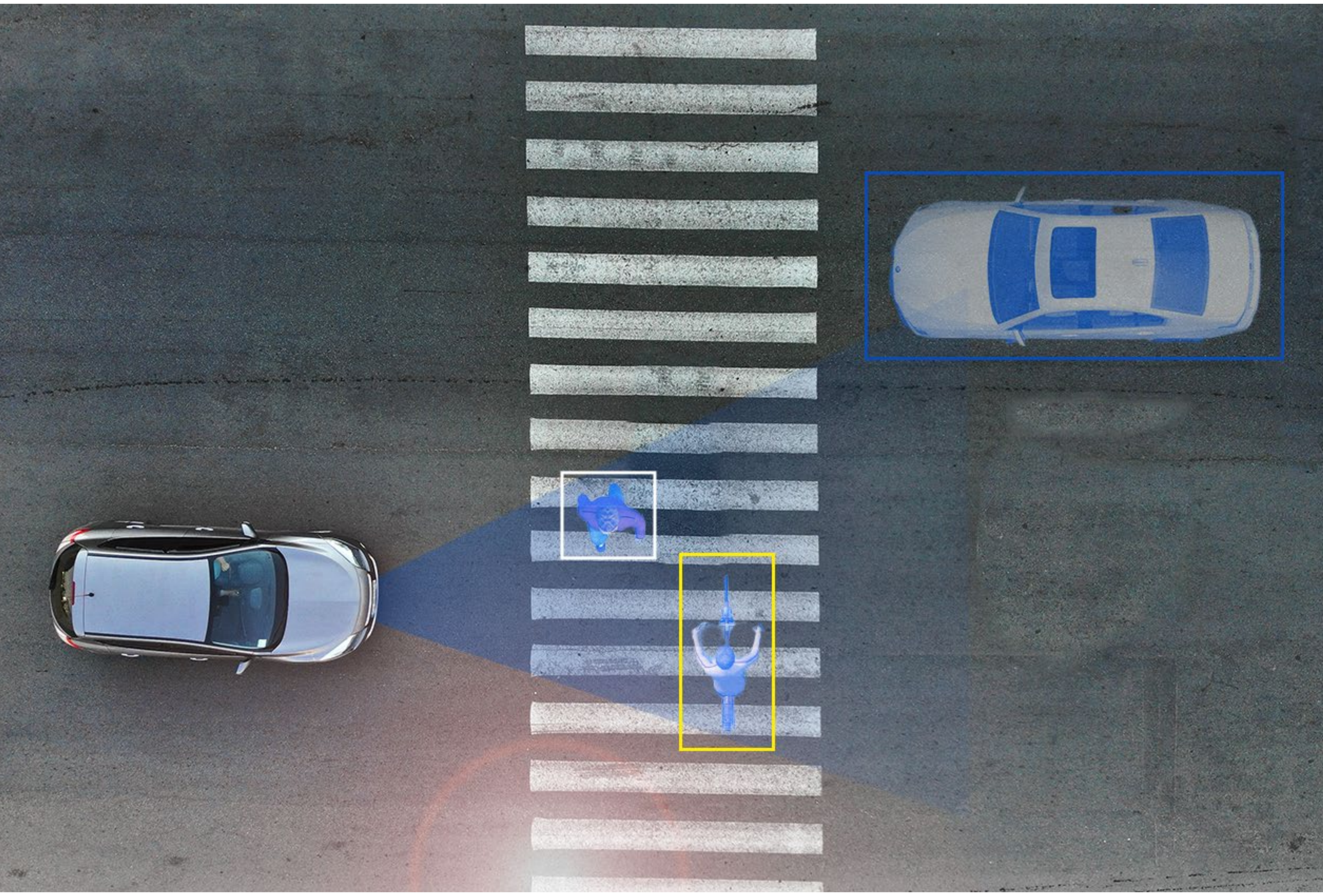
Whitepaper

The Vehicle-in-the-Loop Method



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1. Introduction

In the automotive industry, virtual test driving is necessary to develop, test and validate automated driving functions adequately. Due to their complexity and the interconnectedness of systems, the requirements for testing and software release are extremely high [1] (see Figure 01).

