Challenges in Functional Testing on the Way to Automated Driving

Steffen Wittel*, Daniel Ulmer* and Oliver Bühler*
*Steinbeis Interagierende Systeme GmbH, Esslingen, Germany
Email: {steffen.wittel,daniel.ulmer,oliver.buehler}@interagierende-systeme.de

***Abstract*—The transition to automated driving poses a major challenge for the automotive industry in the field of functional testing. In current vehicles, the automobile manufacturers are not yet taking full responsibility for the driving maneuvers automatically performed by the vehicles. This will change with automated driving, which means the temporary or complete loss of the human driver as a fallback level in traffic situations that cannot be handled by the vehicle software. During the automated driving, the automobile manufacturers have the responsibility for the vehicle behavior until the handover of the vehicle control to the human driver. The handover requires a reasonable warning period in which the automated driving is to be maintained. Depending on the distraction, the human driver needs some time to perceive the traffic situation and to react appropriately. The warning period will grow due to the increasing automation of driving tasks, which allows the human driver to focus her or his attention on non-driving activities and no longer on a permanent monitoring for an immediate intervention in case of a system malfunction. Extensive testing activities are therefore required to verify the functionality and the safety of the vehicles. This paper presents a systematic approach for the functional testing of automated driving. Especially, the spectrum of possible traffic situations, which the vehicles might be getting into, and the test process have been taken into account by the approach.**

Keywords–Automated Driving; Automotive Testing; Functional Testing; Test Process.

I. INTRODUCTION

As published in [2], about 94 % of the road accidents are caused by the human driver due to carelessness, wrong decisions or incorrect performing of driving maneuvers. The human driver is therefore the main cause of the majority of all road accidents and thus offers the greatest potential to improve the traffic safety. Thereby, the driving automation can contribute to the traffic safety by relieving the human driver or taking over partial or complete driving tasks for the longitudinal and lateral control of the vehicle in as many driving scenarios as possible.

The term ”automated driving” or ”autonomous driving” is used in many different meanings. Several institutions, e.g., the Germany Federal Highway Research Institute (BASt), the US National Highway Traffic Safety Administration (NHTSA), the Society of Automotive Engineers (SAE), as well as the German Association of the Automotive Industry (VDA), have classified the different levels of driving automation. In this paper, the driving automation levels according to SAE J3016 [1] are used:

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 control is done 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, and 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.

With the increasing automation of the driving tasks, the automobile manufacturers are taking over more and more responsibility from the human driver and thus 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) [3] or the Antilock Braking System (ABS) [3], only supported the driver to cope with critical situations, the advanced driver assistance systems that are nowadays on the market additionally provide comfort functions for specific driving scenarios. But until now, the automotive manufacturers were able to use the human driver as a fallback level in a case where the system could not handle the situation. With each step in the direction towards automated

TABLE I. OVERVIEW ABOUT THE DRIVING AUTOMATION LEVELS BASED ON SAE J3016 [1].

Name	*Functions*	*Monitoring*	*Controlling*	*Fallback*	*Responsibility*
No Automation	None	Human Driver	Human Driver	Human Driver	Human Driver
Driver Assistance	Some	Human Driver	System / Human Driver	Human Driver	Human Driver
Partial Automation	Some	Human Driver	System	Human Driver	Human Driver
Conditional Automation	Some	System	System	Human Driver	Automobile Manufacturer / Human Driver
High Automation	Some	System	System	System	Automobile Manufacturer
Full Automation	All	System	System	System	Automobile Manufacturer

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driving, the operating hours, as well as the time until the takeover of the vehicle control, is increased and in consequence the period of time for which the automotive manufacturers are responsible for the vehicle.

Current testing activities do not adequately take into account the large number of different environmental conditions and timing behaviors, which occur in the real road traffic. They are primarily used to test representative driving scenarios previously selected by test methods. A dynamic variation of the test scenarios is usually performed on rare occasions and if only in narrow limits. But the reality shows that two test drives carried out on different days between the same starting point and destination can have significant differences. They differ in the number of road users and their driving behaviors. Moreover, different weather conditions cause varieties in the information provided by the sensors and the driveability of the road. In both cases, the vehicle has to reach the destination complying with the road traffic regulations without endangering occupants or other road users.

