Validation of vehicles with automated features through the detection of behavioral differences between humans and machines

DI Manuel Schwarz, MSc
School of Computing, Engineering and Physical Sciences
University of West Scotland
Paisley PA1 2BE, UK
b00340019@studentmail.uws.ac.uk

Luc Rolland, P.Eng (NL), M.A.Sc. PhD
School of Computing, Engineering and Physical Sciences
University of West Scotland
Paisley PA1 2BE, UK
luc.rolland@uws.ac.uk

James Bruce Johnston
Management Information and New Technology, School of Business and Enterprise
University of West Scotland
Paisley PA1 2BE, UK
jamesb.johnston@uws.ac.uk

Abstract— The development of automated vehicles has not achieved the desired success over the past decade, despite numerous technological and methodological successes. Currently, no production-ready autonomous vehicle on the market can operate without a human driver in a wide range of regions and environmental conditions. Due to the high complexity of the systems and the varied traffic scenarios, development, and validation are challenging and time-consuming. With the aid of simulation technology, good validation in a scalable form can be performed during development. However, the current standards for traffic safety validation require a final validation under real conditions. In this work, a framework called Shadow System (SS) is presented, which independently captures the control commands of the human driver and the vehicle. This unique approach enables the detection of problems in automated systems by identifying behavioral differences. Up to a defined safety range allows the human driver and the vehicle to execute control commands without affecting each other. This makes it possible, for example, to determine how a human driver steers the vehicle compared to the automated system in a given traffic situation. The developed method enables safe use under real conditions, as control can be taken over directly by the human driver at any time. Scenarios identified as critical will provide information about the safety of the system during the validation process.

Keywords—autonomous vehicles, road safety, vehicle validation, critical scenarios, human behavior, difference detection, real-world testing

I. INTRODUCTION

A. Motivation

The mobility of the future should drastically reduce the number of traffic accidents through the use of new technologies. The introduction of autonomous vehicles, which can be operated without a human driver, is intended to increase road safety and provide access to mobility for additional target groups, such as the elderly or children. However, several problems must be solved before this can happen, and the systems must prove their robustness and safety under real-world conditions.

B. Context

On May 7, 2016, while the Tesla autopilot mode was active, a vehicle driver died in a fatal crash when the system did not detect the motorway crossing tractor-trailer correctly [1]. In 2018, another fatal accident occurred during one of Uber's self-driving tests during the night [3]. The vehicle could not sense and avoid a crossing pedestrian, and the driver was not actively looking at the street since she was engaged on her mobile phone. Consequently, the vehicle hit the pedestrian at about 70 km/h, causing instant death [2].

The newly available driving freedom brings many benefits and some critical safety drawbacks. The various activities which can be performed during a trip increase distraction, which significantly increases the stopping distance when a problem occurs [3]. As long as the industry and consumers are in a transition phase, special caution is required when utilizing new systems. The complete and seamless validation of automated vehicles is still an unresolved issue.

C. Objective of the Research

This work aims to introduce and demonstrate a framework called the SS for the validation of automated vehicles under real conditions, to objectively identify critical problems safely in real-time. Further, the system should help us to understand in which situations during a trip a human would act differently, compared to the automated system, which should improve the systems in the future. This constitutes the main contribution of this research work.

The approach shall be based on a human driver response, since vehicles in the future have to achieve at least the equivalent level of safety (ELOS,) to be accepted by society and legislators.

As safety is paramount, the developed approach should ensure that a takeover by the human driver is possible with the least delay at any time during the tests. By independently comparing the behavior of the driver and the vehicle, a proposal is presented on what a safe validation of systems on the road could resemble.

A generic design of the SS components is intended to enable universal reusability without adaptation to the respective test vehicle. A selected component, called Shadow Steering Wheel (SSW), will be designed to demonstrate the basic concept of the SS Framework and to illustrate a possible realization. The component should be capable of being used for detection of steering movement differences between the human driver and the automated system.

