Optimized Merging of the Virtual World and Reality on the Vehicle-in-the-Loop Test Bench

Dr. Pascal **Piecha**, IPG Automotive GmbH, Karlsruhe, Germany
Contact: pascal.piecha@ipg-automotive.com

Philip **Rautenberg**, Karlsruhe Institute of Technology, Karlsruhe, Germany
Contact: philip.rautenberg@kit.edu

Michael **Friedmann**, APL Automobil-Prüftechnik Landau GmbH, Germany
Contact: michael.friedmann@apl-landau.de

Abstract

To overcome the upcoming complexity of testing future vehicles with versatile technologies and changing legal requirements, this research focuses on a development method and validation on full vehicle level based on combining simulation and test bench operation. The goal is to enhance realism and achieve a reproducible and controllable environment for full vehicle development and testing. While conventional test environments face challenges such as limited reproducibility or constraints of stationary test execution, integrating simulation with test bench operation presents significant advantages.

This research utilized a highly dynamic and steerable vehicle-in-the-loop test bench coupled with CarMaker from IPG Automotive to conduct holistic tests where the full vehicle operates within a simulated environment. Based on the drive shaft torques, the wheel-specific rotational speeds resulting from the defined scenarios are adjusted in a closed-loop approach. A driving robot, sensor stimulators or interconnections to control units can extend this testing environment. The vehicle can thus be the tested in a variety of situations with respect to safety, comfort and efficiency.

Furthermore, this research extends the discussion to incorporate virtual reality on the vehicle-in-the-loop test bench. Leveraging virtual reality technology, a novel approach is proposed where a driver on the test bench experiences a virtual environment through wearable virtual reality headsets. This integration enhances test environment realism, providing a more immersive and accurate representation of real-world driving conditions.

On this basis, it is demonstrated how the vehicle-in-the-loop test bench, augmented with virtual reality capabilities, facilitates development and validation of different vehicle subsystems. By enabling engineers to assess various driving scenarios in a controlled yet immersive environment, this approach holds promise for advancing the accuracy and reliability of testing, particularly in the field of autonomous driving and electric vehicles.

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1 Objectives

The key objective of this contribution is to evaluate the testing framework of a vehicle-in-the-loop (VIL) test bench linked with a simulation environment and extended by virtual reality (VR) technology for an immersive driving experience.

For this, different implementations with different VR headsets will be realized and drawbacks, advantages and chances will be discussed. The investigations aim at evaluating the effectiveness of this VIL testing method for the simulation of handover situations, where control is transferred between the driver and the assistance system.

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2 Scope and Structure

The contribution is structured to first provide an overview of the Vehicle-in-the-Loop test bench, detailing its components, capabilities and limitations, and explaining how it is linked to a full vehicle simulation environment through hardware-in-the-loop (HIL) integration supported by CarMaker. This section also examines potential extensions, such as sensor spoofing, and presents various use cases that can be tested using this methodology.

The contribution then introduces VR technology, examining the role of VR in vehicle testing and outlining the necessary hardware and software requirements to integrate VR into the Vehicle-in-the-Loop test bench. This section further elaborates on the technical aspects of the integration process and how VR enhances the realism and effectiveness of the testing environment.

Following this, the contribution presents a case study that demonstrates the application of the proposed method by describing the specific scenarios and test cases used for analysis as well as the setup and testing procedures. The results and findings are discussed along with the challenges and limitations encountered during the testing process.

The work concludes by summarizing the key findings, highlighting the effectiveness and potential of the VIL testing framework with VR integration for vehicle development and testing and discussing future directions for further improvement and wider application of this method.

3 Overview of the Vehicle-in-the-Loop Test Bench

The Vehicle-in-the-Loop test bench of the Institute of Vehicle System Technology (FAST) at the Karlsruhe Institute of Technology (KIT) is a powertrain test bench, which can be used for vehicle measurements in longitudinal and lateral dynamic driving situations. Therefore, the tires have to be dismounted. The test bench consists of four three-phase synchronous machines (Figure 1). These are mechanically connected to the four wheel flanges of the vehicle via four constant velocity drive shafts and four rotatably mounted wheel adapters, and can thus transmit forces and simulate the load-dependent driving resistances as well as the operating point relevant tire characteristics. The torque is measured directly at the connection between the wheel hub and wheel adapter, so that possible losses due to the shaft and load machine have no influence. The speed can be measured directly at the load machines due to the connection to the vehicle via constant velocity drive shafts. The load machines are fed by highly dynamic frequency converters.

