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Automated Driving – Testing at the Functional Limits

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***Abstract*—As vehicles move toward a high degree of automation, the control of the vehicles is taken over from the human drivers for increasing periods of time. This will allow the human drivers to turn their attention away from the vehicles and to focus on non-driving activities instead. With the takeover of the vehicle control, the automobile manufacturers also take over the responsibility for the driving maneuvers automatically performed by the vehicles. As a result, they can no longer rely on immediate interventions of the human drivers in case of critical situations, where the vehicles cannot cope with the road traffic or if the vehicles behave in an unexpected way. Intensive testing activities are necessary to ensure the safety of the vehicles in any situation. Even when the vehicles do not work as expected, a safe state must be achieved without endangering the passengers or other road users. To test automated driving, the established software testing techniques, which have been in use so far in the automotive development, seems no longer sufficient due to the temporary unavailability of the human driver as an immediate fallback level. Revised test approaches that do not require immediate human interventions to ensure the safety of the vehicles are therefore needed. This paper depicts the characteristics of automated driving from a functional point of view and presents an approach based on those characteristics to test the system at its functional limits. Therefore, it makes no difference whether the system reaches its limits by itself or by the individual behavior of other road users on the street.**

Keywords–Automated Driving; Automotive Testing; Functional Limits; Individual Behavior.

I. Introduction

This paper extends our previous approach to test automated driving [1], which distinguishes between the functional and temporal behavior of the system, as well as demands the use of automation for the test case generation and the test execution. The approach presented here in addition incorporates the functional system limits [2] of the vehicle for increased testing activities in areas, where fallback strategies are necessary to ensure the safety of the vehicle. Each function of the vehicle which is looked at is pushed to its limits to evaluate the vehicle behavior in situations that exhibit behaviors different from the original functionality while exceeding limits. Moreover, the approach also takes the individual behavior of the road users who surround the vehicle into account as they can also take the vehicle beyond its functional limits. Therefore, the evaluation of the vehicle behavior is done at the system level as introduced in [3].

With technological progress, human activities are being shifted to technical systems. Automation can help to execute actions that are difficult for humans to perform or go beyond human abilities. But it also changes the role of humans working with systems. The use of automation transforms the human participation in the execution of tasks from the execution of activities through the supervising of activities to the complete replacement by the automated systems. Thereby, the level of automation differs in the way of human interaction. As the level of automation rises, the systems are increasingly independent in executing actions. At a low automation level, the systems only support the humans while an action is executed autonomously without human confirmation at a high degree of automation. The automation levels can be categorized like it is in [4]:

a) There is no automation.
b) The system proposes different possibilities of action and highlights its favorite action.
c) The system proposes a single possibility of action, but it does not execute the action.
d) The system executes the action after a confirmation by a human.
e) The system executes the action, when it is not contradicted by a human within a certain time.
f) The system executes the action and informs the humans in retrospect.
g) The system executes the action and informs the humans on demand.
h) The system executes the action without any interaction with a human.

It is assumed that automation can contribute to the traffic safety by taking over the vehicle control and thus remove the human driver out of the loop in as many situations as possible. Incorrect performing of driving maneuvers, carelessness or wrong decisions lead to road accidents, which are caused by the human drivers. The human driver is therefore one of the causes for road accidents and thus offers the potential to improve the traffic safety.

The term ”automated driving” or ”autonomous driving” is used in many different meanings. Several institutions, e.g., the German Federal Highway Research Institute (BASt), the US National Highway Traffic Safety Administration (NHTSA), the Society of Automotive Engineers (SAE) and the German Association of the Automotive Industry (VDA), have classified the different levels of driving automation. In this paper, the driving automation levels are used according to the definition specified in SAE J3016 [5]:

No Automation: The system does not take over the vehicle control with the exception of short-term interventions of emergency functions in critical traffic situations. The human driver is fully responsible for the vehicle.

Driver Assistance: The vehicle is controlled either in the lateral or longitudinal direction by the system. The human driver controls the remaining direction, while she or he has to monitor the behavior of the vehicle and has to intervene immediately in case of a critical situation.

Partial Automation: The system controls the longitudinal and lateral direction. The human driver has to monitor the behavior of the vehicle and has to intervene immediately in case of a critical situation.

Conditional Automation: The vehicle is controlled in the longitudinal and lateral direction by the system. The human driver has to react within a reasonable time after a warning by the system.

High Automation: The system controls the longitudinal and lateral direction. It has to handle all traffic situations, even if the human driver does not react appropriately.

Full Automation: The system has to handle all traffic situations on its own.

With the increasing automation of the driving tasks, the automobile manufacturers are taking over more and more responsibility from the human drivers for the driving maneuvers automatically performed by the vehicles as shown in Table I. While the first safety assistance systems, like the Electronic Stability Control (ESC) [6] or the Antilock Braking System (ABS) [6], only supported the driver to cope with critical situations, nowadays the Advanced Driver Assistance Systems (ADAS) [7] provide comfort functions for specific driving scenarios. But until now, the automobile manufacturers were able to use the human driver as an immediate fallback level in case the system could not handle the situation or if the vehicle behaved in an unexpected way.

It is not sufficient for automated driving that the vehicles are working as expected in known environments, but also in unknown traffic situations. Each drive is different from the previous one, e.g., with respect to the encountered environmental conditions like traffic or weather. With each step in the direction towards automated driving, the operating hours of the vehicle functions, as well as the time required for a handover of the vehicle control to the human driver, is increased. In consequence, this means that the period of time for which the automobile manufacturers are responsible for the vehicle also increases. A technical solution to keep this time as short as possible would be an early and safe handover to the human driver. But in the premium market especially the customers do not tolerate vehicle functions, which have been degraded by the safety concept of the vehicle and are therefore not available in a large number of situations. Hence, the automobile manufactures have to find a balance between the safety of the vehicle and the availability of the vehicle functions.