II. EXISTING THEORIES & PREVIOUS WORK

A. Current State

Matt Mcfarland of CNN Business, in an article on a recent reality check, reveals that most manufacturers probably underestimate the complexity of the task at hand, as evident from the vehicles with limited functionality we see on public roads [4].
The most significant development of self-driving vehicles started about ten years ago when a few companies promised availability by 2019 [5]. Today, we can see advancements in assistance systems, but the need for a quantum leap to reach fully autonomous vehicles persists. Google started the development of self-driving vehicles with an artificial intelligence (AI) approach in 2009 [6]. Over the last few years, they have presented promising results with their supervised training of deep neural networks [7]. However, the question arises: Why do we not observe Full Self-Driving (FSD) vehicles on the road yet [8]? Hence, it becomes essential to highlight a few core differences if we compare the environment of a game like "Go" with the reality of a traffic situation.

TABLE I. CONTROLLED VS. UNCONTROLLED ENVIRONMENT [9]

<table>
<thead>
<tr>
<th>Environment Comparison</th>
<th>Controlled (e.g., GO Game)</th>
<th>Uncontrolled (e.g., Road Traffic)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td>Simple detection of the situation (2D)</td>
<td>Complex detection with sensor fusion (3D)</td>
</tr>
<tr>
<td><strong>Rules</strong></td>
<td>A fixed set of rules</td>
<td>General traffic rules and intuition based on experience</td>
</tr>
<tr>
<td><strong>Processing</strong></td>
<td>The result need not be provided within seconds</td>
<td>Output is required in milliseconds</td>
</tr>
<tr>
<td><strong>Training</strong></td>
<td>A move can be repeated at any time</td>
<td>A real traffic scenario cannot be repeated</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>A move of a stone</td>
<td>System action plan and control activation</td>
</tr>
<tr>
<td><strong>Consequences</strong></td>
<td>A bad decision can be corrected in the next moves</td>
<td>Traffic accident (worst case: death of a person)</td>
</tr>
</tbody>
</table>

Eliot describes the contrast with a simple but straightforward statement [11]: "On the freeway, you are playing a game of life-and-death." The accurate and reliable handling of complex environmental conditions on the road and challenging traffic scenarios are slowing down the progress of development. To achieve the safety level of a human driver, a very high level of accuracy and reliability is required. Achieving the final milestone, that is, the "last mile," as Eliot [10] describes it, is a challenge. Currently, no single vehicle with fully automated self-driving features (L5 of the SAE framework [11]) has reached the production stage and is available on the market.

The certification of automated vehicles is a major challenge for legislators, testing organizations, and Original Equipment Manufacturers (OEM). There, already exist some published international standards (ISO, ETSI, SAE, and CEN). These include definitions such as functional safety (ISO 26262) or On-Road L3+ Testing (SAE), [12]. Various national and international working groups are in the process of defining new standards. However, there is currently no standardized certification framework that has been harmonized internationally, by the legislature, or by OEMs.

### B. Key Challenges

Each self-driving project is tackling similar challenges during the systems development phase [13]:

- Data processing speed, as it is necessary to obtain data in real-time.
- Driving in the absence of road markings.
- Influence of weather conditions and lighting.

- Obscure visual landmarks.
- Actions in an unforeseen situation.

Another challenge concerns the "language of the road" since there are many complications that humans overcome with visual communication and by ignoring rules. For the operation of an autonomous vehicle, a set of five common sense-driven rules can be determined [14]:

- Do not hit someone from behind.
- Do not cut in recklessly.
- The right of way is given, not taken.
- Be careful in areas with limited visibility
- Avoid an accident without causing another one.

Regardless of strategy or technology, for the realization of automated vehicles, safety is the most important factor. Consequently, self-driving vehicles must always be able to navigate safely under all conditions [16].

Many problems can be resolved in advance through simulation, but due to the increased complexity in validation, certain problems may not be identified and resolved. Thus, if a software update, plagued with an unknown problem, is rolled out in a public fleet, it can lead to devastating outcomes.

