BMW'S SAFETY GUIDELINES FOR THE TESTING AND DEPLOYMENT OF AUTOMATED VEHICLES

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ABSTRACT

As automobile manufacturers take the leap from Advanced Driving Assistance Systems and implement Automated Driving Systems into their vehicles, certain aspects of vehicle safety become increasingly important. Whereas in today's level 2 automation, the human driver is involved in the dynamic driving task, in level 3 and above, more technological measures are necessary to ensure safety, therefore requiring a newly designed electronic architecture. Nonetheless, analysis of human factors remain a key element to ensure the safe operation of the vehicle. Though conventional techniques may be employed to solve some of these challenges, others require new tools to be developed. In the absence of an international standard, the foundation for discussions of completeness is missing. With an expert analysis of topics and tools a focus can be brought into discussions and serve as a basis for further development. This analysis may also lead to uncover areas where final answers and methods are missing, but serves also to identify areas where effort must be concentrated. When members of the industry apply these principles to the development of automated driving systems, the number of accidents will be minimized following the testing and deployment of this new technology, therefore maximizing safety and customer acceptance.

This submission represents the culmination of multiple sessions within industry, but also with contracting parties and government agencies with the goal of the creation of a comprehensive list of guidelines for the safe development of automated driving systems.

BMW has defined 12 different areas that have been focused into guidelines for the development of a vehicle with a safe automated driving system. These areas include topics from functional safety through the human factors aspects of system handovers to the consideration of passive safety.

While the 12 guidelines are selected to be a comprehensive list of safety topics, they are general in form and do not contain the details necessary to apply it as a blue print for the development. As these automated driving systems are not on the roads in appreciable numbers, the data from real world events are missing. Also the projects to develop the methods to generate and analyze data are still underway, which also forces some guidelines to remain broadly formulated.

The proposed guidelines concentrate the capabilities and limitations of today's safety evaluation for vehicles when applied to automation. By following the guidelines, the industry can ensure that this technology meets an acceptable level of safety when it comes to market.

INTRODUCTION

Automation has defined many areas of development for the past decades and will continue for many to come. From the automation of our digital daily planner to the robots used in manufacturing, our lives have been enabled to move more comfortably, faster and in many ways safer. This trend also continues in the cars we drive. Many areas secondary to the driving task such as automatic climate control and lighting simply make it easier for the driver to drive. Other areas of assistance have a more direct influence on safety as they take action to apply corrective measures to the brakes or steering to avoid an accident at the last moment. Still other features also actuate the brakes, accelerator and steering, but to increase comfort through constant input. Not surprising, these features are all examples of what are called Advanced Driver Assistance Systems, as they assist the driver, who remains in control and responsible at all times.

Based on German accident statistics [1], the errors that these human drivers make cause over 98% of recorded accidents. For that reason, further automation sounds like it would be a simple answer to have a major effect on the worldwide number of accidents. Many have claimed that removing the human from the equation would quickly result in safer streets. After further analysis of the statistics, it is apparent just how challenging this task would be. Overall, accidents are actually quite rare occurrences. Again according to German statistics, once the total life time mileage of 700,000km is taken into account, there is an average distance of approximately 300,000 km between two accidents with any severity. This number raises to 228 million km if fatal accidents are considered, and the distance increases to even 661 million km if we solely look at highways.

These statistics show that the human drivers are actually quite adept at handling the complexities of on-road traffic, and the endeavor of creating technology to accomplish this much is quite daunting. Just reaching this level could be considered difficult enough, but in June 2017, the German Ethical Commission [2] recommended that manufacturers show that the technology used to automate the vehicles perform better than the statistics indicate humans do today. Whereas humans have an amazing capacity to use intuition and anticipation for complex situations, technology has the advantage of offering a 360° view of surroundings, simultaneously processing the information and does not fatigue. When it comes to a safe development of automated vehicles, we need to understand and learn from both the capabilities and limitations of the human driver, while simultaneously taking the risks into account that may emerge from their interaction with an automated vehicle. That could be the handover between a driver and the automated vehicle, or the interaction of road users in a mixed traffic scenario. Therefore, even with higher levels of automation, taking the human factors into account is key to generate a safe system.