According to [8], current software testing techniques do not adequately take into account the temporary unavailability of the human driver as an immediate fallback level for automated driving. Most of them are based on the assumption that the human driver continuously monitors the vehicle and its surroundings, and is able to intervene immediately in case of a critical situation that cannot be handled by the vehicle itself. The software testing techniques that have been used so far in the automotive development expect certain abilities from human drivers, which they prove by passing the driving test necessary to legally control vehicles in most countries. With the driving license, a person can show that she or he meets the necessary physical and mental requirements to be responsible for the vehicle behavior at any time. The complete takeover of responsibility by the human driver at present still allows the automobile manufactures to reduce the number of test cases required for ensuring the safety of the vehicles. Due to the temporary unavailability of the human driver as an immediate fallback level, the software testing techniques have to deal with the large number of different environmental conditions and timing behaviors, which occur in the road traffic. Without revised or new software testing techniques, representative driving scenarios can no longer be used for the testing to show that the vehicle reaches its destination without endangering occupants or other road users in the automated driving mode.

The following section shows the related work. Section III evaluates the road accident statistic of Germany to give an idea about the current accident situation and how the number of accidents has changed in recent years due to automation. In Section IV, the human factor in the road traffic is investigated as a cause for road accidents, whereas Section V shows how driving automation can play a part in contributing to a higher level of traffic safety and how otherwise it can affect the human driver in a negative way. Section VI addresses the challenges in the field of automated driving with the view of functional testing. Finally, Section VII presents the extended approach for increased testing activities at the functional limits of the system.

II. Related Work

While so far the complexity and performance of the vehicle were limited by the hardware, the embedded software, as well as the development and test process, which now seem to be the limiting factors as elaborated in [9]. The report predicts that the distribution of the functionality over several components leads to a level of testing beyond the economical and temporal feasible possibilities. Thus, the authors see the testing of such systems, which have to work in any traffic situation, as one of the highest technical hurdles for automated driving.

The national research project with the name ”PEGASUS” [10], founded by the Federal Ministry for Economic Affairs and Energy (BMWi) in conjunction with automobile companies, suppliers, small and medium-sized companies and research institutes from Germany, should provide standards

TABLE I. Overview about the driving automation levels based on SAE J3016 [5].

Level	*Name*	*Functions*	*Monitoring*	*Controlling*	*Fallback*	*Responsibility*
0	No Automation	None	Human Driver	Human Driver	Human Driver	Human Driver
1	Driver Assistance	Some	Human Driver	System / Human Driver	Human Driver	Human Driver
2	Partial Automation	Some	Human Driver	System	Human Driver	Human Driver
3	Conditional Automation	Some	System	System	Human Driver	Automobile Manufacturer / Human Driver
4	High Automation	Some	System	System	System	Automobile Manufacturer
5	Full Automation	All	System	System	System	Automobile Manufacturer

for the automated driving to close essential gaps in the field of testing and the release of vehicles. Among others, the research project should answer the questions about the requirements that must be met by self-driving vehicles, how the safety and reliability of these systems can be demonstrated and the role the human factor plays in the future. As published by the project, new and uniform quality standards and methods are necessary for the accreditation of automated driving functions. The project goal is to establish generally accepted quality criteria, tools and methods. Moreover, scenarios and situations shall be provided for the release of automated driving functions, as well as procedures for the testing. The main project objectives are:

a) Definition of a common approach for the testing of automated vehicle systems in the simulation, at test benches and in real-world environments
b) Development of a continuous and flexible tool chain for the testing of automated driving
c) Integration of the tests in the development process at an early stage
d) Creation of a test method for automated driving features among manufactures

According to [11], the formal verification is currently the only known way to ensure that a system works as specified. This means that the implementation strictly follows the specification and thus it is possible to determine its behavior in any situation. To perform a formal verification, the specification must meet some preconditions. Among others, the specification must be complete and correct. This precondition can be a big challenge, especially in large projects with many dependencies to external components from different suppliers.

Driving automation can bypass current risks as described in [12], but can also lead to new risks, which have not existed before. The paper shows that ”demonstrating safety of automated driving in advance of introduction is nearly impossible”. Thereby, they illustrate that the necessary number of kilometers to demonstrate the safety of a system cannot be provided economically by real test vehicles due to the complexity of the possible traffic situations. The statement is based, among others, on the assumptions that it is not possible to drive the required number of kilometers in the available time for testing and that the testing must be at least partially repeated after changes in the software or hardware.

III. Road Accidents Statistic

Over the years, the number of road accidents rose with the increasing number of road users in Germany as shown in Figure 1. But this did not lead to an increase in the number of injured or dead people. The technical progress in passive and active safety systems of the vehicles significantly contributed to the mitigation of the road accidents and personal injuries. Safety systems, which already belong to the standard equipment of almost all new vehicles on the market, prevent road accidents or reduce their impact. Thereby, driving automation helps to eliminate weaknesses of human drivers by finding appropriate reactions in critical situations.

As explained in Section I, the human driver is one of the cause of road accidents. The road accidents statistic [13] shows mistakes of human drivers in Germany, which led to road accidents that were reported to the police. These are mainly the accidents with serious consequences. Minor road accidents with only material damages or minor injuries are not covered by the statistic, because they are usually not reported to the police. A list of common areas in which mistakes made by improper human driving can be categorized as presented in the following to show the complexity of today’s road traffic as provided by the Federal Statistical Office of Germany in the road accidents statistic:

a) Use of the road
b) Speed
c) Distance
d) Overtaking
e) Driving past
f) Driving side by side
g) Priority, precedence
h) Turning, U-turn, reversing, entering the flow of traffic, starting off the edge of the road
i) Improper behavior towards pedestrians
j) Stationary vehicles, safety measures
k) Failure to observe lighting regulations

When looking at the road accident statistic of Germany as visualized in Figure 2, it is noticeable that the risk potential varies accordingly with the street location. Within villages or towns, road accidents occur due to the accumulation of road users or confusing traffic situations. There are a lot of different reasons for road accidents in urban environments (66.8 %) that could not be assigned to a single major cause, which can be seen in Figure 2a. In non-urban environments, there are first major causes of accidents that are the result of the increased velocity in comparison with urban environments. With more than 30 percent of all road accidents in non-urban