The approach presented in this paper takes into account the spectrum of possible traffic situations the vehicles might be getting into. Therefore, it proposes a prioritization during the test execution by dividing the system behavior into a functional and a temporal part. Moreover, it recommends an optimization of the test process to overcome with the huge number of tests cases expected for the testing of automated driving.

The following section shows the related work. Section III evaluates the weaknesses of human drivers in the road traffic and shows how driving automation can play a part in contributing to traffic safety. Finally, Section IV presents the challenges of the automobile manufacturers to ensure a safe operation of automated driving.

II. RELATED WORK

The national research project with the name ”PEGASUS” [4], founded by the Federal Ministry for Economic Affairs and Energy (BMWi) in conjunction with automotive companies, suppliers, small and medium-sized companies and research institutes from Germany, should provide standards 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, which requirements must meet self-driving vehicles, how can the safety and reliability of these systems be demonstrated and what role does the human factor play in the future. As published by the project [4], 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 objectives of the project are:

a) Definition of a common approach in 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 across manufactures

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, now seem to be the limiting factors as elaborate in [5]. 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 all possible traffic situations, as one of the highest technical hurdles. The report shows that there is a lack of metrics, which represent the system and allow a comparison between different systems.

According to [6], driving automation can bypass current risks, but can also lead to new risks, which do not exist so far. 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 the number of kilometers cannot be driven in the available time for testing and that the testing must be repeated after changes in the software or hardware.

III. ROAD ACCIDENTS

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 in road accidents. The technical progress in passive and active safety systems of vehicles significantly contributed to the mitigation of the road accidents

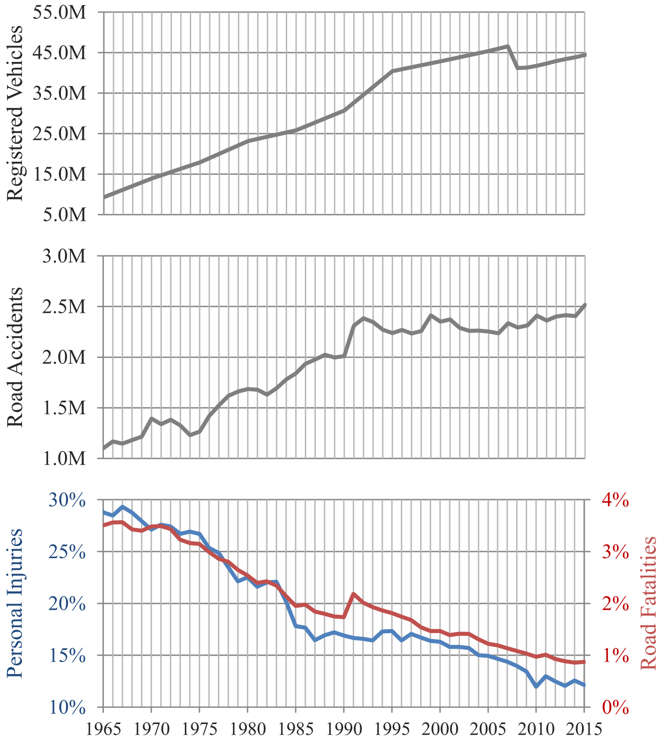

Figure 1. Statistic about road accidents in Germany over a period of 50 years [7].

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 the main cause of the majority of road accidents. The road accidents statistic [7] 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 material damages only 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 an improper driving of human drivers can be categorized, is presented in the following as provided by the Federal Statistical Office of Germany:

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

The list shows the complexity of road traffic and the potential mistakes of a human driver. In addition to the human driver, other road users are usually in the surroundings and their misbehavior must be taken into account as well. According to [8], driving in a dynamic environment is subject to a variety of cognitive demands 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 enough in advance.

When looking at the road accident statistic of Germany as visualized in Figure 2, it is noticeable that the risk potential varies according to 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, which can be seen at the large number of road accidents (14.5 %) that could not be assigned to one of the major causes. In non-urban environments, there are first focus areas 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 environments, leaving the carriageway is the most common reason. On freeways, the human driver is confronted with a simpler road characteristic, 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 facilities and seriously injured people in urban environments (14.5 %) represent in total a lower percentage than in non-urban environments (25.7 %) or freeways (19.1 %) as illustrated in Figure 3. But the absolute values show that most of the people are seriously injured or even killed in 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 represents only a small percent of the entire road network of Germany, road accidents with injured persons occur relatively often in relation to urban and non-urban environments in spite of simpler road characteristics. This can, however, be explained by the high usage of freeways, which is for Germany about one third of all kilometers driven.

