http://dx.doi.org/10.7494/miag.2020.1.541.19

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An overview and review of testing methods for the verification and validation of ADAS, active safety systems, and autonomous driving

The number of advanced driver assistance systems has increased dramatically in recent years. This led to a need for the development of testing methods to prove the quality and reliability of such systems. This publication presents an overview of the testing methods used in the automotive industry for the verification and validation of advanced driver assistance systems (ADAS), active safety, and autonomous driving systems. The first part presents the approach to X-in-the-loop testing such as model, software, hardware, etc., presenting the most interesting implementations. Then it discusses testing in proven areas like road traffic, artificial cities, and test tracks. The last part presents validation in the laboratory using both invasive and non-invasive methods based on virtual test drives, sensor stimulators and chassis dynamometers. Moreover, we identified the most promising approaches for the efficient verification and validation of ADAS, active safety and autonomous driving systems. Finally, we address some gaps in the research which require further investigation.

Key words: *ADAS validation, active safety systems verification, autonomous driving, testing methods, in the loop testing*

1. INTRODUCTION

Modern cars increasingly have more advanced active safety systems. Currently, there are no fully autonomous cars, yet some of them significantly reduce the need for driver interaction. Currently, autonomous driving systems are developed based on SIL (Software in The Loop) and HIL (Hardware in The Loop) methods, while tests are performed manually on test tracks and/or on public roads by test drivers. These methods are far from perfect due to the inability to create many test cases, the required human presence in the car during tests, and above all, the problem of repeated reconstruction of identical road conditions. Such conditions can only be reproduced in the laboratory by using specialized tools. The creation of tests in the laboratory would allow for cars to be tested in identical conditions. This, in turn, would allow cars to be compared to each other and, above all, certified based on defined procedures and test standards. There are many publications that show different approaches to testing active safety and autonomous driving systems, ranging from road traffic tests to laboratory tests. Currently, tests in the laboratory (commonly called Vehicle-in-the-loop) mainly focus on the tests of a single system, such as radar or lidar. For some time, engineers have been trying to create a test system that would be able to test several systems simultaneously, but unfortunately such a system is still not available. Therefore, the following question arises – Is it possible to create a test system that will be able to simulate the external world in the laboratory so that driver assistance or autonomous driving systems can be tested comprehensively? This paper presents a review of this topic and attempts to specify the missing technologies.

2. X-IN-THE-LOOP TESTING

X-in-the-loop is a naming convention, where X denotes an object under test. As testing is not a one-off activity but a cyclic one, it is called loop testing. In the automotive industry, you can test many things in the loop, with the most popular applications presented here. These approaches are ordered in accordance with the chronology within the timeline of the tested system development as shown in Figure 1. However, it should be remembered that not all steps must be performed, because it depends on the specifics and complexity of the system. There is also some difference between verification and validation. Verification is intended to check whether the system meets predefined requirements, standards, and norms, while validation provides evidence that the system performs its role in a real application, in the target environment [1].

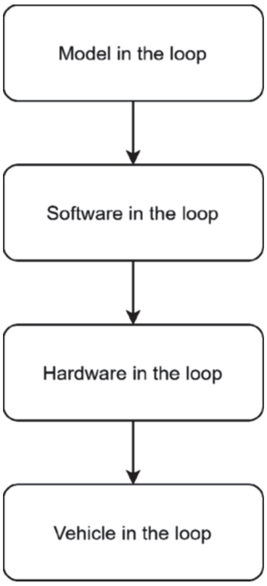

Fig. 1. Steps in a System Development

2.1. Model-in-the-loop (MIL)

The first step in the production of the system is a model in the loop (MIL), where the designed system is in the form of a model created in a modelling tool, e.g., in MATLAB- Simulink. By means of generic components a general, high-level model of the system's operation is created. As a result, we can design the system without entering the implementation details, which depend on the programming language. In addition, having such a model, we can automatically generate code in a specific language using for example, Simulink Coder or Target Link [2], thanks to which we avoid manual code writing [3] as shown in Figure 2. Testing the model involves providing a set of simulated signals to the model and checking its response.