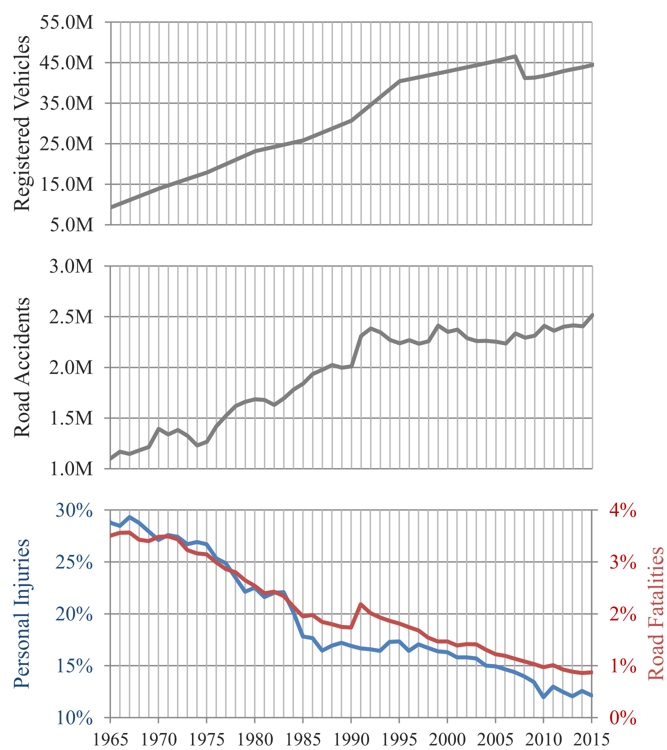

Figure 1. Statistic about road accidents in Germany over a period of 50 years [13].

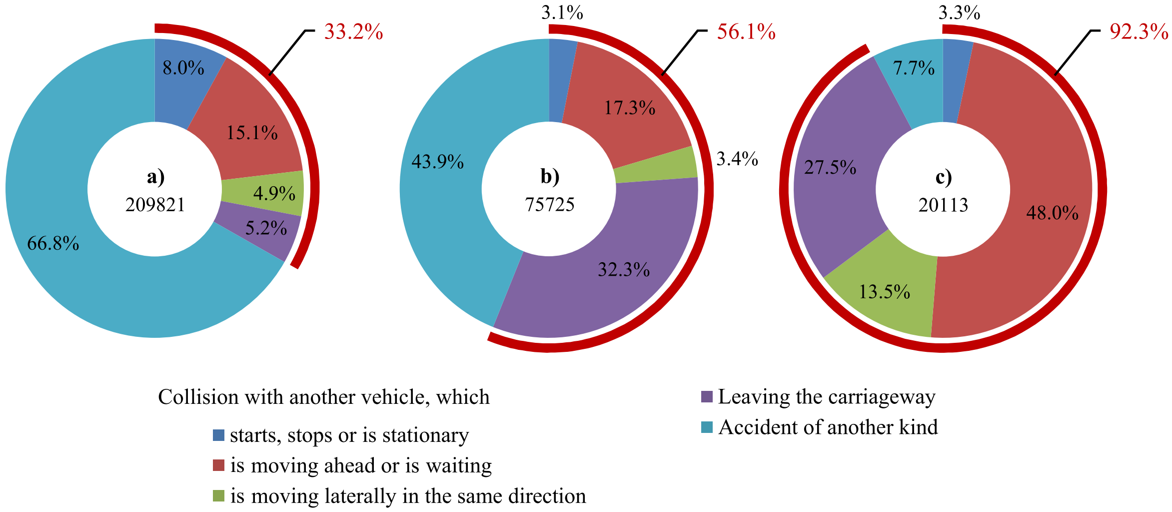

Figure 2. Summary about road accidents in Germany in 2015 [13] separated by the street location: a) urban environments b) non-urban environments c) freeways.

environments, leaving the carriageway is the most common reason. On freeways, the human driver is confronted with a simpler road course, which limits the number of causes for road accidents. Almost half of all road accidents on the freeway are rear-end collisions.

The number of road fatalities and seriously injured people in urban environments (14.5 %) represent in total a lower percentage than in non-urban environments (25.7 %) or on freeways (19.1 %) as illustrated in Figure 3. But in absolute numbers, most of the people are seriously injured or even killed in accidents within towns and villages. A majority of them are pedestrians or cyclists, who hardly have any protection to mitigate the consequences of the road accidents. On freeways, which represent only a small percent of the entire road network of Germany, road accidents with injured people occur relatively more often in relation to urban and non-urban environments. This can, however, be explained by the high usage of freeways, which is about one third of all kilometers driven for Germany.

IV. The Human Factor

According to [14], about 94 % of the road accidents are caused by the human drivers. The human driver is therefore the main cause of the majority of all road accidents. There is not only a single human driver on the road, but also many other road users, whose misbehavior must be taken into account as well. Driving in a dynamic environment is subject to a variety of cognitive demands [15] of the human driver. The human driver has to correctly perceive relevant objects and events, interpret them, and derive his or her actions from them. It is also necessary to recognize new circumstances and make appropriate adjustments well in advance to have time to react.

Research activities on the driving behavior have shown that the personality of a human driver has an impact on the driving style and thus on the involvement in critical traffic situations and road accidents. In the course of life, the personality of a human changes only insignificantly despite external influences. The five-factor model [17], which can be used to describe individual behavior, suggests that the characteristics of personality vary in their intensity for each human. As defined in [18], the five characteristics that lead to the individual behavior of humans are:

Openness (inventive/curious vs. consistent/cautious): Appreciation for art, emotion, adventure, unusual ideas, curiosity, and variety of experience.

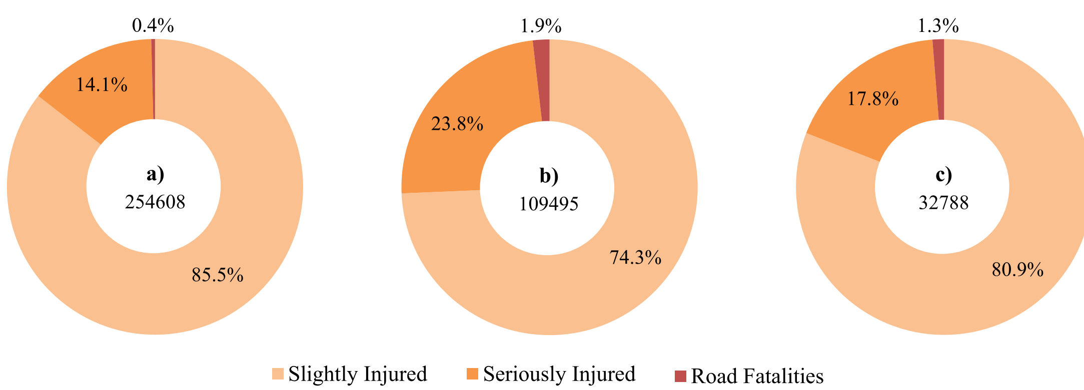

Figure 3. Summary about personal injuries caused by road accidents in Germany in 2015 [13] separated by the street location: a) urban environments b) non-urban environments c) freeways.