In the course of real-world testing or productive use, the so-called edge problems occur repeatedly. Independent of the selected testing strategy, methodology, and invested effort (time and money), these problems do not get identified during development. In the literature, such problems are often referred to as "wicked problems" [15]. The probability of these occurrences is often small, requiring a certain combination of conditions. Nonetheless, such cases must be identified and resolved adequately, if the systems are to be scaled up worldwide; otherwise, more problems could occur, and the acceptance of autonomous vehicles by society would decline.

### C. Real-World Issues

In general, as long as the system has no issue, everything works fine. However, there are outstanding examples of this not always being the case [15]. A safety-critical issue was documented while driving through the city and passing a road site construction. In the video (time: 06:08 seconds), the driver has corrected the steering wheel to avoid a collision with the construction site, since the vehicle calculated the navigation path incorrectly, as shown in Fig. 1. This is just one example of the many issues self-driving vehicles face at the moment.

In the described scenario, nothing unfortunate happened since the driver took over at the right moment. However, in a worst-case scenario, in the same situation with roadworks in a restricted area and without the driver’s interference, this could lead to a grave accident with injuries or even fatalities.
D. Review of Related Research

The development of automated vehicles with complex features will require the use of artificial intelligence, according to experts like Eliot [16] and Isermann [17]. When highly complex black box systems are used, the traditional test methods cannot achieve sufficient test coverage with economically justifiable effort. Experts like Sjafrie [11] and Maurer et al. [18] see the potential here for simulation to achieve a scalable and repeatable way of performing tests. This approach has also been pursued by Waymo for years, and based on a safety report from 2020, 32+ million self-driven kilometers and 15+ billion simulated kilometers have been driven in 10+ years [19].

However, simulation technology has clear limitations, as mentioned by Leitner [20], Milford et al. [21], and Rajabli et al. [22]. Eliot [23] summarizes the use of simulation technology for testing purposes in one simple weakness: a simulated trip does not correspond to a real trip on the road. Due to all the current weaknesses in the simulation system and process, it is still necessary, at the moment, to carry out final track and road tests for the approval of a vehicle under real conditions, as described, for example, by Maurer et al. [19]. In his opinion, testing the limits of systems in reality cannot be avoided.

One area that lacks research at the moment concerns the continuous validation of the safety performance of automated systems under real-world conditions. Takacs et al. [24] see a long-term need for such a system.

Based on the similarity to this work, a connection was observed with the following studies:

<table>
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<tr>
<th>Reference</th>
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<tr>
<td>Online sensing of human steering intervention torque for autonomous driving actuation systems. [25]</td>
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<tr>
<td>Analyzing driver behavior under naturalistic driving conditions: A review [26]</td>
</tr>
<tr>
<td>Inertial detection of unusual driving events for self-driving [27]</td>
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<tr>
<td>Validation of a human cooperative steering behavior model based on differential games [28]</td>
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<tr>
<td>Robust observer-based intermittent forces estimation for driver intervention identification [29]</td>
</tr>
<tr>
<td>Comparison of steering interventions in time-critical scenarios [30]</td>
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Wang, Guo and Jia [25] used a model-based approach to capture human steering input through an additional torque sensor, enabling decoupled detection of the input. The basic concept of the implementation is shown in Fig. 2.

For the measurement of human intervention in real-time, a similar approach was described by Schinkel, Van Der Sande and Nijmeijer [31]. By using a torque sensor, the force applied by the driver on the steering wheel was measured.

The contribution of this research work is the introduction of a novel framework for the validation and certification of automated vehicle control systems. The proposed concept is call the Shadows System (SS) and is based on a measurement system called Shadow Steering Wheel (SSW) which is being reviewed below.

All mentioned works have a common difference compared to the Shadows System (SS) concept. None of the considered works foresees an independent measurement of the behavior without influencing the automated vehicle. From this viewpoint, the main features of the approaches are similar, but the final idea described in this work differs on account of the completely independent capture of the human and vehicle behaviors, without mutual influencing.