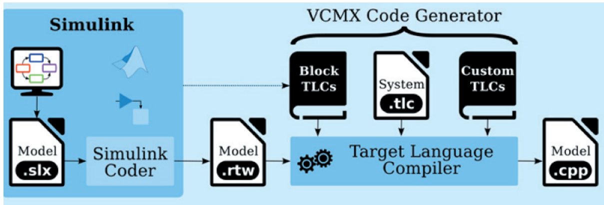

Fig. 2. Code generation process of Simulink [2]

2.2. Software-in-the-loop (SIL)

The next step is software in the loop (SIL), where our subject of testing is no longer the block model, but code in a specific programming language, e.g., C++. We can test this code by providing appropriate artificial or acquired data to its inputs. Thanks to that, we can verify the correctness of the implemented algorithms in a specific programming language in abstraction from dedicated hardware, e.g., with code running on a PC computer [4]. Such an approach brings with it some risks. First of all, if the computer program is compiled with different compiler, so the machine code may be slightly different to a machine code compiled with dedicated compiler. During execution, such programs can behave differently, so there is no 100% certainty that this program will behave exactly the same on the final hardware.

2.3. Hardware-in-the-loop (HIL)

After finishing of SIL tests, there are performed hardware in the loop tests, where the software is already tested on dedicated hardware, but not yet in a dedicated environment. This means that all other cooperating electronic devices must be simulated, so from the perspective of the device under test, there is no difference whether it is in a real or simulated environment. This is probably the most common type of testing in the automotive industry, because usually the manufacturer of the designed device is responsible for only one device and has no access to other cooperating devices. The HIL example can be an ECU, which is responsible for recognizing lines on the road, is tested in a simulated environment [5] oraz HIL as shown in Figure 3. The main drawback is that the device is not tested in real environment with other real ECUs, with real power supplies etc. Therefore, there is a chance that the device will not work correctly in a real environment.

Fig. 3. This vehicle motion control HIL system tests braking, steering, and suspension controllers. The system can act as a stand-alone HIL test setup or be run in co-simulation with the Dynamic Driving Simulator [6]

2.4. Vehicle-in-the-loop (VIL)

The last step of testing is testing a complete car in a laboratory. Such a car is usually set on a chassis dynamometer, which, by applying the right torque to the wheels, simulates, for example, driving on a hill or other traffic resistance. In addition, car sensors are stimulated using various types of devices that work with driving simulators that are responsible for virtual test drives. In this testing method, it is often possible to meet the terms of testing in the open and closed loop, which are worth introducing here.

2.4.1. Open loop testing

Open loop testing occurs when the system under test is stimulated from the outside, but its response is not fed back to the simulator. For this reason, we do not have information about the car's reaction in the simulation. An example of testing in an open loop can be an ECU which is responsible for car detection [7]. The first step was recording the video during a real test drive, then an identical test drive was performed in the simulator, and at the end the cars were separated from the virtual drive and added to the recorded movie as shown in Figure 4. The test consisted of sending this video with added cars to the camera and analysing whether the ECU detected other vehicles. Under such conditions, it is not possible to test how the active safety system works because a recorded video cannot react to the system's behaviour.

Fig. 4. Real test drives augmented with virtual car [7]

2.4.2. Closed loop testing

Closed loop testing occurs when the response of the tested system is fed back into the simulator. Thanks to this, the reaction of the car is visible in the simulation. Closed loop testing provides an interactive simulated environment to the system under test, but it is much more demanding for a test system than the open loop method.

2.5. Other methods

In addition to the general methods described above, there are a number of other, more specific ones, such as Engine-in-the-loop (EIL) or Battery-in--the-loop (BIL), where the engine [8] or the batteries are tested [9]. Sometimes, humans are also tested to evaluate likely behaviour in specific situations or cooperation with safety systems.

2.5.1. Driver-in-the-loop (DIL)

In addition to testing the manufactured system, one can also test driver behaviour while driving a car (Fig. 5).

Thanks to this, one can obtain information about the behaviour of the driver in certain situations and thus better design the system in the car. Moreover, it is also possible to acquire information about cooperation, e.g., with active safety systems to validate if additional safety systems improve or worse the driver's reaction. An example would be testing the reaction time of the driver during braking with cooperation with intelligent lamps [10]. Of course, the driver can be tested in different environment. The less real conditions are when the driver's behaviour is tested during completely virtual test e.g., by using VR goggles. Even better is to test the driver in a real vehicle, but in a simulated environment. The most accurate is to test driver's behaviour in a real vehicle during a real test drive. Such approach gives the most precise results and certainty that the designed safety system improves or worse the driver's safety.

