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Next Generation X-in-the-Loop Validation Methodology for Automated Vehicle Systems

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ABSTRACT Testing self-driving vehicles is still a new and immature process; the globally harmonised procedure expected much later. The resource-demanding nature of real-world tests makes it indispensable to develop and improve the efficiency of virtual environment based testing methods. Accordingly, a novel X-in-the-Loop framework is proposed to fully exploit the recent advances in info-communication technologies, vehicle automation, and testing and validation requirements. This methodology real-time connects physical and virtual testing with high correlation while completely blurs the sharp boundaries between them. Measurement results confirm the superior performance of the 5G communication link in providing a stable, real-time connection between the real world and its virtual representation. The live demonstration proved the presented concept at the newly constructed Hungarian proving ground for automated driving. The performed investigation also includes comprehensive benchmarking, focusing on the most up-to-date automotive testing frameworks. The analysis considers the methodologies and techniques applied by the most relevant actors in the automotive testing sector worldwide. Accordingly, the newly developed testing framework is evaluated and validated in light of the state-of-the-art methods used by the automotive industry.

INDEX TERMS Automotive proving ground, automated vehicle control, autonomous vehicle, co-simulation, digital twin, mixed-reality testing, scenario-based testing, testing and validation, virtual and mixed reality, V-model, X-in-the-loop testing.

I. INTRODUCTION

The availability of harmonised testing and validation methodology for self-driving vehicles is crucial for the future of automated mobility. There are currently standardised test procedures available only for testing ADAS functions with a lower level of automation [1], [2]. Modelling and simulation that has been started decades earlier [3] will undoubtedly play an increasingly important role in validation processes. In today's simulation procedures, at most, the Vehicle Under Test (VUT) or its components are physically used, while the surrounding environment is fully simulated with either generated sensor signals or projected visual effects. Testing in a real-world environment usually appears as a separate process. However, in Vehicle-in-the-Loop (ViL) simulations, the vehicle is often tested in a relatively clean test site, where the vehicle can move in any direction and can be tested with real vehicle dynamics. Still, each disturbance or interaction and event virtually appears in a simulation platform. In such cases, not only the connection between the vehicle and the driver can be examined [4], [5], but also advanced driving assistance systems can be tested using virtual obstacles [6]. These require a truly multidisciplinary approach since beyond automotive, transportation and electrical engineering, computer science and telecommunication related aspects have to be considered during the research and development process.

This paper introduces a novel X-in-the-Loop (XiL) framework (where X denotes anything, e.g. object, algorithm, SW, HW) that takes full advantage of the recent advances in info-communication technologies, vehicle automation as well as testing and validation requirements.

The newly developed XiL concept is compared with the state-of-the-art methodologies available in the automotive testing and validation domain. However, considering the high number of actors in the sector, this study does not aim to provide an exhaustive list of the leading organisations

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developing test and validation solutions. Instead, the aim is to provide a comprehensive investigation focusing on test and validation frameworks preferred or developed and used by the automotive industry. Accordingly, the evaluation's objective is neither the ranking nor the criticism of the market solutions. Furthermore, the author would like to avoid any subjective or potentially biased statements during the evaluation process. Thus, the paper applies anonym codes for the introduction of the different market solutions (*SYS1... SYSN*).

The evaluation includes the XiL system of AB Dynamics [7], Applus+ IDIADA [8], HORIBA-MIRA [9], Hyundai MOBIS [10], i-MAR [11], IPG ViL [12], K-city [13], M-City [14] and ZalaZONE [15]. It has to be emphasised that specific and detailed information has limited availability in case of the mentioned actors.

The paper is structured as follows: Section II provides an insight into automotive testing and validation, Section III discusses the related work, presenting different approaches and introducing the X-in-the-Loop methodology, while Section IV presents eight state-of-the-art XiL system implementations. Section V discusses the proposed ZalaZONE developed Scenario-in-the-Loop methodology in detail, its architecture, the required system components, the applied techniques during realisation and the proof of concept demonstration with measurement results. Section VI provides a comparison of the different XiL solutions based on selected criteria. Finally, Section VII concludes the paper.

II. BACKGROUND OF AUTOMOTIVE TESTING AND VALIDATION

The automotive industry's testing and validation activities are strongly related to the legislative background and mainly implemented in three different segments. These segments are connected to the product life cycle of automobiles.

In the first phase of the product life-cycle, manufacturers are responsible for developing a safe and well-functioning vehicle. During this phase, the developers strictly follow the sector-specific industrial standards to minimise safety risks [16] and quality gaps related to the specific product. Product assessment and quality evaluation are permanently performed following the sector-specific standards, which process plays a vital role in the final quality of the product [17]–[19]. In this field, one has to mention the International Organization for Standardization (ISO), one of the most well-known industrial-standard providers worldwide.

In phase two of the product life-cycle, the vehicles are launched into the market. In Europe, if an automotive manufacturer wants to place its product on the market, the product needs to fulfil the requirements of the United Nations Economic Commission for Europe within a so-called type approval process (or homologation) [20]. This also covers the conformity of production, where the manufacturer "certifies that each vehicle, equipment, or parts put on the market were produced to be identical with the approved product" [21]. Accordingly, all vehicles, having the same type as the approved product, have to be identical with the tested and validated unit from both safety and quality point of view. Only after that they can be placed on the member countries' market (contracting parties). During the type approval process, the vehicle inspections are carried out (witnessed) by an independent third party (e.g. TÜV, Dekra) and the approval is granted by government authorities. In contrast, it is essential to mention the self-certification procedure as well, where it is the vehicle manufacturer itself who performs vehicle inspections and issues a certification of conformity (e.g., in the USA), validating that its product does fulfil the requirements of the given market [22]. The future challenge is especially the successful integration of new aspects into these processes, like safe driving without a human driver in the control loop [23], [24], automotive cybersecurity [25]–[27] and artificial intelligence based system control [28], to mention a few.

In the third phase of the life-cycle, when products are available on the market, consumer protection organisations need to control product quality to protect the customers from the risk of unfair commercial interactions. In the automotive industry, the New Car Assessment Program (NCAP) can be highlighted as one of the most well-known consumer protection organisations. However, based on recent years' experiences, it became evident that even in the case of the largest and most reliable manufacturers, the unfair interventions on validation procedures are no longer unconceivable. This problem raised the issue of regulation interpretation, in particular, what does society expect from the manufacturers? To follow the written rules word by word or to implement the legislative will?

III. RELATED WORKS

The methodological background of testing and validation in the automotive industry can be characterised as an evolutionary process. When vehicles were less automated, safety was defined by the reliability of components, so the testing and validation of software and hardware could deliver the required safety level [29]. However, the spreading of highly automated vehicles made it necessary to investigate and model integrated vehicle dynamics [30] or the complete vehicle system [31], and also get prepared for their public road operation, e.g. using the VAAFO approach (Virtual Assessment of Automation in Field Operation) [32].

Vehicle systems became increasingly complex, and as a result, testing and validation tasks went far beyond the vehicle itself, reflecting the complexity of the entire transport systems [23], [33]–[35].

Based on the automotive sector's current methodology [36], the development process is implemented according to the V-model. This procedure sets the system requirements in parallel with their verification and validation throughout the entire development process, including the software development phase, hardware development phase, and corresponding testing activities, especially considering the various X-in-the-Loop testing solutions [37]–[40].

Nowadays, the most important innovations related to autonomous and connected vehicles are driven by software development [41]. Software components in vehicular systems are responsible for increasingly complex control processes such as braking, overtaking or stability [42]. Accordingly, any wrong decision made by a vehicular system's software can lead to a safety-critical event. Therefore, it is crucial to ensure the proper safety characteristics also for automotive software components. Following ISO 26262, the fundamental safety standard of the automotive domain, the requirements' compliance is investigated through comprehensive testing methods [18]. According to ISO 26262, the software of safety-critical vehicular functions should be tested in its real system environment. On the other hand, the identification and the correction of a software error in the final stage of the automotive development process can be less cost-efficient than in the earlier stages. Following the objectives of cost-effectiveness, to identify and correct software errors in the earliest development stages, vehicular software can also be evaluated in a reduced test environment [43]. Accordingly, special attention has to be paid to the identification and work out of the test environment for the developed automotive function module (such as software, hardware or component).

The traditional testing approach, especially ISO 26262 proposes to using the final hardware environment to evaluate safety-critical systems [44]. However, this approach results in a considerably time- and resource-consuming testing process [45]. Therefore, it becomes reasonable to test only a part of the vehicle since, removing a failure in the tested vehicle module can be much more cost-efficient. This approach resulted in the Hardware-in-the-Loop (HiL) testing method. The application of the HiL method makes it necessary to develop a comprehensive environment framework. This external system shall provide model-based input signals for the tested component on the one hand and shall also be able to integrate different components and external, model-independent signals for the tested component on the other hand. Such an environment may also support fault-injection related tests as well [45]–[48].

In the application of the Vehicle-in-the-Loop test approach, the tested vehicle's complex system is embedded into an artificially controlled, virtual testing environment [49], [50]. So, the real hardware and software framework of the investigated vehicular system is tested. According to the state-of-the-art testing approach, the autonomous vehicle's environment is simulated by a comprehensive software framework, covering the most relevant decision factors and sensor types, such as traffic simulation, graphical representation, or point cloud generation [51]. Such a system can connect the tested vehicle and other simulation modules in real-time. Even some of the simulated vehicles can be replaced by real vehicles [52]. This way, the effect of the surrounding traffic can be directly fed into the autonomous vehicle's decision-making module [51]. Following this approach, one can easily implement open-loop or closed-loop tests on a traditional roller test bench or in a proper test field by applying the ViL model.

The generic X-in-the-Loop model contains an efficient and outstandingly realistic simulation framework for automated cars, taking into account [53]–[55]:

- Different sensor representation methods in simulation
- Vehicle dynamics and its relation to different actuators
- A wide range of scenarios especially considering different traffic situations in the simulation
- Control models for automated vehicle systems

In X-in-the-Loop solutions, the investigated system elements (model, software, hardware or the complete vehicle) have continuous interaction with its simulated environment. Accordingly, virtual and real factors have to be synchronised to enable the development of a coherent and reliable evaluation methodology. In all, the X-in-the-Loop concept can be identified as a generic framework involving the different MiL, SiL, HiL or ViL models.

IV. XiL SYSTEM IMPLEMENTATIONS

Vehicle-in-the-Loop type testing is the most advanced testing and most promising validation technology today for automated vehicle systems. It is far from being complete and is subject to further research in many places; however, complex solutions appeared on the market and started to be used by automotive companies. I would like to present eight different implementations in this section to provide a comprehensive picture of the state-of-the-art in this field. The presented systems are anonymously numbered from SYS1 to SYS8 as a reference and will be evaluated and compared later in Section VI based on their functional characteristic in Table 2.

A. SYS1

The dSPACE based real-time ViL system developed by *SYS1* consists of the vehicle under test (VUT), other cars, vulnerable road users, traffic signs, road pavement signs, road parameters, categories, and traffic rules. Virtual reality provides input for the automated vehicle system control units instead of actual vehicle sensors. This purpose is obtained by developing a virtual representation of the VUT integrated into the constructed mixed reality. The VUT and its virtual model have the same sensors (RADAR, LiDAR and video camera). The system enables any cars, any kind of traffic flow and any VRUs from any direction in the tested scenarios. Based on the performed literature review, one can conclude that *SYS1* developed a considerably complex testing system. Following the developers' introduction, the system places less emphasis on the cooperative and comprehensive simulation control of different scenario components integrating real (e.g., Soft Crash Target (SCT), Guided Soft Target (GST)) and virtual environment.