The rotatably mounted wheel adapters are mechanically connected to two additional synchronous machines at the front axle via a chain drive. These simulate the self-aligning torque that occurs at the wheels steered. This allows steering manoeuvres to be carried out without any changes to the test specimen [6, 7]. The vehicle on the test

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bench is cooled by a fan and ensures an air flow for the heat dissipation of different vehicle parts, for example, powertrain and brake disks. For a more detailed description of the test bench, see [1, 5]. The main technical data of the test bench is presented in Tab. 1.

Tab. 1 Technical data of the test bench.

Description	Data
Max. vehicle weight	12,000 kg
Max. wheel load	3000 kg
Wheelbase	1.8 m–4.9 m
Track width	1.2 m–3.9 m
Max. wheel speed	2000 /min (260 km/h with rdyn = 0.34 m)
Max. wheel load torque at nom. speed	2500 Nm (@800 /min)
Nominal wheel load power	209 kW
Max. steering angle at the front wheels	±20°
Max. self-aligning torque at the front wheels	1000 Nm
Max. air fan wind speed	135 km/h

Fig. 1 Powertrain test bench – vehicle-in-the-loop

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4 Linking the Vehicle-in-the-Loop Test Bench with Simulation

To expand the testing capabilities of the test bench, a realistic simulation of the virtual digital world for various driving scenarios is realized through the simulation software CarMaker. Route data based on GNSS information can be imported and real routes can be simulated and tested on the test bench. To replicate the loads on the powertrain as they would occur on a real road, the wheel speeds are determined using wheel models (including tire models) that utilize the measured torques from the drive shafts and interact with a vehicle body model. These models are calculated in real time on the test bench, with the resulting wheel speeds serving as reference values for speed control [9]. In detail, the following steps are executed within a single control cycle (see Figure 2):

- The torques and speeds on the side shafts are measured.
- The wheel models use these torque values along with data from the vehicle body model, such as contact forces and vehicle speed, to perform their calculations.
- The vehicle body model returns values such as longitudinal forces and the wheel models output wheel speeds.
- These speeds then serve as setpoints for the speed controllers, which subsequently generate the trigger pulses for the frequency converter.

This precise speed control at the wheel hub enables accurate reproduction of road loads, even under extreme conditions like icy patches or regenerative braking.

