Methodology of highly automated and autonomous road vehicle testing from the perspective of the test track and related simulation technologies

Thesis Booklet

Author:
Bálint Tóth

Supervisor:
Dr. Zsolt Szalay

Industrial expert:
Ferenc Finszter

MŰEGYETEM 1782

Budapest University of Technology And Economics
Kandó Kálmán Doctoral School
Faculty of Transportation Engineering and Vehicle Engineering
Department of Automotive Technologies

2025

1. Introduction

Since the second half of the 2010s up to the present day—over the past nearly ten years—significant changes have taken place in the automotive industry, the societal impact of which is unquestionable. In addition to the spread of electric vehicles and the smart devices that can be integrated into them, a wide range of new advanced driver assistance systems have emerged and become mandatory, substantially enhancing road safety. Furthermore, the broader uptake of automated vehicles is also expected, as regulatory frameworks, directives, laws, and international standards facilitating their approval and entry into service are already on the horizon. Although considerable progress has been made in this field, it can be stated that, due to the complexity of their operational conditions, there are still no unified testing and approval procedures for automated vehicles that would support their large-scale adoption, particularly in Europe.

With my research and the preparation of my dissertation, entitled "Methodology of highly automated and autonomous road vehicle testing from the perspective of the test track and related simulation technologies", I aim to contribute to this domain, in the hope that the methods and procedures I have developed may assist future testing and approval processes of automated vehicles.

The present work constitutes the thesis booklet related to my doctoral dissertation, in which I briefly introduce the background of the research, the theses I have formulated, as well as my future research plan.

1.1. Research motivation

In 2016, a governmental decision was made to establish a Hungarian automotive proving ground, the location of which was ultimately selected to be Zalaegerszeg. Since I originate from the region of Zalaegerszeg, it was of particular significance for me to join the work aiming at the creation of ZalaZONE already in the early stages of the project. From 2017 onwards, I had the opportunity to participate in numerous research and development projects related to the proving ground, through which I gained deeper insights into the challenges associated with the testing of advanced driver assistance systems (ADAS) and automated driving systems (ADS). With the help of simulation software applied at the proving ground, I began to investigate various testing procedures, and I also contributed to the development of the Scenario-in-the-Loop (SciL) concept [P1]. This experience encouraged me to continue my engineering activities along a scientific path as of 2019, when I started to investigate the topic formulated in the title of my doctoral studies.

Since May 2020, I have continued my work at the proving ground within TÜV Rheinland-KTI Ltd., where my primary responsibility was the establishment of the local branch at Zala-ZONE and the coordination of the ongoing projects there. Through these tasks, I became more familiar with the approval and homologation processes of vehicles and gained confirmation that my research topic may also be relevant from an industrial perspective. An excellent opportunity in this regard was provided by the Cooperative Doctoral Program (KDP-2021)[1], within which my research work could be aligned with my daily professional responsibilities through the collaboration between the company and the university, enabling me to directly utilize the research results in my everyday tasks. In most cases, the development of new regulations and testing procedures is also based on scientific research and measurement campaigns, and dedicated working groups address these topics, for example, within the framework of the United Nations or the European Union.

As a result, the focus of my research shifted towards type approval and other independent testing procedures of vehicles, during which I identified several key open issues. In particular, the testing of various ADAS and ADS functions is highly complex and costly, thus it may be worthwhile to develop procedures that – by also involving simulation-based methods – can make the tests more efficient, especially those aiming at functional validation prior to official approval examinations. Furthermore, as I already mentioned in the introduction, there are still no internationally harmonized testing and approval procedures for automated vehicles, therefore the development of more unified methods could also facilitate this process.

In this context, I carried out my research and prepared my dissertation, in which I sought to combine both the scientific knowledge gained at the university and the practical experience obtained from my parallel daily industrial work.

1.2. Objectives

The lack of harmonized testing and approval procedures for automated vehicles hinders their market entry. Although there are countries where more flexible regulations exist (e.g., the USA, China), even in these cases a continuous tightening of rules can be observed. In the European

[1] *This doctoral research was carried out within the framework of project no. C1781139with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the KDP-2021 funding scheme*

Union (EU), the practice of type approval is followed, an administrative procedure by which the transport authority certifies that a vehicle, system, component, or separate technical unit complies with the relevant regulatory provisions and technical requirements. A synonymous concept is homologation. Among the countries where this procedure is applied (beyond EU member states, e.g., Japan, Australia), there are already cases allowing the registration of automated vehicles (e.g., Germany [1]); however, these regulatory processes are typically complex, and achieving market entry remains challenging. In most European countries (including Hungary), the more common practice is to obtain permits for public road testing. In Hungary, this possibility has been included in the KöHÉM regulations since 2017–2018 [2][3].

In most cases, neither for operational use nor for pre-market testing use are there harmonized procedures that would reliably ensure a vehicle can be released into public traffic. The conditions vary case by case across EU member states. Therefore, one of my objectives was to develop proving-ground-based testing procedures that facilitate the market introduction of automated vehicles. These procedures are intended to build on established and industry-accepted test cases, while remaining flexible enough to adapt to automated functions at different maturity levels.

Another objective of mine was to support the success of ADAS-related type approval examinations through the development of functional validation methods preceding them. In many cases, it is during the official procedure that errors or deficiencies are revealed, which prevent a vehicle from receiving approval for a given function. As a result, further development and repeated approval testing generate significant additional costs and time losses. In this regard, my goal was to design complex test scenarios that can facilitate functional validation tests preceding the type approval of advanced driver assistance systems, thereby enabling manufacturers and suppliers to obtain a more comprehensive overview of the maturity of their developed functions through simplified testing procedures before entering the official examinations.

