moving traffic. Both scenarios can lead to severe or fatal injuries. | E4 | Drive to and from location of road works via roads and motorways occurs for each road work. | C3 | Experience of Bosch Automotive Steering: Full steering angle due to failures is not controllable. | D | SG17 |
| 3 | Manual Mode | Brake | Unintended braking with anti-lock functionality | Drive on road in convoy. Unpredictable maximum deceleration without anti-lock functionality leads to rear-end collision of succeeding vehicle. Multifunction possible due to the planned technical implementation. | S2 | Assuming succeeding traffic participants use seat belts and brakes intuitively, the collision will happen with medium velocity which leads to severe injuries. | E4 | Drive to and from location of road works via roads and motorways occurs for each road work. | C3 | Traffic participants not complying with traffic rules is commonly observable on German motorways (accorded velocities, tailgating, etc.). Reaction time 1.5 s, distance 35 m, deceleration 4 m/s². | C | SG04 |
| 4 | Manual Mode | Brake | Unintended braking without anti-lock functionality | Drive on road or motorway. Unpredictable maximum deceleration without anti-lock functionality leads to rear-end collision. Lateral guidance is not possible, the APA becomes uncontrollable. The APA leaves its lane and collides with stationary objects or other vehicle. Multifunction possible due to the planned technical implementation. | S3 | Collision with uncontrollable vehicle at high velocities leads to severe or fatal injuries. | E4 | Drive to and from location of road works via roads and motorways occurs for each road work. | C3 | According to ISO26262-3, Table B4: Failure of brakes → brakes unnecessarily stopping the vehicle | D | SG16 |
| 5 | Manual Mode | Drive | Unintended acceleration | Drive on road in convoy. Unpredicted acceleration leads to rear-end collision with preceding vehicle. | S3 | Traffic participant skids, resulting crash leads to severe and life-threatening injuries. | E4 | Drive to and from location of road works via roads and motorways occurs for each road work. | C0 | Controllable in general. Due to inertia enough time for driver of APA to react, driver brakes intuitively. | QM | SG05 |
| 6 | Manual Mode | HMI | HMI displays wrong operating mode | No Hazard: Only road workers with special training are deployed on APA. In Manual Mode, the APA is driven as usual. A wrong display of operating modes leads to no more than short confusion. | S0 | — | — | — | — | — | — | QM |
| 7 | Manual Mode | Detection of driver intervention | Driver intervention is not detected | Test operation on hard shoulder, driver intervention is not detected. | S0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | E0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | C0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | QM | SG06 |
| 8 | Safe Halt | Detection of driver intervention | Driver intervention is not detected | Test operation on hard shoulder, driver intervention is not detected. | S0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | E0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | C0 | Driver intervention not detected in Safe Halt does not lead to a hazardous event. | QM | SG06 |
| 9 | Safe Halt | HMI | HMI displays wrong operating mode | No Hazard: APA and leading vehicle in standstill. Operating mode change can only be triggered by operator in leading vehicle. | S0 | — | — | — | — | QM |
| 10 | Safe Halt | Operating mode change | Unintended or not permitted transition to Manual Mode | Truck convoy on right lane. APA on hard shoulder starts to roll (slope, automatic gearbox). This leads to unpredictable behavior including intrusion into right lane. Truck avoids APA, following truck touches APA as the APA is masked by front truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E4 | Scenario (sloped road, traffic on right lane) usually met at each deployment. | C2 | APA drills slowly (e.g. 0.4 m/s²) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG01 |
| 11 | Safe Halt | Operating mode change | Unintended or not permitted transition to Coupled Mode | Moving car traffic on right lane. APA on hard shoulder starts to roll (slope, automatic gearbox). This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible APA. | S3 | Collision with high differential velocity. | E4 | Scenario (sloped road, traffic on right lane) usually met at each deployment. | C1 | APA drills slowly (e.g. 0.4 m/s²) into right driving lane. Following traffic is easily able to recognize this and react appropriately (braking, avoiding). | B | SG01 |