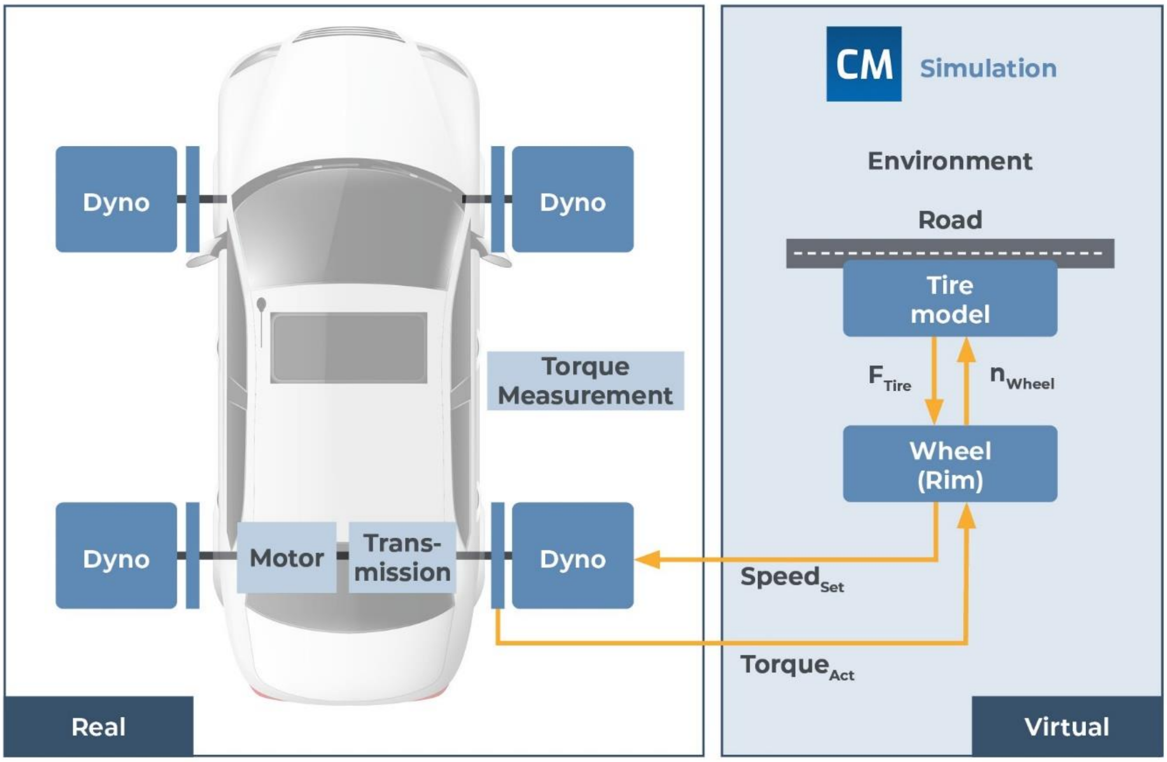

Fig. 2 Control concept

5 Extending the Full Vehicle-in-the-Loop Test Bench with Sensor Spoofing

In addition to simulating the mechanical and dynamic behavior of a vehicle, it is crucial to accurately replicate the sensor environments when testing advanced driver assistance systems (ADAS) and autonomous driving functions. To achieve this, the full Vehicle-in-the-Loop test bench can be extended with sensor spoofing capabilities.

Sensor spoofing involves manipulating or stimulating the signals received by various vehicle sensors, such as radar, GNSS and cameras, to create a test environment interacting with the virtual world. Various sensor spoofing methods have already been applied into the VIL test bench, such as radar target simulation, GNSS spoofing and camera HIL simulation, to evaluate the performance and robustness of various vehicle systems in different scenarios [4].

Radar sensors are critical for detecting objects and measuring distances, speed and direction, especially in ADAS applications like adaptive cruise control, collision avoidance and blind spot detection. Extending the VIL test bench with a radar target simulator allows for a precise emulation of various objects, such as vehicles, pedestrians or static obstacles within the radar sensor’s detection range [2, 4].

A radar target simulator generates artificial radar echoes that mimic the reflections from real-world objects. By adjusting parameters like distance, speed and size of the simulated targets, engineers can create complex scenarios involving multiple moving objects. This capability is particularly useful for testing the sensor's performance in challenging situations, such as heavy traffic or cluttered environments where the radar must distinguish between multiple targets [3].

The extension of the test bench with the module for GNSS allows for exact simulation of the GNSS signals in the test cabin based on the time and position of the vehicle simulated in CarMaker. In this way, the vehicle placed in the test cabin can receive the GNSS position via the GNSS antenna and transmit it to all the control units and functions provided for this purpose. Especially for battery electric vehicles, the GNSS position plays an important role due to the customer's potential range anxiety, battery conditioning and thermal boundary conditions.

Figure 3 shows a possible configuration for execution on the Vehicle-in-the-Loop test bench. For this purpose, the simulation system, consisting of the open integration and test platform CarMaker and Xpack4 hardware, is coupled with hardware and software to simulate high-frequency GNSS signals. The electromagnetic waves can be injected directly into the vehicle's antenna via a mechanical connection using a cable. Alternatively, they can reach the vehicle antenna via propagation in the test bench cabin.