IV. CHALLENGES

For current advanced driver assistance systems available on the market, the automobile manufacturers are not yet taking full responsibility for the driving maneuvers automatically performed by the vehicles. This also applies to emergency functions like the Collision Mitigation System, which are usually to intervene only in case of critical situations. The interventions of the emergency functions are limited in time and thus their effects on the moving vehicle are also limited. During the usage of the comfort functions, the human driver

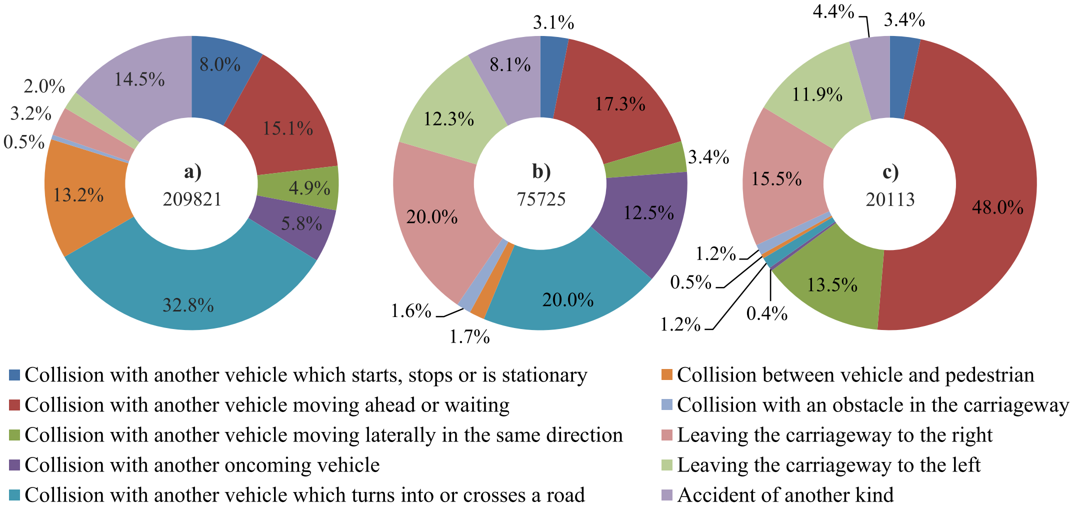

Figure 2. Summary about road accidents in Germany in 2015 [7] separated by the street location: a) urban environments b) non-urban environments c) freeways.

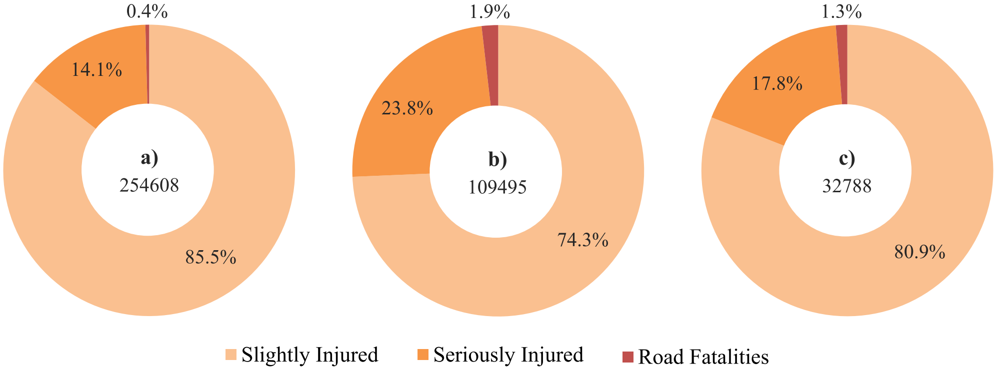

Figure 3. Summary about personal injuries caused by road accidents in Germany in 2015 [7] separated by the street location: a) urban environments b) non-urban environments c) freeways.