To better understand where automation technology in automobiles currently stands, as well as the areas that development is currently engaged in, a brief review of the accepted definitions is necessary. Presently in its 3rd iteration, SAE J3016 [3] is the internationally agreed upon standard to define different levels of automation.

While a detailed discussion on the wide range of topics described in the standard is beyond the scope of this paper, several terms shall be described here and referred to in the guidelines. Divided into 6 discrete levels of automation and based upon the separation of tasks required to drive a vehicle, one of the key areas is the operative control of longitudinal and lateral systems (accelerator, brake, steering) which is referred to as the Dynamic Driving Task (DDT). Independent of whether the system or the human is performing this control, the decisions necessary are based on the recognition of objects and events that occur surrounding the vehicle (Object and Event Detection and Recognition- OEDR). In order to group the conditions such as environmental, geographic or similar which are necessary for the system to operate, the term Operational Design Domain (ODD) has been generated.

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	OEDR		
Driver performs part or all of the *DDT*						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS ("*System*") performs the entire *DDT* (while engaged)						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 1, table of SAE Automation levels [3]

Today, the technology available on large scale production vehicles allows a maximum of level 2 partial driving automation. As the driver is still responsible for the object and event detection the system can actually only assist them in driving the vehicle. The fact that this responsibility is transferred to the system in level 3 and beyond leads to a paradigm shift and a technological quantum leap is necessary to attain it. For simplification, systems capable of level 3 functionality and beyond can be referred to as Automated Driving Systems (ADS)[3]. As discussed in WP29 of UNECE [4] one of the major changes that an ADS brings is that at these levels of automation, activities secondary to the driving task would be explicitly allowed to be undertaken by the driver. Since the system performs the DDT, the driver no longer has this responsibility and is free for other activities such as watching a film on the vehicle displays. The driving task is no longer considered the primary task of the driver in these scenarios, therefore, secondary tasks are also referred to as Non-Driving-Related-Tasks, or NDRTs [5].

It is widely acknowledged that transition between level 2 and level 3 is not trivial [6], and for that reason a common language is necessary to discuss the challenges both inside and outside of the automotive industry. Expert groups within BMW gathered topics and clustered them to generate a comprehensive list of 12 guidelines for the development of automated driving systems. Through review of other recommendations and publications from government bodies or consumer associations such as NHTSA [7], Thatcham Research [8], NTSB [9], GDV [10], the German StVG [11] and the German Ethical Commission [2], it was found that there was much communality between the collections. Nonetheless, additional aspects as well as new viewpoints are introduced here.

To organize BMWs 12 guidelines, an arrangement in three overall groups with common areas of influence were found. The first four guidelines represent technological areas necessary for the system. As in all three groups, though initially simple in form, the details to develop the answer are currently engaging the entire automotive industry. Next is the area of human factors which are also extremely important even for higher levels of automation. While the last four guidelines do not directly create requirements for the automation system, they are areas necessary to be addressed during development of vehicles.