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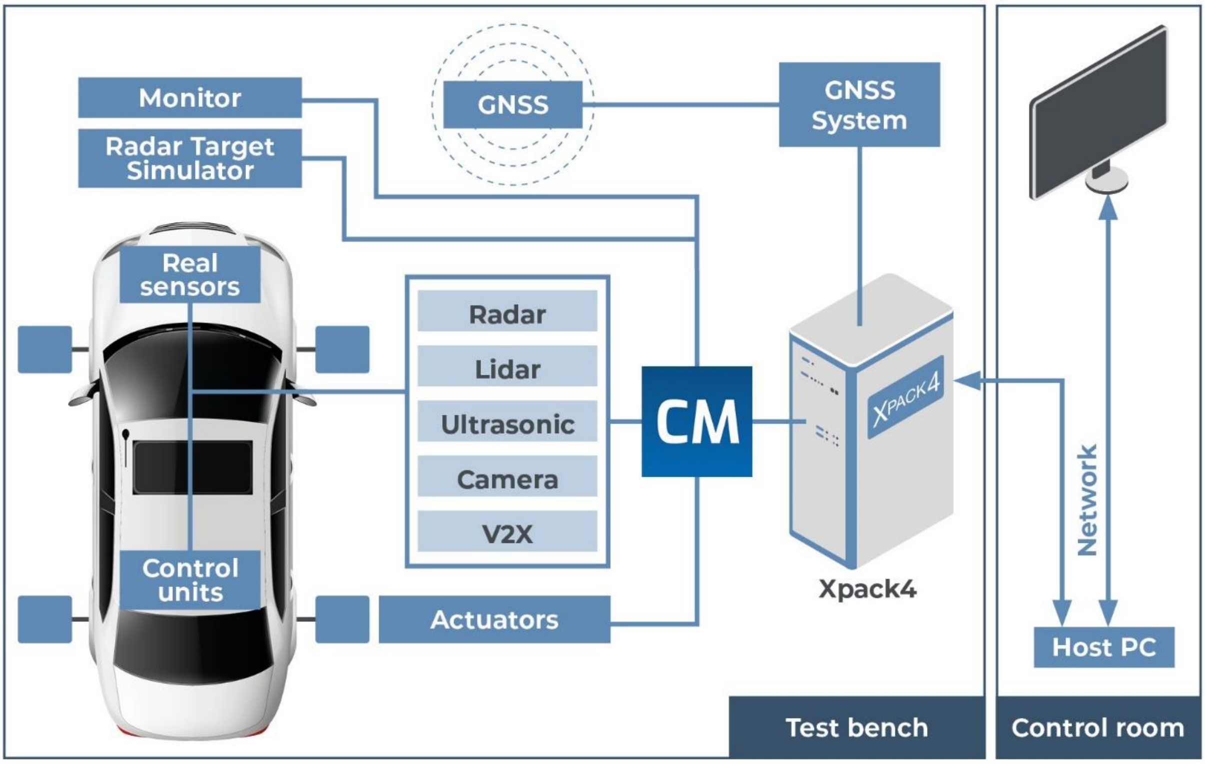

Fig. 3 Abstract structure of the test bench and control room

In modern passenger cars, cameras are used for object detection, lane recognition, traffic sign identification and driver monitoring systems. The effectiveness of camera-based ADAS functions heavily relies on the quality and accuracy of the visual data captured by these sensors. Extending the VIL test bench with camera HIL simulation enables an assessment of the vehicle's camera systems and the entire sensor data processing.

This can be realized by feeding video data directly into the vehicle's camera processing unit, bypassing the actual optical sensor, or through a monitor or video screen in front of the camera. These approaches allow engineers to test the camera-based systems under a wide range of lighting conditions, weather effects and road environments without needing to physically alter the test environment. For example, complex traffic situations involving pedestrians, cyclists or other vehicles can be simulated to evaluate the performance of features like automatic emergency braking, pedestrian detection or lane departure warning.

Extending the full VIL test bench with sensor spoofing capabilities, such as radar target simulation, GNSS spoofing and camera HIL simulation, represents a powerful enhancement to the existing VIL testing framework. These extensions provide a more comprehensive and realistic test environment, enabling the evaluation of ADAS and autonomous driving features under a wide range of challenging conditions.

6 Incorporating Virtual Reality Technology

Integrating VR technology into full vehicle test benches enhanced with sensor spoofing provides an opportunity for advancing the development and testing of advanced driver assistance systems and autonomous vehicle technologies. This combination can create a highly immersive and realistic environment that enhances the evaluation of vehicle performance under a wide range of conditions.