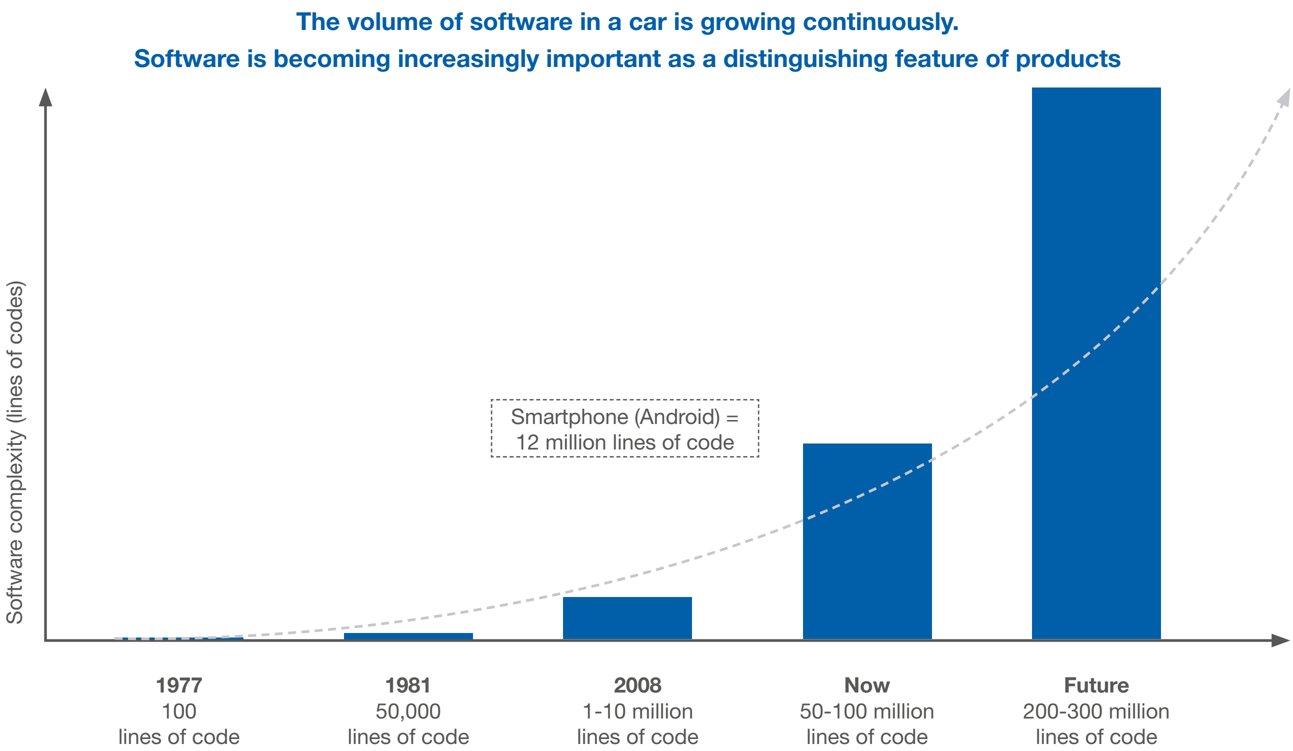

Figure 01: The number of lines of code in vehicles is soaring [1]

To implement driving functions such as automatic emergency braking, data from various sensors are fused. This allows to generate a precise representation of the traffic situation. In development, the ability to ensure that the driving functions work properly in all imaginable traffic situations is key. The fast and accurate detection of the entire vehicle environment is a prerequisite. In automated driving from SAE level 3 onwards, the system takes over from the driver and controls the environment [2]. This results in extremely high release requirements that are impossible to be mastered with conventional test drives. In addition, the human driver cannot be used as a fallback level, because he is not responsible anymore.

The vehicle-in-the-loop method (VIL) can help overcome the limitations of the established test methods. The method is based on the principle to replace the physics-based sensor signals of a physical vehicle with simulated sensor signals, to emulate a virtual environment for the physical vehicle. This allows to circumvent limitations from numerical simulation and physics-based tests. Complex test scenarios can be carried out reproducibly, test drives are made safer, the efficiency in coordination phases increases and the collaboration between test and simulation is improved. The method enables seamless integration into established test processes and tool environments at OEMs and Tier1s.

2. Test methods

2.1 The V-model

The V-model provides a basis for system development for OEMs and Tier1s. As a process model, it divides vehicle development into different stages. It lays the foundation to classify all operations according to the different development stages. The use of simulation solutions in this process model allows to test against requirements at any time (see Figure 02). Vehicle development is therefore facilitated, because the required effort when testing with conventional test drives is rising substantially due to the increasing complexity of advanced driver assistance systems and automated driving functions (ADAS/AV).