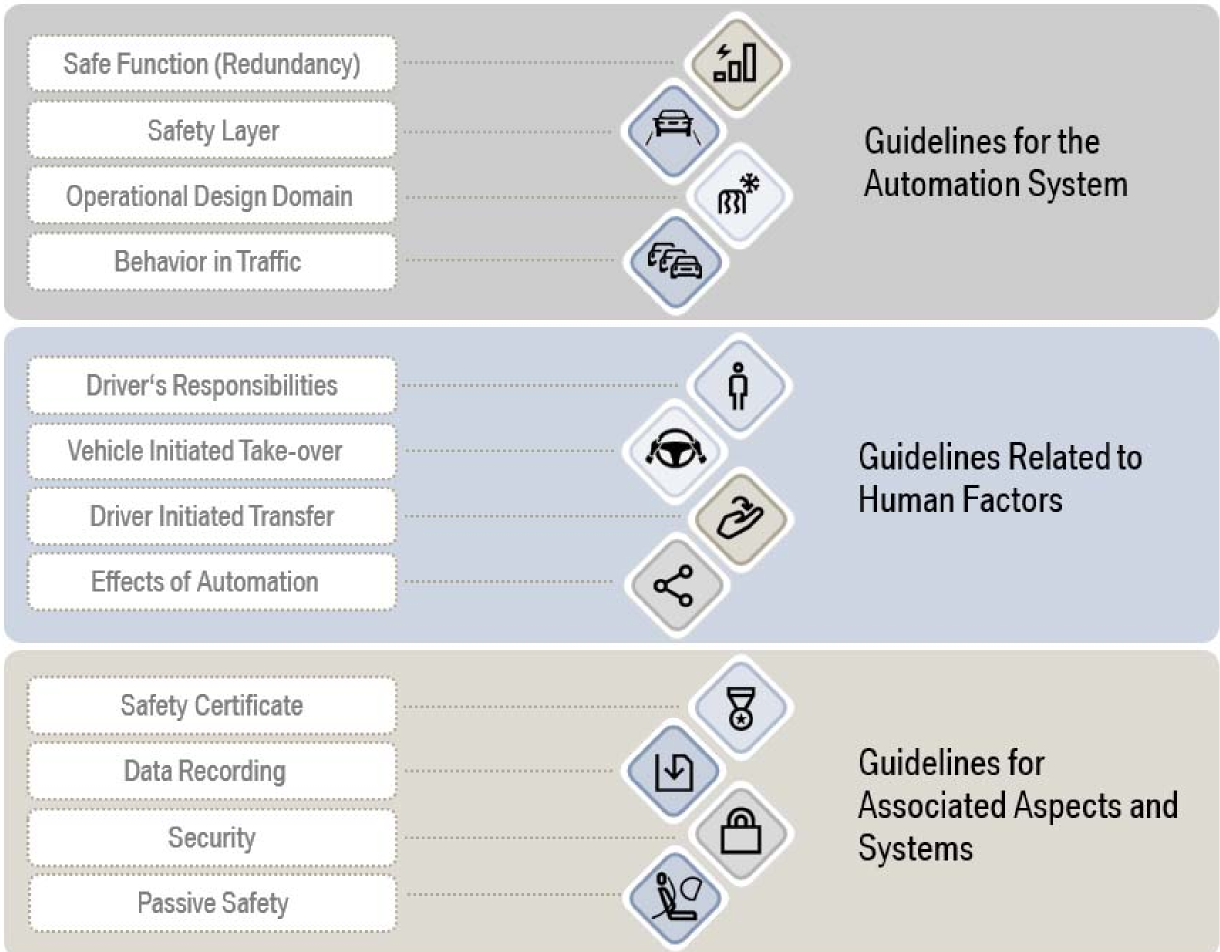

Figure 2 – BMW's 12 Guidelines for Safe Automated Driving Systems

GUIDELINES FOR AUTOMATED SYSTEMS

1. Safe Function (Redundancy)

With automotive systems becoming ever more complicated, the concepts gathered under the term functional safety have become ubiquitous in all areas of automotive development. Either bundled under automotive best practices as ISO 26262-Road Vehicles Functional Safety [12] or other standards from other industries and the military, the processes as well as the measures which result from them have an even higher relevance for automated driving systems. In this list of guidelines, the following aspects gather two of the key elements.

<u>Dealing with Degradation</u>

> If system components relevant to the function or individual functions become non-available, the automation system must be capable of compensating or ensuring a sufficient time budget for safe transfer of control to the driver.

This aspect embodies one of the major differences between how a level 2 and level 3 or higher automated driving system must be capable of reacting. As mentioned above, level 2 systems merely assist the human driver and therefore the driver must react if the system does not respond to a relevant object or event. For this reason they can never completely relinquish control and if an aspect of the assistance is no longer available, the driver continues to drive. Once the driver is involved in NDRTs at Level 3+, additional time is necessary before they can resume the responsibility of the DDT from the ADS.