In addition, the integration of VR with sensor spoofing allows researchers to study human-machine interactions, including driver behavior, responses to ADAS feedback and the effectiveness of warning systems, providing insights to optimize system design and user acceptance. This approach also enables the safe and reproducible testing of critical scenarios that are difficult or dangerous to replicate on real roads, such as emergency maneuvers, sudden pedestrian crossings or multi-vehicle interactions, allowing engineers to evaluate system performance, identify potential issues and make necessary optimizations without compromising safety.

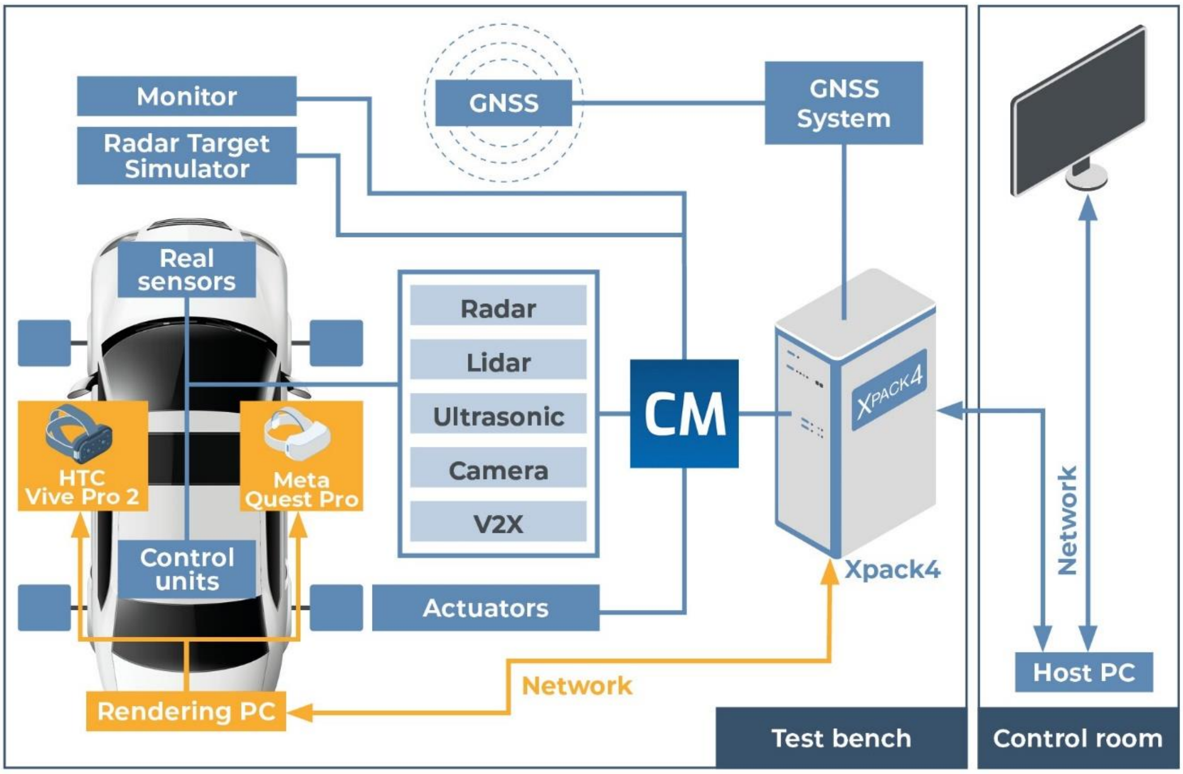

Fig. 4 Simplified structure of the test bench and control room extended with VR technology

To successfully integrate VR technology into a full vehicle test bench using CarMaker, both hardware and software systems must meet specific performance criteria to ensure seamless real-time visualization and interaction between the virtual world and the physical test bench. In the presented use case on the test bench, it is necessary to visualize the simulated image from the real-time computer both in the test bench control room and inside the vehicle. This is achieved by using a front monitor for visualization in the control room and a VR headset within the vehicle, providing immersive visualization directly to the driver. Therefore, it is necessary to connect an additional (rendering) computer through Ethernet, either close to or inside the vehicle under test, to connect the VR headset and ensure smooth operation (see Figure 4).The minimum hardware requirements include a computer equipped with a 8-core processor, paired with a minimum of 32 GB of RAM and an USB 3.0 port. Regarding the GPU of the rendering computer, the minimum requirement is an NVIDIA RTX 2080 Ti. To achieve smooth and realistic visualizations in the VR environment during full vehicle test bench simulations, it is recommended to use a high-performance GPU capable of handling highly detailed scenarios. Scenarios with a large number of elements, such as densely populated urban environments with numerous buildings, vehicles, pedestrians and other road users, place significant demands on the GPU's processing power.