B. SYS2

SYS2 offers a Vehicle-in-the-Loop model as well. This system provides a well-applicable connection between HiL methods and real-world test techniques. This approach makes it possible to operate the VUT in an open test track while its input signals are provided virtually. The system also allows embedding real components into the virtual environment; thus, realistic tests can be performed with well reproducible characteristics. *SYS2* highlights that their ViL platform is well applicable to support the execution of a wide range of Euro NCAP tests. According to reviewed research studies, one can draw the conclusion that *SYS2* is rather focused on the vehicle simulation characteristics of the system (such as vehicle dynamics or communication) instead of covering the integration of real components into the testing process (e.g., less focus on Spatial Localization (SPT) or Real-Time capability referring to the proper time synchronisation of reality and the virtual environment (RT)).

C. SYS3

SYS3 offers a complex test and validation framework for the actors of the automobile segment. The company provides solutions for a large number of testing issues derived from the analysis of simple physical components to the evaluation and validation of complex control systems, including automated driving assistance systems and fully autonomous vehicle systems. Their solutions cover a wide range of testing approaches starting from the completely virtual testing environment to real-world testing applications.

SYS3 developed a comprehensive system testing approach supporting proving-ground based development processes. The testing system's foundation is laid on a central software module that controls the testing processes (covering tasks from component control to general scenario coordination) in a simple and efficient way. Among others, test functions include the following modules:

- Vehicular sub-systems: suspension, chassis, steering
- Investigation of vehicle-dynamics on proving-ground
- Evaluation of autonomous vehicle systems (applying special target objects like remotely controllable dummies and vehicles)
- Virtual testing (simulation and model environment)

D. SYS4

SYS4 was established by the local government as an artificial urban environment to support the testing and validation processes of connected and highly automated vehicles. *SYS4* is a test track built for supporting the development processes of autonomous vehicles. *SYS4* consists of numerous authentic road environments such as bus lanes, bicycle lanes, highways, built-up urban areas and a parking bay. Due to the strong cooperation with the domestic global supplier of telecommunication solutions, a 5G network is going to be established around the test track to provide the capability of developing cellular communication based V2X applications. Besides this, 4G LTE and Dedicated Short Range Communication (DSRC) systems will be deployed on the proving ground. To sum up the available information, *SYS4* has an impressive infrastructural background in the field of vehicular communication testing.

E. SYS5

Based on the reviewed literature, one can state that *SYS5* is one of the leading actors in testing procedure developers for autonomous vehicles. *SYS5* offers an urban test environment for highly automated vehicles. However, one can conclude that this actor has less focus on comprehensive scenario simulation and control, especially on including real guided objects in the test scenarios. Besides this, *SYS5* pays less attention to cellular communication-related testing solutions.

The integrated system's general framework involves the tested vehicle, roadside units, detectors, the related controller units, and traffic signal controllers. Communication processes between the vehicle under test and the other system components are performed through a DSRC communication channel. The control system takes into account the outputs of the simulation system as well and the digital twin of the VUT is able to follow in real-time the path on the digitalised virtual road network in accordance with the real-world vehicle.

F. SYS6

SYS6 provides a wide range of testing solutions in highly automated vehicle development, where the testing processes can apply both DSRC and cellular network (even 5G) based wireless communication channels. The proving ground can cover the complete development cycle (from MiL to ViL) by applying dSPACE and NI based control modules.

SYS6 also has special solutions for virtual testing. However, virtual and real environment's the integrated control is not interpreted in a detailed way in the available documentation. Following this, there is less emphasis placed in the available documentation on the connection and synchronisation process connecting the real and the virtual environment.

G. SYS7

The solution of *SYS7* proving ground implements an own developed interface application providing an interoperable environment for the combination of different industrial solutions available on the market. The proving ground puts special emphasis on the realistic simulation of the transportation system based on the integrated traffic simulation techniques and vehicle modelling tools. They also provide strong support for the whole vehicle development process, including test systems from MiL to ViL solutions. On the other hand, *SYS7* pays less attention to the overall control of complex scenario-based multi-agent test cases.

Summing up the performed literature review, *SYS7* has a particular focus on simulation and visualisation. Still, methods related to the overall control of complex scenarios received less attention during the development process.

H. SYS8

SYS8 developed a comprehensive framework by integrating a wide range of testing and simulation systems, emphasising real-time localisation and communication. It offers an outstandingly efficient scenario control framework. However, it dedicates less attention to the application of realistic traffic simulation solutions.

According to the available background materials, the system concept of *SYS8* is especially powerful in reproducibly controlling complex traffic scenarios and testing the communication- and localisation-related characteristics of the investigated automated driving functions.

V. SCENARIO-IN-THE-LOOP BASED MIXED REALITY VALIDATION

A beyond state-of-the-art X-in-the-Loop validation system was developed, tested and demonstrated at ZalaZONE proving ground, which will be presented in details within this section. The aim of the Scenario-in-the-Loop testing and validation concept is to support cutting-edge research effectively and soon become a standard service at ZalaZONE. ZalaZONE is an automotive proving ground, where the traditional test track features focusing on endurance and driving stability are implemented together with the future mobility requirements supporting the test and validation of autonomous vehicles [56].

Since the Scenario-in-the-Loop framework combines physical and virtual environment, it is necessary to clarify the difference between virtual reality and mixed reality in automotive testing. Virtual-reality based systems provide an entirely artificially simulated environment independent of physical reality (beyond reproducing a real establishment in the virtual space). On the other hand, mixed-reality based systems provide the possibility to integrate simulated components and objects into the real testing environment. Summarising in short, whereas virtual reality replaces reality, mixed-reality adds to it.

A. INTRODUCTION OF THE MODEL

Further than implementing a complete traffic scenario, one of the most relevant contributions of the Scenario-in-the-Loop (SciL) approach to the testing domain, compared to the Vehicle-in-the-Loop concept, is the ability to combine simulated and real-world data, feeding them to different layers of embedded vehicular control within the complex vehicular system in an integrated way (Fig. 1). It means in practice that some of the input signals can be perceived directly from the real environment [57], and other signals can be parallel simulated by the applied comprehensive software framework, connected to the lower layers of the perception and communication architecture.

Moreover, SciL can represent all types of combined transition concepts between ViL and real-world testing. Comparing the two concepts, one can conclude that in the ViL approach, the model provides the input signals solely for the vehicle, while in the case of the SciL model, the framework provides the input for the complete traffic scenario [58].

The main distinguishing factor or added value of the Scenario-in-the-Loop concept is that it indeed blurs the previously straight boundaries of reality and virtuality. Within SciL, there is full freedom in determining what part of the test should be executed in reality and what part should be simulated during the test. Using the SciL concept for the composition of a test scenario, there is no restriction on setting the borderline between reality and virtuality. This methodology connects physical and virtual testing in real-time with high correlation while completely blurs the sharp boundaries between them.

According to the expectations, the scenario-based testing, thus the SciL approach, will be the next generation of the simulation and X-in-the-Loop testing methodology applied in the development process of the automotive industry [59]. Beyond providing a feasible test coverage [60], this novel technique can support the achievement of the following advantageous characteristics [61]:

- reproducibility,
- flexibility,
- scalability,
- cost-efficiency,
- and realistic representation.

To make Scenario-in-the-Loop testing an outstandingly powerful tool, it needs broad compatibility with other industrial simulation and testing tools, providing versatile interfaces not only on the input side but also on the output side. The SciL input interface is required to embed industry-standard simulation tools, for example CarMaker, VTD, CarSim, PreScan, into the scenario definition, while the actuator side SciL interface is necessary to support the usage of targets and objects of different suppliers, enabling the composition of extremely complex scenarios with many simultaneous road users simulated or controlled at the same time.

B. REQUIRED COMPONENTS

To obtain the required safety and reliability, automated vehicle technologies must be analysed and evaluated in a very complicated way [62]. These requirements make it necessary to apply intelligent, cost-effective, safe, measurable and accurate methodologies and systems during the tests [63], [64]. Accordingly, state-of-the-art autonomous vehicle functions can only be evaluated through extensively designed scenarios [65] on a test track, applying real and virtual testing objects with a precisely controlled testing system.

1) DIGITALISED TEST ENVIRONMENT

To perform parallel and simultaneous automated vehicle test processes with reality, it is also necessary to create the virtual representation of the testing environment. Virtual environments with advanced visualisation capabilities also make it possible to train, test and validate artificial intelligence based solutions of ADAS systems. Additionally, a detailed high quality graphical and physical model, including effects related to the weather, real-time reflections, shadows and lighting conditions, can considerably increase test resource demands. On the other hand, these advanced solutions can strongly contribute to system reliability improvement [66].

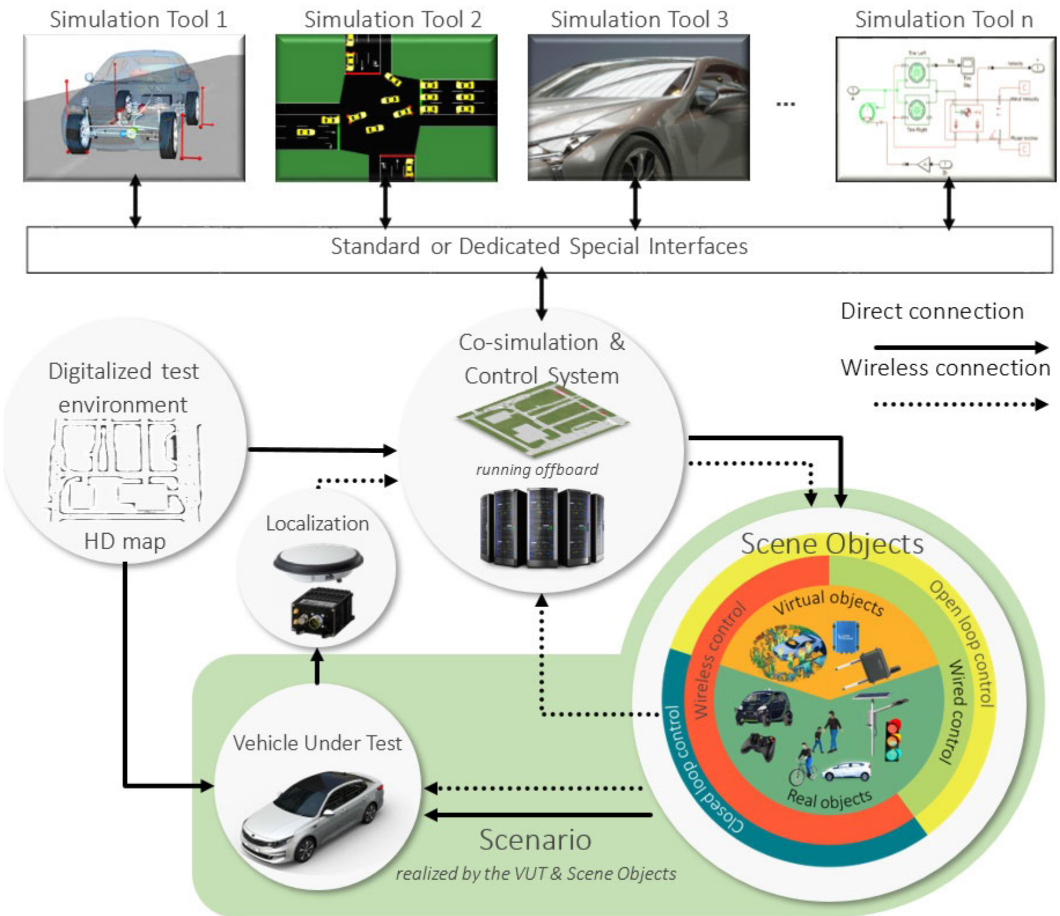

FIGURE 1. **The architecture of the Scenario-in-the-Loop (SciL) validation methodology. Real-time interfacing to several automotive simulation tools, implementing millimetre precision digital representation of the physical testing environment and connecting all elements with the VUT by ultra-reliable low-latency communication. The developed SciL architecture can reproduce complete traffic scenarios in mixed reality for advanced testing and validation of automated vehicles.**

Accordingly, the whole testing environment, i.e. the entire proving ground must be digitalised for the virtual simulation environment, in which buildings, road markings, traffic signs, roadside objects, vegetation exactly correspond to the actual testing area [67], [68].