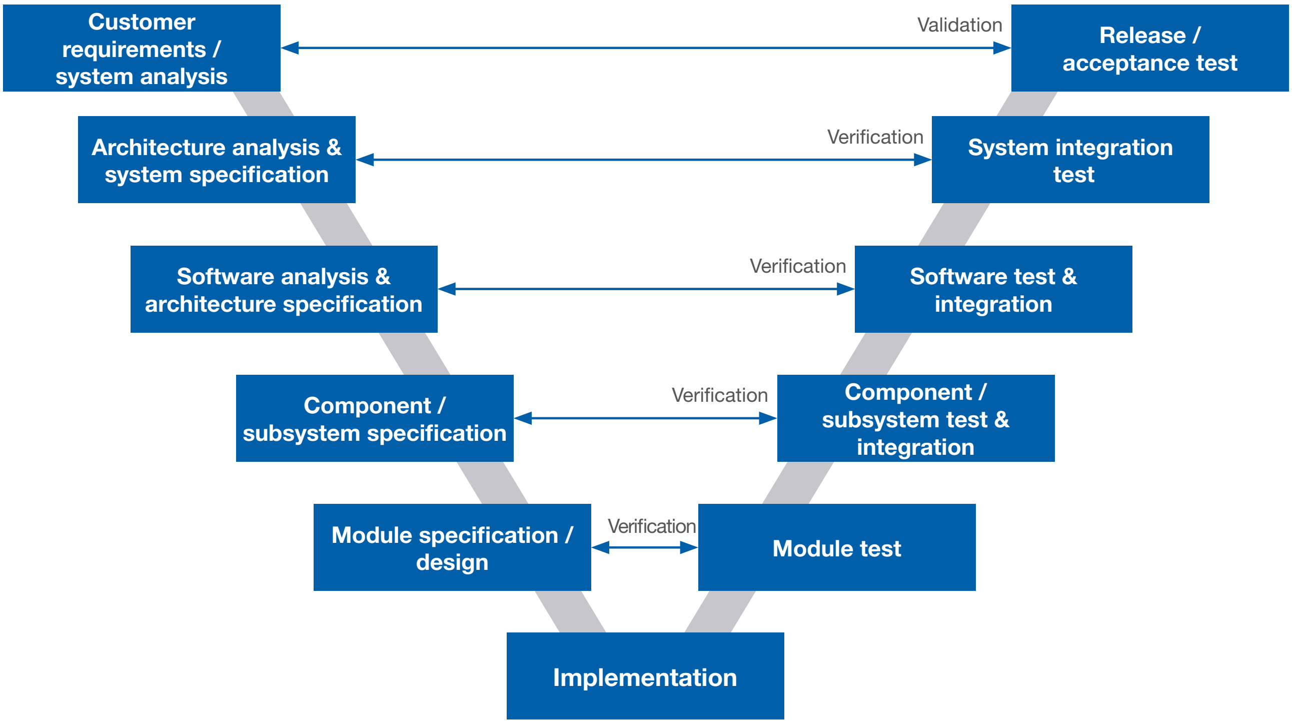

Figure 02: The V-model in the vehicle development cycle according to Winner [3, 4]

When testing simple systems such as park assist systems, variation is mainly needed for steady-state objects. However, more complex systems have different requirements. To avoid accidents for example, at least one potentially involved road user has to be moved dynamically. One possibility in conventional test driving is the deployment of professional test drivers that drive one or more vehicles on a proving ground. In practice, however, dummy targets are commonly used for collision scenarios in longitudinal traffic for safety reasons. But only a few objects can be coordinated at the same time. Examining more complex traffic situations, such as cross traffic on an intersection, is almost impossible without simulation solutions. The risk of damage for people and material and the considerable effort involved are too high. In addition, such maneuvers are not exactly reproducible.

2.2. Common simulation methods

To test and evaluate advanced driver assistance systems holistically with simulation, different processes are applied to the development stages. During early development stages, simulation methods such as model-in-the-loop (MIL), software-in-the-loop (SIL) and hardware-in-the-loop (HIL) are used. These methods allow to integrate systems into a virtual vehicle and to test them in simulation. In the following, X-in-the-loop (XIL) is used as an umbrella term to describe the different simulation methods.

The XIL methods offer various advantages in comparison to real test drives. During conventional test drives, the sensor perception of the environment can cause problems that are usually difficult to differentiate from false decisions made by the ADAS/AV electronic control units (ECUs). Yet, with simulation, the simulated sensor signals are accurately and directly transmitted from a reproducible environment to the ADAS/AV function under test. This allows to perform a high number of tests under freely configurable and reproducible conditions in a very short time.

However, the complete mapping of all vehicle and actuator models is very complex. The growing number of ADAS/AV functions leads to an exponential increase in the number of required validations due to the interactions between the systems. Every single system has to be embedded in the simulation environment, resulting in highly complex models.

The real test drive should be complemented by simulation methods in such a way that it can be used efficiently as a final step to enable comparison with reality. Moreover, a subjective evaluation of the real test drive remains essential to ensure human driver acceptance. The presented VIL method allows to combine the advantages of simulation and real test drives.

3. Definition of the vehicle-in-the-loop method

The functional principle of VIL is similar to the XIL methods, because the same sensor information are used. In comparison to other test methods, VIL uses a physical vehicle instead of a virtual prototype. The ADAS/AV function under test can be a model or a real, hardware ECU. Information on the environment from simulation are transmitted to the ADAS/AV function, which in turn sends its own information to the physical vehicle. By sending the position of the physical vehicle in the real environment to the simulation environment, the control loop is closed. The simulation environment then assures the realtime positioning of the real vehicle in the virtual environment.

No additional infrastructure or personnel is needed apart from the vehicle and the driver. The VIL method therefore combines the advantages of simulation and real test drives: A physical vehicle – a car or a truck – is embedded in a virtual environment (including traffic, road infrastructure etc.) and driven in a real, open area. During the test drive, the driver sees the virtual environment as well as the real environment, which allows him to evaluate the physical vehicle and function behaviors. The driver can therefore experience and feel the overall performance in a subjective way.

The VIL method enables a very reliable execution of tests with high integration. Development profits from all advantages of the virtual world: reproducibility in dynamic scenarios, reduced test effort, ability to reuse test cases and automated test analysis. To be able to test all functions as well as the performance in the physical vehicle and in the same scenarios and environments as with other XIL methods, continuity in the use of the simulation environment is crucial.

If continuity is given, the VIL method can be applied to all stages of model-based development and therefore enables rapid prototyping. At very early development stages, in which only models or algorithms are available, the VIL method allows to develop and calibrate new functions in the physical vehicle in addition to pure simulation (see Figure 03). Where the V-model ends, the VIL method fills the gap between HIL simulation and real test drives. Complex autonomous driving functions can hence be tested at all development stages in virtually flowing traffic. This cannot be realized with conventional test methods.