While some have called for redundancy to be the only option to deal with the risk emerging from a degradation, there are also other strategies which can be followed to ensure a safe system behavior. As such, simply the reduction of speed, or avoiding a lane change are two examples of strategies to safely increase the time and reduce risks when aspects of the automated driving function are no longer available. The key is that some form of compensation is necessary.

Fail Operational

The loss of sub functions or system components shall not lead to a safety critical situation.

Continuing along the same idea is that if any component or portion of the system fails, the result shall not be safety critical. This applies to both hardware malfunction which could come from mechanical damage or software/electronic errors.

Due to the new vehicle architecture necessary to fulfill this higher requirement, a level 3+ system is intrinsically different to a level 2 system, independent of the increased competence of the object detection and reaction. For that reason, a system designed as level 2 cannot become a level 3 system simply due to improvements in software. It is the way the system is networked and the measures in the actuators that make it inherently different.

2. Safety Layer

To reduce the frequency of critical situations, automated driving systems of every level are generally designed to drive defensively. Unfortunately even at a reduced frequency, these events will occur and the system must react.

Safety Layer

The automation system must recognize system limits, especially those that do not allow a safe driver take-over, and react to minimize the risk.

There has been a misunderstanding of level 3 automated driving systems in exactly this area. As stated in SAE J3016, it is expected that the fallback ready user regains control in short notice when the system requests it. Of course they are likely performing a task unrelated to driving, so the reaction by the human to an emergency situation may not be possible or inadequate [13]. Further has to be considered that the driver may need additional time for executing the required maneuver to react to the event. For this reason, even in a level 3 system, the system must react to minimize the risk of situations where a transition to the driver is not possible or reasonable, in order to reach an acceptable safety level.

This safety layer must be present below the system carrying out the long term control. Using humans as an analogy, we all have a cognitive layer that allows us to perform complicated activities. As critical situations are rare, a majority of the time is processed in this area. In emergency situations, a faster reaction is necessary to reduce following risk. This is akin to the nervous system, which must quickly react.

Just as human senses provide the information for these quick reactions, the sensors in automated driving systems provide the information for this layer. Therefore, these active safety systems can be found in all levels of automation, though their importance increases in level 3 and above.

Though discussed in further detail in the following section, other system limits may be observed and recognized by the system which are not immediately time critical, as illustrated in Figure 3. For this reason, the fallback ready user of a level 3 system must be able to intervene in these situations with a time allowance on the order of seconds.