| 12 | Safe Halt | Operating mode change | Unintended or not permitted transition to Follow Mode | No Hazard: Supervision works as defined in Coupled Mode. Immediate operating mode change to Safe Halt since conditions for Coupled Mode are not met (distance to leading vehicle, transmission of odometry data of leading vehicle etc.) | S0 | — | — | — | — | QM |
| 13 | Safe Halt | Operating mode change | Intended and permitted transition to Manual Mode | No Hazard: APA still in standstill. | S0 | — | — | — | — | QM |
| 14 | Safe Halt | Operating mode change | Intended and permitted transition to Coupled Mode | No Hazard: APA still in standstill. | S0 | — | — | — | — | QM |
| 15 | Safe Halt | Operating mode change | Intended and permitted transition to Follow Mode | No Hazard: APA still in standstill. | S0 | — | — | — | — | QM |
| 16 | Safe Halt | Longitudinal guidance | Unintended (slow) acceleration | Truck convoy on right lane. APA on hard shoulder starts to roll (slope, automatic gearbox). This leads to unpredictable behavior including intrusion into right lane. Truck avoids APA, following truck touches APA as the APA is masked by front truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E4 | Scenario usually not met at each deployment. | C2 | APA drills slowly (e.g. 0.4 m/s²) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG08 |

*For reference cf. [2, Part 3] and [11]*
| ID | Operating Mode | Function | Multifunction | Hazard Scenario and Consequence | S | Rationale | E | Rationale | C | Rationale | A | SG |
|----|----------------|----------|---------------|---------------------------------|---|-----------|---|-----------|---|-----------|---|------|
| 17 | Safe Halt      | Longitudinal | Unintended maximum deceleration | No hazard. Minimal impact and no adverse consequences | S0 | —         | E0 | —         | C0 | —         | QM | —    |
| 18 | Safe Halt      | Longitudinal | No stop | Truck converys on right lane. As there is no environment perception active in Safe Halt, intrusion into right lane is possible. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck | S2 | Collision with high differential velocity, vehicles slightly touch | E4 | Safe Halt active at each deployment | C2 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding) | B | SG | 09 |
| 18a| Safe Halt      | Longitudinal | No stop | Moving car traffic on right lane. As there is no environment perception active in Safe Halt, intrusion into right lane is possible. Car on right lane collides with visible AFA | S3 | Collision with high differential velocity | E4 | Safe Halt active at each deployment | C1 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Following traffic is easily able to recognize this and react appropriately (braking, avoiding) | B | SG | 09 |
| 19 | Safe Halt      | Longitudinal | No stop | Obstacle, e.g. an emergency stopping vehicle, on hard shoulder: A person stands between vehicle and AFA. AFA collides with vehicle | S2 | Very low velocity of AFA. Person between AFA and vehicle. This is expected to lead to severe but not fatal injuries | E2 | Obstacles on hard shoulder occur approximately once per week. A vehicle stopping between AFA and leading vehicle is even more unlikely | C1 | People between AFA and obstacle can easily react to a non-stopping AFA by pushing aside due to its low velocity. | QM | SG | 09 |
| 19a| Safe Halt      | Longitudinal | No stop | Obstacle, e.g. an emergency stopping vehicle, on hard shoulder, passengers in vehicle. AFA collides with vehicle. | S0 | Very low velocity of AFA. No injures expected as people in vehicle are protected by passenger cabin. | E2 | Obstacles on hard shoulder occur approximately once per week. A vehicle stopping between AFA and leading vehicle is even more unlikely. | C3 | People in a stopping vehicle only have a very small chance to react to the AFA colliding unexpectedly. Driver might press the brake pedal intuitively. | QM | SG | 09 |
| 24 | Coupled Mode   | Operating mode change | Unintended or not permitted transition to Manual Mode | Truck converys on right lane. AFA on acceleration or deceleration lane. Manual Mode without human driver. This leads to unpredictable behavior including intrusion into right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck | S2 | Collision with high differential velocity, vehicles slightly touch | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C2 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG | 01 |