I also aimed to investigate how the SciL concept could be applied within the type approval examinations of vehicles. As the use of virtual methods is currently only possible to a limited extent in approval practices, I developed an application framework through which simulation results can be integrated into approval procedures in a manner that allows bypassing the current limitations of virtual methods. My theses were formulated along these objectives.

1.3. Research background

The various highly automated and autonomous driving functions can be categorized according to the SAE J3016 standard [4], which is detailed in **Figure 1**. Based on this classification, ADAS functions are typically assigned to Levels 0, 1, and 2 (marked in blue), and are also defined in the standard as driver assistance functions, whereas Levels 3 to 5 are referred to as automated driving functions (marked in green). In my dissertation, I generally use the abbreviations ADAS and ADS to denote these categories.

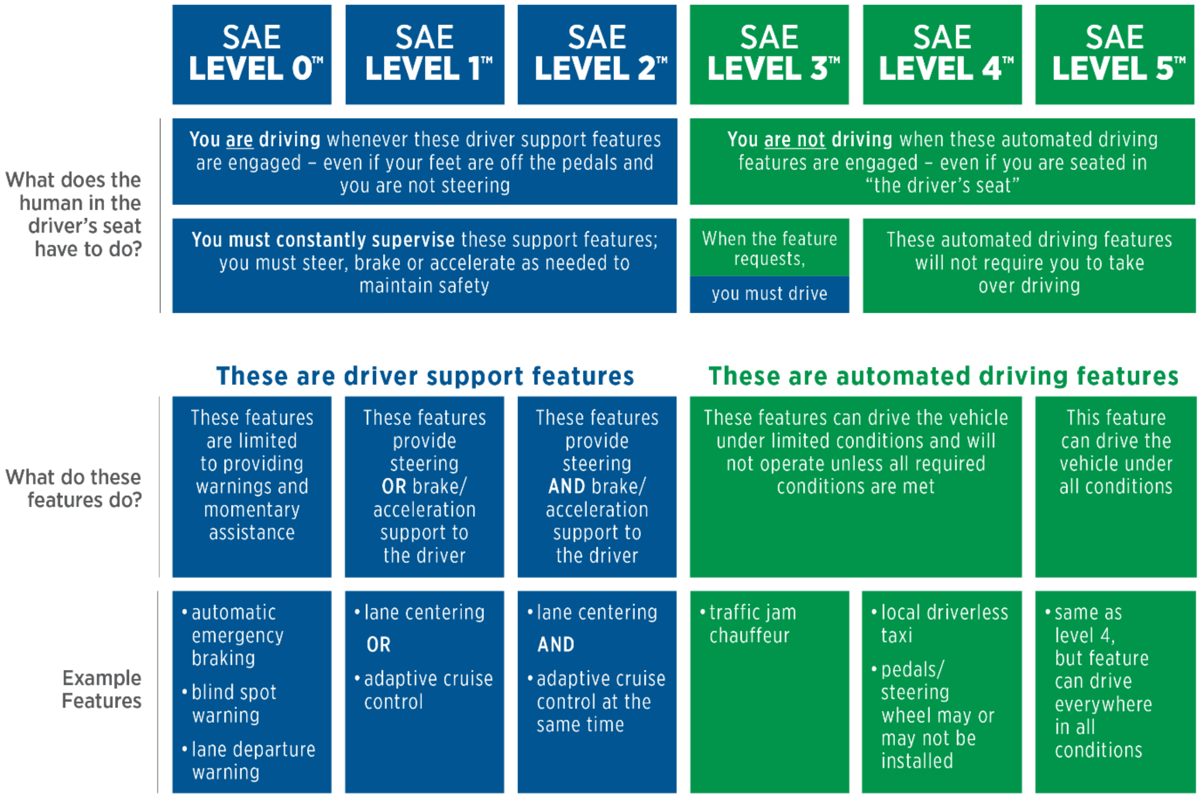

Figure 1: SAE Levels of Driving Automation™ Refined for Clarity and International Audience, source: [4]

In recent years, the European type approval system has undergone significant transformation regarding ADAS functions. One of its main catalysts was the adoption of EU Regulation 2019/2144 in November 2019, commonly referred to in the field as the new *General Safety Regulation* (GSR) [5]. The regulation introduced the mandatory implementation of ADAS functions in multiple phases: first for new vehicle types, and from the summer of 2024, for the majority of newly registered vehicles. As a result, several well-known functions—such as automatic emergency braking and lane keeping—became mandatory, the full list of which is included in the regulation [5]. The associated requirements also define all the testing procedures necessary from a type approval perspective.

For ADAS functions, the protocols of the European New Car Assessment Programme (EuroNCAP) are also widely applied and highly influential, as they contribute to the independent evaluation of vehicles. While EuroNCAP was previously known primarily for awarding up to five stars based on crash test performance, today active safety systems are also considered in the rating.

It is important to emphasize once again that every new vehicle type must successfully pass most of the listed tests in order to obtain the approvals and ratings required for market entry. Consequently, any issues discovered at this stage result in significant additional costs and time losses, since these tests are typically expensive and may take several weeks to complete.

The development of ADS has gained considerable momentum in recent years, increasingly becoming a key element of the future of mobility. Technological progress not only promises enhanced mobility and reduced environmental impact but also envisions accident-free transportation. At the same time, societal interest and expectations play an increasingly prominent role, as road safety, efficiency, and sustainability directly affect everyday life. Before introducing advanced automated systems, however, it is essential to define and evaluate their behavioral competencies. Relevant literature can be found addressing their development, applicability in transportation, and appropriate testing procedures [6]–[16][P4].