has to monitor the vehicle and to immediately take over the vehicle control in case of an unexpected system behavior. In the event of damage, she or he is fully responsible and not the automobile manufacture. Extensive test activities are performed, particularly in the premium segment, at test benches and with test vehicles to make sure that the human driver is left out as often as possible. Thereby, a balance between safety and availability must be found by the automobile manufactures. With automated driving, the automobile manufacturers are responsible as soon as they allow the human driver to be distracted towards the environmental conditions. Especially, the period of time until the human driver has taken over needs a closer look. Within this period of time, automated driving has to be maintained by the system. This means, e.g., that a takeover just before a collision, in which the 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 in 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 [9], will be required after the notification.

The degradation of the functionality in case of automated driving is built on the assumption that the system knows its state and its operating limit at all times. On the basis of the current system state and the exact characteristic of the operating limit [10], the system can decide when and how it comes into a safe state in the event of a fault. A certain tolerance between the operating limit and the actually used limit for the degradation ensures thereby the robustness of the system, even if there are deviations due to certain tolerances of individual components. But in practice, it is difficult to determine any operating limit in advance for all traffic situations and to specify procedures to a safe system state that do not endanger the passengers or other road users. Moreover, the system has to predict its state to have enough time to react appropriately to a traffic situation that may only happen because of changes of the environmental conditions.

The previous sections argue that automated driving has the potential to save lives, which requires a correct operation of the system at all times and in any traffic situation without an immediate available human fallback level. State of the art test methods [11][12] 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, Equivalence Class Analysis and the Classification Tree Analysis. These approaches on 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 results in a misconduct of the system. As a worst case scenario, this misconduct 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.

According to [13], 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 the obtaining of 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, it is not sufficient to test only static input patterns, but also variations of the test scenarios that differ over the time. Changes in the timing of the input sequence can affect the system, e.g., feedback control loops. The same input sequence 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 functional 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. Especially, the temporal behavior is important for systems that are time-variant or have memories as explained in [14]. For this kind of systems, the times, e.g., at which a vehicle performs a specific action, are crucial factors.

Given the expected number of tests cases derived from the system input, a manual creation of the test cases is unfeasible. 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 search space. 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. 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 also the handling of the test execution 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) Approaches to effectively use the 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

V. CONCLUSION AND FUTURE WORK

Already today, automation facilitates the driving and helps to reduce or even eliminate risks caused by human drivers. 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 specific driving scenarios. However, the human driver has to monitor the vehicle during the whole time to be immediately available as a fallback level in case of a system malfunction. The responsibility for the vehicle and possible damages lies with the human driver. With further steps in the direction of automated driving, the automobile manufacturers will have to assume the responsibility for the driving maneuvers automatically performed by the vehicles until the handover of the vehicle control to the human driver.

Automated driving, which does not endanger the passengers or other road users, can only be achieved, if the system recognizes its misconducts in case of failure well enough in advance to reach a safe state. To do this, it is necessary that the system knows its state and its operating limit at all times taking into account possible tolerances of the components. Moreover, the system has to predict its state to have enough time to react appropriately to a situation.

Automation of driving only has the potential to improve the traffic safety, if a correct operation of the system is ensured at all times and in any situation. Common test methods are based on human tasks and therefore error-prone. Even a systematic testing of the system does not allow that all possible combinations and timings of the system input can be tested and thus no misconduct exists. Thus, it is proposed by the presented approach to separate the functional and the temporal behavior of the system to enable a prioritization during the testing.

A mostly manual test process is unfeasible for automated driving due to the expected number of test cases required for the testing. Thus, the presented approach demands test resources that are fully automated to increase the throughput and scalability that compensate the increased test volume. Moreover, it further demands specialized test case generators for the automated driving domain that provide the expected system behavior for the evaluation based on the generated stimulation. Overall, an effective testing is necessary to cope with the challenges of automated driving.

It is left for future work to provide test methods, which have high search space coverages and can be used for an effective testing of the system behavior in different traffic situations. Furthermore, metrics are needed to obtain information about the system performance and the environmental conditions encountered during the test drives. It is thereby assumed that a single metric has no significance and that comparability can only be achieved by using several independent metrics if possible.

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