Merely for simulation purposes, it is sufficient that a proving ground's digital model is generated from the design plans, which provides only rough precision. For the combined test, where the simulations are followed by real-world tests or real-time mixed reality tests, this resolution may not be enough. Those cases require an ultra-precise vectorised digital map (HD or UHD map), potentially in standardised format [69], that can be derived from a high-resolution laser-scanned point cloud survey.

For powerful visualisation of the virtual environment, one can use any available cross-platform 3D graphical engines (such as Unity or UnRreal) [70]. Accordingly, the selected developer engine shall support as many platforms as possible. Due to the further application possibilities, it could also be used to create virtual or mixed reality applications, as well as serve simulations and other experiments [71]. The virtual model of ZalaZONE is publicly available in several data formats under MIT License for further research and evaluation. The road models of the test tracks and the extended UHD maps in vectorised formats are continuously updated [72].

2) REAL-TIME LOCALISATION

All vehicles and scene objects participating in a specific test scenario (such as ego-vehicle, VUT, VRU, GST, SCT) have to be localised in real-time with high precision and managed by the simulation and control software. As a state-of-the-art solution, this requires an RTK supported differential GNSS system extended with an inertial navigation unit, resulting in less than 2 cm accuracy in real-time positioning [73]. According to the introduced SciL concept, the model environment provides the input signals for the Scenario-in-the-Loop, while the vehicle under test receives the necessary input signals from the scenario level. The simulation and control module has two main inputs, the precise three-dimensional digital representation of the real test track and the accurate localisation information of the different road users participating in the test scenario.

By mounting an inertial measurement unit (IMU) linked with a differential GNSS to the real car, its position on the test track can be located with the desired accuracy. The combination of the IMU and DGNSS are commonly referred to as inertial navigation sensors (INS) [73]–[76]. Following the state-of-the-art trends [77], [78], the ZalaZONE SciL testing solution is being prepared to provide the possibility to test automated vehicle systems in combination with intelligent infrastructure based cooperative positioning and navigation, as well [79], [80].

3) ULTRA-RELIABLE LOW-LATENCY COMMUNICATION

In Vehicle-in-the-Loop tests, the vehicle is driven on a proving ground or a test bench, and the external surroundings are modelled through simulation. Beyond this, Scenario-in-the-Loop tests cover all the evolutional steps between the tests performed in a completely virtual and in a completely real environment. Accordingly, in Scenario-in-the-Loop testing, some of the test objects can be real, and others can be virtual.

The nature of the Scenario-in-the-Loop concept inherently involves the testability of components with heterogeneous characteristics at different development stages (e.g., model, software, or hardware testing in a completely or partly simulated environment, applying real or virtual test objects). Accordingly, the prerequisite of SciL testing is the availability of an ultra-reliable low-latency communication (URLLC).

Recent developments in info-communication technologies [81], [82] provide two different physical layers at the same time for vehicle-to-vehicle or vehicle-to-infrastructure (V2X) communication applications. Both of them enable and support SciL testing, especially considering the European dedicated short-range (ITS G5) and the fifth-generation cellular network (5G) communications, also called as vehicular ad hoc networks (VANETs) [83]–[85].

Following this, the availability of dedicated short-range communication possibilities, such as WAVE [86] or ITS G5 [87], is strongly recommended at the testing facility if the performed tests implement the SciL testing concept. Similarly, the latest advances in cellular communication, especially 5G provided the specific characteristics that significantly enhanced its potential for CAV testing, also enabling the cellular communication-based implementation of SciL testing (depending on the use-cases, 4G LTE may also fulfil the requirements of CAV testing). 5G wireless devices in the covered region not only can communicate with each other but can connect to the infrastructure by radio waves through the local station allowing a significantly larger bandwidth and guaranteed low-latency, in a secure way [88]–[90].

4) CONTROLLABLE SCENE OBJECTS (Disturbances)

Following the concept of Fig. 1, SciL testing is about to artificially create a complete traffic scenario with all the participants and the model of the surrounding environment, which continuously provides the necessary data for the testing [91]. The generated scenario involves the motion planning and control of the tested vehicle system [92], including potentially critical situations [93] and the other interacting components of the whole transportation process (such as vulnerable road users, other vehicles, or the road traffic in general). Furthermore, the SciL model may also reflect the relevant external influencing factors like weather and lighting conditions, infrastructure characterisation, or road environment properties.

The SciL architecture can distinguish five different types of interfering scene elements or, in other words, disturbances (see Fig. 2), these are:

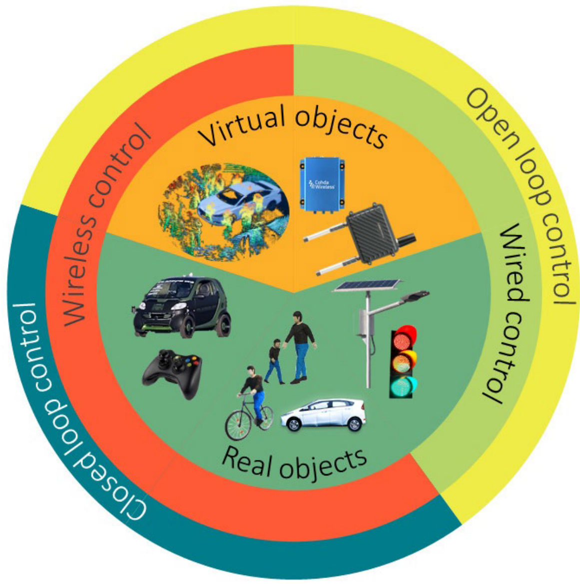

FIGURE 2. The component level categorisation of the controllable scene objects (disturbances) used within the SciL mixed-reality validation model.

- **VUT sensor spoofing**: this means the ability to inject any sensor signal information into the sensing path of the VUT's perception system, resulting in that the VUT "feels" something in its surrounding that is physically not there. It works with different types of sensors.
- **V2X communication spoofing**: this means that without the physical presence of another vehicle or an infrastructure element, the VUT may recognise them based on just communication.
- **Infrastructure elements**: within a proving ground, every infrastructure element is centrally controlled (e.g. traffic lights, variable road signs, road lighting), so integrating them into the scenario generation is merely a proper interface to the SciL control system.
- **Moveable targets**: this means the more or less standardised test elements of the NCAP tests, like moving platforms, soft pedestrian targets, bicycle targets, soft vehicle targets. These elements may have specific or standardised interfaces to control them.
- **Full-control real vehicles**: real-world vehicles that are fully by-wire controlled remotely by the SciL

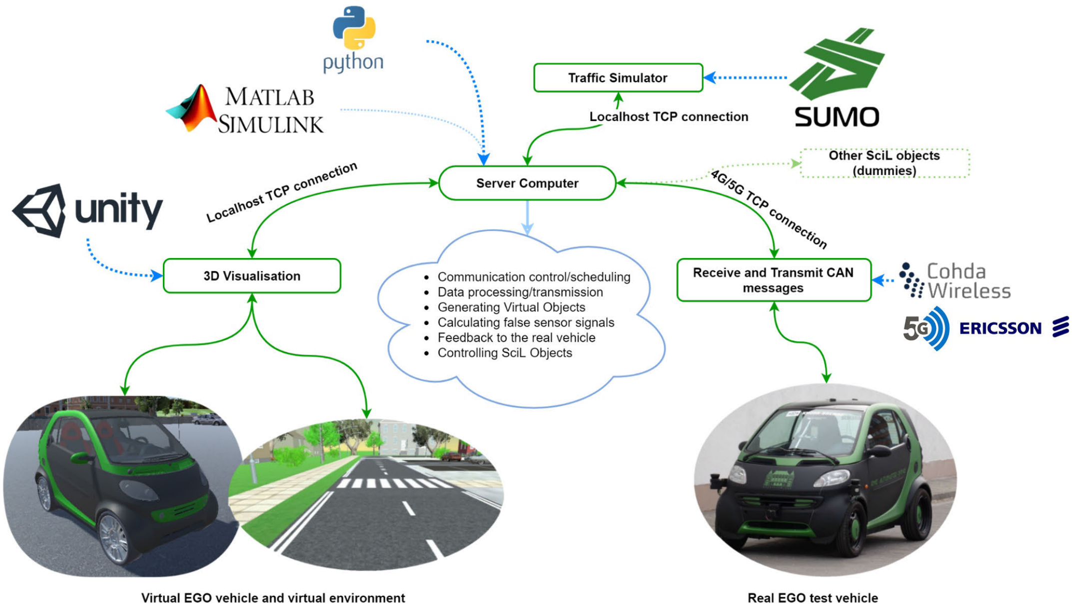

FIGURE 3. Co-simulation framework of the implemented proof-of-concept SciL validation model. Real-time interfacing several simulation tools, incorporating different wireless communications and adding realistic visualisation, co-simulation techniques create unprecedented opportunities for software tool combination.

architecture create absolute realistic moving target vehicles within the traffic scenario being tested.

In accordance with principal attributes of the SciL concept, the system has to be capable of operating and implementing a particular scenario by the combined application of virtual and real system components. This approach makes it necessary to develop and use a digital twin of the testing environment and the other interacting components of the transportation process (such as vulnerable road users or other vehicles), entirely faithful to reality. This way, the tested scenario can contain both virtual and real components in an arbitrary proportion, thereby enabling the developer to optimise the test scenario's composition according to the development level and the project's required resource efficiency. The model components can be controlled in a closed-loop (e.g. the vehicles and other road users) or in an open-loop (e.g. traffic lights or the traffic itself). The control can use wireless communication channels (for vehicles and the other road users) or wired communication channels (for the traffic lights).

An obvious advantage of combining the SciL framework with the closed and controlled ecosystem of a test track is that the virtual and real interactions within the SciL concept can be executed in the same test environment. It enables the pre-designed and pre-simulated scenario to be tested in a real-world environment in a repeatable way. The new concept provides an opportunity to create test scenarios that can be applied in parallel, generated from virtual and real obstacles mixed. The main advantage is that the concept can be applied incrementally, starting from full simulation and piece-by-piece replacing the virtual elements to real elements until the optimum level, while running the same test sequence within the same environment for a specific traffic scenario.

C. CO-SIMULATION TECHNIQUES

1) SIMULATION AND CO-SIMULATION

There is a long history of simulation techniques applied in the automotive industry. Based on the initial objectives, different simulation tools were developed for specific tasks. As a result, one tool performs outstandingly (e.g., visualisation) [94]. On the other hand, certain tools perform well, e.g. in traffic simulation, while they cannot handle vehicle dynamics at all [51]. For this reason, most users implement the so-called co-simulation technique [95], where two or more simulation tools are interfaced and used simultaneously together to perform one complex task [96]. In the presented mixed-reality based SciL architecture, traffic simulation, vehicle simulation and high-quality graphical representation were combined in one co-simulation framework (Fig. 3), supporting the real-time operation and control [58].

The architecture of SciL enables it to be interfaced with different Simulation and Co-Simulation Tools. The target is to implement standardised interfaces that can be interconnected with all state-of-the-art simulation tools used in the automotive industry. These interfaces would enable testers to perform and evaluate their virtual tests in their preferred simulation environment and later use the same model and simulation tool in the validation phase at the proving ground.