| 24a| Coupled Mode   | Operating mode change | Unintended or not permitted transition to Safe Halt | Moving car traffic on right lane. AFA on acceleration or deceleration lane. Manual Mode without human driver. This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible AFA | S3 | Collision with high differential velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C1 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Following traffic is easily able to recognize this and react appropriately (braking, avoiding). | B | SG | 01 |
| 25 | Coupled Mode   | Operating mode change | Unintended or not permitted transition to Safe Halt | Moving car traffic on right lane. AFA on acceleration or deceleration lane. Vehicle entering or leaving the motorway collide with AFA. | S2 | Rear-end collision with reduced velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C0 | Driver of vehicle changing to deceleration lane is already braking or ready for braking. Vehicle on acceleration lane in general has moderate velocity. | QM | SG | 01 |
| 26 | Coupled Mode   | Operating mode change | Unintended or not permitted transition to Follow Mode | Moving car traffic on right lane. AFA on acceleration or deceleration lane in order to build up required distance for Follow Mode. Vehicle entering or leaving the motorway collide with AFA. | S2 | Rear-end collision with reduced velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C0 | Driver of vehicle changing to deceleration lane is already braking or ready for braking. Vehicle on acceleration lane in general has moderate velocity. | QM | SG | 01 |
| 27 | Coupled Mode   | Operating mode change | Intended and permitted transition to Manual Mode is not executed | No Hazard: Only for testing purposes. Driver can stop AFA pneumatically by foot brake. | S0 | —         | E0 | —         | C0 | —         | QM | —    |
| 28 | Coupled Mode   | Operating mode change | Intended and permitted transition to Safe Halt is not executed | Truck converys on right lane. Operating mode change to Safe Halt when exceeding functional system boundaries is not executed. This leads to unpredictable behavior including intrusion into right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck | S2 | Collision with high differential velocity, vehicles slightly touch | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C2 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG | 02 |
| 28a| Coupled Mode   | Operating mode change | Intended and permitted transition to Safe Halt is not executed | Moving car traffic on right lane. Operating mode change to Safe Halt when exceeding functional system boundaries is not executed. This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C1 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Following traffic is able to recognize this and react appropriately (braking, avoiding). | B | SG | 02 |
| 30 | Coupled Mode   | Longitudinal and lateral guidance | Vehicle does not follow in defined distance (tolerance range lateral or longitudinal) | Truck converys on right lane. AFA follows leading vehicle with lateral and longitudinal offsets which exceed the tolerance ranges. AFA is partially driving on right lane. Car on right lane collides with visible AFA. | S2 | Collision with high differential velocity, vehicles slightly touch | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C0 | Traffic participants can control the AFA protruding into the right lane as the warning device is active as well as lateral and longitudinal guidance function as intended apart from the lateral offset. | QM | SG | 10 |
| 31 | Coupled Mode   | Longitudinal and lateral guidance | Vehicle does not follow in defined distance (tolerance range lateral or longitudinal) | Moving car traffic on right lane. AFA follows leading vehicle with lateral and longitudinal offsets which exceed the tolerance ranges. AFA is partially driving on right lane. Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C0 | Traffic participants can control the AFA protruding into the right lane as the warning device is active as well as lateral and longitudinal guidance function as intended apart from the lateral offset. | QM | SG | 10 |