V Virtual world R Real world	MIL	SIL	ECU HIL	System HIL	PT HIL/ Stat. VIL	Dynamic VIL	Real World
ECU-Code / Function	V	R	R	R	R	R	R
ECU	V	V	R	R	R	R	R
System (e.g. Steering gear)	V	V	V	R	R	R	R
Vehicle	V	V	V	V	R	R	R
Road and static environment	V	V	V	V	V R	R	R
Vehicle Dynamics	V	V	V	V	V	R	R
System experience	V	V	V	V	V	R	R
Driver	V	V	V	V	V	V R	R
Surrounding traffic	V	V	V	V	V	V	R

Figure 03: Virtual components (V) and real components (R) at different development stages [4]

In case the ECU is already integrated in the vehicle, the VIL method can be applied at the end of the V-model to reach a very high maturity of the ADAS function before starting with real test drives (see Figure 04). As the boundary conditions of the test drives can be tested variably and reproducibly, only random tests under completely realistic conditions are necessary for validation. Multiple iterations in the release process can therefore be avoided.

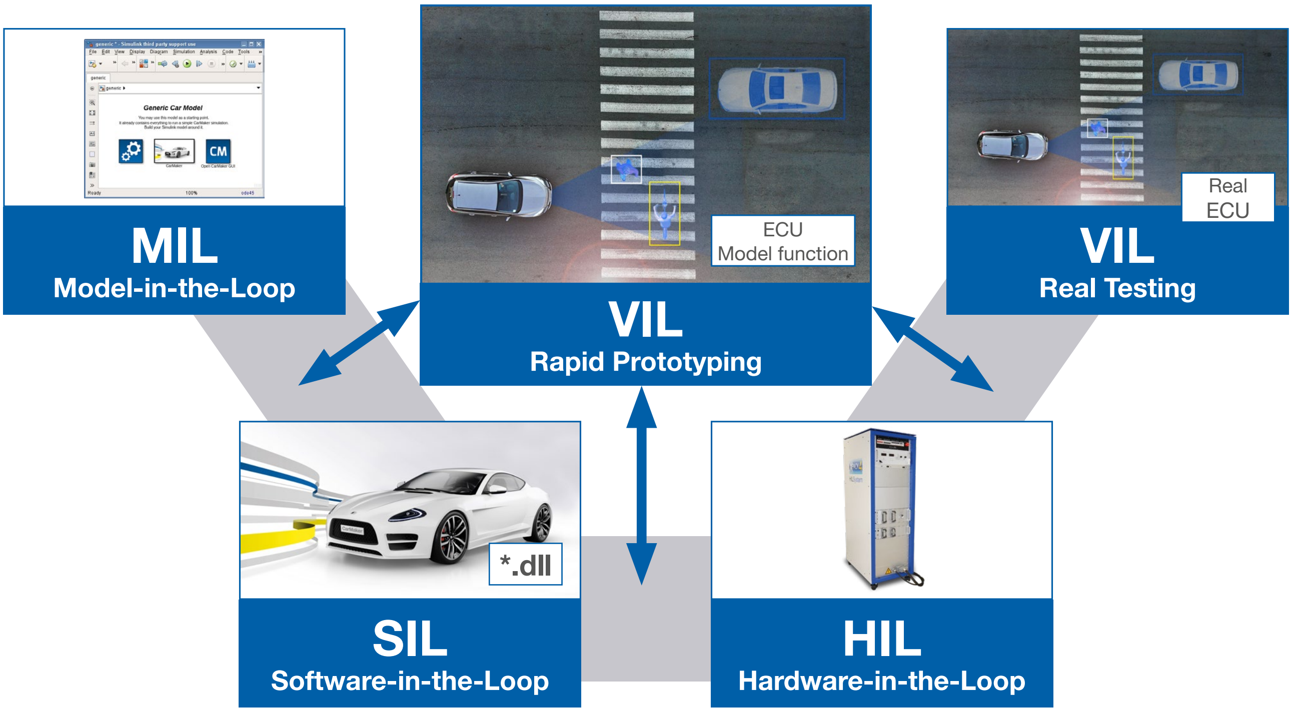

Figure 04: The VIL method plays a vital role in the V-model and allows for rapid prototyping

4. Scenario-based testing

To test ADAS/AV, realistic traffic scenarios are needed. A traffic scenario is a representation of a traffic situation and can be divided into five different layers [5] (see Figure 05). Layer 1, the road, includes basic elements such as course of the road, number of lanes and topology. Layer 2, the road features, comprises the road infrastructure including speed limits, traffic signs etc., as well as steady-state objects such as buildings. Layer 3 describes the temporary influences on layers 1 and 2, caused by a construction site for example. Layer 4 includes dynamic objects, namely other road users such as cars and pedestrians [6]. The environment conditions are defined in layer 5. They include the weather and time of day for example.

