Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 14.6
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.14.6

ScaTERS Laboratory: A Structured Approach to a Scaled Environment for Railway Automation

R. Kling, T. Hofmeier and M. Cichon

Institute of Vehicle System Technology, Karlsruhe Institute of Technology, Germany

Abstract

On-sight Automatic Train Operation requires development environments that support perception-based low-speed operation, realistic sensor interaction, and repeatable scenario execution before full-scale field testing becomes feasible. Previous work proposed a scaled laboratory concept for the development and testing of on-sight ATO functions. This paper extends that work by presenting the methodical derivation and initial realization of ScaTERS, a Scaled Test Environment for Railway Systems.
The contribution is a structured design process that links representative on-sight ATO use cases to functional laboratory requirements, selected solution principles, and a finalized physical track layout. The method considers automated shunting, depot movements, infrastructure-supported perception, hybrid physical–virtual testing, and mixed railway/tram-style operating conditions. Based on this process, the resulting ScaTERS layout is organized into dedicated zones for shunting, depot and siding operation, station-related maneuvers, and digital-twin-supported scenario augmentation.
In contrast to the previous conceptual proposal, this paper reports the updated layout resulting from the detailed design process and documents the first construction stage of the laboratory. ScaTERS is positioned as an intermediate research platform between purely virtual simulation and full-scale field testing, enabling early experimentation with real sensors, scaled infrastructure, and synchronized virtual representations.

Keywords: automatic train operation, on-sight ATO, scaled development and testing, digital twin, physical–virtual coupling, infrastructure-supported perception

1 Introduction

Railway automation is increasingly expected to contribute to more efficient, predictable, and resource-efficient transport systems. While high grades of automation have already been demonstrated in protected or strongly supervised railway environments, perception-based low-speed operation remains substantially more challenging. This is particularly true for on-sight Automatic Train Operation (ATO), where the vehicle cannot rely solely on infrastructure-based protection but must continuously perceive its environment, localize itself within the track plan, and adapt its motion according to the observable range ahead. Such operating conditions are characteristic for shunting yards, depots, industrial sidings, degraded mainline operation, and tram-like environments with mixed traffic or shared spaces. [1], [2], [3]

In contrast to mainline ATO under signalling supervision [4], [5], on-sight ATO requires the automated system to take over tasks that are traditionally performed by the human driver. These include obstacle detection, interpretation of track geometry and switch states, monitoring of the clearance gauge, estimation of safe stopping distances, and the execution of cautious low-speed manoeuvres under uncertain environmental conditions [6]. The corresponding perception and localization functions are safety-relevant and must therefore be evaluated within a structured test process. Scenario-based assessment approaches provide a suitable methodological basis, because they allow operational situations, infrastructure states, environmental conditions, and sensor-related effects to be described systematically rather than through isolated test runs [7]. For the railway domain, Greiner-Fuchs et al. propose a database-supported methodical approach for ATO evaluation, linking operational knowledge, scenario descriptions, simulation environments, and test results across different test levels [8].

However, the practical implementation of such structured evaluation processes remains challenging for on-sight ATO. Full-scale field testing offers high operational representativeness, but it is constrained by the availability of suitable vehicles, track infrastructure, operating personnel, safety supervision, and test windows. These constraints limit the frequency, repeatability, and systematic variation of perception-critical scenarios, especially during early development stages.

Purely virtual simulation, in contrast, enables broad scenario variation and early closed-loop testing. Existing railway simulation environments support the generation and execution of structured scenarios, but perception-oriented ATO development also requires real sensor setups to capture measurement characteristics, calibration effort, occlusions, latency effects, and interactions with physical scene elements [9], [10]. Simulation and full-scale testing therefore address complementary parts of the evaluation problem, leaving room for intermediate test environments that combine repeatability with real sensor interaction.

Scaled physical test environments therefore provide such an intermediate development layer between purely virtual simulation and full-scale field testing. They allow real sensors, embedded computing platforms, control algorithms, and infrastructure components to be integrated in a controlled laboratory environment. At the same time, they make it possible to repeat selected scenarios, vary environmental and operational conditions, and investigate perception-based functions with substantially lower effort and risk than in full-scale operation. [11]

Building on previous work [12], this paper presents the methodical derivation and initial realisation of a Scaled Test Environment for Railway Systems (ScaTERS). The contribution is not another model railway layout, but a traceable design approach that links on-sight ATO use cases, laboratory capabilities, selected solution principles, and spatial implementation decisions. Compared with the previous conceptual proposal, the present work focuses on the transition from general design guidelines to a concrete laboratory concept and its first implementation stage. The resulting ScaTERS concept covers automated shunting, depot and siding operation, station-related manoeuvres, infrastructure-supported perception, hybrid physical–virtual testing, and selected tram-style operating conditions.