| 31a| Coupled Mode   | Longitudinal and lateral guidance | Vehicle exceeds maximum-speed of 12km/h | Truck converys on right lane. The functional components are designed for velocities up to 12km/h. AFA drives at not excessively higher velocity. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles slightly touch | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C2 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG | 11 |
| 31b| Coupled Mode   | Longitudinal and lateral guidance | Vehicle exceeds maximum-speed of 12km/h | Moving car traffic on right lane. The functional components are designed for velocities up to 12km/h. AFA drives at not excessively higher velocity. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C1 | AFA drifts slowly (e.g. 0.4 m/s laterally) into right driving lane. Following traffic is able to recognize this and react appropriately (braking, avoiding). | B | SG | 11 |
| 33 | Coupled Mode   | Longitudinal and lateral guidance | Unintended deceleration | Moving car traffic on right lane. AFA on acceleration or deceleration lane. Vehicles entering or leaving the motorway collide with AFA. | S2 | Rear-end collision with reduced velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment | C0 | Driver of vehicle changing to deceleration lane is already braking or ready for braking. Vehicle on acceleration lane in general has moderate velocity. | QM | SG | 04 |

**TABLE II: Continued from previous page**

For reference cf. [2, Part 3] and [11]
| ID | Operating Mode | Function | Multifunction | Hazard Scenario and Consequence | S | Rationale | E | Rationale | C | Rationale | A | SG |
|----|----------------|----------|---------------|-------------------------------|---|-----------|---|-----------|---|-----------|---|-----|
| 34 | Coupled Mode | Radio communication | Vehicle drivers without radio communication | AFA stops due to inconsistent data of radio communication and environment perception on acceleration or deceleration lane. Vehicles aiming or leaving the motorway collide with AFA. | S2 | Rear-end collision with reduced velocity | E4 | Panning acceleration and deceleration lanes occurs on each deployment. | C0 | Driver of vehicle changing to deceleration lane is already braking or ready for braking. Vehicle on acceleration lane in general has moderate velocity. | QM SG10 |
| 35 | Coupled Mode | Lateral guidance | Staying angle change beyond maximum specification (angle change rate) | AFA drifts with up to maximum possible yaw rate into right lane. | S3 | Collision with high differential velocity. | E4 | Panning acceleration and deceleration lanes occurs on each deployment. | C3 | AFA drifts quickly (e.g. >0.14 m/s²) laterally into the right lane. It follows a circular arc to the guardrail on the left of the left lane. This is difficult to control by traffic participants. | D SG10 |
| 36 | Follow Mode | Detection of driver intervention | Driver intervention is not detected | Test operation on hard shoulder, driver intervention is not detected. | S0 | Only for testing purposes. Driver can stop AFA pneumatically by foot brake. | E0 | Only for testing purposes. Driver can stop AFA pneumatically by foot brake. | C0 | Only for testing purposes. Driver can stop AFA pneumatically by foot brake. | QM SG16 |
| 37 | Follow Mode | HMI | HMI displays wrong operating mode | Truck convoy on right lane. Leading vehicle in standstill, AFA or in Follow Mode, HMI displays Safe Halting or Coupled Mode. AFA starts delayed to follow leading vehicle and enters acceleration or deceleration lane. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | A SG07 |
| 37a | Follow Mode | HMI | HMI displays wrong operating mode | Moving car traffic on right lane. Leading vehicle in standstill, AFA or in Follow Mode, HMI displays Safe Halting or Coupled Mode. AFA starts delayed to follow leading vehicle and enters acceleration or deceleration lane. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible AFA. | S2 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | A SG07 |
| 38 | Follow Mode | Operating mode change | Unmaintained or not permitted transition to Manual Mode | Truck convoy on right lane. Manual Mode without driver. This leads to unpredictable behavior including intrusion into right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E4 | Operation on hard shoulder occurs on each deployment. | C2 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | B SG01 |
| 39a | Follow Mode | Operating mode change | Unmaintained or not permitted transition to Manual Mode | Moving car traffic on right lane. Manual Mode without driver. This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | B SG01 |