III. FRAMEWORK DESIGN

A. Background

The theoretical concept of this work relies on the fundamental idea of detecting the difference in behaviors between a human driver and an artificial one. Over the past decades, human drivers have developed proficiencies that enable them to navigate worldwide in all environmental conditions. However, there are a large number of traffic accidents that can be attributed to human error. From 2015 to 2016, in the US alone, about 39,000 deaths and 4.4 million injuries resulted from traffic accidents [12]. Moreover, according to the World Health Organization’s (WHO-OMS) statistics, [32], since 2020, 1.35 million people have died in traffic accidents worldwide. In most traffic accidents, human error is considered the primary cause.

Recent studies show severe gaps in the safety of autonomous vehicles compared to that of human drivers [33]. With a human driver as a benchmark, on average, every 500,000 miles driven results in an accident [34]. Humans are excellent drivers, capable of handling most traffic situations safely, if not distracted or influenced. The idea of this work is to capture the behaviors of a human and an automated vehicle during a trip, such that they do not influence each other. The main actions executed by a human during a drive are:

- Steering (left or right)
- Braking
- Acceleration
• Using the indicator, lights, or horn

The ultimate goal of automated vehicles is to replace the human driver and execute the listed activities safely and reliably.

B. Testing Methods

For the validation of self-driving vehicles, two primary variants of test methods are available. Validation can be achieved by simulation, which offers very good scaling and repeatability [18]. Alternatively, testing can be performed under real conditions. Both variants have their advantages and disadvantages. To achieve the highest degree of realism and validate complex scenarios, a "Measurement-based" approach under real conditions offers an excellent way to gather data.

C. Humans as a Reference

Over the years, human drivers tend to develop their own driving behavior, considering the underlying traffic guidelines. This tendency leads to different behaviors and driving styles. Some considerate drivers tend to use a conservative driving style and place emphasis on safety [35]. Such drivers always try to reduce the risk to a minimum by keeping a safe distance and adjusting speed, wherever required.

Conversely, a sporty driving style reflects a much more dynamic driving behavior, with the driver usually taking more risks. In daily driving behavior, this profile is reflected by reduced distances between vehicles and higher speeds, compared to a conservative driver. Potential distractions from cell phones or the like can also provide a higher safety risk in this context [36]. In the middle range lies the standard driving style, representing the average driver. Depending on these three classifications of drivers, the subjective perception of each individual can lead to a slight difference in the result when using the SS. For example, a conservative driver would intervene much earlier compared to a sporty driver, in which case a critical situation would not occur for the sporty driver because the automated system would handle the situation on its own; however, for a conservative driver, it would already have been a critical scenario.

IV. METHODOLOGY

A. Shadow System (SS)

By detecting critical scenarios under real traffic conditions based on the independent measurement of a behavior, a validation method is proposed to be created to obtain an objective statement about existing deviation in the context of development and certification tests.

The overall concept is referred to as SS in this work and can be used independently of the underlying vehicle. The SS is based on a "black-box" concept, which treats a vehicle and its components, technology, and software version as an unknown system. For the measurement of behavioral differences between the human driver and the automated system during a test drive, additional hardware equipment is installed on top of the existing vehicle system to collect the required information. This allows the generic reuse of the system on different vehicles. The most essential feature of this concept and the associated system is the detached execution of driving activities such as steering or braking actions. Up to a defined safety limit, the human driver should not influence the vehicle and vice versa.

Fig. 3 shows the overall idea, which is divided into two categories. The area with the blue background (existing data) refers to general and context information that can be easily determined before, during and after a test drive. This area also includes the international On-Board Diagnostics (OBD) II standard, since all modern vehicles generally support it to collect more data for future analysis and statistical comparison.

The yellow-shaded area shows the extension by individual components of the SS. These additional data sources are used to collect data that cannot be collected through the existing vehicle systems and methods. This work focuses on the SSW component (highlighted in red). All other components could be considered and realized in more detail in future research work to gain further information relating to the detection of critical traffic scenarios.

B. Illustrative Example

Fig. 4 shows an illustrative scenario representing the basic concept based on a steering movement. A fully developed variant of the SS concept could consist of different system components to measure differences in pedals or control levers like turn signals or lights also. However, in the following description, the focus is purely on the steering movement. General activities like gear shifting, checking the mirrors, and using swipers are excluded to simplify the concept.