2) SciL INTERFACING STRUCTURE

The traffic simulation framework serves as an external environment for the decision-making layer of the ego-vehicle. This way, traffic simulation provides an input for the ego-vehicle, depending on the surrounding traffic situation. The other way round, in accordance with the vehicle's decision, the system generates signals for the traffic simulation component, based on the calculations of the vehicle-dynamics simulation [97]. Simultaneously, all vehicle operation related processes have to be represented and simulated in the virtual in-vehicle network (IVN). Based on the simulated IVN messages, the system can provide the necessary information for the real-world IVNs (such as CAN). Finally, the graphical module has to visualise all the detected spatial processes in the SciL test environment in an attractive way (see Fig. 3).

3) SciL CONTROL

There are two control levels separated within the control processes of the SciL framework. The first control level handles the decision making processes of the individual scenario components, like the vehicle/vehicles under test, the pedestrians, the cyclists or the simulated or real traffic management system [98]–[100]. The higher-level control manages the overall coordination of the traffic scenario, taking into account the critical states of the systems, the corner cases, and the implemented test scenario [101]. Moreover, the control operations can follow a closed-loop or an open-loop model. The control can be implemented through wired or wireless communication channels regarding either virtual or real objects (see Fig. 2) [102].

D. DIGITAL TWIN ARCHITECTURE

The Scenario-in-the-Loop concept strongly builds on the digital twin architecture, which implements a physical entity's digital replica from the real world. The digital twin may also refer to a physical asset, a process, people, places, or equipment. The digital twin has to have the same or very similar graphical representation (Fig. 4) and characteristics as the original physical object [103].

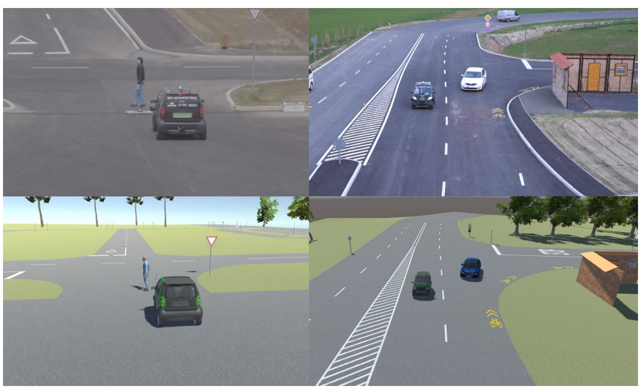

FIGURE 4. The digital twin architecture of the implemented mixed-reality SciL validation model. It demonstrates simultaneous physical and virtual testing through the real-time connected physical world (top) and its digital replica (bottom).

This technique is already widely applied in several industrial segments. It provides a solid basis for the virtual representation of the test environment and the real-time visualisation of the SciL system components. Furthermore, the supplemental application of an intelligent infrastructure (equipped with sensors like video and infra cameras, LiDARs, RADARs) can significantly enhance functionality by the real-time recognition and identification of real road users, even supporting their automated representation in the virtual environment. The SciL concept's mixed-reality framework provides a real-time operating environment, where simulation can affect reality, and reality can also influence simulation. Actually, within the SciL framework, reality and virtuality can almost limitless influence each-other concurrently.

E. V2X COMMUNICATION

To ensure the connectivity of smart transportation systems, the development of a vehicle-to-everything (either V2X or C-V2X) communication framework requires new testing and validation approaches to evaluate the related communication systems on a reliable and solid basis [104]. Besides this, the demand for controlling complex testing processes following a scenario-based concept makes it also necessary to establish all state-of-the-art communication infrastructure nearby the testing facilities, also supporting cellular 5G (Fig. 5) and dedicated short-range (ITS-G5) communication [105]. Although, the SciL architecture is independent of the communication medium, the proof-of-concept demonstration used 5G new radio (NSA) cellular communication.

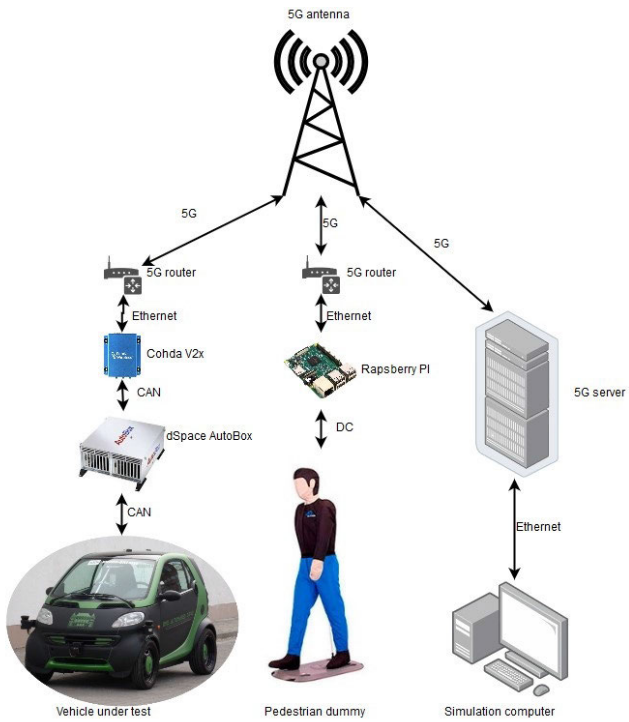

FIGURE 5. 5G (non-standalone architecture) communication scheme in the implemented SciL demonstration model.

F. PROOF-OF-CONCEPT DEMONSTRATION

Two different scenarios were selected and implemented in a complete digital-twin environment to demonstrate the feasibility of the Scenario-in-the-Loop concept. Both had use-cases first with a virtual object, then with a real object as well, so actually, four cascaded scenarios were presented after each-other.

The first scenario was about automated valet parking. The human driver was standing at the parking lot entrance, waiting for his vehicle to come out from the parking lot fully autonomously. This scenario focused on the unexpected pedestrian crossing situation, where the vehicle under test (the EGO vehicle) had to detect the crossing pedestrian and give him the right-of-way. First, an inattentive virtual pedestrian stepped out suddenly from behind a virtual car parking in the parking lot. After that, a real pedestrian dummy went across the EGO vehicle's path in the parking lot entrance, making the EGO vehicle stop automatically again. The EGO vehicle's reaction was exactly the same in both test cases, regardless of the virtual or real excitation.

The second scenario represented a simplified adaptive cruise control (ACC), implementing a car-following situation where the EGO vehicle had to recognise the car in front and adjust the EGO vehicle's velocity according to the safe following distance. In the first part of this scenario, the EGO vehicle had to follow a virtual car in front of the EGO vehicle, and in the second part, it had to follow a real car. The EGO vehicle's behaviour was exactly the same in both test cases, regardless of the virtual or real excitation. After that, the EGO vehicle also performed an automated overtaking manoeuvre, leaving the actual car in the front behind.

Although there are many challenges in the real-time realisation of such complex scenarios, I propose investigating the mathematical model and the timing of the two scenarios that are specifically important from a testing and validation point of view. The question is whether the EGO vehicle's perception system can detect the object due time to stop within a safe distance. However, beyond the examined vehicle function, there is another control task regarding the tested vehicle function: the objects of the scenario have to interact with the central control system to challenge the operation of the EGO vehicle's ADAS system under test. The key objective, furthermore, the scenario control process is to ensure the absolute and relative position of the objects in the t_2 moment depending on the t_1 starting moment of the scenario.

1) PEDESTRIAN CROSSING SCENARIO

The pedestrian crossing scenario consists of two objects: the EGO vehicle and the pedestrian (Fig. 6). The EGO vehicle's role is to approach the pedestrian crossing, where the pedestrian dummy will cross the street.

According to the identified concept, it is an essential requirement related to the applied model that the scenario has to be analysable as a continuous function of the influencing factors. Accordingly, the system needs to perceive and control the spatial relationship of the actors of the given scenario at every moment.

Accordingly, based on the EGO vehicle's and the pedestrian's absolute and the relative position in the starting moment ($X_{EGO_0} = X_{EGO}(t_1)$, $Y_{EGO_0} = Y_{EGO}(t_1)$, $\varphi_{EGO_0} = \varphi_{EGO}(t_1)$, $X_{PED_0} = X_{PED}(t_1)$, $Y_{PED_0} = Y_{PED}(t_1)$, $\varphi_{PED_0} = \varphi_{PED}(t_1)$), the expected relative position (distance) of the two components in the t_2 moment is as follows (D_X, D_Y):

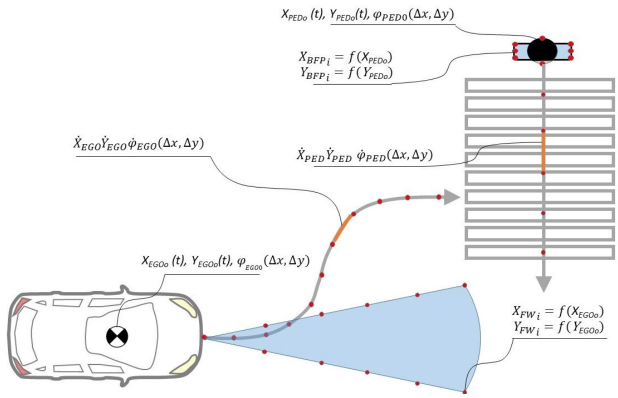

FIGURE 6. Modelling the pedestrian crossing scenario.

$$X_{EGO}(t_2) - X_{PED}(t_2) + \sigma = D_X \tag{1}$$
$$Y_{EGO}(t_2) - Y_{PED}(t_2) + \sigma = D_Y, \tag{2}$$

where

- $X_{EGO}(t_2)$ and $Y_{EGO}(t_2)$ are the X and Y coordinates of the EGO vehicle in the t_2 moment,
- $X_{PED}(t_2)$ and $Y_{PED}(t_2)$ are the X and Y coordinates of the pedestrian in the t_2 moment,
- $\varphi_{EGO}(t_1)$ is the heading of the EGO vehicle in the t_1 moment,
- σ is a normally distributed error function.

With regard to the distance taken by the scenario objects:

$$X_{EGO}(t_2) = \int_{t_1}^{t_2} \dot{X}_{EGO} + X_{EGO_0} \tag{3}$$
$$Y_{EGO}(t_2) = \int_{t_1}^{t_2} \dot{Y}_{EGO} + Y_{EGO_0} \tag{4}$$
$$X_{PED}(t_2) = \int_{t_1}^{t_2} \dot{X}_{PED} + X_{PED_0} \tag{5}$$
$$Y_{PED}(t_2) = \int_{t_1}^{t_2} \dot{Y}_{PED} + Y_{PED_0} \tag{6}$$

Under the identified concept, the applied model can evaluate the investigated scenario as a continuous function of the scenario components' spatial relationship. Thus, the introduced approach enables the system to perceive and control the actors' spatial relationship at every moment.

2) CAR-FOLLOWING SCENARIO

The car-following scenario also consists of two objects: the EGO vehicle and the front vehicle (Fig. 7). In this case, the EGO vehicle's role is to safely approach the car in front, driven by a constant velocity. The question of the scenario is whether the EGO vehicle's perception system can detect the front vehicle in due time to keep a safe distance from it [16].

Based on the introduced framework, the system should evaluate scenarios as a continuous function of the influencing factors. Accordingly, the model should detect and influence

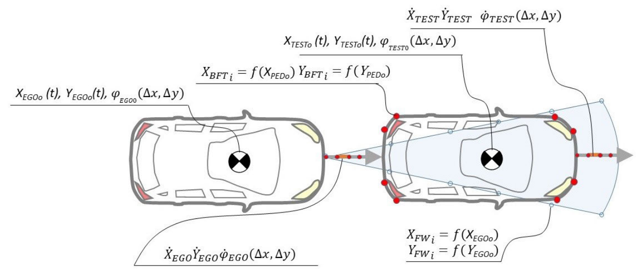

FIGURE 7. **Modelling the car-following scenario.**

the spatial relationship of the participating scenario components at every moment.