The level of detail directly correlates with the required performance; as the complexity of the scenario increases, so does the need for advanced graphical processing to maintain high frame rates. For this reason, it is recommended to use an nVidia RTX 3080 or better, to ensure that the VR experience remains smooth and immersive, to avoid motion sickness and to provide a natural, responsive driving experience. Therefore, the selection of a powerful GPU is critical when creating and simulating detailed and demanding scenarios in VR on a vehicle test bench, as it ensures that both the visual complexity and performance requirements are met effectively. In the research, an nVidia GeForce RTX 2060 on the host PC was utilized to ensure smooth operation of the test bench automation with the simplified visualization (IPGMovie). For the rendering PC running Movie NX, an nVidia GeForce RTX 3060 Ti was used.

On the software side, CarMaker is used to simulate the vehicle and environment dynamics in real time, with a dedicated VR integration plugin (VR add-on) allowing synchronization between the vehicle's behavior, driver movements and the virtual display. The VR setup also requires headset-specific software to ensure proper integration between the hardware and simulation software.

In the described implementation, both the Meta Quest Pro (Figure 5 – bottom) and the HTC Vive Pro 2 (Figure 5 – center) VR headsets were used, deviating from the common setup without VR headsets (Figure 5 – top). For both devices, the VR add-on from IPG Automotive is essential to synchronize the virtual scene with the headset itself. Additionally, for the Meta Quest Pro, Meta's proprietary software is required to manage the VR headset's operation and correctly interpret the virtual scene. Similarly, for the HTC Vive Pro 2, both Steam software and Vive software are mandatory to ensure the correct rendering of the virtual environment and proper synchronization between CarMaker and the VR hardware. These software components ensure that the virtual scenarios are accurately displayed.

The Meta Quest Pro is a standalone VR headset with built-in processing power. In contrast, the HTC Vive Pro 2 is a tethered, PC-powered headset that offers superior visual clarity with a 5K resolution and wide field of view, but requires external sensors (see Figure 5 – center, right side) for precise tracking and relies on a connected high-performance PC for operation.

Fig. 5 Top: Standard implementation without VR headset; Center: VR headset – HTC Vive Pro 2; Bottom: VR headset – Meta Quest Pro

This integrated hardware and software setup enables a fully immersive, high-fidelity virtual driving environment that is synchronized with the Vehicle-in-the-Loop test bench, providing the possibility of effective testing and development of advanced driver assistance systems and autonomous driving technologies.

7 Testing Driver Assistance System Using the Proposed Method

In the following, the selected driving scenarios are described, followed by an explanation of how the test were carried out. The results and findings from these tests are then used to assess the effectiveness of the method.

7.1 Scenario Overview

The driving scenarios used within the simulation environment for this testing method were created either manually or product examples were utilized. The scenarios are exclusively synthetically generated. Special attention was given to ensure that the test scenarios have a high level of detail and include numerous traffic participants to accurately reflect real-world conditions. In addition to the fundamental evaluation of this method, a key focus was on use cases involving handover situations between ADAS and the driver, or vice versa. These scenarios include various driving situations, such as starting at traffic lights using an Adaptive Cruise Control (ACC) with stop&go function (Figure 6 – top left), entering construction zones with corresponding takeover situations (Figure 6 – top right), or exiting highway sections, where the control is handed back to the driver by the highway driving assist (Figure 6 – bottom right). For sensor spoofing and testing perception and/or sensor fusion functions, complex scenarios like driving through a tunnel with challenging lighting conditions can also be explored (Figure 6 – bottom left). These diverse driving scenarios serve as the foundation for evaluating the effectiveness of this testing method, especially when integrating VR at a full vehicle test bench.