The driver in this fictitious illustration is in an automated vehicle running on a three-lane roadway. Oncoming traffic is on the left of the lanes. The center and right lanes are aligned in the direction of travel and can both be used by the vehicle. It is assumed that the Highway Autopilot (HAP) is activated at the time of the scenario, and thus the vehicle should act entirely autonomously. Based on the SAE framework, this function would correspond to Level 3. Vehicles on the market today already support this functionality.
In this example, an obstacle in the form of another stationary vehicle (target vehicle) suddenly appears while the vehicle is moving, thereby blocking the middle lane. Marker 1 represents that the automated vehicle (hereafter referred to as the ego vehicle) has a neutral steering position on the real steering wheel of the vehicle at this time. The basic idea of the SSW, shown in the illustration above Marker 2 (blue), involves adding a layer to the normal steering wheel, to enable the driver to perform steering movements independent of the vehicle. In the illustration, it can be seen by Marker 7 that the driver's hand movement is applied to the SSW, representing the behavior of the human driver in the current situation. Thus, through this method, the difference between the vehicle and the human driver can be measured.

In the example shown in Fig. 4, a human in the situation would make a steering movement to the right to avoid a collision with the target vehicle, which is shown through Marker 3. Due to the speed of the ego vehicle in this example, it is assumed that full braking would not prevent an accident.

Marker 4 represents the navigation path the human driver follows to avoid an accident. In the area of Marker 5, a simplified form of the measurement signal is shown, to be detected through the SS. The blue line shows the difference in the movement of the human driver, compared to the steering wheel of the vehicle. Through Marker 6, a threshold value that serves as a safety mechanism is shown. The moment the threshold value is exceeded, as can be seen in the graphic, the steering movements of the SSW are transmitted directly to the steering wheel of the vehicle, allowing the driver to take control of the vehicle's steering movement and independently control the traffic situation.

By exceeding the threshold value, a point is identified, which is to be classified as critical based on the stored threshold values. The detection of such points forms the basis for the recognition of critical scenarios based on a differential measurement and is the main objective of this work. The threshold values for triggering a lock-up of the SSW must support a dynamic range of values. Depending on the speed of the vehicle, a limitation of the movement range for the SSW component is required. For example, at a vehicle speed of up to 50 km/h, the SSW component may perform a deviation of +/- 2 cm. If the speed changes to between 100 and 130 km/h, the range of movement may only be +/- 0.5 cm. This limitation is necessary because, at higher speeds, only the slightest steering movements are allowed.

C. Safety Feature

In Fig. 4, the difference between the actual steering wheel and the SSW is shown by the red reference points, using Marker 6 as an example.

The second variant determines the pressure applied by the driver, which is applied to the SSW component. Higher pressure indicates the driver’s desire to perform a faster movement. If the pressure exceeds a pre-defined limit, this immediately leads to the blocking of the component.

When implementing an SS component, both safety variants should be implemented and used parallelly. When the limiting value for the distance or the pressure is exceeded for the first time, the component should be blocked. Importantly, the lockout must remain active until the driver informs the system that the situation is again under control and the system can be restored to an active state. After reactivation, the system should automatically reset itself to the initial position so that the differential measurement can start from zero for further scenarios.

The described example can be compared in certain aspects with the traffic accident of a Tesla vehicle on a motorway in connection with a fallen-over truck. Fig. 5 shows the real scenario recorded on a motorway.

D. Difference Visualization

To display the difference between the vehicle system and the SSW component, the representation form shown in Fig. 6 is used in the context of this work. The given example demonstrates the basic idea based on the distance variant presented in the previous section. The same representation can also be used for the second variant, where the applied pressure on the SSW component would have to be displayed.

The primary measurement signal is displayed through a line diagram, which shows the time course of the measurement in seconds on the x-axis and the difference of
the components in cm on the y-axis. In Fig. 6, the difference signal is represented by blue color and Marker 1. There are two threshold values, represented by orange and red horizon lines. At the end of the graphic, the direction of the steering movement is indicated. The difference can deviate to the left or right.