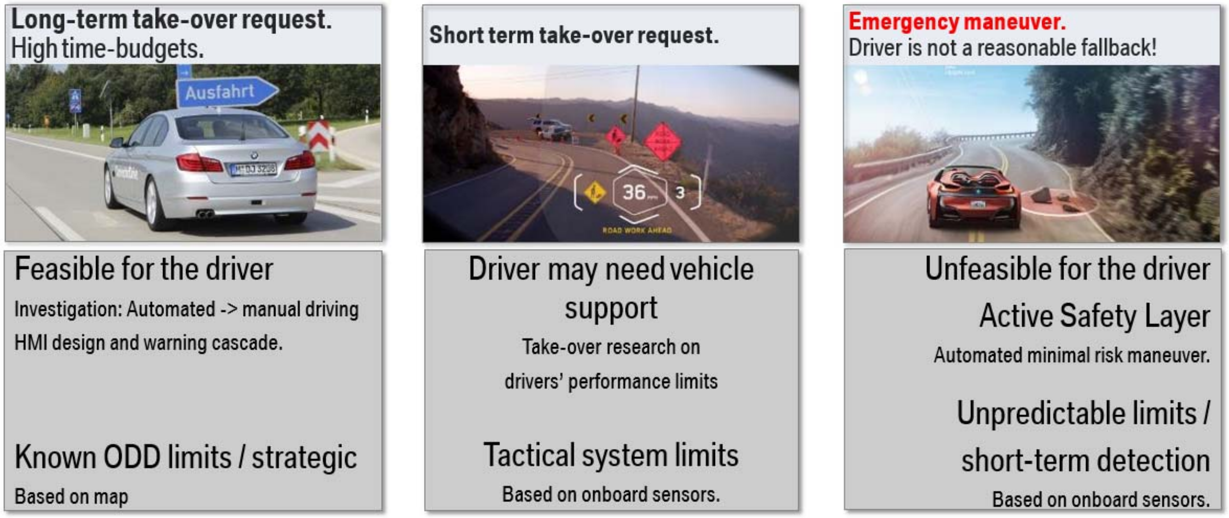

Figure 3 – Comparison of emergency maneuver with other situations

3. Operational Design Domain

Another driving force behind the requirements on the system for higher levels of automation originate in the definition of the operational design domain (ODD). As previously mentioned, the ODD as defined by SAE J3016 is the collection of conditions where the system is designed to operate. Examples can be geographic as in the country or state, environmental as from sunshine to snow, or a collection of roadway characteristics such as a divided highway. As the function is designed to operate safely in this domain, sensors shall confirm at all times that the vehicle is still in that domain.

ODD recognition

> As soon as system limits, which restrict the safe functionality of the automation system, are recognized, the system must react to compensate, or request a take-over from the driver with adequate time reserve.

Since the automated driving system is limited to an ODD and while activated in this domain, it is responsible for vehicle control until it requests the fallback ready user to intervene. While this may sound trivial, in lower levels of automation, it is ultimately the driver's responsibility to recognize when the limits are reached. The system may provide assistance to that effect, but only higher levels of automation need to definitively register the limits as a reaction is necessary.

Manage typical situations

> The automated driving system must take situations into account, which can typically be expected to be encountered in the ODD and address the risks that may result.

The sensor arrays of vehicles equipped with automated driving systems need to register and classify much more than only the most common objects and the situations they are associated with. Even when they only make up a small percentage of the time spent on the road, there are a multitude of events such as an unexpected lane change, which happen often enough that they cannot be considered unusual. The system shall therefore be able to deal with all situations that are foreseeable to occur within the ODD which have an inherent risk of relevant magnitude.

4. Behavior in Traffic

In the near future, production vehicles capable of conditional automated driving will be on the road. Nonetheless that will only be the beginning of the phase of mixed driving with some conventional vehicles and some automated vehicles sharing the road. Even in today's traffic with solely conventional vehicles, one contributing factor to safe driving is the relatively similar behaviors of most drivers.

Manners on the road

> The behavior of the automated function needs to not only be comprehendible to the surrounding road users, but also predictable and manageable.

As mentioned in the introduction, human drivers are often able to apply their intuition and anticipate the actions of other road users based on their experiences. This predictability allows for traffic flow and cooperation between drivers with remarkably limited possibilities for communication. For instance, on the highway using only turn indicators and brake lights, a somewhat complicated coordination of maneuvers can be accomplished to allow a lane change in traffic. Additional lines of communication may even create confusion as human drivers learn how to interpret new signals. Furthermore, an unobtrusive behavior of the automated system reduces the implications emerging from new interaction patterns of a mixed traffic environment.

Conforming to Rules

> The applicable traffic rules are to be taken into account.

One method to ensure that driving behavior is similar among drivers is to establish rules. These traffic rules have developed over the last century of human driven vehicles and are often based on human traits such as average reaction time and visibility. Even with these rules there is room for interpretation of the applicable law and in certain situations, drivers are allowed to deviate to a certain extent in some aspects. This poses the question as to whether these rules apply to vehicles with automated driving systems with faster reaction times, a 360 degree field of view, and sensors such as radar, and how the applicable law is interpreted for ADS. As our society develops, the rules and interpretations may change, but the algorithms behind the automated driving systems need to bear them in mind.