One of the key documents related to the testing and approval of automated vehicles is the *New Assessment/Test Method for Automated Driving* (NATM) [17], published by the United Nations. This framework defines testing and evaluation processes along six pillars: scenario catalogues, simulation and virtual testing, proving ground testing, public road testing, auditing and assessment, and in-service monitoring. This approach largely builds upon the methodology developed in the PEGASUS project, according to which test scenarios can appear at different abstraction levels (functional, logical, concrete) throughout the development process [18]. In the conceptual phase, high-level natural-language descriptions are used, whereas during detailed technical development, parameter-space-based definitions are required, and for execution, test cases must be specified in a precisely defined, standardized data format.

Among the EU regulations, Commission Implementing Regulation (EU) 2022/1426 [19] is noteworthy as it is the first to provide explicit guidelines and recommendations for the approval and assessment of automated vehicles. It emphasizes that test cases must be aligned with the pre-defined *Operational Design Domain* (ODD) of the given vehicle. Analysis of NATM and the above EU regulation makes it clear that although several fundamental scenarios have been defined, the variety of automated vehicles and the theoretically infinite number of possible traffic situations make it impossible to create concrete test cases for every eventuality. Therefore, regulations instead define groups of test cases that cover the ODD of the vehicle. If the vehicle can safely complete these, it can be reasonably assumed to operate safely within its intended environment. In general, it can thus be stated that no harmonized, internationally accepted test case collections or approval procedures yet exist for automated vehicles.

To enable the definition of appropriate test situations nonetheless, numerous scientific methods and technologies have been developed in the field of test scenario generation [20]–[27].

As noted earlier, defining the ODD properly is essential for selecting suitable test cases, and ideally, the *Object and Event Detection and Response* (OEDR) framework should also be taken into account. Standardized approaches to describing the ODD already exist, such as SAE and BSI standards, but even in this field there is no fully harmonized terminology for ODD elements and related concepts [28][29]. Defining the ODD is typically an iterative process, which should ideally be carried out in the relatively early stages of automated driving function design. However, it may need to be refined throughout the testing process, and additional, previously unforeseen attributes may also need to be defined [30].

Based on the reviewed literature, it is evident that while several useful approaches exist both for creating test cases and for properly defining the ODD, none truly address how a relatively small number of already industry-accepted test cases could be selected and combined to create a tailored test case collection for a given automated driving function or vehicle. Such an approach could provide a reliable measure of the vehicle’s safety level in critical situations, thereby improving the efficiency of verification tests prior to test-use market entry.

In recent years, simulation-based testing approaches have gained increasing importance in the development and validation of automated vehicle systems. These methods enable the identification and analysis of the most critical traffic situations in a safe and controlled environment. Simulations not only allow for faster detection and evaluation of potentially hazardous situations but also make the testing process significantly more efficient and cost-effective [31].

Modern simulation environments, however, must serve not only the replay of test cases. They should also support the development and fine-tuning of various algorithms—such as those for vehicle motion control, modeling of other road users (e.g., pedestrians, cyclists), or simulation of infrastructure elements (e.g., traffic lights, sensor networks). In this way, developers can receive real-time feedback on system behavior and identify potential errors or shortcomings more quickly [32].

Thus, simulation is not merely a testing tool but a comprehensive development platform that enables the integrated evaluation of different components of automated systems. This is particularly important for future transportation systems requiring high levels of automation, where real-world testing is not only costly but often risky as well [33].

The application of simulation could therefore offer solutions for accelerating testing procedures and reproducing extreme situations that cannot be realized in reality. Nevertheless, according to both NATM [17] and EU Regulation 2022/1426 [19], simulation still has numerous limitations when applied in type approval processes.

In line with the above, the focus of my theses and the corresponding research activities can be summarized as follows:

- Creation of test case collections based on industry-accepted test cases, supported by a preliminary questionnaire.
- Development of specific testing procedures for functional validation prior to approval and other assessment examinations.
- Utilization of simulation-based methods (particularly SciL) in type approval processes.

2. New scientific results

In this chapter, I summarize the theses I have formulated and briefly outline the approach I applied to develop them.

2.1. Thesis I.

I developed a methodology that enables the identification, from a database of industry-applied test case variations, of those covering the Operational Design Domain of a highly automated or automated vehicle. By executing these test cases, it can be reliably determined whether the given vehicle is capable of safe operation within its intended environment.

In the chapter related to this thesis of my dissertation, I present a methodology that allows the definition and selection of test cases for automated vehicles, with which safety-critical situations can be examined in a proving ground environment. When defining the test cases, I relied on existing and industry-accepted testing procedures that are applied in vehicle evaluation (e.g., EuroNCAP) or in type approval processes, thereby formulating test cases that can reliably cover and evaluate the behavior of an automated vehicle in safety-critical situations [P9]. Although currently only a limited number of standardized or approval-oriented test cases tailored specifically to automated vehicles are available, it can be stated that several ADAS functions exhibit significant technological and testing-related overlap with automated driving systems. Accordingly, in my work I primarily used industry-accepted ADAS test cases as the starting point. It is important to emphasize that generating new scenarios was explicitly not an objective of the methodology, as their parameterization would be highly time- and resource-intensive, while the number of test cases would increase substantially, rendering the process costly and difficult to manage.