The so-called warning limit is defined by Marker 2 and the organic line connected to it. All deviations between the centerline (gray, 0-cm deviation) and the orange line are classified as normal. This difference does not influence safety, nor cause any unpleasant feelings to the driver. Deviations between Marker 2 and Marker 3 are in the warning range, indicating that the deviation does not yet represent a safety risk but can no longer be classified as comfortable for humans. An example of this would be an overtaking maneuver by a truck where the distance between the vehicles is too small. This situation does not pose an immediate safety risk but would be navigated differently by a human driver.

Next, the area represented by Marker 3 indicates the threshold value for the critical limit and is shown as a red line in Fig. 6. Exceeding this value should trigger the safety function and activate a lockout of the component. Through Marker 4, a corresponding exceedance is shown. From this point on, all steering movements of the driver are directly transferred to the real steering wheel of the vehicle. This safety mechanism enables the immediate takeover of control in safety-relevant scenarios. Using these identified points, it should thus be possible to detect critical events under real-world driving conditions.

E. Use Cases

During a specification phase, the following primary use cases were identified, which the component must have:

- **Synchronization**: To simulate natural steering behavior, the left and right sides of the SSW component must be moved in opposite directions.

- **Real-time**: Interventions on the SSW system by the driver must be processed and executed with the least possible delay, to simulate natural behavior.

- **Dynamic Limits**: For the best possible protection of a trip, the limit values for distance and pressure of the SSW component must be continuously adjusted based on the vehicle speed.

- **Locking**: When a safety-relevant limit is exceeded (distance or pressure), an automatic lockout of the SSW component must occur to allow the direct takeover of the vehicle.

- **Reactivation**: Reactivation and associated resetting of the SSW component after a lockout may be performed only upon an explicit instruction from the driver.

- **Standardization**: The applicability of the SSW component is to be designed generically, so that the system can be used regardless of the vehicle type, make, model, and level of automation.

V. RESULTS AND DISCUSSION

The theoretically described concept of the SS and the SSW component selected therefrom will be explained in detail below using two design proposals. The system is a combination of hardware components and software applications to capture the primary signals of the individual components, such as the SSW. In addition, other data such as metadata, time series, videos, Global Navigation Satellite System (GNSS), etc. are collected during the test drives. The recorded data will be used for the detection of critical events during a test drive. Further, the additional context information (vehicle, driver, weather, road) will enable detailed analysis and statistical comparison in future research activities.

A. General Components

Fig. 7 shows the basic building blocks required to use the SSW and the associated data analysis. Besides the component (shown in blue), a data logger for persistence and a visualization system that displays the data in real-time are required. At the end of a test drive, the data must be stored in a central system where they are harmonized, followed by the reporting and analysis based on this information.

![Fig. 7. Shadow Steering Wheel (SSW)—Building Blocks](image)

B. Shadow Steering System (SSW)

In this work, the SSW component is selected for measuring the steering behavior difference during a journey and detecting critical traffic scenarios. The concept presented below was developed with three essential challenges in mind. One of them is ensuring safety while driving. Under no circumstance should the component compromise traffic safety. Further, the system must be designed such that the two steering wheel systems (vehicle and SSW) do not influence each other up to a defined point. The last one is related to the accuracy and responsiveness of the system. As the component is to be used under real conditions and allows only a minimal deviation at higher speeds, the implementation must be highly precise and react in near real-time.

1) Mechanical Design

In the mechanical version shown in Fig. 8, the so-called trades (200) are mounted on the left and right of the original steering wheel (100). Two fixed guide rails (201) allow an independent steering movement. Brackets (204) are used to fix the additional construction to the actual steering wheel (100). A motion bar (202) transfers the driver's movements from one side to the other. A data collection box (300) records the movements through a laser sensor (301) and transmits them to an external device through a radio link. Blockers (203) are used to define the maximum range of motion.
The image shows a steering movement to the right, which can be seen through the shifted handles (200). By default, the handles are synchronized and positioned in the center between the two brackets (204). In the image, it can be seen that the blocker (203) abuts the housing of the data collection box (300). All further steering movements performed by the driver would have a direct influence on the real steering wheel (100) in further sequence.