GUIDELINES RELATED TO HUMAN FACTORS

5. Driver's Responsibility

Depending on the level of automation being offered by a vehicle, the driver's responsibilities may change. At lower levels, the driver is responsible for all actions of the vehicle except those attributed to a defect. At the highest level, the driver can be relegated to an operator. For the portions of the trip where it is active, an ADS is responsible for all parts of the DDT, but at a minimum the driver needs to ensure that vehicle maintenance has been taken care of. Other responsibilities of the driver may include a reaction after the failure of a suspension component, the correct loading of cargo and maintaining an appropriate seating position if a takeover may be necessary. Complicating matters further, a single vehicle can offer multiple levels of automation depending on the situation. For instance in one operational design domain limited to the highway, there may be a level 3 function available, but once the vehicle is in an urban environment only level 2 or 1 functions may be available.

Responsibilities

> The portions of the driving task which remain under the driver's responsibility must be clearly communicated to him/her.

From passages in the owner's manual to the way information is displayed in the vehicle, the manufacturer shall take care to take advantage of the various lines of communication so that the driver understands their responsibilities and act accordingly.

Driver's State

> To promote safety, systems need to be integrated that support the driver to recognize driver conditions that are not acceptable.

Though it does not obviate the driver's awareness of their responsibilities, technology can assist the driver if they are presenting characteristics, which conflict with system requirements on the driver. For instance, by using information provided by simple seatbelt contacts, the system can provide a reminder to the driver that they may not leave their seat. Nevertheless, as it is not possible to reliably detect all forms of misuse, no technology can replace the driver's conscious heeding of their responsibilities.

Mode Awareness

The automated function must ensure that the currently active driving mode can be recognized explicitly and unmistakably at any time. If the driver must react, this must be clearly communicated.

As the single vehicle can offer multiple modes of operation, the driver must be aware of which level of automation is currently operational in the vehicle, in order to enable a correct use of the respective assistance or automation system. Through countless hours of simulator studies [14], measures are being defined and implemented in the human machine interface to give this awareness to the driver. While a level 2 system could expect the driver to recognize the necessity to take action, higher levels of automation must communicate whether there is a need for it.

6. Vehicle initiated handover

Even for higher levels of automation, the vehicle may request that a driver take over control of the vehicle. One example is when a portion of the trip is no longer within the system's ODD, and the driver simply would need to once again takeover with the vehicle controls. Other extenuating circumstances may require a takeover in vehicle concepts without conventional controls in level 4. Here the human requested to drive the vehicle may do so remotely, continuing to use the vehicle's sensors and actuators.

Minimal Risk Condition

If the driver does not comply with a take-over request, the ADS must perform a maneuver to minimize risk. The correct maneuver depends on the situation.

Though the reasons for initiating a handover may vary, automated driving systems need to follow a strategy between the time that the request is given and when the driver takes control. Depending on the technology available on the vehicle as well as the situation, the reaction can be as simple as reducing speed to reduce the risks, or as complicated as changing lanes and pulling over to a safe harbor parking space. It is important to note that this minimal risk condition may have a different character depending on whether it is an emergency maneuver, triggered by a loss of sub functions or system components, or a long term take-over request (Figure 3).

Take-Over requests

Handovers must be manageable for the driver.

Hand in hand with the safety layer, time critical emergency situations would not be manageable if the driver is requested to take over in those situations. As with other guidelines associated with human factors, studies taking place in simulators [13] and other controlled environments indicate what time budget and take-over scenario is manageable for the average driver [15] and how an adequate take-over request should be designed [16], and how control elements and human machine interfaces [17] can be adopted to support the driver in taking over control.

7. Driver initiated transitions

Often neglected when considering automated driving systems, there are situations when a driver would want to regain control of the vehicle. A simple example would be to have the full driving experience along an engaging stretch of road. However, there are situations where the driver may touch the controls without actually desiring to regain control.

Take-Over (driver)

Activating and deactivating the automated driving system requires explicit driver‘s intent.