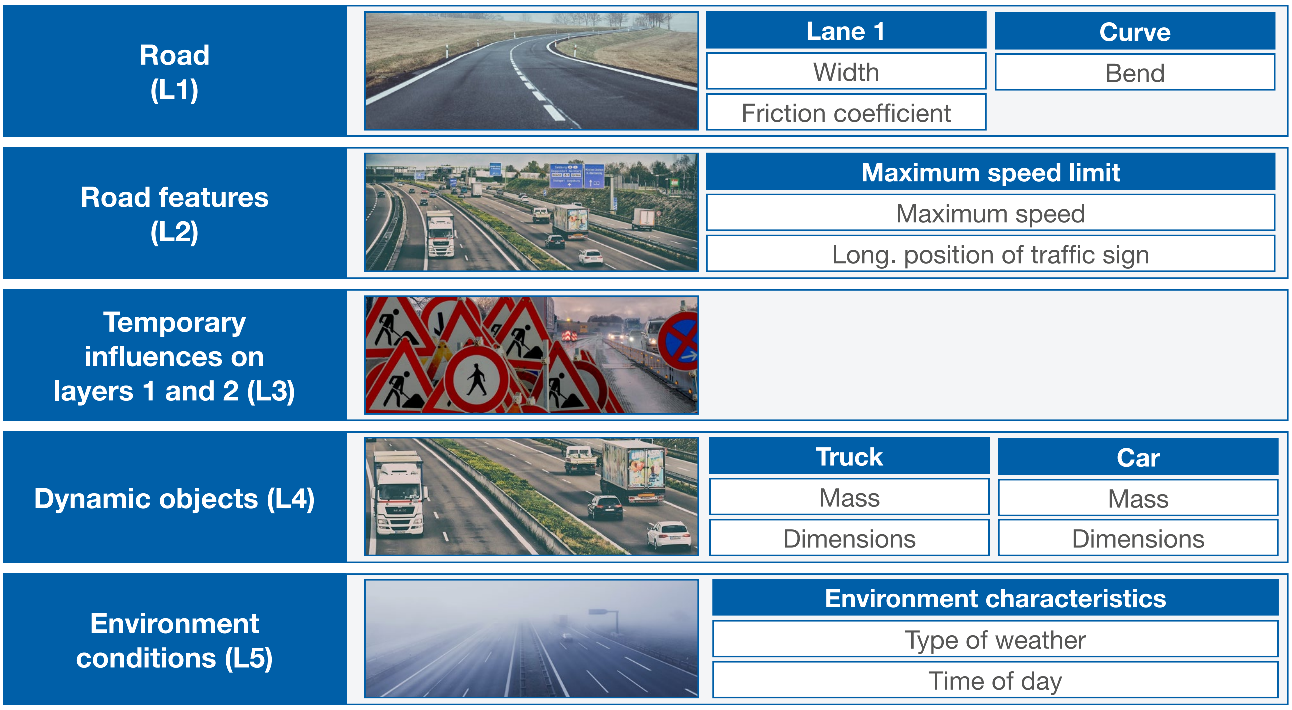

Figure 05: The different model layers [5]

The traffic scenarios are created independently from the vehicle under test and can be reused in future tests. Already existing data from performed real test drives or from accident data bases can be transferred to simulation to create basic scenarios.

Maneuvers configuring the movement of every traffic object (layer 4) in the traffic scenario are defined. The maneuver sequences consist of instructions for lateral and longitudinal dynamics that can be parameterized and combined individually. Alternatively, traffic objects can move autonomously in the environment by following the traffic rules of the virtual test track and by reacting to the behavior of other road users.

Regardless of the scenario sources, it is not only possible to run the basic scenario, but also to create parameter variations and assure the robustness of the system by extending the test scope.

5. Implementation of the vehicle-in-the-loop method

To use physical vehicles for scenario-based testing with the VIL method, the handling of the test vehicle needs to be integrated into simulation. In addition, the virtual environment information must be transmitted to the real ECU in the physical vehicle (see Figure 06).