The steps of the methodology I developed are illustrated in **Figure 2**. As a first step, I created a database of more than 1000 test case variations extracted from the aforementioned regulations, protocols, and standards, which I then processed according to the key aspects relevant for testing. Based on the knowledge gained in this process, as well as my prior industrial experience [P8], I defined a preliminary set of input parameters that enable the selection of the most suitable test cases for a given vehicle in the examinations mentioned above. These parameters can be determined through a questionnaire I also developed, which is to be completed in advance by the potential customer or manufacturer. Based on the similarity parameters thus defined, I constructed 22-dimensional vectors from both the questionnaire responses and from each row of the test case variations.

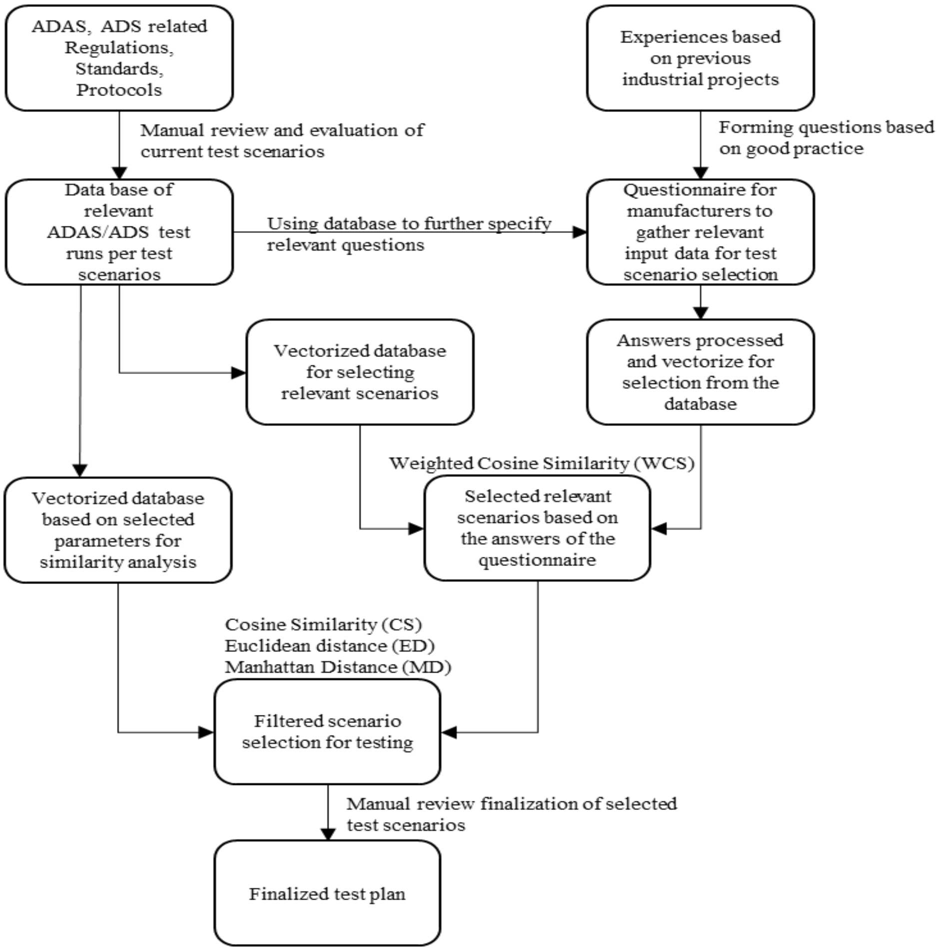

Figure 2: Process of the developed methodology

To select the most suitable variations for a given vehicle, I compared the questionnaire vector with each row of the database using Weighted Cosine Similarity (WCS) [34]. Subsequently, to further narrow down the set of selected test cases, I developed a method based on Manhattan and Euclidean distances, which supports the elimination of potentially redundant variations [35]. I validated the procedure using the properties of existing vehicles and insights from previous projects.

In my view, the resulting methodology is particularly applicable for pre-market safety checks of road vehicles—whether for operational or testing purposes—for which neither authorities nor technical services currently have harmonized and efficient solutions. Since such testing plans are often prepared in an ad hoc manner, relying on engineering intuition and experience, another objective of mine was to establish a more systematic and scientifically grounded selection process. It was along this motivation that I developed the methodology related to this thesis.

2.2. Thesis II.

I developed a methodology that enables the selection and combination of test scenario variations to create complex test scenarios. By applying these scenarios, it can be determined whether a vehicle equipped with advanced driver assistance systems will comply with the homologation requirements set by the relevant ADAS regulations or meet the challenges of other vehicle assessment protocols. In this way, well-founded decisions can be made before initiating time-consuming and costly test series.

In relation to this thesis, I present a procedure I developed for creating so-called complex test scenarios, which largely builds upon the methodology and test case variation database introduced in Thesis I [P9]. The aim of the research was to design a testing procedure that accelerates the functional validation examinations preceding vehicle type approval, while still providing a reliable and comprehensive understanding of how the vehicle will perform in type approval tests.

During the process, I reviewed the database of more than 1000 test case variations and analyzed them according to additional criteria. First, I examined whether a given test case variation primarily challenged the vehicle's sensor layer or its actuator layer. I then determined the level of challenge posed to the sensors or actuators by each variation, as well as the practical complexity of executing the test case. The evaluation system was developed based on objective criteria, supported by measurement results and testing experience from my previous projects, and applied on a 1–4 scale.

For filtering the appropriate test case variations, I first selected those associated with the GSR requirements. Consequently, non-relevant requirements from EuroNCAP protocols or other standards were excluded. From the remaining test case variations, I initially selected those that could serve as the basis for the so-called "minimum complex test scenario," consisting of the simplest cases. These included test case variations rated with a value of 1 in terms of sensing or actuation, combined with a complexity rating of 1. Among these, several highly similar cases were expected; therefore, I applied Euclidean Distance (ED) to eliminate redundancies. I applied the same method to identify the elements of the so-called "maximum complex test scenario," which contains the most complex cases. In this case, however, I aimed to select the highest values for each filtering criterion (sensing, actuation, and scenario complexity). For sensing, I allowed level 3 values in addition to level 4, and for complexity I also considered level 2, since the most complex cases in these aspects are mainly found in the EuroNCAP protocols.