| 41 | Follow Mode | Follow hard shoulder | Vehicle does not follow hard shoulder | Truck convoy on right lane. AFA intrudes right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E4 | Operation on hard shoulder occurs on each deployment. | C2 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B SG12 |
| 41a | Follow Mode | Follow hard shoulder | Vehicle does not follow hard shoulder | Moving car traffic on right lane. AFA intrudes right lane. Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | B SG12 |
| 42 | Follow Mode | Keep defined distance | Vehicle does not follow defined tolerable range | No Hazard: AFA continues following hard shoulder based on lane marking. Obstacle detection functions. AFA stops if distance to leading vehicle is too large (leading vehicle out of right interception of radio communication). | S0 | — | E0 | — | C0 | — | QM — |
| 43 | Follow Mode | Obstacle detection | Vehicle does not react to obstacle | Obstacle, e.g. an emergency stopping vehicle, on hard shoulder. A person stands between vehicle and AFA. AFA collides with vehicle. | S2 | Very low velocity of AFA. Person between AFA and vehicle. This is expected to lead to serious yet not fatal injuries. | E2 | Obstacle on hard shoulder occur approximately once per week. A vehicle stopping between AFA and leading vehicle is even more unlikely. | C1 | People between AFA and obstacle can easily react to a non-stopping AFA by stepping aside due to its low velocity. | QM SG13 |
| 44a | Follow Mode | Obstacle detection | Vehicle does not react to obstacle | Obstacle, e.g. an emergency stopping vehicle, on hard shoulder. A driverless vehicle in passenger cabinets. | S0 | Very low velocity of AFA. No imminent expected as people in vehicle are protected by passenger cabin. | E2 | Obstacle on hard shoulder occur approximately once per week. A vehicle stopping between AFA and leading vehicle is even more unlikely. | C3 | People in a stopping vehicle only have a very small chance of reacting to the AF A unexpectedly. Driver might press the brake pedal intuitively. | QM SG13 |
| 44 | Follow Mode | Longitudinal guidance | Uncontrolled deceleration | No Hazard: AFA stops on hard shoulder with active warning device and transitions to Safe Bath. | S0 | — | E0 | — | C0 | — | QM — |
| 45 | Follow Mode | Perceive leading vehicle | Vehicle keeps distance to wrong object | Truck convoy on right lane. AFA follows wrong leading vehicle which does not step in front of acceleration or deceleration lanes. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. Truck avoids AFA, following truck touches AFA as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles slightly touch. | E1 | Vehicle driving on hard shoulder for a longer period of time and with velocity < 10 km/h occures very rarely. | C2 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | QM SG14 |
| 45a | Follow Mode | Perceive leading vehicle | Vehicle keeps distance to wrong object | Moving car traffic on right lane. AFA follows wrong leading vehicle which does not step in front of acceleration or deceleration lanes. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. Car on right lane collides with visible AFA. | S2 | Collision with high differential velocity. | E1 | Vehicle driving on hard shoulder for a longer period of time and with velocity < 10 km/h occures very rarely. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | QM SG14 |
| 46 | Follow Mode | Perceive leading vehicle | Vehicle follows hard shoulder without leading vehicle | Truck convoy on right lane as well as vehicles driving on acceleration and deceleration lane. AFA does not detect begin of acceleration or deceleration lane. Thus, it exceeds its functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. | S2 | Collision with high differential velocity, vehicles slightly touch. | E0 | Operating instructions prohibit activation of automated operation without leading vehicle. | C2 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | QM SG15 |
| 46a | Follow Mode | Perceive leading vehicle | Vehicle follows hard shoulder without leading vehicle | Moving car traffic on right lane as well as vehicles driving on acceleration and deceleration lane. AFA does not detect begin of acceleration or deceleration lane. Thus, it exceeds its functional system boundaries. This leads to unpredictable behavior including intrusion into right lane. | S3 | Collision with high differential velocity. | E0 | Operating instructions prohibit activation of automated operation without leading vehicle. | C1 | AFA drifts slowly (e.g. <0.4 m/s) laterally into right driving lane. Following traffic is usually able to recognize this and react appropriately (braking, avoiding). | QM SG15 |