Accordingly, based on the EGO vehicle's and the front vehicle's (target) absolute and the relative position in the starting moment ($X_{EGO_0} = X_{EGO}(t_1)$, $Y_{EGO_0} = Y_{EGO}(t_1)$, $\varphi_{EGO_0} = \varphi_{EGO}(t_1)$, $X_{TRG_0} = X_{TRG}(t_1)$, $Y_{TRG_0} = Y_{TRG}(t_1)$, $\varphi_{TRG_0} = \varphi_{TRG}(t_1)$), the expected relative position (distance) of the two components in the t_2 moment is as follows (D_X, D_Y):

$$X_{EGO}(t_2) - X_{TRG}(t_2) + \sigma = D_X \tag{7}$$

$$Y_{EGO}(t_2) - Y_{TRG}(t_2) + \sigma = D_Y \tag{8}$$

where

- $X_{EGO}(t_2)$ and $Y_{EGO}(t_2)$ are the X and Y coordinates of the EGO vehicle in the t_2 moment,
- $X_{TRG}(t_2)$ and $Y_{TRG}(t_2)$ are the X and Y coordinates of the front vehicle in the t_2 moment,
- σ is a normally distributed error function.

With regard to the distance taken by the scenario objects:

$$X_{EGO}(t_2) = \int_{t_1}^{t_2} \dot{X}_{EGO} + X_{EGO_0} \tag{9}$$

$$Y_{EGO}(t_2) = \int_{t_1}^{t_2} \dot{Y}_{EGO} + Y_{EGO_0} \tag{10}$$

$$X_{TRG}(t_2) = \int_{t_1}^{t_2} \dot{X}_{TRG} + X_{TRG_0} \tag{11}$$

$$Y_{TRG}(t_2) = \int_{t_1}^{t_2} \dot{Y}_{TRG} + Y_{TRG_0} \tag{12}$$

Following the introduced approach, the system can analyse the given scenario as a continuous function of the participating actors' spatial relationship. Accordingly, the identified model can detect and influence the scenario components' spatial relationship at every moment.

3) SCENARIO CONTROL USING A DETAILED SENSOR MODEL

I propose to use the introduced scenario control models if the perception module is assumed to be a black box. However, if there is detailed information about the investigated perception module, a model-based representation of the tested perception system is suggested [57]. Let us now describe the perception modules by the bounding points of their field of view (X_{FW1}, Y_{FW1} ... X_{FWi}, Y_{FWi} ... X_{FWn}, Y_{FWn}), where i means an intermediate point in the bounding area represented by n points. The detectable objects should be represented by their bounding points such as the bounding field of the pedestrian (X_{BFP1}, Y_{BFP1} ... X_{BFPj}, Y_{BFPj} ... X_{BFPk}, Y_{BFPk}) where j means an intermediate point in the bounding field represented by k points, and respectively the bounding field of the front vehicle or target (X_{BFT1}, Y_{BFT1} ... X_{BFTl}, Y_{BFTl} ... X_{BFTm}, Y_{BFTm}).

In this case, the control process aims to determine the expected relative position for a specific region of the sensor's field-of-view and the detectable object's bounding field in the t_2 moment. So equation (1) and (2) can be replaced by equation (13) and (14), while equation (7) and (8) can be replaced by equation (15) and (16). The optimisation problem's objective is to minimise the distance between the overlapping points of the field-of-view and the bounding-field of the object in the t_2 moment.

$$X_{FW_i}(t_2) - X_{BFP_j}(t_2) + \sigma \rightarrow min \tag{13}$$

$$Y_{FW_i}(t_2) - Y_{BFP_j}(t_2) + \sigma \rightarrow min \tag{14}$$

$$X_{FW_i}(t_2) - X_{BFT_l}(t_2) + \sigma \rightarrow min \tag{15}$$

$$Y_{FW_i}(t_2) - Y_{BFT_l}(t_2) + \sigma \rightarrow min \tag{16}$$

The above introduced detailed sensor model was used during the proof of concept demonstration of the Scenario-in-the-Loop methodology.

The scenarios mentioned earlier were implemented in a digital-twin environment and using mixed-reality enabled the combination of real and virtual objects simultaneously during the tests (see Fig. 8).

FIGURE 8. **The proof of concept demonstration of the mixed-reality based SciL concept at ZalaZONE 20/05/2019. The green Smart (VUT) moves fully autonomously in a valet parking scenario; the white Skoda is simply parking. The big screen on the left side displays the digital twin of ZalaZONE and the real-time movement of the VUT in it. The parking lot is empty in reality, while it is occupied by virtual vehicles in its digital representation. A virtual pedestrian is just stepping out from behind one of the virtual cars, making the VUT stop in reality as well. (video available: https://youtu.be/Ue3W7cjUtf8).**

The successful public demonstration - organised on the 20th of May in the year 2019 – proved that the developed model could control real-time test scenarios implemented in reality and virtual environment at the same time.

4) TIMINGS AND COMMUNICATION LATENCY

The real-time operation of the SciL system was also tested with 4G and with 5G (new radio, non-standalone architecture) communication networks installed at ZalaZONE. Measurements were also taken during the proof of concept demonstration. The round trip time (ping) measurement results between the SciL central server and the endpoint router are summarised in Table 1.

TABLE 1. Communication latency (time delay) measured during the test of the SciL concept using 4G/5G cellular network at the ZalaZONE proving ground.

	Mean delay (ms)	*Range (ms)*
4G	13	10-15
5G	8	7-11

The excellent performance results of the 4G network can also be traced back to the fact that although we used a commercial 4G cell, the usage was quasi-exclusive without having civil users. Regarding the acceptable level of communication latency, it can also be stated that the more elements (objects) are controlled within the scenario, the more time consuming the computation is behind.

Consequently, a tolerable threshold for the computational delay can also be specified. Fig. 9 shows the measured computational time values depending on the number of objects within the scenario. These suggest that the cycle time is proportional to the number of virtual objects in the simulation. Besides, the variance of the results does not change significantly. An arbitrary line at 25 ms is specified as a tolerable threshold for the cycle time. Above this value, the delay may be too high to perform scenario-based testing accurately.

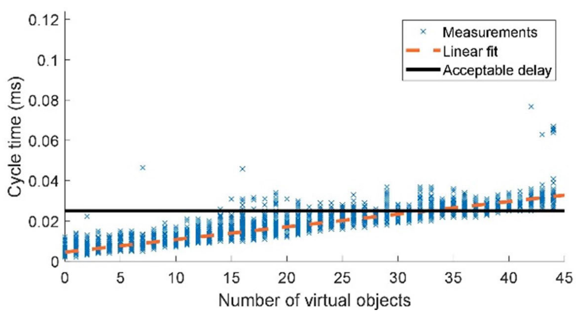

FIGURE 9. Computational time versus object number in the scenario.

VI. COMPARISON OF THE SOLUTIONS

Referring back to Section IV, the essential system properties of state-of-the-art ViL and beyond ViL testing frameworks are introduced in this section. By analysing the available methodological frameworks [106], selected evaluation factors are explained, such as simulation, visualisation, type of control used for the environmental components and the accuracy of the implemented mixed-reality.

A. SIMULATION OF THE ENVIRONMENT COMPONENTS

Quality simulation enables the realistic virtual representation of the environment components. In this regard, simulation is responsible for representing the characteristics and behaviour of these components. Consequently, the more detailed (closer to reality) the applied components' model, the better the simulation quality is.

Traffic scenarios can be quite complex. It is important to simulate road traffic characteristics, pedestrian and cyclist decisions, vehicle dynamics, and traffic signal timing control as realistic as possible to achieve a reliable result from the performed tests. In this respect, there is also a need to investigate the issue of co-simulation. Since different solutions are developed to handle the different simulation tasks (such as vehicle dynamics simulation or microscopic traffic modelling), it is reasonable to apply the proper tool for simulating a specific process. Therefore, it is becoming essential to provide a flexible and interoperable interface-environment for the co-simulation framework.

All these factors will be represented during the evaluation, indicated under SIM abbreviation in the comparison table.

B. VISUALIZATION OF THE ENVIRONMENT COMPONENTS

The visualisation module is responsible for the realistic representation of the objects. Accordingly, a high-quality visualization module should be capable of either injecting input signals, generated based on the simulated model's visualised objects, into the lower layers of the vehicular sensors; or transmitting output signals directly to the decision-making module of the central vehicular control system.

Subsequently, the more realistic the visualisation is, the more reliable testing results are generated. Thus it is essential to visualise the environment and the system components with the highest available quality to obtain reliable test processes [107]. The realistic visualisation related factor is represented in the evaluation table with the abbreviation VIS.

C. COMPREHENSIVE AND CONSISTENT CONTROL OF THE ENVIRONMENT COMPONENTS

The control framework makes it possible to connect the external components of the specific model architecture. The system can generate signals from the external components, such as the location, velocity, or acceleration values or can directly use their sensor signals. External components can be real objects (such as other test vehicles or vulnerable road user dummies) or simulated objects, enabling the system to generate signals and trigger information without physical items. Furthermore, infrastructure components contain traffic lights, variable message signs, and other smart info-communication solutions.

The control of the complex automotive testing and validation environment goes far beyond controlling a single

TABLE 2. System component level comparison of the investigated X-in-the-Loop (XiL) testing and validation frameworks.

Evaluated systems	*SIM*	*VIS*	*CTRL*	*MR-SPT*	*MR-RT*
SYS1	dSPACE ASM	dSPACE	dSPACE Autobox; no CSOC	GNSS, IMU based	NDA
SYS2	OWN APP	OWN APP	iSWACO-ARGUS; no CSOC	GNSS, IMU based	NDA
SYS3	OWN APP, no CTS	OWN APP	OWN APP; complex scen. coordination	GNSS, IMU based	NDA
SYS4	MATLAB, Simulink, no CTS	Unreal Engine	MATLAB, Simulink; no CSOC	GNSS, IMU based	DSRC, 5G
SYS5	PTV VISSIM	PTV VISSIM	OWN APP; no CSOC	GNSS, IMU based	DSRC
SYS6	VI-Grade; CarRealTime	VI-Grade; CarRealTime	NDA	GNSS, IMU based	DSRC, 5G
SYS7	OWN APP	WAC	OWN APP	NDA	NDA
SYS8	WAC	WAC	OWN APP	GNSS, IMU based	DSRC, 5G
ZalaZONE	VISSIM/SUMO, IPG, MATLAB Simulink	Unity Engine	OWN APP	GNSS, IMU based	DSRC, 5G

automated vehicle; the whole test system needs to be regulated simultaneously. Furthermore, the control can be closed-loop or open-loop; the communication's physical layer can be wired or wireless and focused on virtual or real objects. According to this, the evaluation factor describing each test environment's control-related aspects will refer to the above characteristics. This factor is represented in the evaluation table with the abbreviation CTRL.

D. ACCURACY OF THE MIXED-REALITY

Together with ViL testing's appearance, the requirement for embedding the vehicle under test (VUT) into a virtual environment has arrived too. From simple solutions like inserting the real car's bounding box into the simulation environment to complex solutions like implementing real-time control of the real-world elements directly from the simulation environment, different quality implementations were born. Some of them use the digital twin architecture by that mixed-reality or even augmented reality applications can be realised.

In high-end X-in-the-Loop systems in the automotive industry, mixed-reality is responsible for the accurate integration of the real-world environment and the computer-generated perceptual information by applying a wide range of sensors and supportive systems. Mixed-reality is a framework that fits the following three fundamental requirements: integrating the real and the virtual worlds, representing real-time operations, and implementing high accuracy spatial localisation and visualisation of virtual and real objects [108]. This factor is represented by MR in the evaluation table.