Fig. 5. Volvo Dynamic Driving Simulator [6]

2.5.2. Pedestrian-in-the-loop (PIL)

Pedestrian behaviour can be tested similarly to driver behaviour. By observing the pedestrians in different situations, one can assess how they interact with the car. An interesting example was given in the publication [11], where the behaviour and movement of several people is observed during a dangerous event with an autonomous car. The people have VR goggles on their heads, in which a virtual test drive is displayed. Similar tests were carried out with one passer-by, whose task was to enter a pedestrian crossing at the right moment to check whether the emergency braking algorithm of the vehicle worked properly [12] as shown in Figures 6 and 7.

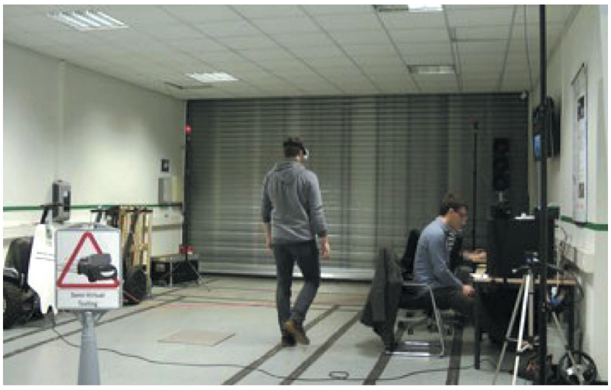

Fig. 6. Pedestrian with VR goggles [12]

Fig. 7. Image seen by pedestrian [12]

3. VEHICLE TESTING METHODS

So far, the X-in-the-loop approach was presented. In the final step, vehicle tests are performed in a real environment. There are mainly three types of proving ground tests – road traffic, artificial cities, and test tracks.

3.1. Road traffic testing

Test drives in road traffic are the most popular methods of testing autonomous driving and active safety systems. In addition to the obvious advantage of driving in a natural, targeted environment, it has many disadvantages. The first drawback is the low repeatability of test conditions, which are basically non-reproducible. Secondly, the car must be fully functional, so these tests must be carried out at the end of product development, extending the development time. Test drives can cause danger to other users and the driver himself, so it is required to avoid testing immature systems. Also, testing on public roads is inconvenient and time-consuming, as every modification of hardware or software requires returning to the company's site. Unfortunately, more and more countries have prohibited the testing of autonomous cars in road traffic due to accidents, something which is driving the development of novel alternative testing methods. An example of test performed in road traffic environment is shown in Figure 8.

Fig. 8. Road traffic test [13]

3.2. Closed area testing

In addition to road traffic tests, tests are carried out in closed areas specially adapted for testing.

3.2.1. Artificial cities

An alternative can be testing cars under artificial conditions, such as in an artificial city that has been built specifically for testing purposes. Such cities exist, among others, in South Korea – K-city [14] or in the USA – Mcity [15]. The map of such city is shown in Figure 9.

Fig. 9. Mcity map [16]

For example, Mcity consists of 40 building facades, from a tunnel, a bridge, a four-lane highway, and even mechanical pedestrians who can enter the pedestrian crossing. In addition, it is equipped with standard road markings and traffic lights [15]. A part of Mcity is shown in Figure 10. Testing in such conditions has many advantages, such as the ability to test in conditions that do not threaten other road users. Moreover, all test conditions are reproducible except for weather conditions. An important advantage is the possibility of any configuration of the environment, for example by changing signs or traffic lights. Despite all these advantages, there are still some drawbacks in this method, including a degree of danger to the driver during the tests. Furthermore, building such a city is very expensive and time consuming, and the car itself still must be fully functional.

Fig. 10. Mcity test facility [16]

3.2.2. Test tracks

A cheaper alternative is testing on test tracks or all kinds of empty squares. Usually, on the track there are individual obstacles that allow validating a given system of active safety, e.g., emergency braking. An example of test performed on empty square is shown in Figure 11. This kind of testing is probably the most popular because it is the cheapest and fastest in implementation. It is often the initial phase before testing in road traffic.

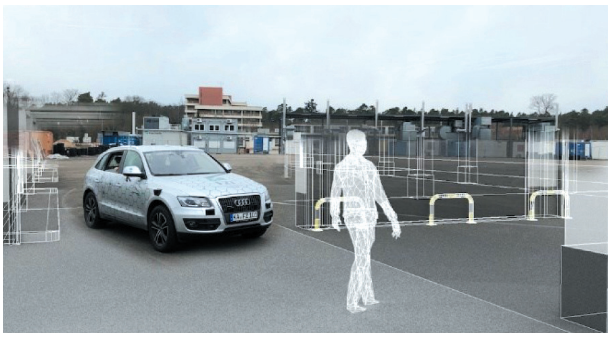

Fig. 11. Car is being tested on test track under the influence of a mixed reality environment [17]