Conscientiousness (efficient/organized vs. easy-going/careless): A tendency to show self-discipline, act dutifully, and aim for achievement; planned rather than spontaneous behavior.

Extroversion (outgoing/energetic vs. solitary/reserved): Energy, positive emotions, urgency, and the tendency to seek stimulation in the company of others.

Agreeableness (friendly/compassionate vs. cold/unkind): A tendency to be compassionate and cooperative rather than suspicious and antagonistic towards others.

Neuroticism (sensitive/nervous vs. secure/confident): A tendency to experience unpleasant emotions easily, such as anger, anxiety, depression, or vulnerability.

Various studies [19][20][21][22][23][24][25][26] have revealed that traffic violations and road accidents are related to risky driving, which is motivated by the personalities of the human drivers. Particularly vulnerable to risky driving are humans who score low on conscientiousness, have a high level of openness, extroversion and neuroticism, as well as indicate a lack of agreeableness as illustrated in Figure 4. A human that score low on conscientiousness is described as impulsive and careless, while somebody with a high level of openness, extroversion and neuroticism is keen to experiment, willing to improvise, distracted and prone to react to stress. This mix of personal traits in combination with a lack of agreeableness, which leads to aggression in terms of emotions as well as behavior, makes the involvement in road accidents more likely.

In the road traffic, people with different personalities meet each other. There is an interaction between the road users in a specific area and their behavior. The road users influence each other through different behaviors they show in certain traffic situations. The behavior of a road user is not only influenced by the current traffic situation, but can also vary based on situations experienced previously. A human driver has to cope with her or his personality and with the personalities of the other road users in the road traffic.

V. Automated Driving

Current vehicle generations already have the necessary technical equipment, i.e., sensors and actuators, to automatically cover a distance in the road traffic independent from the human driver, if certain conditions are fulfilled. On the freeway, it is already customary for premium vehicles that the human driver can preset a time interval to the vehicle ahead, which is automatically maintained by the vehicle. If the traffic situation requires, the vehicle can decelerate to a standstill and then continue to drive as soon as the traffic flow allows it. In addition, the vehicle is able to keep the lane by steering interventions, if a wheel of the vehicle is close to the left or right lane mark when a lane change is not indicated.

It is hardly surprising that the automobile manufacturers will provide their first automated vehicle functions for the use on freeways [27], because 92.3 % of all road accidents on freeways can be avoided or significantly reduced in their consequences by automation as shown in Figure 2. Road accidents in non-urban environments (56.1 %) and urban environments (33.2 %) are much less suitable for introducing automated driving due to the high number of different accident causes. Simplified, it can be said that the freeways offer a manageable complexity, both in the driving tasks and the road characteristics, and thus the vehicle control is limited to approaching and overtaking. From the view point of automation, it would make more sense to introduce automated driving in urban environments, since human drivers there fail most often and thus the greatest impact can be had through the driving automation.

Currently it is accepted in the literature that automated driving contributes to increasing traffic safety. Automated driving can usually achieve a better performance than human drivers in situations which lead to a high degree of criticality or even traffic accidents due to the misconduct of the human driver. However, the vision of accident-free driving still seems far away. Automation can not only contribute to the traffic safety, but also leads to a contrary effect. The use of automation can lead to new critical situations and road accidents that were not present before when the vehicle was controlled only by the human driver. It is also assumed that the number of serious accidents will be reduced by automated driving. However, the number of minor accidents will increase as it is not possible to completely avoid all accidents and only a mitigation of the consequences of the accidents is achieved. Moreover, the use of automated driving can lead to a reduction of the awareness of the situation, which means that the driver is overwhelmed

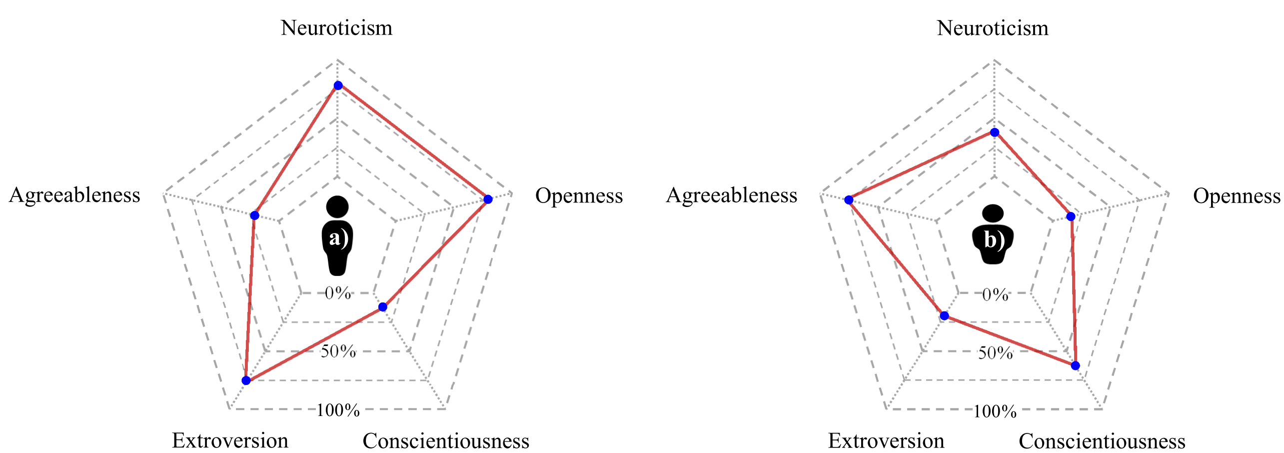

Figure 4. Characterization of two human drivers with different personalities and therefore with individual driving styles illustrated according to [16]: a) higher risk of road accident b) lower risk of road accident.

by the takeover of the vehicle control and misjudges the traffic situation. The cognitive demands described in Section IV, which a human driver must satisfy in order to participate in the road traffic, are lost without an adequate training and thus are either not available, or only to an insufficient degree. Studies [28][29] have already shown that the use of a low degree of automation can lead to a deteriorated lane-keeping and to delayed reactions in critical situations. In addition, the speed is underestimated and it is driven too fast.