To integrate the real and the simulated environment precisely, high-level compliance and consistency between real and virtual objects from a spatial perspective are critical [109]. These make necessary the application of RTK differential GNSS-based and INS extended high accuracy localisation systems, HD mapping techniques, and imaging-based sensor fusion-localisation solutions [110].

Besides this, it has to be mentioned that the rapid development of 5G communication networks will soon result in the more robust integration of localisation and communication since 5G networks can effectively support the high accuracy positioning. The accuracy of positioning can be further improved by intelligent infrastructure based localisation techniques, using, e.g. RSUs, video and infra cameras, LiDAR or RADAR sensors [111]. The smart infrastructure has the additional advantage of being able to localise also non-smart, sensorless vehicles. That could effectively support the navigation of non-smart vehicles by utilising information generated by sensor-rich vehicles and road-sensor systems established in the infrastructure. This sub-factor is represented in the evaluation table with the abbreviation SPT.

For the proper time synchronisation of reality and the virtual environment, a reliable data transmission channel must be set-up with a potentially ultra-low, but with minimum a guaranteed low latency communication. Accordingly, a 5G cellular or a high-density DSRC communication network is needed to fulfil real-time process control requirements. This factor is represented by RT in the evaluation table.

E. COMPARISON OF CERTAIN ADVANCED XIL SYSTEMS

As Table 2 shows, the simulation modules of the investigated systems are considerably different. While some frameworks emphasise quality vehicle dynamics, other systems aim to implement a comprehensive traffic modelling framework and consider realistic traffic situations in the simulation environment. The adapted visualisation techniques also vary from the less detailed "functional-only" applications to the high-fidelity "just like real" approaches, incorporating professional industrial or open-source solutions, such as Unreal or Unity Engine. From a control point of view, it is the scope of the control that makes the difference. One system focuses only on the VUT's decision-making process, while another system can cover the whole test scenario's coordination, including scene objects. Based on the reviewed documentation, it can be concluded that all frameworks use high-accuracy localisation systems to support the implementation of the mixed-reality environment. For many XiL systems, there is no detailed information about the applied communication channels, though they are vital for supporting real-time processes, especially considering a mixed reality environment. There are a few XiL frameworks that provide only DSRC network availability for testing purposes. On the other hand, several XiL systems place critical emphasis on the communication domain, and they also offer both DSRC and 5G networks for their CAV testing processes.

Based on the evaluation of the introduced key system properties (such as SIM, VIS, CTRL, SPT, RT), it can be concluded that visualisation (VIS) and localisation (SPT) are the domains in which most of the system developers could achieve outstanding results. There is only one system in both fields with an ''earlier stage'' solution related to the given system property. Following this, most system developers have an ''advanced'' solution in the simulation domain too. In contrast, the field of control (especially considering the scenario level control concept) and real-time communication supporting the mixed reality implementations have relevant development potential; less than half of the systems have ''advanced'' solutions in these domains.

From a generic viewpoint, most of the systems have two or three ''earlier stage'' modules, while only four systems have one or no ''earlier stage'' solutions (such as SYS6, SYS7, SYS8 and ZalaZONE). Based on the comparison, the mixed reality based SciL methodology of ZalaZONE is among the most advanced methodological frameworks on the scenario-based CAV testing and validation domain.

Throughout the analysis of the state-of-the-art XiL solutions, the study was limited to a literature-based comparison, not having the chance to participate in experiments and testing processes of the different investigated systems.

VII. CONCLUSION

The first section of the paper provides a situation assessment of automotive development and testing. In light of this, testing self-driving vehicles is still a critical and challenging issue. At the moment, there are no generally accepted test procedures for testing completely autonomous road vehicles. However, simulation plays non-questionably an increasingly important role in the validation process of highly automated vehicles. In state-of-the-art simulation-based testing procedures, the vehicle under test or its components are real. At the same time, the environment is fully simulated with either generated sensor signals or, for example, projected visual effects with the environment. The automotive industry's testing and validation activities are mainly implemented in three different segments, strongly linked to the automobiles' product life-cycle.

Automotive system tests are based on the V-model approach, using the generic X-in-the-Loop (XiL) methodology. Starting with a Model-in-the-Loop environment, each development phase can be tested separately on the next level, corresponding to its complexity. Most advanced or state-of-the-art is the Vehicle-in-the-Loop testing, where the whole vehicle is investigated in a closed-loop or an open-loop test environment. With the application of X-in-the-Loop testing solutions, the investigated system elements (software, hardware or the complete vehicle) have continuous interaction with the simulated environment. Accordingly, virtual and real factors have to be synchronised for proper functionality, making the evolution of a coherent and reliable evaluation methodology possible.

The newly developed mixed-reality based Scenario-in-the-Loop (SciL) testing and validation methodology was presented in details. The SciL concept enables the seamless integration of simulation, physical test environment and real-time vehicle control, thus provides a framework for functional testing to an unprecedented level. A comprehensive comparison was carried out as a benchmark based on the analysis of state-of-the-art XiL solutions for CAV testing. The unified criteria for XiL system characterisation and component-level comparison of the investigated solutions helped identify the specific strengths and weaknesses as well as the research trends. This benchmark analysis also showed that the presented mixed-reality based Scenario-in-the-Loop testing methodology has various attributes beyond the state-of-the-art, proving to be one of the most comprehensive methodological frameworks in the field of scenario-based testing and validation.

Measurement results showed that recent developments in wireless communication technologies could already reliably fulfil the timing requirements of controlling such a complex real-time system. Based on this, it seems reasonable to consider SciL architecture as the potential basis for future standard testing methodologies. I expect that scenario-based testing and the mixed-reality based SciL approach will be the next generation X-in-the-Loop validation methodology in automated vehicle systems development.

Summing up the research's key findings, scenario-based testing and mixed-reality, blending physical testing environment and virtual model representation are expected to play a significant role in the CAV validation process. These techniques will reduce testing costs and risks by limiting physical tests and potentially dangerous real test situations [112]. Furthermore, the new framework can enhance testing capabilities by enabling the investigation of extreme cases that may not be feasible in reality.

As for the future perspectives of the introduced framework, beyond ground transportation, the extension of the model to the field of unmanned aerial vehicle (UAV) testing and validation is also an option, especially considering the soon inevitable approval processes of drone-transportation related devices, facilities and vehicles.

REFERENCES

[1] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, Standard SAE J3016, SAE Int., Warrendale, PA, USA, 2018, Art. no. 201806.

[2] *European New Car Assessment Programme, Assessment Protocol–Safety Assist*, Standard Version 7.0, Euro NCAP, Leuven, Belgium, Nov. 2015.

[3] B. A. Guvenc and E. Kural, ''Adaptive cruise control simulator: A low-cost, multiple-driver-in-the-loop simulator,'' *IEEE Control Syst. Mag.*, vol. 26, no. 3, pp. 42–55, Jun. 2006.

[4] Y. Xing, C. Lv, H. Wang, D. Cao, E. Velenis, and F.-Y. Wang, ''Driver activity recognition for intelligent vehicles: A deep learning approach,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5379–5390, Jun. 2019.

[5] L. Pariota, G. N. Bifulco, G. Markkula, and R. Romano, ''Validation of driving behaviour as a step towards the investigation of connected and automated vehicles by means of driving simulators,'' in *Proc. 5th IEEE Int. Conf. Models Technol. Intell. Transp. Syst. (MT-ITS)*, Jun. 2017, pp. 274–279.

[6] M. Überbacher, P. Wolze, and T. Burtsche, ''Experiencing safety function testing,'' *ATZ Worldwide*, vol. 119, nos. 7–8, pp. 54–57, Jul. 2017.

[7] AB Dynamics. *AB Dynamics Can Offer a Suite of Products to Conduct Vehicle Testing on Proving Grounds and Test Tracks*. Accessed: Jun. 22, 2020. [Online]. Available: https://www.abdynamics.com/en/products/track-testing

[8] Applus+ IDIADA. *XiL and Vehicle Validation*. Accessed: Jun. 22, 2020. [Online]. Available: https://www.applusidiada.com/global/en/what-we-do/service-sheet/xil-and-vehicle-validation

[9] I. Kyriakopoulos, P. Jaworski, and S. Kanarachos, "DigiCAV project: Exploring a test-driven approach in the development of connected and autonomous vehicles," in *Proc. IEEE Int. Conf. Connected Vehicles Expo (ICCVE)*, Nov. 2019, pp. 1–6.

[10] T. Kim, "Vehicle-in-the-Loop (ViL): Validating driver assistance systems with synchronous virtual and real test drives," *dSPACE Mag.*, vol. 2019, no. 2, pp. 14–17, Jun. 2019. [Online]. Available: https://d2368tcediwknr.cloudfront.net/bkm/magazin_2019_02_en/index.html#page_14

[11] iMAR. *Automatized Vehicle-in-the-Loop Testing of Automated Vehicles on Arbitrary Proving Grounds*. Accessed: Jun. 22, 2020. [Online]. Available: https://www.imar-navigation.de/en/products/by-product-names/item/iswaco-argus-proving-ground-infrastructure-for-testing-vehicles-up-to-sae-level-5

[12] IPG Automotive. *ViL Systems: Connecting Real-World and Virtual Test Driving With Ease*. Accessed: Jun. 22, 2020. [Online]. Available: https://ipg-automotive.com/products-services/test-systems/vil-systems/

[13] A. Herrmann, W. Brenner, and R. Stadler, *Autonomous Driving: How the Driverless Revolution Will Change the World*, 1st ed. Bingley, U.K.: Emerald, 2018.

[14] Y. Feng, C. Yu, S. Xu, H. X. Liu, and H. Peng, "An augmented reality environment for connected and automated vehicle testing and evaluation," in *Proc. IEEE Intell. Vehicles Symp. (IV)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Jun. 2018, pp. 1549–1554.

[15] Z. Szalay, Z. Hamar, and P. Simon, "A multi-layer autonomous vehicle and simulation validation ecosystem axis: ZalaZONE," in *Intelligent Autonomous Systems*, M. Strand, R. Dillmann, E. Menegatti, and S. Ghidoni, Eds. Cham, Switzerland: Springer, 2019, pp. 954–963.

[16] D. Zhao, X. Huang, H. Peng, H. Lam, and D. J. LeBlanc, "Accelerated evaluation of automated vehicles in car-following maneuvers," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 3, pp. 733–744, Mar. 2018.

[17] *Quality Management Systems—Requirements*, Standard ISO 9001, ISO 9001:2015, International Organization for Standardization, Geneva, Switzerland, 2015.

[18] *Road Vehicles—Functional Safety*, Standard ISO 26262, ISO 26262-1:2018, International Organization for Standardization, Geneva, Switzerland, 2018.

[19] *IATF 16949:2016: Quality Management System for Organizations in the Automotive Industry*, Standard IATF 16949, International Automotive Task Force, Turin, Italy, 2016.

[20] M. Zöldy, "Investigation of autonomous vehicles fit into traditional type approval process," in *Proc. Int. Conf. Traffic Transp. Eng. (ICTTE)*. Belgrade, Serbia: City Net Scientifics Research Center, 2018, pp. 428–432.

[21] *Agreement Concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts Which Can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of These United Nations Regulations*, United Nations Transport and Communications, Geneve, Switzerland, United Nations Regulation E/ECE/TRANS/505/Rev.3, Oct. 2017.

[22] H. Martins, "Overview of type approval homologation and self-certification," Ford Motor Company, Dearborn, MI, USA, Tech. Rep., 2010, doi: 10.13140/RG.2.2.31708.39041.