2) Electronic Design

In the electronic version, the fixed connection through a motion bar (202), shown in Fig. 8, is omitted. Due to this difference, the movement is realized through an additional intermediate layer, which here is referred to as a sledge and is located between the base (201) and the handle (202). A hand detection sensor (203) is used to detect the hand of the human driver and the associated activation of the component. Through built-in force sensors in the sledge, driver movements are detected and passed on to the data collection box (300), which includes the program logic and calculates the sledge movements based on the received values. The result leads to a movement on the sledge to perform the steering action of the driver on the electronic component to achieve a change in position. In addition, all the data is made available via wireless connection for external applications to persist and visualize the current state. The measured result is the same as in the mechanical version. The steering movement of the driver is executed independently of the steering wheel (100).

C. Discussion

Another form for capturing behavior differences could be realized through direct integration. In this variant, as shown in Fig. 10, an additional component (201 + 202) placed between the original steering (100) wheel and the steering axle (101) would be used, allowing detection of the driver's difference without adding additional components on top of the original steering wheel. The implementation is similar to the general SS method but would require direct intervention in the components of the vehicle, posing an increased safety risk in case there is a critical event. The approach could theoretically be applied to production vehicles also in the future, to measure deviations by the human driver in a scalable form.

Alternatively, the whole SS concept could be integrated directly into vehicles with electronically equipped components. If steering movements are not transmitted directly through a mechanical path in the vehicle, the logic could be mapped through its control software.

The various activities which can be performed during a trip increase distraction, which significantly increases the stopping distance when a problem occurs. Especially in scenarios where a human takeover is required, an experienced and attentive driver can make a significant contribution to road safety.

With the proposed method, a driver must always pay attention to the road while driving as part of the validation process, to execute his or her own control commands. This approach can prevent situations like the Uber accident due to the distraction that occurred.

VI. Conclusion

The concept explained in this work and the associated test method using the SS and associated components, such as the SSW, should provide a safe test method. By applying the method and including humans as a reference and a fallback scenario, the approach can ensure high safety throughout the execution of a real-world test. In addition, the method provides data as they occur in reality, unbiasedly. Thus, it can be explicitly proven which vehicles under which configurations have led to a problem when using certain features in an automated vehicle. In another work, a realization of the SSW component including validation and analysis of a real-world example is shown [38].

The concept of the SS is designed primarily for the validation of features during the development and certification phase. However, the concept could be further developed for industrialized use, as shown in Fig. 10. This extension would have the advantage of more data being collected, from private drivers as well.
Based on the results of the SS component, a system similar to the one used in the aviation industry could be built in the future, where all safety-critical problems must be reported by legislation. For aircrafts, the Flight Data eXchange (FDX) system exists. Any intervention by the human driver above a defined safety-critical threshold could thus be detected and recorded automatically. The advantage of such a system would be that manufacturers could share critical scenarios from the past with their systems.

A. Contribution

The developed SS framework is intended to demonstrate a new validation method to detect critical events based on the difference deviation in the behavior between humans and machines. This capability is intended to provide a safe and standardized way to carry out feature validation under real-world conditions. Owing to the safety-first approach on which the entire system is based, validations can be carried out under real-world conditions in a safe and standardized manner on a wide range of vehicles.

A concrete proposal for the realization of the SS concept was presented on the basis of the selected component called SSW.

B. Limitations

The realization of the SS concept was carried out in this work based on the SSW component. With an implementation of the component, only steering movements can be recorded and analyzed. For a more comprehensive observation of behavioral differences such as pedal activities or the activation of control commands (e.g., turn signals, light signals or horn), further hardware components have to be developed.

Another limitation of the overall idea concerns the human factor. Human behavior can vary and, in the worst case, can even have negative effects, if inappropriate or incorrect behavior is used as a reference. In addition, each person’s driving style represents a potential bias in the results. Individuals with a high level of safety awareness are likely to respond more rapidly during critical situations. In addition, the type of intervention may also differ, based on the experience level of the driver.

ACKNOWLEDGMENT

This research has been conducted with no funding.

REFERENCES