VI. Challenges for Automated Driving

With automated driving, the automobile manufacturers are responsible for the driving maneuvers to be performed automatically by the vehicles as soon as they allow the human drivers to divert attention from the environmental conditions and the vehicle. Until now, it was not necessary for the automobile manufacturers to take full responsibility as the human driver was an immediate fallback level in the case of an unintended vehicle behavior. This applies not only to ADAS, but also to emergency functions like the Collision Mitigation System (CMS) [30], which usually intervene only in critical situations. The automated interventions of the emergency functions are additionally limited in time and thus their effects on the moving vehicle. The human driver has to monitor the vehicle all the time and immediately take over the control of the vehicle to perform an intervention. In the event of damage, the human drivers have the sole responsibility and not the automobile manufactures. Extensive test activities are nevertheless performed at test benches and with test vehicles, particularly in the premium segment, to make sure that the human driver rarely has to intervene. Especially for automated driving, the period of time, until the human driver has taken over the vehicle control, needs a closer look. Within this period of time, automated driving has to be maintained by the vehicle. This means, e.g., that a takeover just before a collision, in which the human driver has no possibility to avoid the collision, is not a suitable measure for handing over the vehicle control. Depending on the degree of distraction and the complexity of the current traffic situation, the necessary time until the takeover differs. In addition, characteristics of the human driver, e.g., the age and the mental state, play an essential role for the time required for the takeover of the vehicle control. The automobile manufacturers must assume that an appropriate time, which is expected to be in the double-digit seconds range [31], will be required by the human driver after the takeover notification from the vehicle.

Automation takes the human driver out of the loop from the driving task as often as possible to contribute, among other things, to an increase in the road safety. However, driving automation cannot avoid all accidents, which happen on the road. On the one hand, it is to be assumed that due to the complexity of automated driving, faultlessness cannot be guaranteed. On the other hand, unpredictable actions by other road users can also result in accidents, which can sometimes only be mitigated and not avoided. Individual behavior of road users is a challenge. Especially in the transition, where there is a mixed operation between conventional and automated vehicles in the road traffic, individual behavior must be taken into account. Individual behavior occurs not only with human drivers, but also with different implementations of automated vehicles. There are already initial efforts to develop global standards, e.g., World Forum for Harmonization of Vehicle Regulations [32], which define conditions and limits with the goal of harmonization across manufacturers. Even in the case of harmonization, individual behavior can still occur as long as the human driver can intervene at any time by taking over the vehicle control.

The degradation of the vehicle's functionality, which is part of the safety concept for automated driving, is based on the assumption that the vehicle knows its state and its operating limits at all times. On the basis of the current vehicle state and the exact characteristics of its functional limits [33], the vehicle can decide when and how it comes into a safe state in the event of a fault. A certain tolerance between the operating limits and the limits used for the degradation thereby ensures the robustness of the automated driving, even if there are deviations due to tolerances of individual components. But in practice, it is difficult to determine the limits in advance for all situations and to specify fallback strategies to reach a safe vehicle state, which do not endanger the passengers or other road users. Moreover, the vehicle has to predict its state so as to have enough time to react appropriately to changes in the environmental conditions.

While the emergency functions are active for only a few seconds, comfort functions are often activated for several hours at a time. Over this long period of time, the testing for automated driving must ensure that the vehicle can cope with all situations that occur. The diversity of environmental conditions can no longer be tested only with real vehicles. Simulation allows the execution of the tests on the computer by representing the reality, which is reproduced as a model with some precision. If a comparison between the real vehicle and the simulation shows deviations, which affect the test result, an improvement of the model is necessary in order to get closer to the real world. The closer to reality, the greater the effort involved for the modeling. A perfect representation of reality would be desirable, but for many test scenarios a less precise representation is sufficient, if it does not affect the test result. However, it is not possible to dispense with real vehicles, since they are required to demonstrate the significance of the simulated test result.

As described in [8], current test activities for vehicles primarily focus on the controllability of the vehicles by the human drivers. Even emergency functions of the vehicle, which should only become active in the event of a loss of control by the human driver, can be overruled. The responsibility for the behavior of the vehicles stays with the human drivers for the entire time and does not pass over to the automobile manufacturers. Technical solutions, e.g., the hands-free detection, explicitly point out the driver's responsibility for the vehicle through acoustic and haptic signals. The human driver thereby constitutes a mainstay for the vehicle testing. The safety of the vehicle is built on the combination of the vehicle and the human driver, implicitly assuming that each human driver has the ability to drive the vehicle. Usually, the human driver learns this ability, if not already present, in the driving school and proves them by passing the driving test. Due to the fact that the human driver is at least temporarily distracted from the driving activity during the automated driving, the mainstay is increasingly moving away from the human driver as the degree of automation increases. As a result of this, the vehicle must assume the tasks of the human driver for this period. The responsibility for the driving maneuvers performed independently by the vehicle is handed over to the automobile manufacturer, while the human driver is allowed to be distracted from the vehicle and its surroundings. In the case of a handover, it is no longer possible to refer to the human driver until the vehicle control has been taken over again. This changes the perspective on the vehicle testing, which means that the safety must now only be ensured by the vehicle and no longer by the combination of the vehicle and the human driver. With the increasing automation level, the human drivers can take over the vehicle control after the notification from the vehicle, but they do not have to until the end of the takeover period. The testing will still have to ensure the controllability of the vehicle by the human driver, but it does not play such a decisive role as before. Until the vehicle is taken over by the human driver, the vehicle is placed on its own and has to cope with the environmental conditions encountered during this time.