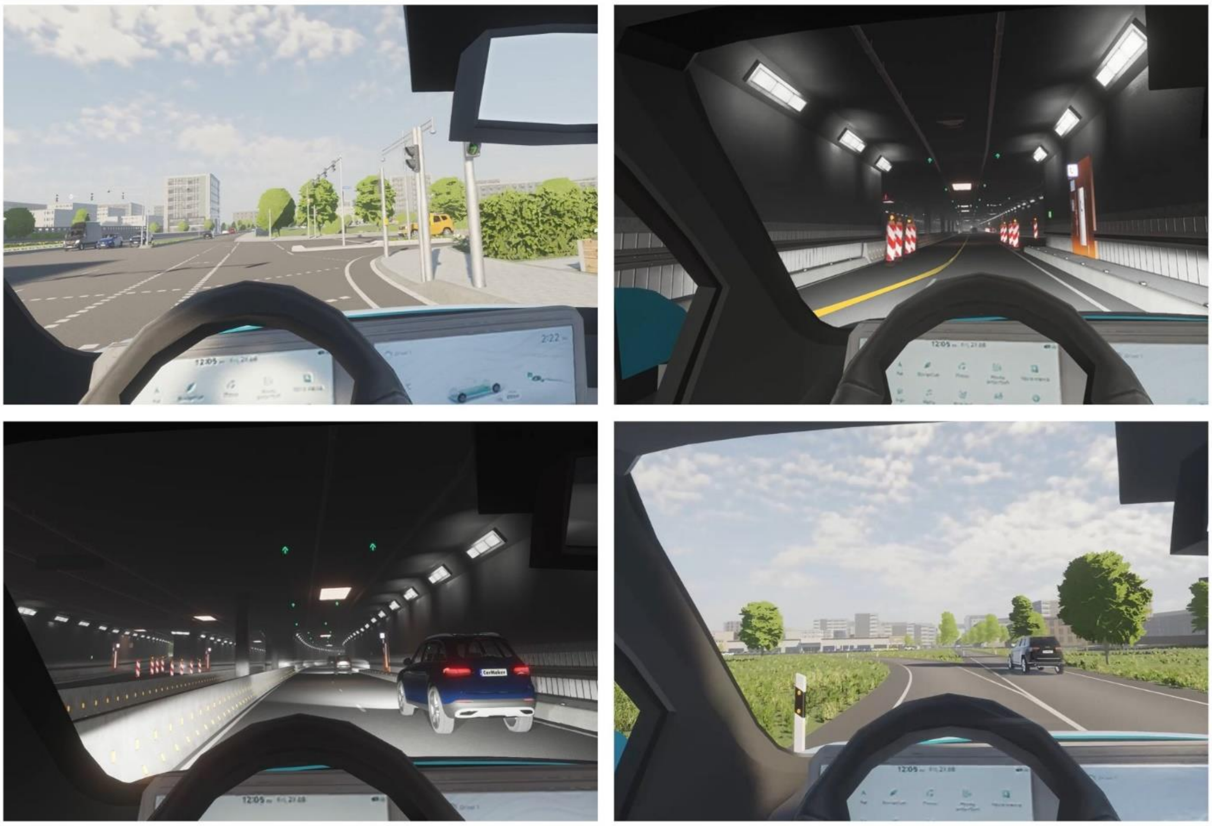

Fig. 6 Possible test cases – Top left: ACC with stop&go function; Top right: construction zones with corresponding takeover situations; Bottom left: challenging lighting condition; Bottom right: handover function for highway driving assist

7.2 Testing Procedure

A diverse group of drivers with a wide range of experience was selected to test the presented method. This group included drivers already familiar with the test bench, those who had never used VR goggles or operated a vehicle on such a setup, and individuals who have experienced VR goggles but were new to the test bench. Additionally, drivers with experience in motion platform-based driving simulators were involved. Each driver participated in the previously described identical driving scenarios, both without a VR headset and with the two presented VR headset variants. Particular attention must be paid to the correct adjustment of the VR headset. The digital seat position in the car must be readjusted according to the stature of the real person. Feedback was collected on key aspects of immersion, such as the perception of speed and acceleration, steering behavior, visual fidelity, and overall driveability. Moreover, the handover situations between the driver and a possible driver assistance system were tested to further assess the method's effectiveness. Fundamental differences were considered and an assessment was made regarding the suitability of this method.