| 47 | Follow Mode | Radio communication | Vehicle leaves range of radio communication | No Hazard: Interruption of radio communication causes transition to Safe Bath. AFA stops on hard shoulder with active warning device. | S0 | — | E0 | — | C0 | — | QM — |
| ID | Operating Mode | Function | Malfunction | Hazard Scenario and Consequence | S | Rationale | E | Rationale | C | Rationale | A | SG |
|----|----------------|----------|-------------|---------------------------------|---|-----------|---|-----------|---|-----------|---|-----|
| 48 | Follow Mode    | Operating mode change | Intended and permitted transition to Safe Halt is not executed | Truck convoy on right lane. AFA must transit to Safe Halt, e.g. due to exceeding a functional system boundary. Transition to Safe Halt does not function. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Truck avoids AFA, following truck touches AFA, as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles collide. | E4 | Operation on hard shoulder occurs on each deployment. | C2 | AFA drifts slowly (e.g. 0.4 m/s lateral) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG02 |
| 48a| Follow Mode    | Operating mode change | Intended and permitted transition to Safe Halt is not executed | Moving car traffic on right lane. AFA must transit to Safe Halt, e.g. due to exceeding a functional system boundary. Transition to Safe Halt does not function. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. 0.4 m/s lateral) into right driving lane. Following traffic is easily able to recognize this and react appropriately (braking, avoiding). | B | SG02 |
| 49 | Follow Mode    | Operating mode change | Intended and permitted transition to Manual Mode is not executed | No Hazard: Only for testing purposes. Driver can stop AFA pneumatically by foot brake. | S0 | — | E0 | — | C0 | — | QM | — |
| 50 | Follow Mode    | Radio communication | Vehicle drives without radio communication | No Hazard: Detection of lane markings and obstacles as well as HMI function as intended. AFA stops when leading vehicle stops according to work instructions before passing acceleration or deceleration lanes. Then, malfunction becomes obvious by missing transition to Coupled Mode. | S0 | — | E0 | — | C0 | — | QM | — |
| 51 | Follow Mode    | Longitudinal guidance | Vehicle exceeds maximum speed of 12km/h | Truck convoy on right lane. The functional components are designed for velocities up to 12 km/h. AFA drives at not excessively higher velocity. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Truck avoids AFA, following truck touches AFA, as the AFA is masked by first truck. | S2 | Collision with high differential velocity, vehicles collide. | E4 | Operation on hard shoulder occurs on each deployment. | C2 | AFA drifts slowly (e.g. 0.4 m/s lateral) into right driving lane. Despite of masking by truck in front, following traffic is normally able to recognize this and react appropriately (braking, avoiding). | B | SG11 |
| 51a| Follow Mode    | Longitudinal guidance | Vehicle exceeds maximum speed of 12km/h | Moving car traffic on right lane. The functional components are designed for velocities up to 12 km/h. AFA drives at not excessively higher velocity. AFA exceeds functional system boundaries. This leads to unpredictable behavior including intrusion into right lane (e.g. oscillating steering angle control). Car on right lane collides with visible AFA. | S3 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C1 | AFA drifts slowly (e.g. 0.4 m/s lateral) into right driving lane. Following traffic is easily able to recognize this and react appropriately (braking, avoiding). | B | SG11 |
| 52 | Follow Mode    | Lateral guidance | Steering angle change beyond maximum specification (angle & change rate) | AFA drifts with up to maximum possible yaw rate into right lane. | S3 | Collision with high differential velocity. | E4 | Operation on hard shoulder occurs on each deployment. | C3 | AFA drifts quickly (e.g. >)0.4 m/s lateral) into the right lane. It follows a circular arc to the middle of the left lane. This is difficult to control by traffic participants. | D | SG03 |