State of the art test methods [34][35] are based on the approach that a certain selection of the system input represents the complete input range. Examples of such test methods are the Boundary Value Analysis, the Equivalence Class Analysis and the Classification Tree Analysis. These approaches to the system input can reduce the number of tests tremendously. To apply such an approach, it is necessary that the test method divides the system input into classes in which the test object is expected to show the same response independently of the value taken out of the class. However, the classes are usually derived from the system requirements. Both, the requirement process and the derivation of the classes are human tasks and are therefore error-prone. In complex implementations with a large number of parameters, there might be branches implemented, which cannot be seen in the requirements. Even with systematic testing, it is sure that not every input pattern is tested, which can result in a misbehavior of the system. As a worst case scenario, this misbehavior can lead to a road accident, if it is either not compensated by the system itself or recognized and corrected by the human driver. Since the human driver is assumed to be distracted, the system either has to avoid such traffic situations or has to be able to cope with them, if they are in the period of time before the vehicle control is taken over. As a result of the possible distraction of the human driver during the automated driving, the human driver can no longer be used as an immediate fallback level. Thus, a limitation of the input space on the basis of the human fallback level can no longer be performed according to [8]. During the testing, the additional tasks of the vehicle must now be taken into account that are otherwise assumed by the human driver. The test methods must be adapted in such a way that human errors are largely excluded and that they can be used with an economically justifiable effort for the testing of automated driving.

VII. The Approach

According to [36], the test aim is transformed into an optimization problem in which the input of the test object creates the so called search space. The search space is a numeric representation for the possible stimulations that can be applied to the test object to obtain a response. For obtaining a specific system response, it is necessary to stimulate the system with the corresponding input pattern from the search space. The other way round, a specific input pattern from the search space causes a specific response of the system. Since automated driving algorithms are time variant [3], it is not sufficient to test only static input patterns, but also variations of the test scenarios that differ over time. Changes in the timing of the input sequence can affect the system, e.g., feedback control loops. The same input values with a different timing might lead to a different response of the system. For this reason, it is proposed that the search space shall be divided into the following two parts:

a) Functional behavior
b) Temporal behavior

The consideration of the temporal behavior adds another dimension to the system input many times over. However, the proposed separation between the functional and the temporal behavior allows a prioritization during the test execution. Thus, it is possible to test the functional behavior of the system at first, followed by the testing of the temporal behavior. The temporal behavior is especially important for systems that have memories as explained in [3]. For this kind of systems, the points of time, e.g., at which a vehicle performs a specific action, are crucial factors.

Given the expected number of test cases derived from the system input, a manual creation of the test cases is infeasible. Common sense is that test case generators must be used for the test creation. The usage of test case generators multiplies the number of test cases, but not necessarily increases the quality of the tests or the covered system input. Generated test cases, which are redundant or outside the operating limit of the system, do not contribute to the improvement of the system. Hence, test case generators shall be optimized to focus on the relevant parts of the test object. Having said that, from a coverage point of view, many test cases are needed to ensure the safety of the vehicle. It is to be stated that an execution of these test cases is only feasible, if the test execution is fully automated. This requirement is valid to both test generation and test execution. In contrast to today's available test case generators, which mostly leave the specification of the expected system response to the testers, they must be able to provide the system response based on the generated stimulation even for complex systems. But the handling of the test execution also takes a lot of time, if the allocation of the test cases to the test resources is not automated. A huge number of generated test cases require the corresponding amount of test resources, which can be optimized without human interaction. In summary, it can be said that the usage of test case generators leads to the following requirements:

a) Effective test case generators for the automated driving domain
b) Test resources that are fully automated to increase the throughput
c) Scalable test resources to cope with the number of generated test cases
d) Test case generators that also provide the expected system behavior for the evaluation

Particularly critical in automated driving is the unexpected exceeding of a system limit, where the provided functionality of the vehicle is no longer available. With the approach of a functional limit, the vehicle behavior changes increasingly until it has deteriorated to such an extent that the functionality of the vehicle can no longer be provided within an acceptable manner as shown in Figure 5. Even before such a functional limit is crossed, the vehicle must have a strategy, which ensures that the vehicle retains its control. In order to prevent the vehicle from exceeding the limit, taking a safe state is considered to be an effective means. According to [37], a safe vehicle state is achieved, when the current and future risk is below a threshold accepted by the society and therefore no unreasonable risk exists. The threshold represents the value up to which the risk is still accepted from an ethical, moral, and social point of view. Depending on the situation and its criticality, a safe state can be achieved in different ways. The higher the criticality of a situation, the more drastic measures are used in order to achieve a safe state for the vehicle. The range varies from changing the lane to stop the vehicle at the edge of the road to the immediate stop of the vehicle at the current position as described in [38]. In order to test the vehicle behavior shortly before the loss of functionality, the approach suggests that the test activities are intensified at the transition area around the functional limits. However, since the functional limits of a system are situation-dependent and only partially known in advance, the used method must be systematic and with the greatest possible variation of the test scenarios as is possible to push the vehicle functions to their limits. The variation, which is necessary to take the different environmental conditions and the individual behavior of the road users into account, results in a large number of test cases that must not only be executed, but also evaluated. For the evaluation, the approach proposes an evaluation at the system level from the viewpoint of an external observer as described in [3].

VIII. Conclusion and Future Work

Automation plays an important role in the technical progress. Technical systems are increasingly taking on human tasks. Some of the technical systems overcome human beings at present. Currently, automation facilitates driving and helps to reduce or even eliminate risks caused by human drivers. However, the human driver has to monitor the vehicle and its surroundings for the whole drive to be immediately available as a fallback level in case that the vehicle cannot cope with a situation or a malfunction occurs. The responsibility for the vehicle and possible damages lies with the human driver. In contrast to emergency functions, which only intervene in critical traffic situations for a short period of time, the latest comfort functions temporarily take over the lateral and longitudinal control of the vehicle for longer time. With further steps in the direction of automated driving, the automobile manufacturers will have to take over the responsibility for the driving maneuvers automatically performed by the vehicles until the human driver takes over the vehicle control from the vehicle.

The safety of current vehicle generations is built on the combination of the vehicle and the human driver. If the vehicle has a malfunction or cannot handle the situation, the human driver should be ready to take over the vehicle control immediately. This means that the test activities for vehicles primarily focus on the controllability of the vehicle by the human driver. With the transition in the direction of automated driving, the human driver is less and less often available for a takeover of the vehicle control and if the human driver is up to it, it will take longer due to the possible distraction from the driving task. The temporary unavailability of the human driver as an immediate fallback level requires new or revised test concepts and test methods, which take these changes into account for the testing of the vehicle's functionality.