[23] P. Junietz, W. Wachenfeld, K. Klonecki, and H. Winner, "Evaluation of different approaches to address safety validation of automated driving," in *Proc. 21st Int. Conf. Intell. Transp. Syst. (ITSC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Nov. 2018, pp. 491–496.

[24] M. Zöldy, "Legal barriers of utilization of autonomous vehicles as part of green mobility," in *Proc. 4th Int. Congr. Automot. Transp. Eng. (AMMA)*, N. Burnete and B. O. Varga, Eds. Cham, Switzerland: Springer, 2019, pp. 243–248.

[25] T. Becsi, S. Aradi, and P. Gaspar, "Security issues and vulnerabilities in connected car systems," in *Proc. Int. Conf. Models Technol. Intell. Transp. Syst. (MT-ITS)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Jun. 2015, pp. 477–482.

[26] A. Torok, Z. Szalay, and B. Saghi, "New aspects of integrity levels in automotive industry-cybersecurity of automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, early access, Aug. 21, 2020, doi: 10.1109/TITS.2020.3011523.

[27] Á. Török and Z. Petho, "Introducing safety and security co-engineering related research orientations in the field of automotive security," *Periodica Polytechnica Transp. Eng.*, vol. 48, no. 4, pp. 349–356, Aug. 2020.

[28] M. Zöldy, Z. Szalay, and V. Tihanyi, "Challenges in homologation process of vehicles with artificial intelligence," *Transport*, vol. 35, no. 4, pp. 447–453, Nov. 2020.

[29] C. Zauner, J. Edelmann, and M. Plöchl, "Modelling, validation and characterisation of high-performance suspensions by means of a suspension test rig," *Int. J. Vehicle Design*, vol. 79, nos. 2–3, pp. 107–126, 2019.

[30] A. S. A. Rachman, A. F. Idriz, S. Li, and S. Baldi, "Real-time performance and safety validation of an integrated vehicle dynamic control strategy," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 13854–13859, Jul. 2017.

[31] W. Huang, K. Wang, Y. Lv, and F. Zhu, "Autonomous vehicles testing methods review," in *Proc. IEEE 19th Int. Conf. Intell. Transp. Syst. (ITSC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Nov. 2016, pp. 163–168.

[32] W. Wachenfeld and H. Winner, "Virtual assessment of automation in field operation, a new runtime validation method," in *Proc. Workshop Fahrerassistenzsysteme FAS*, C. Stiller, Ed. Darmstadt, Germany: Uni-DAS e.V., 2015, pp. 161–170.

[33] Y. He and C. Csiszár, "Concept of mobile application for mobility as a service based on autonomous vehicles," *Sustainability*, vol. 12, no. 17, p. 6737, Aug. 2020.

[34] Z. Szalay, "Structure and architecture problems of autonomous road vehicle testing and validation," in *Proc. 15th Mini Conf. Vehicle Syst. Dyn., Identificat. Anomalies (VSDIA)*, I. Zobory, Ed. Budapest, Hungary: BME ITS, 2016, pp. 229–236.

[35] P. Junietz, U. Steininger, and H. Winner, "Macroscopic safety requirements for highly automated driving," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2673, no. 3, pp. 1–10, Mar. 2019.

[36] T. Weilkiens, *Systems Engineering Mit SysML/UML: Anforderungen, Analyse, Architektur*. Heidelberg, Germany: Dpunkt.verlag GmbH, 2014.

[37] V. Schreiber, V. Ivanov, K. Augsburg, M. Noack, B. Shyrokau, C. Sandu, and P. S. Els, "Shared and distributed X-in-the-loop tests for automotive systems: Feasibility study," *IEEE Access*, vol. 6, pp. 4017–4026, 2018.

[38] S. Moten, F. Celiberti, M. Grottoli, A. van der Heide, and Y. Lemmens, "X-in-the-loop advanced driving simulation platform for the design,development, testing and validation of ADAS," in *Proc. IEEE Intell. Vehicles Symp. (IV)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Jun. 2018, pp. 1873–1878.

[39] J. Zhou, R. Schmied, A. Sandalek, H. Kokal, and L. del Re, "A framework for virtual testing of ADAS," *SAE Int. J. Passenger Cars Electron. Electr. Syst.*, vol. 9, no. 1, pp. 66–73, Apr. 2016.

[40] P. Nitsche, R. H. Welsh, A. Genser, and P. D. Thomas, "A novel, modular validation framework for collision avoidance of automated vehicles at road junctions," in *Proc. 21st Int. Conf. Intell. Transp. Syst. (ITSC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Nov. 2018, pp. 90–97.

[41] M. Broy, I. H. Kruger, A. Pretschner, and C. Salzmann, "Engineering automotive software," *Proc. IEEE*, vol. 95, no. 2, pp. 356–373, Feb. 2007.

[42] H. Jiang, H. Tian, Y. Hua, and B. Tang, "Research on control of intelligent vehicle human-simulated steering system based on HSIC," *Appl. Sci.*, vol. 9, no. 5, p. 905, Mar. 2019.

[43] E. Bringmann and A. Krämer, "Model-based testing of automotive systems," in *Proc. 1st Int. Conf. Softw. Test., Verification, Validation*. Piscataway, NJ, USA: IEEE Computer Society, Apr. 2008, pp. 485–493.

[44] N. Wiechowski, T. Rambow, R. Busch, A. Kugler, N. Hansen, and S. Kowalewski, "Arttest—A new test environment for model-based software development," in *Proc. SAE Tech. Paper Ser.*, Mar. 2017, p. 11.

[45] I. R. Kendall and R. P. Jones, "An investigation into the use of hardware-in-the-loop simulation testing for automotive electronic control systems," *Control Eng. Pract.*, vol. 7, no. 11, pp. 1343–1356, Nov. 1999.

[46] Y. Chen, S. Chen, T. Zhang, S. Zhang, and N. Zheng, "Autonomous vehicle testing and validation platform: Integrated simulation system with hardware in the loop," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2018, pp. 949–956.

[47] S. Chen, Y. Chen, S. Zhang, and N. Zheng, "A novel integrated simulation and testing platform for self-driving cars with hardware in the loop," *IEEE Trans. Intell. Vehicles*, vol. 4, no. 3, pp. 425–436, Sep. 2019.

[48] D. Iqbal, A. Abbas, M. Ali, M. U. S. Khan, and R. Nawaz, "Requirement validation for embedded systems in automotive industry through modeling," *IEEE Access*, vol. 8, pp. 8697–8719, 2020.

[49] T. Bock, ''Vehicle in the Loop: Test- und Simulationsumgebung für Fahrerassistenzsysteme,'' Ph.D. dissertation, Dept. Elect. Comput. Eng., TU München, Munich, Germany, May 2008.

[50] C. Miquet, ''New test method for reproducible real-time tests of ADAS ECUs: 'Vehicle-in-the-Loop' connects real-world vehicles with the virtual world,'' in *Proc. 5th Int. Munich Chassis Symp.*, P. E. Pfeffer, Ed. Wiesbaden, Germany: Springer Fachmedien, 2014, pp. 575–589.

[51] T. Tettamanti, M. Szalai, S. Vass, and V. Tihanyi, ''Vehicle-in-the-loop test environment for autonomous driving with microscopic traffic simulation,'' in *Proc. IEEE Int. Conf. Veh. Electron. Saf. (ICVES)*, Sep. 2018, pp. 1–6.

[52] O. Gietelink, J. Ploeg, B. De Schutter, and M. Verhaegen, ''Development of advanced driver assistance systems with vehicle hardware-in-the-loop simulations,'' *Vehicle Syst. Dyn.*, vol. 44, no. 7, pp. 569–590, Jul. 2006.

[53] S. Zang, M. Ding, D. Smith, P. Tyler, T. Rakotoarivelo, and M. A. Kaafar, ''The impact of adverse weather conditions on autonomous vehicles: How rain, snow, fog, and hail affect the performance of a self-driving car,'' *IEEE Veh. Technol. Mag.*, vol. 14, no. 2, pp. 103–111, Jun. 2019.

[54] C.-S. Lee, Y.-H. Huang, and I.-W. Lan, ''Hardware-in-the-Loop test case specification for verification of software safety requirements in the context of ISO 26262,'' in *Proc. Int. Conf. Electr. Electron. Technol. Automot.*, Jul. 2018, pp. 1–6.

[55] S. Riedmaier, T. Ponn, D. Ludwig, B. Schick, and F. Diermeyer, ''Survey on scenario-based safety assessment of automated vehicles,'' *IEEE Access*, vol. 8, pp. 87456–87477, 2020.

[56] Z. Szalay, Z. Hamar, and A. Nyerges, ''Novel design concept for an automotive proving ground supporting multilevel CAV development,'' *Int. J. Vehicle Design*, vol. 80, no. 1, pp. 1–22, 2019.

[57] S. Wei, D. Yu, C. L. Guo, L. Dan, and W. W. Shu, ''Survey of connected automated vehicle perception mode: From autonomy to interaction,'' *IET Intell. Transp. Syst.*, vol. 13, no. 3, pp. 495–505, Mar. 2019.

[58] M. T. Horváth, T. Tettamanti, B. Varga, and Z. Szalay, ''The Scenario-in-the-Loop (SciL) automotive simulation concept and its realisation principles for traffic control,'' in *Proc. 8th Symp. Eur. Assoc. Res. Transp. (hEART)*. Budapest, Hungary: BME ITS, 2019, pp. 4–6.

[59] M. Elgharbawy, I. Scherhaufer, K. Oberhollenzer, M. Frey, and F. Gauterin, ''Adaptive functional testing for autonomous trucks,'' *Int. J. Transp. Sci. Technol.*, vol. 8, no. 2, pp. 202–218, Jun. 2019.

[60] C. Amersbach and H. Winner, ''Defining required and feasible test coverage for scenario-based validation of highly automated vehicles,'' in *Proc. IEEE Intell. Transp. Syst. Conf. (ITSC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Oct. 2019, pp. 425–430.

[61] H. Németh, A. Háry, Z. Szalay, V. Tihanyi, and B. Tóth, ''Proving ground test scenarios in mixed virtual and real environment for highly automated driving,'' in *Mobilität Zeiten der Veränderung : Technische und betriebswirtschaftliche Aspekte*, H. Proff, Ed. Wiesbaden, Germany: Springer Fachmedien, 2019, pp. 199–210.

[62] M. Ghadi and Á. Török, ''A comparative analysis of black spot identification methods and road accident segmentation methods,'' *Accident Anal. Prevention*, vol. 128, pp. 1–7, Jul. 2019.

[63] K. Czarnecki, ''Requirements engineering in the age of societal-scale cyber-physical systems: The case of automated driving,'' in *Proc. IEEE 26th Int. Requirements Eng. Conf. (RE)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Aug. 2018, pp. 3–4.

[64] M. Jamshidi, *System of Systems Engineering*. Hoboken, NJ, USA: Wiley, 2008.

[65] M. Koschuch, W. Sebron, Z. Szalay, Á. Török, H. Tschiürtz, and I. Wahl, ''Safety & security in the context of autonomous driving,'' in *Proc. IEEE Int. Conf. Connected Vehicles Expo (ICCVE)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Nov. 2019, pp. 1–7.

[66] G. Pauer, T. Sipos, and Á. Török, ''Statistical analysis of the effects of disruptive factors of driving in simulated environment,'' *Transport*, vol. 34, no. 1, pp. 1–8, Jan. 2019.

[67] M. Butenuth, R. Kallweit, and P. Prescher, ''Vehicle-in-the-loop real-world vehicle tests combined with virtual scenarios,'' *ATZ Worldwide*, vol. 119, no. 9, pp. 52–55, Sep. 2017.