Differentiating the intent can mean the difference between accidentally contacting one of the driver controls (i.e. steering wheel) while reaching for an object, and explicitly taking the wheel to negotiate a curve. Relinquishing control in the former could result in a critical situation. While the driver should be able to take-over control if he intends to do so, an unintended take-over could result in a handover to a driver who is not ready or able to take on the driving task. For that reason concepts must be developed to differentiate between the two situations. Furthermore, there is a wide range of vehicle functions relevant or connected to the functioning of the ADS. Driver interaction with those functions should neither lead to an inexplicable hand-over, nor to a safety relevant change of the ADS state.

8. Effects of Automation

Made evident from other industries with high levels of automation, such as the commercial aviation industry, humans adapt to the automation they experience.

Effects of Automation

> In the overall evaluation of system safety, effects on the driver due to automation need to be taken into account, even when they occur after the automated portion of the drive has ended, when a direct link to the drive while automated can be drawn.

Studies continue to be performed to analyze these effects in the automotive context [18]. Acknowledging that these occur is the first step to implementing measures to counteract them. These measures may include optimizations to the human machine interface [19], which further support mode awareness.

GUIDELINES FOR ASSOCIATED ASPECTS AND SYSTEMS

9. Safety Assessment

In addition to BMW's long history of striving to improve road safety, the German Ethics Commission [2] has also tasked the automotive industry to ensure that the automated driving system, which in some ways replaces the driver in performing the DDT, is safer than the average driver.

Safety Assessment

> Verification and validation shall be used to ensure that the safety goals are met, in order to reach a consistent improvement of the overall safety balance, while minimizing new risks induced by the automation system.

In order to compare the performance of the system to that of human drivers, methods are being developed to quantify and assess how they perform. Simulation and prospective safety analysis [20] is playing a key role in generating the data. As this task effects a multitude of companies and institutions developing this technology, several cooperation projects have been initiated. One showing promise to deliver some of the answers is the PEGASUS project [21] supported by the German state. Summarized in Figure 4, a process of scenario collection, abstraction, database generation and validation is described. An international project titled L3 Pilot [22] is also poised to deliver pieces to the puzzle in quantifying safety and performance.