Driving automation can contribute to the traffic safety by removing the human driver out of the loop in as many situations as possible. But driving automation, which does not endanger the passengers or other road users, can only be achieved, if a correct operation of the vehicle is ensured at all times and in any situation. The presented approach proposes that the search space of the system shall be divided into the functional behavior and the temporal behavior, which allows a prioritization during the test execution. It demands in addition the full automation of the test generation and test execution to increase efficiency. The approach assumes that the number of test cases required for a release of a vehicle will increase considerably in order to meet the variety of different environmental conditions. The expected number of test cases will

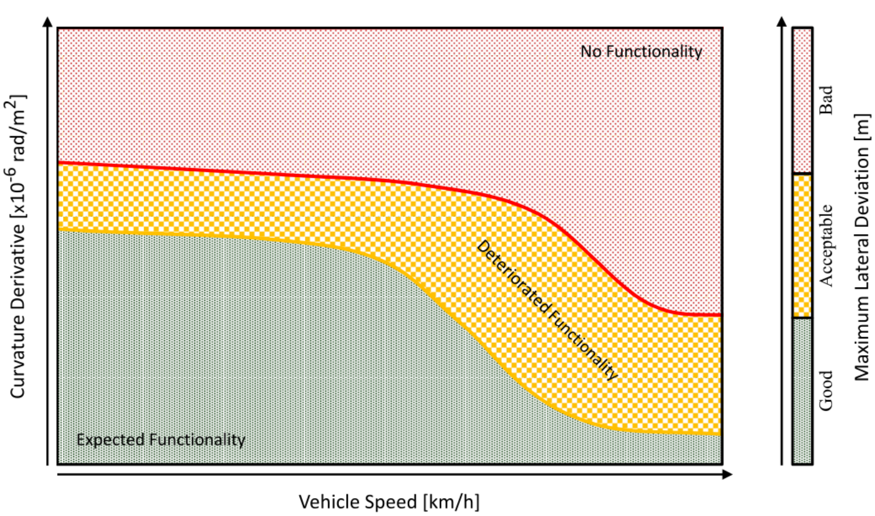

Figure 5. Schematic representation of a functional limit (marked with a red line) on the example of lane keeping assistant.

result in mostly a manual test process with low throughput and poor scalability infeasible for automated driving. An increased test activity is intended by the approach to find situations, where functional limits are crossed unexpectedly and neither the provided vehicle's functionality is no longer available nor the time remaining to reach a safe state is sufficient. It proposes therefore a systematic method, which considers the environmental conditions and the individual behavior of the road users to bring the generated test scenarios iteratively closer to the functional limits of the system by evaluating the vehicle behavior on the system level.

It is left for future work to implement the presented approach and to apply it to a real vehicle function in a case study. Furthermore, efficient techniques are needed to push the function which is looked at specifically to its limits. Metrics must be determined to evaluate the vehicle behavior. From the vehicle behavior, the distance to the functional limits can be estimated. It is assumed that the vehicle behavior does not change abruptly, but continuously deteriorates if the safety strategies are not active.

REFERENCES

[1] S. Wittel, D. Ulmer, and O. Bühler, "Challenges in Functional Testing on the Way to Automated Driving," in The Twelfth International Conference on Systems, 2017, pp. 16–21. [Online]. Available: https://www.thinkmind.org/download.php?articleid=icons_2017_1_30_40051

[2] S. Wittel, D. Ulmer, and O. Bühler, "The Testing Aspects of Automated Driving," 2017, [Online]. Available: http://www.steinbeis.de/fileadmin/content/Publikationen/transfermagazin/191523-2017-02.pdf [retrieved: December, 2017].

[3] S. Wittel, D. Ulmer, and O. Bühler, "Automatic Test Evaluation for Driving Scenarios Using Abstraction Level Constraints," in The Eighth International Conference on Advances in System Testing and Validation Lifecycle, 2016, pp. 14–19. [Online]. Available: https://www.thinkmind.org/index.php?view=article&articleid=valid_2016_2_20_40023

[4] S. Eschen, Personality as predictor for performance in highly automated man-machine teams in aviation (Persönlichkeit als Prädiktor für Leistung in hoch automatisierten Mensch-Maschine-Teams der Luftfahrt). Shaker Verlag, 2014. [Online]. Available: http://elib.dlr.de/89149/

[5] SAE International, "Automated Driving - Levels of Driving Automation are Defined in New SAE International Standard J3016," 2014, [Online]. Available: https://www.smmt.co.uk/wp-content/uploads/sites/2/automated_driving.pdf [retrieved: December, 2017].

[6] A. Zanten and F. Kost, Handbook of Driver Assistance Systems: Basic Information, Components and Systems for Active Safety and Comfort. Cham: Springer International Publishing, 2016, ch. Brake-Based Assistance Functions, pp. 919–967. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-12352-3_40

[7] A. Paul, R. Chauhan, R. Srivastava, and M. Baruah, "Advanced driver assistance systems," in SAE Technical Paper. SAE International, 02 2016. [Online]. Available: https://doi.org/10.4271/2016-28-0223

[8] W. Wachenfeld and H. Winner, The Release of Autonomous Vehicles. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016, pp. 425–449. [Online]. Available: https://doi.org/10.1007/978-3-662-48847-8_21

[9] Fraunhofer Institute for Industrial Engineering IAO, "Highly Automated Driving on Freeways - Industrial Policy Conclusions ("Hochautomatisiertes Fahren auf Autobahnen Industriepolitische Schlussfolgerungen")," 2015, [Online]. Available: http://www.bmwi.de/Redaktion/DE/Downloads/H/hochautomatisiertes-fahren-auf-autobahnen.html [retrieved: December, 2017].

[10] German Aerospace Center, "Research Project PEGASUS," URL: http://www.pegasus-projekt.info [retrieved: December, 2017].