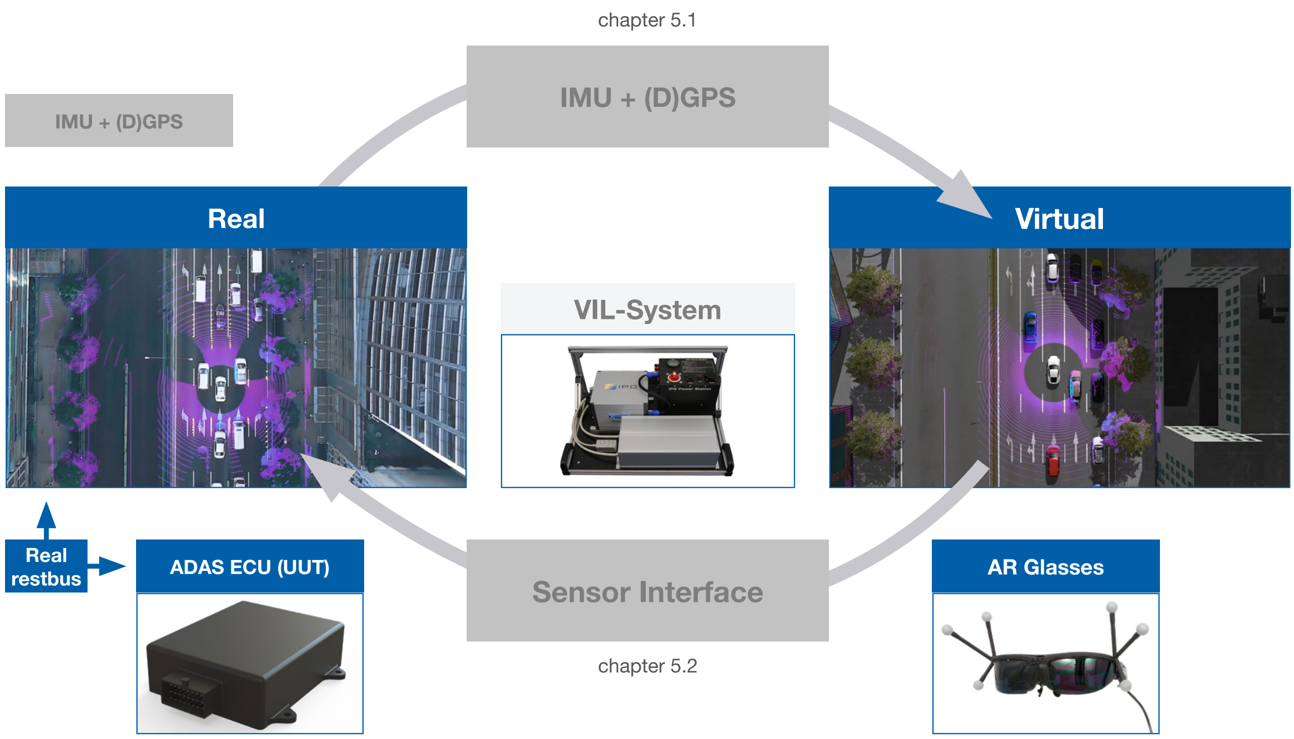

Figure 06: Integration of the physical vehicle into the virtual world

5.1 Transferring the behavior of the physical vehicle into simulation

The behavior of the physical vehicle is measured by an inertial navigation system (INS), which transfers its measured variables to simulation. Generally, an INS combines inertial sensor systems (inertial measurement unit, IMU) with a (D) GPS receiver for drift compensation. The IMU contains accelerometers and angular rate sensors.

The six degrees of freedom of the vehicle can be determined with the three translational and rotational accelerations. The relative position is derived from the double integration over time of the acceleration measurements. Known starting conditions such as location, velocity and direction are a prerequisite. To compensate the cumulative amplification of errors through integration over time, the obtained signal is supported by a (D) GPS signal providing the absolute position.

In addition, avoiding irregularities in the movement data of the virtual ego vehicle and in the resulting sensor data (for example distances, relative velocities) is mandatory.

To this end, the following extrapolation applies:

$$\vec{v}_{Ext}(t) = \vec{v}_{Ext}(t-1) + \left(\vec{a}_{Meas} + \frac{\overrightarrow{ds} * k}{dt^2}\right) * dt$$

$$\vec{s}_{Ext}(t) = \vec{s}_{Ext}(t-1)\left(\vec{v}_{Ext} + \frac{\overrightarrow{ds} * k}{dt}\right) * dt$$

$$\overrightarrow{ds} = \vec{s}_{Meas} - \vec{s}_{Ext}$$

Equation 01: The extrapolation

The extrapolation allows to calculate continuous signal sequences on the basis of the measured accelerations a $\vec{a}_{Meas}$. The deviations $\overrightarrow{ds}$ of position, which can be caused by measurement faults, are minimized under the influence of the filter constant k. Figure 07 presents the results of the extrapolation. The signal values run along the measured values continuously without irregularities. By implementing a standstill detection, the position and velocity remain stable in stationary

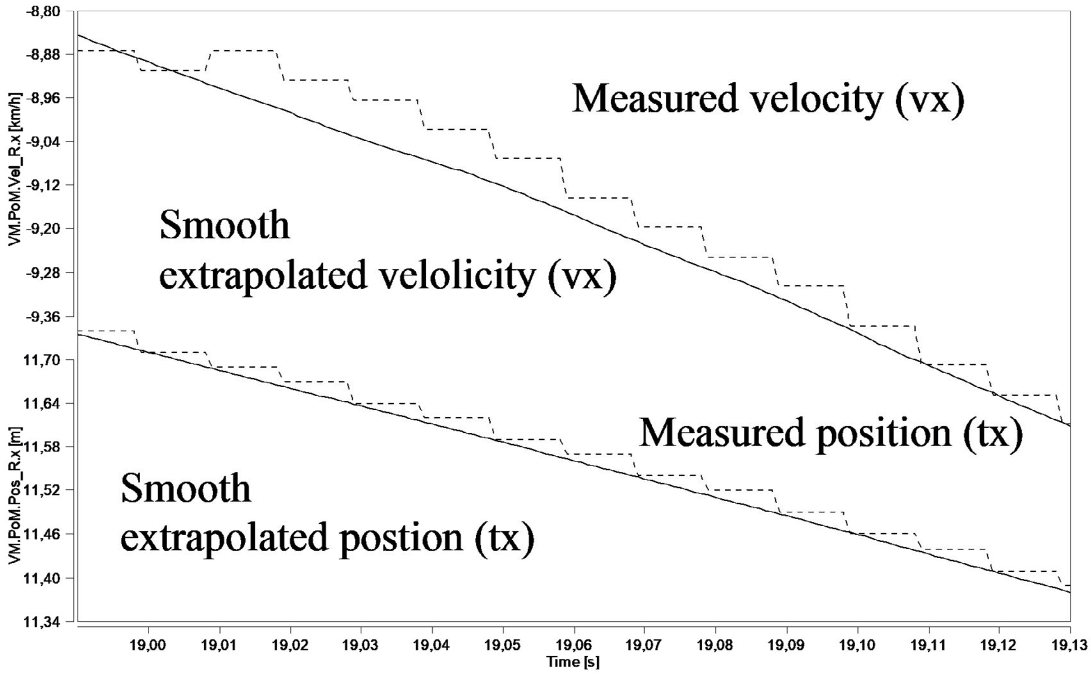

Figure 07: Extrapolated movement and position signals

Two different modes are available as a basis for the VIL method: the free mode and the absolute mode. In free mode, the entire environment is simulated. The physical vehicle has to be standing in a completely open area without buildings, uneven road surfaces etc. With the start of the simulation, the environment around the vehicle is built. The driver has the possibility to launch the test drive relative to the position of the vehicle. Applying this method is useful when no real circumstances are considered, and when everything, except for the vehicle, is simulated.