Following the selection process, the chosen test case variations were organized into a logical execution sequence to form the complex test scenarios. Based on my industrial experience, several aspects were taken into account, including the choice of appropriate track elements and measurement techniques, as well as sequencing similar scenarios into series while preserving the cyclic nature of the testing process.

The developed minimum and maximum test scenarios were then compared with the conventional type approval procedure, and time and cost analyses were carried out to demonstrate their advantages. The proposed test scenarios have already been partially validated in real-world projects.

2.3. Thesis III.

Building on the Scenario-in-the-Loop architecture, and using a co-simulation environment created by me, I developed a methodology that offers a novel approach to improving the efficiency of certain vehicle type approval examinations, by mitigating the current limitations associated with virtual homologation.

Despite being among the most advanced methods currently applied in the automotive industry, existing approaches still have numerous limitations, particularly in whole-vehicle testing, proving ground applications, and in their applicability within type approval processes [36]. To bridge some of these limitations, the Scenario-in-the-Loop (SciL) framework was introduced, representing a novel, proving-ground-based testing approach supported by simulation [P1][37]. Through the real-time link between physical and virtual test environments, the framework is capable of blurring the boundary between the physical and the digital domain [P2][P3][P5][P7]. At the same time, a deeper understanding and further development of the framework requires the use of input data from real environments, or their generation through simulation tools in the absence of such data.

The objective of my work related to this thesis was to integrate the SciL concept into the Simcenter Prescan© simulation environment and to establish a co-simulation framework through the combined application of IPG CarMaker® and Simcenter Prescan©. During the development process, I identified three major shortcomings for which my methodology provides solutions:

- Although numerous simulation tools are available for vehicle testing, each has different advantages. Co-simulation makes it possible to combine these strengths; however, interconnecting simulation tools and operating them in real time is always a significant challenge. The solution I developed for coupling the two examined software platforms may also be useful for other researchers pursuing similar applications.
- Traditionally, simulation is applied before real-world testing. In contrast, I used data derived from physical measurements to construct the simulation framework. This ensures compatibility between simulation and real testing, while making the simulation environment more flexible and easier to connect with real test equipment in later phases.
- Although the application of simulations in type approval is still limited, the simulation framework I developed based on the SciL architecture enables certain steps of the testing procedures to be made more efficient, thereby achieving significant cost reductions in proving ground experiments.

In connection with my work, I present the potential applications of simulation in vehicle testing, followed by the fundamental principles of the SciL framework, and then a detailed description of its integration into Simcenter Prescan©, which has thus become one of the central components of SciL. A key element of my methodology is that the first two steps in building the simulation model environment are the acquisition of real test data and their integration into the simulation software. Subsequently, I present a control algorithm designed for testing purposes, developed in accordance with the EuroNCAP AEB protocol [38]. As part of this, I created a dedicated co-simulation environment by coupling IPG CarMaker® and Simcenter Prescan© via MATLAB Simulink® [39]. In this setup, Prescan© served as the platform for running the control algorithm, while CarMaker® provided the simulated motion signals of the tested vehicle [P6].

The proposed methodology thus provides a reproducible development environment for the evaluation of advanced and highly automated driving functions, significantly reducing the time and cost associated with real proving ground testing. These advantages can also be exploited in type approval procedures, for which I present a case study in this research.

2.4. Summary and future development opportunities

Due to the close link with my everyday professional work, the research and theses presented in my dissertation have been strongly focused on facilitating the type approval processes of vehicles. In developing the proposed methodologies and procedures, a key aspect was ensuring their seamless integration into my industrial work at TÜV Rheinland, which was also an important requirement of the 2021 scholarship program. For the problems I identified, I aimed to provide practice-oriented solutions grounded in scientific foundations. These problems and my responses to them can be briefly summarized as follows:

- Creation of test case collections based on industry-accepted test cases to facilitate the pre-testing and market entry of automated vehicles, for which harmonized procedures are still lacking.
- Development of specific testing procedures for functional validation prior to approval and other assessment examinations, with the objective of creating more efficient yet reliable processes that can lead to significant time and cost reductions.
- Application of simulation-based methods (in particular SciL) in type approval processes, in a way that mitigates the limitations of virtual methods and also achieves testing time and cost reductions.

The methods presented in the dissertation—structured questionnaire-based scenario selection and complex scenario generation based on the test case variation database, as well as the SciL-based co-simulation framework—enable testing processes to be executed in a more targeted and cost-efficient manner. The test case selection algorithm (combining WCS, Manhattan, and Euclidean metrics) makes it possible to select scenarios most closely aligned with the functional capabilities of the vehicle, thereby providing relevant feedback to manufacturers already during the development phase.

Structured scenario selection and the construction of complex test scenarios make it possible for vehicles to undergo tests during the development phase that anticipate type approval outcomes. This allows manufacturers to identify critical functions in time and improve compliance through targeted development.

The practical application of the SciL methodology—demonstrated particularly in the testing of the BSIS function—showed that, by integrating real trajectory data into the simulation environment, critical activation points can be defined in advance, reducing testing time and cost by up to 40%. This is particularly important in cases where type approval tests require narrow tolerances and complex synchronization of target objects. Thus, the proposed methods are not only theoretical frameworks but also practical tools applicable in industrial validation and approval processes.