[68] V. Rau Aparow, A. Choudary, G. Kulandaivelu, T. Webster, J. Dauwels, and N. de Boer, ''A comprehensive simulation platform for testing autonomous vehicles in 3D virtual environment,'' in *Proc. IEEE 5th Int. Conf. Mechatronics Syst. Robots (ICMSR)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, May 2019, pp. 115–119.

[69] R. Ladstädter, P. Luley, S. Ladstätter, and H. Mayer, ''UHD mapping von teststrecken für automatisiertes fahren,'' in *Wissenschaftlich-Technische Jahrestagung der DGPF e.V.*, T. P. Kersten, Ed. Hamburg, Germany: Deutschen Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation, Feb. 2019, pp. 1–13.

[70] C. Olaverri-Monreal, J. Errea-Moreno, A. Díaz-Álvarez, C. Biurrun-Quel, L. Serrano-Arriezu, and M. Kuba, ''Connection of the SUMO microscopic traffic simulator and the unity 3D game engine to evaluate V2X communication-based systems,'' *Sensors*, vol. 18, no. 12, p. 4399, Dec. 2018.

[71] B. H. Thomas, ''A survey of visual, mixed, and augmented reality gaming,'' *Comput. Entertainment*, vol. 10, no. 1, pp. 1–33, Oct. 2012.

[72] BME Automated Drive. *ZalaZONE Automotive Proving Ground Virtual Simulation Models*. Accessed: Aug. 27, 2020. [Online]. Available: https://github.com/BMEAutomatedDrive/ZalaZONE-automotive-proving-ground-virtual-simulation-models

[73] *GNSS-Aided Inertial Navigation System for Automotive Testing*, Oxford Technical Solutions, Oxfordshire, U.K., 2020, Accessed: Aug. 27, 2020. [Online]. Available: https://www.oxts.com/products/rt3000/

[74] *Automated Guidance of Cars, Trucks and Other Transportation Systems*. iMAR Navigation GmbH, St. Ingbert, Germany. Accessed: Aug. 27, 2020. [Online]. Available: https://www.imar-navigation.de/index.php/en/products/by-application/category/advanced-driver-assistance-systems-adas-inertial-gyro-navigation-imu-ims-ins-control-verification-automotive-car-had-adas-haf

[75] *Using IMU Integration With VB3iS*. Racelogic Limited, Buckingham, U.K., 2020. Accessed: Aug. 27, 2020. [Online]. Available: https://racelogic.support/01VBOXAutomotive

[76] *ADMA Family GPS/Inertial System Automotive/Railway*, GeneSys Elektronik GmbH, Offenburg, Germany, 2020. Accessed: Aug. 27, 2020. [Online]. Available: https://www.genesys-offenburg.de/en/products/adma-family-gpsinertial-system-automotiverailway/

[77] S. Eckelmann, T. Trautmann, H. Ußler, B. Reichelt, and O. Michler, ''V2V-communication, LiDAR system and positioning sensors for future fusion algorithms in connected vehicles,'' *Transp. Res. Procedia*, vol. 27, pp. 69–76, Jan. 2017.

[78] I. Passchier, G. Van Vugt, and M. Tideman, ''An integral approach to autonomous and cooperative vehicles development and testing,'' in *Proc. IEEE 18th Int. Conf. Intell. Transp. Syst.* Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Sep. 2015, pp. 348–352.

[79] Z. Szalay, T. Tettamanti, D. Esztergár-Kiss, I. Varga, and C. Bartolini, ''Development of a test track for driverless cars: Vehicle design, track configuration, and liability considerations,'' *Periodica Polytechnica Transp. Eng.*, vol. 46, no. 1, pp. 29–35, 2018.

[80] H. Digel, M. Gabb, L. Erlinghagen, and E. Sax, ''Vehicle localization using infrastructure sensing,'' in *Intelligent System Solutions for Auto Mobility and Beyond*, C. Zachäus and G. Meyer, Eds. Cham, Switzerland: Springer, 2021, pp. 3–13.

[81] I. Vajk, G. Harsányi, A. Poppe, S. Imre, B. Kiss, Á. Jobbágy, G. Katona, L. Nagy, G. Magyar, and I. Kiss, ''BME VIK annual research report on electrical engineering and computer science 2015,'' *Periodica Polytechnica Electr. Eng. Comput. Sci.*, vol. 60, no. 1, pp. 1–36, 2016.

[82] Y. Yang and K. Hua, ''Emerging technologies for 5G-enabled vehicular networks,'' *IEEE Access*, vol. 7, pp. 181117–181141, 2019.

[83] N. Varga, L. Bokor, A. Takacs, J. Kovacs, and L. Virag, ''An architecture proposal for V2X communication-centric traffic light controller systems,'' in *Proc. 15th Int. Conf. ITS Telecommun. (ITST)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, May 2017.

[84] P. Varga, J. Peto, A. Franko, D. Balla, D. Haja, F. Janky, G. Soos, D. Ficzere, M. Maliosz, and L. Toka, ''5G support for industrial IoT applications—Challenges, solutions, and research gaps,'' *Sensors*, vol. 20, no. 3, p. 828, Feb. 2020.

[85] X. Ge, ''Ultra-reliable low-latency communications in autonomous vehicular networks,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 5005–5016, May 2019.

[86] *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, Standard 802.11p-2010, Institute of Electrical and Electronics Engineers, 2010.

[87] *Intelligent Transport Systems (ITS); ITS-G5 Access Layer Specification for Intelligent Transport Systems Operating in the 5 GHz Frequency Band*, Standard EN 302 663 V1.3.0, European Telecommunications Standards Institute (ETSI), Valbonne, France, 2019. [Online]. Available: https://www.etsi.org/deliver/etsi_en/302600_302699/302663/01.03.00_20/en_302663v010300a.pdf

[88] M. Min, L. Xiao, Y. Chen, P. Cheng, D. Wu, and W. Zhuang, ''Learning-based computation offloading for IoT devices with energy harvesting,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1930–1941, Feb. 2019.

[89] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, ''What will 5G be?'' *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[90] P. Wang, C.-M. Chen, S. Kumari, M. Shojafar, R. Tafazolli, and Y.-N. Liu, ''HDMA: Hybrid D2D message authentication scheme for 5G-enabled VANETs,'' *IEEE Trans. Intell. Transp. Syst.*, early access, Aug. 13, 2020, doi: 10.1109/TITS.2020.3013928.

[91] H. Gao, H. Yu, G. Xie, H. Ma, Y. Xu, and D. Li, ''Hardware and software architecture of intelligent vehicles and road verification in typical traffic scenarios,'' *IET Intell. Transp. Syst.*, vol. 13, no. 6, pp. 960–966, Jun. 2019.

[92] F. Hegedüs, T. Bécsi, S. Aradi, and P. Gáspár, ''Motion planning for highly automated road vehicles with a hybrid approach using nonlinear optimization and artificial neural networks,'' *Strojniški vestnik J, Mech. Eng.*, vol. 65, no. 3, pp. 148–160, Mar. 2019.

[93] H. Wang, Y. Huang, A. Khajepour, Y. Zhang, Y. Rasekhipour, and D. Cao, ''Crash mitigation in motion planning for autonomous vehicles,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 9, pp. 3313–3323, Sep. 2019.

[94] T. D. Son, A. Bhave, and H. Van der Auweraer, ''Simulation-based testing framework for autonomous driving development,'' in *Proc. IEEE Int. Conf. Mechatronics (ICM)*, vol. 1, Mar. 2019, pp. 576–583.

[95] D. Nalic, A. Eichberger, G. Hanzl, M. Fellendorf, and B. Rogic, ''Development of a co-simulation framework for systematic generation of scenarios for testing and validation of automated driving systems,'' in *Proc. IEEE Intell. Transp. Syst. Conf. (ITSC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, Oct. 2019, pp. 1895–1901.

[96] A. Mohamed, A. N. Ouda, J. Ren, and M. El-Gindy, ''Processor-in-the-loop co-simulations and control system design for a scaled autonomous multi-wheeled combat vehicle,'' *Int. J. Autom. Control*, vol. 14, no. 2, pp. 138–160, 2020.

[97] D. Schramm, M. Hiller, and R. Bardini, *Vehicle Dynamics*. Heidelberg, Germany: Springer-Verlag, 2018.

[98] D. Shin, S. Yi, K.-M. Park, and M. Park, ''An interacting multiple model approach for target intent estimation at urban intersection for application to automated driving vehicle,'' *Appl. Sci.*, vol. 10, no. 6, p. 2138, Mar. 2020.

[99] T. Tettamanti and I. Varga, ''Development of road traffic control by using integrated VISSIM-MATLAB simulation environment,'' *Periodica Polytechn. Civil Eng.*, vol. 56, no. 1, pp. 43–49, May 2012.

[100] B. Németh and P. Gáspár, ''LPV design for the control of heterogeneous traffic flow with autonomous vehicles,'' *Acta Polytechnica Hungarica*, vol. 16, no. 7, pp. 233–246, Jan. 2019.

[101] D. Liu, L. Gao, C. Han, and J. Wang, ''Design of network control system for automotive proving ground,'' in *Proc. 28th Chin. Control Decis. Conf. (CCDC)*. Piscataway, NJ, USA: Institute of Electrical and Electronics Engineers, May 2016, pp. 2743–2746.

[102] F. R. Yu, ''Guest editorial connected vehicles for safer, greener, and more efficient transportation,'' *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9455–9456, Dec. 2016.

[103] A. E. Saddik, ''Digital twins: The convergence of multimedia technologies,'' *IEEE Multimedia Mag.*, vol. 25, no. 2, pp. 87–92, Apr. 2018.

[104] P. Gáspár, Z. Szalay, and S. Aradi, *Highly Automated Vehicle Systems*. Budapest, Hungary: BME MOGI, Oct. 2014. [Online]. Available: https://www.researchgate.net/publication/321527129_Highly_Automated_Vehicle_Systems

[105] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, ''FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks,'' *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 218–224, Jan. 2018.

[106] R. Chen, M. Arief, W. Zhang, and D. Zhao, ''How to evaluate proving grounds for self-driving? A quantitative approach,'' *IEEE Trans. Intell. Transp. Syst.*, early access, May 15, 2020, doi: 10.1109/TITS.2020.2991757.

[107] H. Abdellatif and C. Gnandt, ''Einsatz der simulation für die homologation automatisierter fahrfunktionen,'' *ATZelektronik*, vol. 14, no. 12, pp. 70–73, Dec. 2019.

[108] H.-K. Wu, S. W.-Y. Lee, H.-Y. Chang, and J.-C. Liang, ''Current status, opportunities and challenges of augmented reality in education,'' *Comput. Educ.*, vol. 62, pp. 41–49, Mar. 2013.

[109] M. Carraro, M. Munaro, J. Burke, and E. Menegatti, ''Real-time markerless multi-person 3D pose estimation in RGB-DEPTH camera networks,'' in *Proc. Adv. Intell. Syst. Comput.*, vol. 867. Cham, Switzerland: Springer-Verlag, Jun. 2019, pp. 534–545.

[110] C. Li, Y. Fu, F. R. Yu, T. H. Luan, and Y. Zhang, ''Vehicle position correction: A vehicular blockchain networks-based GPS error sharing framework,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 2, pp. 898–912, Feb. 2021.

[111] J. Guo, B. Song, S. Chen, F. Richard Yu, X. Du, and M. Guizani, ''Context-aware object detection for vehicular networks based on edge-cloud cooperation,'' *IEEE Internet Things J.*, vol. 7, no. 7, pp. 5783–5791, Jul. 2020.

[112] H. Lengyel, T. Tettamanti, and Z. Szalay, ''Conflicts of automated driving with conventional traffic infrastructure,'' *IEEE Access*, vol. 8, pp. 163280–163297, 2020.

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