The absolute mode incorporates all features of the real environment into the virtual test scenario, given that the real environment has already been modeled in simulation. This can be practical when the user has a suitable real proving ground with features he wants to integrate into the test. In this case for example, real inclines and traffic signs are transferred to the virtual environment, while all road users are simulated. In absolute mode, the driver can start the test drive automatically based on route or position. The position between the simulation and the physical vehicle must be synchronized.

5.2 Transferring the virtual environment to the physical ECU

There are different options to transfer sensor data to the sensor-based ECU in the vehicle (see Figure 08). The so-called over-the-air (OTA) stimulation is the preferred approach. Here, the sensor interface is controlled by physics-based, sensor-specific components (optic for camera, antenna for radar, etc.). The advantage is that the entire processing chain of the sensor is utilized and tested. The sensor is therefore fully integrated into the test environment. An alternative to OTA stimulation is to feed synthetic raw sensor data directly into the sensor or into the suitable ECU interface (for example video streaming for cameras [7]).

Although a sensor-independent option is also possible. Object lists based on the ground truth information from the environment simulation are available. They can be used as input for the application logic of ECUs. The restbus technique fully circumvents the entire ECU, because the results of the simulation are transmitted directly to the vehicle bus system. This solution is characterized by low cost and allows to test the application logic, including movement control or trajectory planning of the vehicle.

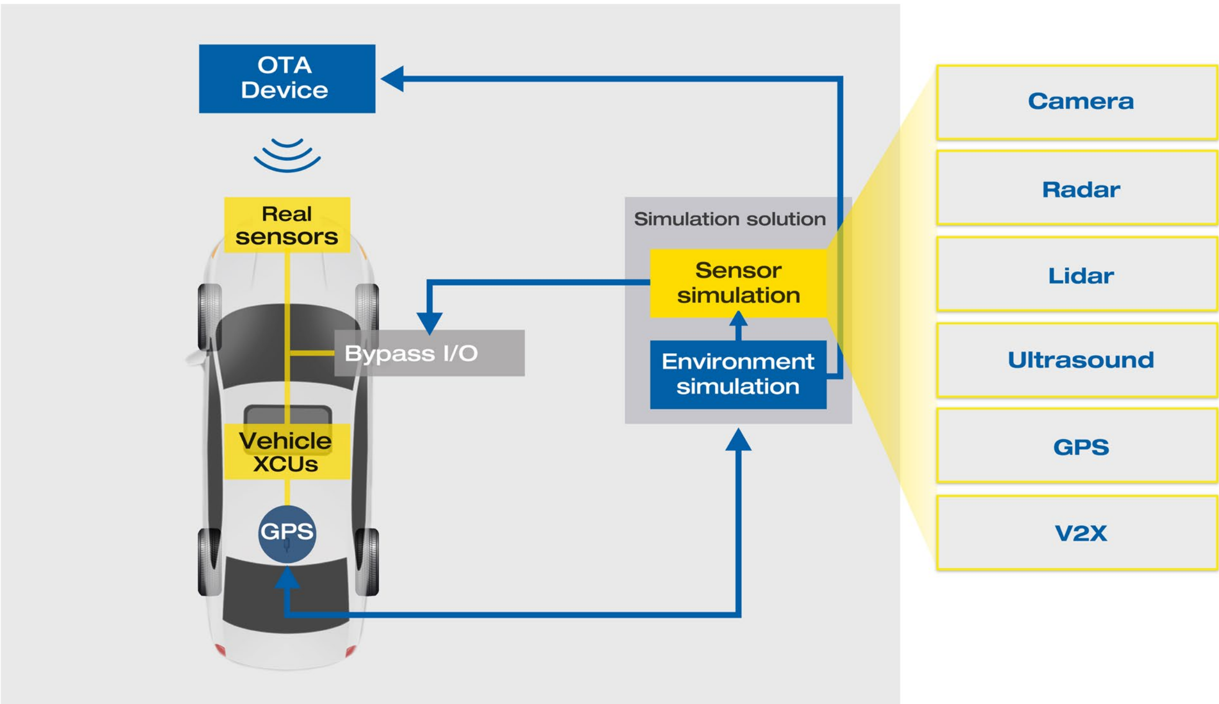

Figure 08: Sensor simulation

The sensor models have to provide the necessary level of detail of the environment information in real time for all subsystems. This ensures that functions such as perception, sensor data fusion as well as planning and performing driving maneuvers on the test bench are covered. Depending on the project, different modeling depths can be sensible. A variety of quality classes of sensor models are available.