The methodologies described in the dissertation also open up several future research opportunities, such as:

- Expanding the test case variation database by integrating new standards, forthcoming UNECE/EU regulations, and EuroNCAP protocols (with annual updates if possible). This would further refine the methodology to enable even more comprehensive and accurate scenario selection.
- Extending the database with rare and extreme cases or conditions (e.g., adverse weather, poor visibility). These so-called “long-tail” scenarios are critical for robust safety evaluation. Their inclusion, along with performance and incident data collected during real-world operation, would further improve coverage and relevance.
- Applying artificial intelligence to the test case variation database to uncover additional correlations and increase the efficiency of the developed methods, for example by enabling adaptive scenario selection tailored more closely to the tested vehicle.
- Adapting the methodology to the significantly expanding EuroNCAP functions and scenarios (expected already from 2026), thus enabling preliminary validation of new protocols in a more time- and cost-efficient manner.
- Further developing the co-simulation framework and integrating it into type approval processes—particularly for functions such as ISA, AEB, or complex test scenarios—thus supporting the digitalization and improved automation of testing while accelerating and reducing the cost of such procedures.

Overall, I believe that the methods presented in this dissertation not only support current testing and approval practices but also provide a foundation for future developments. The results of this research may contribute to making automated vehicles safer, more reliable, and more rapidly approvable, while reducing testing costs and time requirements. I am confident that the methods and procedures I have developed will also prove useful to others and facilitate vehicle type approval processes. I am integrating these methods into my daily work and intend to apply them actively in future projects. The experience gained in this way will hopefully further confirm their validity, while the resulting data will be used for their further refinement, the identification and correction of potential shortcomings, and the development of new procedures.

Publication of the author

[P1] 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 in Zeiten der Veränderung : Technische und betriebswirtschaftliche Aspekte*, H. Proff, Ed., Wiesbaden: Springer Fachmedien, 2019, pp. 199–210. doi: 10.1007/978-3-658-26107-8_15

[P2] Z. Szalay, M. Szalai, B. Toth, T. Tettamanti, and V. Tihanyi, “Proof of concept for Scenario-in-the-Loop (SciL) testing for autonomous vehicle technology,” in *2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Nov. 2019, pp. 1–5. doi: 10.1109/ICCVE45908.2019.8965086.

[P3] K. Gangel, Z. Hamar, A. Háry, A. Horváth, G. Jandó, B. Könyves, D. Panker, K. Pintér, M. Pataki, M. Szalai, Z. Szalay, T. Tettamanti, V. Tihanyi,B. Toth, B. Varga, Z. J. Viharos,. “Modelling the ZalaZONE Proving Ground: a benchmark of State-of-the-art Automotive Simulators PreScan, IPG CarMaker, and VTD Vires,” *Acta Technica Jaurinensis*, vol. 14, no. 4, Art. no. 4, Nov. 2021, doi: 10.14513/actatechjaur.00606

[P4] B. Toth, J. Toth, A. Lakatos, and K. Turoń, “Innovative complex-system-based cooperation between demand responsive transport services, shared mobility and autonomous bus services,” in *2022 IEEE 1st International Conference on Cognitive Mobility (CogMob)*, Oct. 2022, pp. 000127–000134. doi: 10.1109/CogMob55547.2022.10118307

[P5] B. Toth and Z. Szalay, “The role of the virtual environment fidelity in proving ground related vehicle simulations,” presented at the 38th International Colloquium on Advanced Manufacturing and Repairing Technologies in Vehicle Industry, Visegrád, Hungary, May 24-26, 2023.

[P6] B. Toth and Z. Szalay, “Development and Functional Validation Method of the Scenario-in-the-Loop Simulation Control Model Using Co-Simulation Techniques,” *Machines*, vol. 11, no. 11, Art. no. 11, Nov. 2023, doi: 10.3390/machines11111028.

[P7] Tóth B. and Szalay Z., “Virtuális módszerekkel támogatott kontrolált tesztkörnyezet kialakítása tesztpályán fejlett vezetési funkciók vizsgálatára,” *Biztonságtudományi Szemle*, vol. 6, no. 1., pp. 87–99, Mar. 2024. Available online: https://biztonsagtudomanyi.szemle.uni-obuda.hu/index.php/home/article/view/436

[P8] J. Reckenzaun, R. Rott, O. Nikolic, P. Innerwinkler, M. Kirchengast, D. J. Ritter, S. Solmaz, S. Ladstatter, P. Luley, B. Toth, A. M. Hee, L. Hörmann, A. Pötsch, M. Rothacher, A. Rövid, Z. Vincze, M. Csontho,. “Transnational Testing, Operation and Certification of Automated Driving Systems – Building bricks for the NATM multi-pillar framework,” in *2024 IEEE International Automated Vehicle Validation Conference (IAVVC)*, Oct. 2024, pp. 1–7. doi: 10.1109/IAVVC63304.2024.10786414.

[P9] B. Toth and Z. Szalay, “Minimum Critical Test Scenario Set Selection for Autonomous Vehicles Prior to First Deployment and Public Road Testing,” *Applied Sciences*, vol. 15, no. 13, Art. no. 13, Jun. 2025, doi: 10.3390/app15137031.

References

[1] KBA: Autonome-Fahrzeuge-Genehmigungs-Und Betriebs-Verordnung (AFGBV). 2022. Elérhető online: https://www.gesetze-im-internet.de/afgbv/ (accessed: 2025.07.14)

[2] 5/1990. (IV. 12.) KöHÉM rendelet a közúti járművek műszaki megvizsgálásáról. Available online: https://net.jogtar.hu/jogszabaly?docid=99000005.koh (accessed: 2025.07.14)

[3] 6/1990. (IV. 12.) KöHÉM rendelet a közúti járművek forgalomba helyezésének és forgalomban tartásának műszaki feltételeiről. Available online: https://net.jogtar.hu/jogszabaly?docid=99000006.koh (accessed: 2025.07.14.)