7.3 Results and Findings

In the evaluation of the presented method focusing on the two VR headsets, the Meta Quest Pro and HTC Vive Pro 2, as compared to a standard screen setup, several key findings were identified. The Meta Quest Pro had the advantage of not requiring base stations, making setup easier, but it allowed light to enter through a gap at the bottom of the goggles, reducing immersion. While the Meta headset performed smoothly during straight driving and mild curves, it experienced a slight drop in frame rate during tight bends, making the visual experience feel less realistic. Some users also reported mild eye discomfort after extended use, potentially due to a lack of familiarity with VR.

In contrast, the HTC Vive Pro 2 required base stations for tracking, which initially posed challenges in finding a stable setup around the test bench due to vehicle movements and air stream supply. However, once positioned properly, the HTC offered a fully enclosed field of vision, enhancing immersion by eliminating the light gap present in the Meta Quest. The HTC also performed well in terms of smoothness, with some users noting an improvement in image realism, particularly in tighter curves, although this may have been influenced by increased familiarity with VR after using the Meta Quest beforehand.

An issue occurred due to the inability to adjust the rear and side mirrors, which greatly affects the visibility to the rear and therewith the level of immersion. Although this testing method generates minimal acceleration forces on the occupants, the sense of speed can still be partially gauged through the steering feedback and speed dependent adjusted airflow. Unlike motion platform-based driving simulators, which often cause motion sickness, the Vehicle-in-the-Loop test bench does not have this issue when using a VR headset. It is also critical for immersion that the steering wheel does not turn and that the hands of the driver are not visible on the steering wheel. In addition, HMI functions, such as the speed display, cannot be displayed in the cockpit.

For comparison, a traditional screen setup was used, providing an external view from an elevated position behind the vehicle. This made it easier to perceive the vehicle's surroundings and better anticipate corners. However, for realistic driving scenarios, the VR headsets provided a more immersive experience compared to the interior view on the screen without the VR headset, particularly in dynamic situations like faster curves.

Despite this, challenges remained in maintaining lane positioning in VR, partly due to the lack of adjustable mirrors and the difficulty in controlling the vehicle in slow, tight turns. Overall, both the Meta Quest Pro and HTC Vive Pro 2 offered valuable insights into enhancing driver immersion in vehicle test bench simulations, with each headset presenting its own strengths and areas for improvement.

The key takeaway from evaluating the handover scenarios is that they could be effectively tested despite the mentioned limitations in immersion. A restart at traffic lights using the ACC stop&go function was performed without any issues, and the handover of a speed-dependent cruise control function also proceeded smoothly with no negative outcomes. All test subjects consistently rated the method as highly effective for evaluating these types of driver assistance functions.

8 Conclusion and Outlook

This research successfully demonstrates the viability of integrating a Vehicle-in-the-Loop test bench with VR technology to enhance the testing and validation of ADAS and autonomous vehicle technologies. By combining high-fidelity simulation with immersive VR environments, a controlled and reproducible framework was established that allows engineers to assess various driving scenarios and handover situations effectively. The comparative analysis of the Meta Quest Pro and HTC Vive Pro 2 VR headsets highlighted their respective strengths and limitations, revealing that while both devices enhance immersion, each offers a unique user experience that can improve the performance assessments.

Additionally, the incorporation of sensor spoofing capabilities further enriches the testing landscape, enabling comprehensive evaluations under realistic conditions. Ultimately, this innovative approach not only improves the realism of vehicle testing but also paves the way for more effective development of safety-critical systems in future vehicles. Future work should focus on refining the integration of VR technology and addressing identified challenges, such as mirror adjustability, HMI interface and steering feedback, to optimize the testing framework's effectiveness.

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10 Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
EV	Electric Vehicle
GNSS	Global Navigation Satellite System
GPU	Graphics Processing Unit
HIL	Hardware-in-the-Loop
RAM	Random-Access Memory
VIL	Vehicle-in-the-Loop
VR	Virtual Reality

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