They flexibly adjust to the project and feed the subsystems with specially adapted information:

- Raw signal interfaces provide input data for the perception algorithms of the sensor. Material properties of the objects and detailed physical effects are considered when generating raw signals.
- HiFi sensor models provide an object list. Information are enhanced through physical effects and/or with technology-specific, partly stochastic errors, providing a realistic object list for the employed sensor technology.
- Ideal sensor models provide a list of relevant detected objects and guarantee an ideal and technology-independent environment detection.

All mentioned solutions are applicable to all sensor types and can be adapted to the final vehicle architecture.

5.3 Integration of the human driver

A human driver or a test robot can control the entire test set-up from the vehicle. The whole environment simulation can be controlled, started and analyzed on the fly over the touch screen of the integrated operating PC, based on route, position or event. This also includes the import of predefined scenarios for example.

The human driver has to be integrated into the test process as a test driver or subcomponent of the highly automated vehicle. For this purpose, the possibility to visualize the simulated environment in the test process is a key component for the driver. Here, an appropriate interface is necessary. This can be achieved with monitors displaying a 3D real-time animation, or with augmented reality (AR) technology such as AR glasses. All requirements, from simple monitoring to a realistic driving experience, can therefore be met.

For additional convenience, AR glasses display the driving situation including all virtual elements in a realistic way. The see-through technology is well suited for this purpose. A semi-transparent mirror allows to overlay the real environment with the simulated environment. Another possibility are glasses that capture the real environment via (stereo) camera systems, transmit it to the respective algorithms and augment it afterwards. As stereo displays are used in these glasses, the stereoscopic view can be imitated and the degree of reality can be augmented accordingly.

The inertial sensors (angular rate sensor and accelerometer) integrated into the glasses are able to determine the head position of the person wearing the glasses (and therefore also the correct visualization) and subsequently transfer it into simulation. Here, the virtual camera can be adapted gradually to allow the person wearing the glasses to move in the virtual environment. The impacts of vehicle dynamics on the inertial sensors of the glasses present a challenge. They stimulate the accelerometer and the angular rate sensors and measure the apparent motions of the head which are caused by the moving vehicle.

As an alternative, stationary camera-based tracking systems can directly determine the necessary relative movement and orientation of the head in relation to the vehicle. Nevertheless, these systems are slower than systems based on inertial sensors which can result in unwanted latencies in visualization. One option for improvement is fusing sensor data to create a sensor data-based environment model including all relevant information.

6. Application example

The procedure of NCAP tests (New Car Assessment Programme) is going to serve as an example to illustrate the VIL method. The assessment criteria developed by NCAP comprise a one-to-five star scheme, allowing the customer to compare the safety of different vehicles. The assessment results from the performance of a number of different test drives that reconstruct the most common causes of accidents in real traffic. The continuously growing role of this well-known vehicle safety assessment leads to ever higher development efforts. One of the causes is the compliance to new test standards on a regular basis.

Many requirements are involved in the system tests, but most of them cannot be realized in the physical vehicle. To evaluate test scenarios, a subjective experience as well as reproducibility with low effort are necessary. However, the most important requirement is that there is no risk of damage for people and material.

With simulation, and in combination with the VIL method in particular, it is possible to evaluate the interaction of ADAS/AV systems in specific situations and the compliance to the required NCAP criteria early on in the development process. This way, new safety systems can be developed efficiently and without risk, whereas already existing functions can be improved. In the coordination phase and when testing functions at an early development stage, the development time can be reduced significantly.

Testing emergency brake assists for example is very costly and time consuming, because these tests need a high number of different dummy targets. They cause high costs while their handling is realistic only to a limited extend. A study carried out by Bast [8] shows that, with the VIL method, the number of possible test cases can approximately be increased by the factor 4.5 on a regular working day.

This increase is due to the fact that only one test driver is necessary, less time is needed for pre- and post-processing and the test can be carried out at a much faster pace. The VIL method therefore allows to optimize the development and testing of NCAP and to save time and cost.

7. Summary

The VIL method makes it easier to master complex test drives. Whereas conventional physical test methods necessitate a real driver for each vehicle participating in the test, the VIL method allows for tests with only one vehicle and one driver. All other vehicles and their drivers as well as the road infrastructure are simulated.

In the real test drive, all involved drivers have to coordinate their maneuvers with precision. When a certain number of vehicles is reached, coordination becomes almost impossible, even with high efforts involved. With the VIL method on the contrary, an unlimited number of road users can move in a traffic scenario. In addition, they can be synchronized with each other and carry out triggered events. The VIL method also enables the efficient fine-tuning of specific parameters, because their functions can be analyzed individually and independently from external influences. The possible risks that accompany many real test drives are completely eliminated thanks to the virtual environment and the simulated road users.

Due to the mentioned advantages in comparison to conventional test drives, the VIL method leads to a more successful implementation of projects. In project management, the so-called iron triangle is employed to quantify the obtained results. It incorporates the three key parameters which define a project and its success: quality (reach targets), time (duration of project) and cost (compliance to set budget). As soon as one of these parameters is modified, the remaining parameters usually change as well: If the goal is to increase quality, in general, costs are rising and more time is needed.
However, with the VIL method, the quality of results can be increased significantly while reducing the costs as well as the duration of the project. VIL allows to experience and test complex scenarios in a reproducible way. With its functional principle, it also makes a significant contribution to redefine the success of future development projects.

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