3.2.3. Semi-virtual tests

Also, it is a common practice to combine a virtual test drive with a real one. At the beginning, the entire real track is mapped into the simulation. Then, a test car equipped with a high-accuracy Differential GPS (DGPS) sends its location to the simulator, which sends back the data in the appropriate format, e.g., for radar. This information is sent directly to the ECU of the radar, excluding the radar sensor itself, and the active safety system is triggered [18, 19]. Thanks to this the test is performed on a real track where there are no road users, while from the perspective of the car, it is driving along the same track simultaneously with other cars. Also, often in such mixed rides the driver is equipped with goggles, in which the reality is augmented by elements generated by the simulator. Thanks to this approach, the driver avoids motion sickness and is aware of the resulting car maneuvers.

Another approach to semi-virtual tests is to drive on an empty track where the driver is equipped with VR goggles displaying the completely virtual test drive as shown in Figure 12. The advantage of this approach is that the driver experiences all of the relevant forces while conducting a virtual test drive [20].

The semi-virtual tests can also be applied during the testing of a crossover management controller. The controller assigns the time in which each car could pass the intersection. As the tested car was not equipped with actuation systems that would be able to control the car, the car was run by a driver who performed the controller's commands sent to a dedicated smartphone application [21].

Fig. 12. Real test drives augmented with virtual car [20]

Semi-virtual tests often require the presence of a driver in the car, which can be dangerous, especially when the vehicle is a prototype. This risk can be avoided by replacing the driver by actuators which can be controlled wirelessly.

3.3. Laboratory tests

When it comes to Vehicle-in-the loop testing where the car is tested in laboratory conditions, the problem is simulating the outside world and stimulating the sensors, so that you can test the functionality. This can be done in several ways presented below.

3.3.1. Invasive methods

In invasive methods, one must interfere with the construction of the car. The most invasive method is to disconnect the ECU and inject the relevant data directly to the communication bus [22]. For example, radar ECU can be disconnected, and communication bus is fed with frames containing specific values. Then we are able to observe the vehicle reaction to these data. This method is inconvenient and basically not used, because it requires a significant interference into the construction of the car and deep knowledge of transmitted data structures. This effectively limits the use of this method to OEMs only.

A less invasive way is to leave the ECU connected, but disconnect only the sensor itself from the ECU and after that send electrical signals to the ECU in accordance with the sensor datasheet. As it is much easier to obtain the documentation of the sensor than a documentation of car internal communication systems, this method is already sporadically used.

3.3.2. Non-Invasive methods

There are also a few methods that do not disturb the construction of a car. The first method is to move physical objects in front of the car to trigger the tested systems. For example, a large hall can be used, and the car can be placed on a chassis dynamometer, while traffic is carried out using fake cars that are moved relative to the tested car [23] as shown in Figure 13. This solution has many disadvantages. It is very expensive because one must build cars or other objects that will interact with the tested car. Also, a large room of about 100 m in length is necessary [23] and finally, such an enterprise is very dangerous to the surroundings.

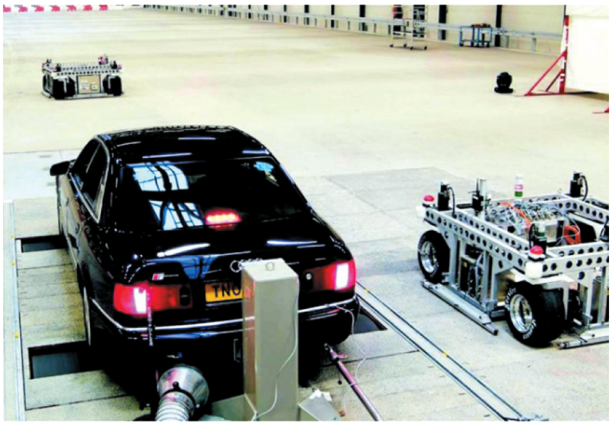

Fig. 13. Tested vehicle on the dyno with fake cars [23]