[4] SAE J3016 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles v_202104, Április 2024. Available online: https://www.sae.org/standards/content/j3016_202104/ (accessed: 2025.07.02)

[5] AZ EURÓPAI PARLAMENT ÉS A TANÁCS (EU) 2019/2144 RENDELETE, November 2019. available online: https://eur-lex.europa.eu/legal-content/HU/TXT/HTML/?uri=CELEX:32019R2144 (accessed: 2025.07.03).

[6] C. Nowakowski, S. E. Shladover, and C.-Y. Chan, "Determining the Readiness of Automated Driving Systems for Public Operation: Development of Behavioral Competency Requirements," *Transportation Research Record*, vol. 2559, no. 1, pp. 65–72, Jan. 2016, doi: 10.3141/2559-08.

[7] W. Wang *et al.*, "An Evaluation Method for Automated Vehicles Combining Subjective and Objective Factors," *Machines*, vol. 11, no. 6, Art. no. 6, Jun. 2023, doi: 10.3390/machines11060597.

[8] D. Zhao, X. Huang, H. Peng, H. Lam, and D. J. LeBlanc, "Accelerated Evaluation of Automated Vehicles in Car-Following Maneuvers," *IEEE Trans. Intell. Transport. Syst.*, vol. 19, no. 3, pp. 733–744, Mar. 2018, doi: 10.1109/TITS.2017.2701846.

[9] D. Zhao *et al.*, "Accelerated Evaluation of Automated Vehicles Safety in Lane-Change Scenarios Based on Importance Sampling Techniques," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 3, pp. 595–607, Mar. 2017, doi: 10.1109/TITS.2016.2582208.

[10] L. Chen *et al.*, "Milestones in Autonomous Driving and Intelligent Vehicles: Survey of Surveys," *IEEE Trans. Intell. Veh.*, vol. 8, no. 2, pp. 1046–1056, Feb. 2023, doi: 10.1109/TIV.2022.3223131.

[11] M. D. Vaio, P. Falcone, R. Hult, A. Petrillo, A. Salvi, and S. Santini, "Design and Experimental Validation of a Distributed Interaction Protocol for Connected Autonomous Vehicles at a Road Intersection," *IEEE Trans. Veh. Technol.*, vol. 68, no. 10, pp. 9451–9465, Oct. 2019, doi: 10.1109/TVT.2019.2933690.

[12] P. Koopman and M. Wagner, "Challenges in Autonomous Vehicle Testing and Validation," *SAE Int. J. Trans. Safety*, vol. 4, no. 1, pp. 15–24, Apr. 2016, doi: 10.4271/2016-01-0128.

[13] S. Vass *et al.*, "Are Low-Speed Automated Vehicles Ready for Deployment? Implications on Safety and Urban Traffic," Mar. 15, 2024, Preprint, *Social Science Research Network, Rochester, NY*: 4760713. doi: 10.2139/ssrn.4760713.

[14] A. Alessandrini, R. Alfonsi, P. D. Site, and D. Stam, "Users' Preferences towards Automated Road Public Transport: Results from European Surveys," *Transportation Research Procedia*, vol. 3, pp. 139–144, Jan. 2014, doi: 10.1016/j.trpro.2014.10.099.

[15] Z. Cao and A. (Avi) Ceder, “Autonomous shuttle bus service timetabling and vehicle scheduling using skip-stop tactic,” *Transportation Research Part C: Emerging Technologies*, vol. 102, pp. 370–395, May 2019, doi: 10.1016/j.trc.2019.03.018.

[16] K. Mouratidis and V. Cobeña Serrano, “Autonomous buses: Intentions to use, passenger experiences, and suggestions for improvement,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 76, pp. 321–335, Jan. 2021, doi: 10.1016/j.trf.2020.12.007.

[17] UNECE: New Assessment/Test Method for Automated Driving (NATM) Guidelines for Validating Automated Driving System (ADS). 2022. Available online: https://unece.org/sites/default/files/2022-04/ECE-TRANS-WP.29-2022-58.pdf (accessed on 25 March 2025).

[18] PEGASUS Projekt: Scenario Description. 2019. Available online: https://www.pegasusprojekt.de/files/tmpl/PDF-Symposium/04_Scenario-Description.pdf (accessed: 2025.03.25.)

[19] Commission Implementing Regulation (EU) 2022/1426 of 5 August 2022 Laying down Rules for the Application of Regulation (EU) 2019/2144 of the European Parliament and of the Council as Regards Uniform Procedures and Technical Specifications for the Type approval of the Automated Driving System (ADS) of Fully Automated Vehicles (Text with EEA Relevance). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R1426 (accessed on 25 March 2025).

[20] S. Feng, Y. Feng, H. Sun, Y. Zhang, and H. X. Liu, “Testing Scenario Library Generation for Connected and Automated Vehicles: An Adaptive Framework,” *IEEE Trans. Intell. Transport. Syst.*, vol. 23, no. 2, pp. 1213–1222, Feb. 2022, doi: 10.1109/TITS.2020.3023668.

[21] S. Feng, Y. Feng, C. Yu, Y. Zhang, and H. X. Liu, “Testing Scenario Library Generation for Connected and Automated Vehicles, Part I: Methodology,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 3, pp. 1573–1582, Mar. 2021, doi: 10.1109/TITS.2020.2972211.