[11] G. Klein, J. Andronick, K. Elphinstone, T. Murray, T. Sewell, R. Kolanski, and G. Heiser, "Comprehensive formal verification of an os microkernel," ACM Trans. Comput. Syst., vol. 32, no. 1, pp. 2:1–2:70, Feb. 2014. [Online]. Available: http://doi.acm.org/10.1145/2560537

[12] H. Winner, W. Wachenfeld, and P. Junietz, "(How) Can Safety of Automated Driving be Validated?" 2016, [Online]. Available: http://www.fzd.tu-darmstadt.de/media/fachgebiet_fzd/publikationen_3/2016_5/2016_Wi_Wf_Ju_ViV-Symposium_Graz.pdf [retrieved: December, 2017].

[13] Federal Statistical Office of Germany, "Road Traffic Accidents - 2015 ("Verkehrsunfälle - 2015")," 2016, [Online]. Available: https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/VerkehrsunfaelleJ2080700157004.html [retrieved: December, 2017].

[14] NHTSA's National Center for Statistics and Analysis, "Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey," 2015, [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115 [retrieved: December, 2017].

[15] D. Rösler, "The relevance of traffic elements in driving situations definition, measurement, and application," Ph.D. dissertation, Chemnitz University of Technology, 2010. [Online]. Available: http://nbn-resolving.de/urn:nbn:de:bsz:ch1-201000403

[16] F. Lorig and I. Timm, "How to model the "human factor" for agent-based simulation in social media analysis? work in progress paper," vol. 46, pp. 89–94, 01 2014.

[17] J. M. Digman, "Brake-based assistance functions," in Annual Review of Psychology, vol. 41, 11 2003, pp. 417–440.

[18] Crowe Associates, "The "BIG 5" PERSONALITY TRAITS," URL: http://www.crowe-associates.co.uk/coaching-and-mentoring-skills/the-big-5-personality-traits/ [retrieved: December, 2017].

[19] W. Arthur and W. G. Graziano, "The five-factor model, conscientiousness, and driving accident involvement," Journal of Personality, vol. 64, no. 3, pp. 593–618, 1996. [Online]. Available: http://dx.doi.org/10.1111/j.1467-6494.1996.tb00523.x

[20] B. A. Jonah, "Sensation seeking and risky driving: a review and synthesis of the literature," Accident Analysis & Prevention, vol. 29, no. 5, pp. 651–665, 1997.

[21] D. F. Cellar, Z. C. Nelson, and C. M. Yorke, "The five-factor model and driving behavior: Personality and involvement in vehicular accidents," Psychological Reports, vol. 86, no. 2, pp. 454–456, 2000. [Online]. Available: http://dx.doi.org/10.2466/pr0.2000.86.2.454

[22] R. Lancaster and R. Ward, The contribution of individual factors to driving behaviour: Implications for managing work-related road safety . HSE Books, 2002. [Online]. Available: http://www.hse.gov.uk/research/rrpdf/rr020.pdf

[23] N. Sümer, T. Lajunen, and T. Özkan, "Big five personality traits as the distal predictors of road accident involvement," pp. 215–227, 01 2005.

[24] E. Constantinou, G. Panayiotou, N. Konstantinou, A. Loutsiou-Ladd, and A. Kapardis, "Risky and aggressive driving in young adults: Personality matters," vol. 43, pp. 1323–31, 07 2011.

[25] J. Vazquez, "Personality factors, age, and aggressive driving: A validation using a driving simulator," 2013.

[26] A. af Whlberg, P. Barraclough, and J. Freeman, "Personality versus traffic accidents; meta-analysis of real and method effects," Transportation Research Part F: Traffic Psychology and Behaviour, vol. 44, pp. 90 – 104, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1369847816304156

[27] Verband der Automobilindustrie e.V., "Automation - From Driver Assistance Systems to Automated Driving," 2015, [Online]. Available: https://www.vda.de/dam/vda/publications/2015/automation.pdf [retrieved: December, 2017].

[28] N. J. Ward, "Task automation and skill development in a simplified driving task," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 44, no. 20, pp. 3–302–3–305, 2000. [Online]. Available: http://dx.doi.org/10.1177/154193120004402020

[29] N. Merat, A. H. Jamson, F. C. H. Lai, and O. Carsten, "Highly automated driving, secondary task performance, and driver state," Human Factors, vol. 54, no. 5, pp. 762–771, 2012, pMID: 23156621. [Online]. Available: http://dx.doi.org/10.1177/0018720812442087

[30] B. Danner, T. Dohmke, J. Hillenbrand, V. Schmid, and A. Spieker, "Method and apparatus for avoiding or mitigating vehicle collisions," Apr. 3 2012, US Patent 8,150,583.

[31] Gesamtverband der Deutschen Versicherungswirtschaft e.V., “Takeover times in highly automated driving - Compact accident research,” 2016, [Online]. Available: https://udv.de/en/publications/compact-accident-research/takeover-times-highly-automated-driving [retrieved: December, 2017].

[32] United Nations Economic Commission for Europe (UNECE), “World Forum for Harmonization of Vehicle Regulations (WP 29),” URL: http://www.unece.org/trans/main/wp29/meeting_docs_wp29.html [retrieved: December, 2017].

[33] A. T. Kleen, “Controllability of partially automated interventions in vehicle guidance (”Beherrschbarkeit von teilautomatisierten Eingriffen in die Fahrzeugführung”),” Ph.D. dissertation, 2014. [Online]. Available: http://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00056694

[34] O. Bühler, “Evolutionary functional testing of embedded systems for distance-based automotive driver assistance functions (”Evolutionärer Funktionstest von eingebetteten Systemen für abstandsbasierte Fahrerassistenzfunktionen im Automobil”),” Ph.D. dissertation, University of Tübingen, 2007.

[35] I. Jovanovic, “Software Testing Methods and Techniques,” in The IPSI BgD Transactions on Internet Research, 2009, pp. 30–41. [Online]. Available: http://tir.ipsitransactions.org/2009/January/Full%20Journal.pdf

[36] F. Rothlauf, Optimization Problems. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 7–44. [Online]. Available: http://dx.doi.org/10.1007/978-3-540-72962-4_2

[37] A. Reschka, Safety Concept for Autonomous Vehicles. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016, pp. 473–496. [Online]. Available: https://doi.org/10.1007/978-3-662-48847-8_23

[38] M. Binfet-Kull and P. Heitmann, “System safety for an autonomous driving vehicle,” 1998.