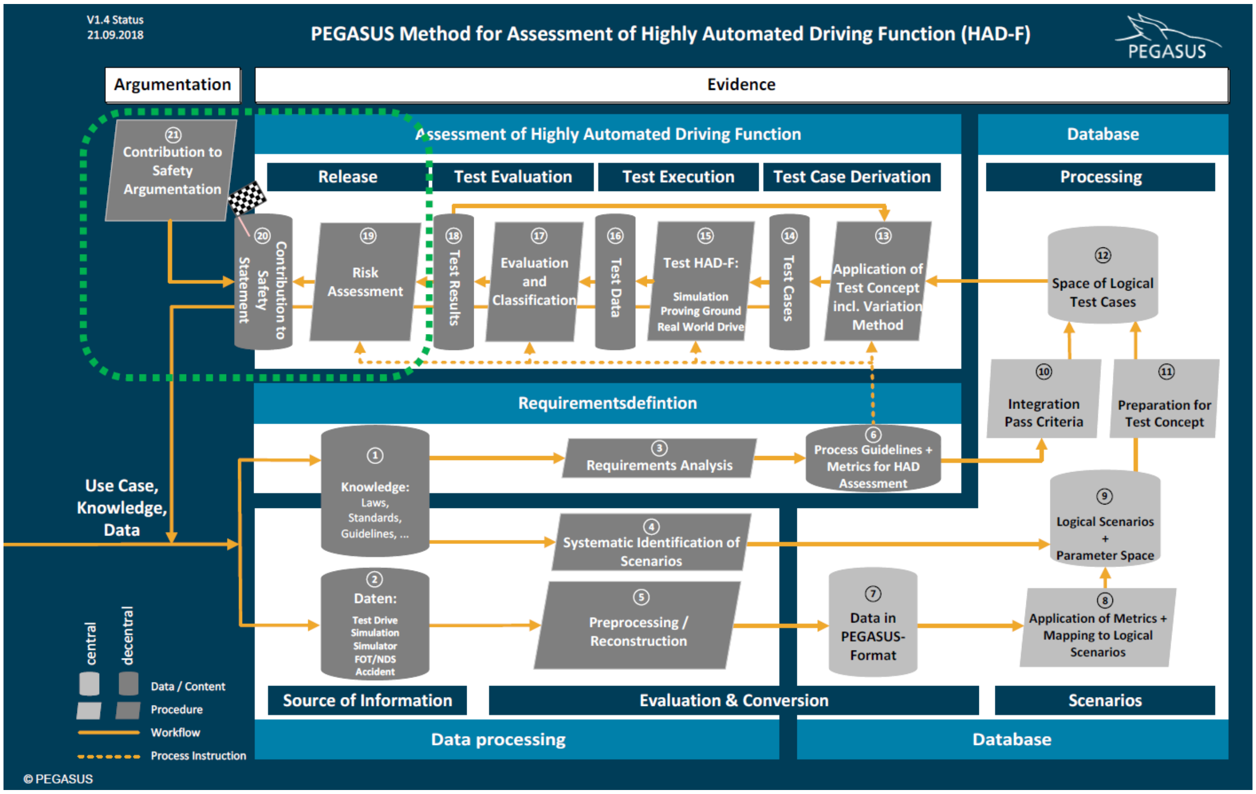

Figure 4 Summary of the Pegasus method [13]

10. Data Recording

Even with today's conventional vehicles, some markets have required that data is recorded in the event of an accident or similar situation. Information about the scenario leading up to the accident can be provided by the driver. Once the driver is no longer performing the DDT, this information will have to be recorded by the system.

Data Recording

While conforming to the applicable data privacy laws, automated vehicles shall record the relevant data pertaining to the status of the functions when an unusual event is recognized.

Just as the today's driver is responsible for driving, their memory serves to aid in reconstructing what happened during a critical or emergency situation. Once this responsibility is transferred to the technology, it must also have the equivalent of a memory to provide information in those situations. As this data contains details, in accordance to privacy laws, access to the data will be limited.

11. Security

In a world of ever increasing connectivity, security is tantamount for information to only flow between appropriate places. In the financial industry or even online trade, the penalty for inadequate security is financial difficulties. In the automotive world, the consequences can be much more drastic.

(Cyber-) Security

When offering an automated driving function, steps shall be taken to protect the function from threats.

With a history of connectivity, BMW has been addressing cyber security for decades. As control systems for the steering and brakes for even level 0 and 1 systems depend on the flow of information from sensor to actuator for a safe operation, even hardware access points are taken into account. Automated driving systems pose additional challenges as the actuators have even higher capabilities and the driver is further removed from the driving task. Just as the attacks evolve from year to year, so must the defense as security directly effects safety.

12. Passive Safety

A motivation for the development of automated driving systems is the overall reduction of accidents which take place on public roads. Nonetheless due to unforeseen circumstances, unfortunately accidents will still occur and the passive safety necessary to protect the occupants will be necessary.

Crash Scenarios

The vehicle layout shall accommodate modifications to crash scenarios brought about by vehicle automation.

The accident statistics stored in all of the databases around the world are generated by vehicles driven by human drivers. The accidents involving automated vehicles will be fewer in number, but it is likely that there will be a shift in the distribution. For that reason, a re-evaluation of relevant scenarios for the development of passive safety systems will be necessary.

Alternative Seating Position

Occupant protection shall be ensured even when new uses for the interior are made possible by automation.

When the driver no longer needs to be involved in the dynamic driving task, new interior possibilities arise for the driver to fully take advantage of the situation. These new interior configurations will also need to be taken into account during the development and verification of passive safety systems.

CONCLUSION

Though there is still much work to be done in the development of large scale automated driving systems, BMW's 12 guidelines for automated driving systems establish a framework and a baseline. Building upon them, a collective discussion can occur both within the industry as well as with important stakeholders outside. This discussion is necessary as questions still remain, and in order to answer them, research continues to take place. Together this common understanding will help bring us forward to a safer future.

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