[22] S. Feng, Y. Feng, H. Sun, S. Bao, Y. Zhang, and H. X. Liu, “Testing Scenario Library Generation for Connected and Automated Vehicles, Part II: Case Studies,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 9, pp. 5635–5647, Sep. 2021, doi: 10.1109/TITS.2020.2988309.

[23] Z. Wang, J. Ma, and E. M.-K. Lai, “A Survey of Scenario Generation for Automated Vehicle Testing and Validation,” *Future Internet*, vol. 16, no. 12, Art. no. 12, Dec. 2024, doi: 10.3390/fi16120480.

[24] S. Li, W. Li, P. Li, P. Ma, and M. Yang, “Novel Test Scenario Generation Technology for Performance Evaluation of Automated Vehicle,” *Int.J Automot. Technol.*, vol. 23, no. 5, pp. 1295–1312, Oct. 2022, doi: 10.1007/s12239-022-0113-z.

[25] T.-H. Nguyen *et al.*, “Generating Critical Scenarios for Testing Automated Driving Systems,” Dec. 03, 2024, *arXiv*: arXiv:2412.02574. doi: 10.48550/arXiv.2412.02574.

[26] X. Wu *et al.*, “LAMBDA: Covering the Multimodal Critical Scenarios for Automated Driving Systems by Search Space Quantization,” Nov. 30, 2024, *arXiv*: arXiv:2412.00517. doi: 10.48550/arXiv.2412.00517.

[27] Z. Zhong, Y. Tang, Y. Zhou, V. de O. Neves, Y. Liu, and B. Ray, “A Survey on Scenario-Based Testing for Automated Driving Systems in High-Fidelity Simulation,” Dec. 02, 2021, *arXiv*: arXiv:2112.00964. doi: 10.48550/arXiv.2112.00964.

[28] A. Shakeri, "Formalization of Operational Domain and Operational Design Domain for Automated Vehicles," in *2024 IEEE 24th International Conference on Software Quality, Reliability, and Security Companion (QRS-C)*, Jul. 2024, pp. 990–997. doi: 10.1109/QRS-C63300.2024.00131.

[29] P. Koopman and F. Fratrik, "How Many Operational Design Domains, Objects, and Events?," presented at the SafeAI@AAAI, 2019. Available online: https://www.semanticscholar.org/paper/How-Many-Operational-Design-Domains%2C-Objects%2C-and-Koopman-Fratrik/a6ef2061fa37d48c28685c9ca009b2fe66c27781 (accessed: 2025.02.15.)

[30] F. Eichenseer, S. Sarkar, and A. Shakeri, "A Systematic Methodology for Specifying the Operational Design Domain of Automated Vehicles," in *2024 IEEE 35th International Symposium on Software Reliability Engineering Workshops (ISSREW)*, Oct. 2024, pp. 13–18. doi: 10.1109/ISSREW63542.2024.00040.

[31] P. Weissensteiner, G. Stettinger, J. Rumetshofer, and D. Watzenig, "Virtual Validation of an Automated Lane-Keeping System with an Extended Operational Design Domain," *Electronics*, vol. 11, no. 1, Art. no. 1, Jan. 2022, doi: 10.3390/electronics11010072.

[32] A. Coppola, L. D. Costanzo, L. Pariota, S. Santini, and G. N. Bifulco, "An Integrated Simulation Environment to test the effectiveness of GLOSA services under different working conditions," *Transportation Research Part C: Emerging Technologies*, vol. 134, p. 103455, Jan. 2022, doi: 10.1016/j.trc.2021.103455.

[33] H. Altamimi, I. Varga, and T. Tettamanti, "Urban Platooning Combined with Dynamic Traffic Lights," *Machines*, vol. 11, no. 9, Art. no. 9, Sep. 2023, doi: 10.3390/machines11090920.

[34] D. Wang, H. Lu, and C. Bo, "Visual Tracking via Weighted Local Cosine Similarity," *IEEE Transactions on Cybernetics*, vol. 45, no. 9, pp. 1838–1850, Sep. 2015, doi: 10.1109/TCYB.2014.2360924.

[35] S. Boyd and L. Vandenberghe, "Introduction to Applied Linear Algebra: Vectors, Matrices, and Least Squares," Higher Education from Cambridge University Press.. Available online: https://www.cambridge.org/highereducation/books/introduction-to-applied-linear-algebra/4D69AF22E38303FE20FFEEFDCE0E7F96 (Accessed: 2025.05.05)

[36] R. Donà and B. Ciuffo, "Virtual Testing of Automated Driving Systems. A Survey on Validation Methods," *IEEE Access*, vol. 10, pp. 24349–24367, 2022, doi: 10.1109/ACCESS.2022.3153722.

[37] Z. Szalay, "Next Generation X-in-the-Loop Validation Methodology for Automated Vehicle Systems," *IEEE Access*, vol. 9, pp. 35616–35632, 2021, doi: 10.1109/ACCESS.2021.3061732.

[38] EuroNCAP TEST PROTOCOL–AEB/LSS VRU Systems, Version 4.4. 2023. Available online: https://cdn.euroncap.com/media/77299/euro-ncap-aeb-lss-vru-test-protocol-v44.pdf (accessed: 2025.07.10.)

[39] MATLAB Help Center: ZalaZONE Automotive Proving Ground Smart City. Available online: https://ch.mathworks.com/help/driving/ref/zalazoneautomotiveproving-groundsmartcity.html?searchHighlight=ZalaZONE&s_tid=srchtitle_support_results_2_ZalaZONE (accessed 2025.07.07).