A very expensive solution, but arguably the most flexible, is to stimulate car sensors using dedicated devices. This approach is commonly used when testing active safety systems or ADAS. Such a test system consists of several components. It comprises a driving simulator which is a computer program that performs virtual test drives. In such a tool, one can also create unique roads, determine the number of lanes, level of road gradient, insert trees and other traffic participants such as cars, pedestrians, etc. [24]. The car is mapped in a simulator and is referred to in the literature as an EGO vehicle. This simulator has built in sensor models such as radar, lidar, etc. Thanks to this, it provides signals in a format dedicated for tested system, which are then sent wirelessly to the corresponding sensors in the car using specialized equipment. The tested car reacts to the received data by changing the trajectories of movement or by activating some active safety system. This reaction is measured, and is sent back to the simulator as physical values. Based on this data, our EGO vehicle reflects the behaviour of the tested vehicle. An example of this is the "Driving Cube" project [25, 26], in which the car was placed on a chassis dynamometer, while special devices were set at the front of the car to wirelessly stimulate the sensors as shown in Figure 14. A special computer program performed the virtual test drive and generated data for stimulators and for the chassis dynamometer.

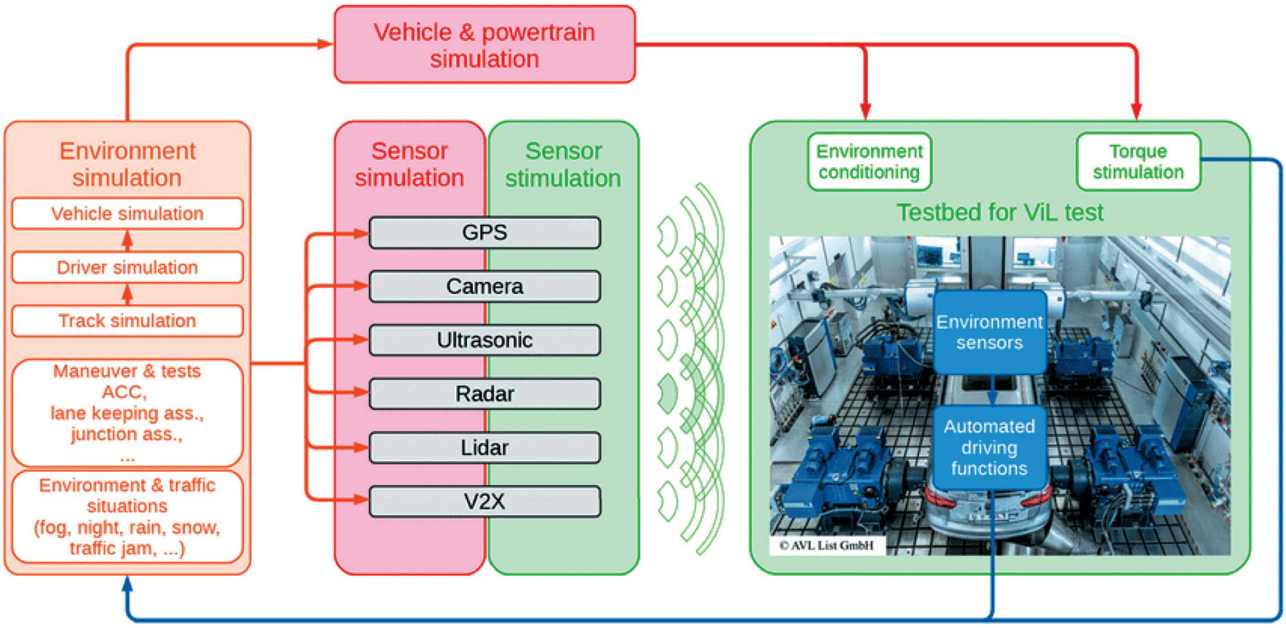

Fig. 14. Driving-Cube test bench for holistic testing of automated driving [27]

4. CONCLUSIONS

There are several ways to verify and validate ADAS and autonomous driving, from road traffic to testing in the laboratory. Currently, laboratory testing is widely used and constantly developed. However, due to the associated costs, only the largest car companies can afford it. Unfortunately, there is no

VIL test system that would be able to stimulate all of the systems used for autonomous driving. From the reviews performed we found that there exist systems that test a single system. Driving Cube is such an example where the radar and camera are tested simultaneously. Such a system primarily lacks the lidar and GPS stimulator, which are crucial systems for autonomous driving. Despite the constantly developing methods, to achieve the above-described goal, it is necessary to answer the following open research question: Is it possible to create a test system that will be able to simulate the external world in the laboratory that driver assistance or autonomous driving systems are tested comprehensively? According to the author, there is a chance to realize such a project, but it can be time-consuming, expensive and requires a multidisciplinary team of people. The main task in such a project would be to integrate existing test systems in a way that they do not disturb each other, and they are able to stimulate all of the tested systems simultaneously.

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