2 Background and Research Gap

Research and development in railway automation have progressed substantially in recent years. Automated train operation is already established in several protected metro systems and has also been demonstrated in mainline contexts under signalling supervision. These applications show that high automation levels are feasible when the operational domain is sufficiently controlled and when movement authority, train separation, and route protection are provided by the infrastructure [13], [14], [15]. However, the development problem changes substantially when the operational focus shifts from protected or signalling-supervised automation to on-sight operation. In ETCS-based or otherwise supervised ATO applications, train movement is embedded in an infrastructure-based safety and control framework in which movement authority, train separation, and route protection are provided by signalling and control systems. For on-sight ATO, these mechanisms do not eliminate the need for the vehicle to assess its immediate environment. Instead, the automated system must continuously evaluate whether the intended low-speed movement remains safe within the currently observable or otherwise monitored range.

This shift changes the requirements for development and testing environments. The system under test is no longer limited to train control under predefined movement authority, but includes perception and interpretation tasks that are directly linked to the local scene. Relevant functions include obstacle and clearance-gauge monitoring, track-relative localization, switch and track-geometry interpretation, detection of operational boundaries, and cautious motion control in confined or partially observable areas. Consequently, a suitable test environment for on-sight ATO must not only reproduce railway operation at the level of routes, signals, and train movements, but also provide controllable physical situations for perception, localization, clearance monitoring, and low-speed decision-making. This includes track sections with switches and stopping points, defined obstacle positions, sensor-observable infrastructure elements, and areas in which infrastructure-supported perception can be investigated.

After this distinction, existing railway test and validation environments can be assessed more precisely. A substantial part of established work addresses infrastructure-side safety logic, route setting, interlocking behaviour, timetable operation, and operational control. Formal and model-based methods have been used to validate interlocking systems and to derive safety requirements from interlocking tables. [16], [17]

Complementary to these analytical approaches, model-railway-based laboratories and demonstrators can reproduce signalling, switch control, dispatcher workstations, PLC-based control, and track-circuit-based operation with high fidelity. [18]

This line of work is highly relevant for safe railway operation, but it addresses a different part of the automation problem than perception-based on-sight ATO. It provides strong support for studying infrastructure logic, operational procedures, and traffic management, but it does not by itself provide a development environment for onboard perception, sensor fusion, track-relative localization, or low-speed vehicle-side decision-making. Railway research on onboard localization, navigation, and visual perception shows that these functions form dedicated development problems with their own data, sensor, and validation requirements. [19], [20]

Scaled ATO platforms address this gap by providing an intermediate experimental layer between virtual simulation and full-scale field testing. Their value lies in combining repeatable laboratory conditions with real sensor, hardware, and infrastructure interaction. In contrast to purely virtual environments, scaled platforms allow cameras, distance sensors, LiDAR units, odometry, onboard computing, communication interfaces, switches, obstacles, and infrastructure sensors to interact with physical scene elements. In contrast to full-scale tests, they allow perception-critical situations to be reproduced and varied with substantially lower operational effort, including different obstacle positions, switch configurations, stopping points, lighting conditions, and infrastructure-supported perception zones. Scaled models are therefore particularly useful for early-stage integration, functional comparison, regression testing, and the systematic investigation of failure modes before selected functions are transferred to larger-scale or real-world experiments. [11]

In contrast to operation-oriented model railway laboratories such as [21], [22] larger-scale ATO-oriented model railways provide sufficient installation space for embedded computing, power supply, communication interfaces, and sensor suites. Previous scaled ATO research has demonstrated the feasibility of this approach by combining onboard sensors and processing, compact distance or LiDAR sensors, odometry, inertial sensing, wireless communication, and infrastructure-supported perception. Digital twins of scaled environments further allow physical tests to be synchronized with virtual representations, making it possible to compare real, simulated, and hybrid sensor streams [11], [23], [24] and [25]. Together, these works show that scaled environments can support real sensor interaction, repeatable scenario execution, and early integration of vehicle- and infrastructure-side automation functions.

Building on these results, the previous scaled-lab proposal [12] consolidated the main boundary conditions for designing such an environment, including scale selection, required installation space, sensor integration, infrastructure interaction, and the role of a digital twin. However, these boundary conditions still have to be translated into a concrete laboratory design. This translation is non-trivial, because operational objectives such as shunting, depot operation, infrastructure-supported perception, and hybrid testing impose different and partly competing requirements on track geometry, functional zoning, sensor placement, supervision interfaces, and virtual representation.

This paper addresses this design step. It derives the ScaTERS laboratory layout from representative on-sight ATO use cases, maps them to required laboratory functions and selected solution principles, and finally translates them into a physical track plan with defined operational zones. The contribution therefore lies not in proposing scaled testing in general, but in moving from general scaled-lab requirements toward a traceable and practically realizable laboratory geometry and system concept.

3 Methodological Approach

The design of ScaTERS follows a use-case-driven engineering process that translates representative on-sight ATO situations into a physical and digital laboratory structure. The approach is based on established product-development methods, where objectives are defined, requirements and functions are derived, solution principles are selected, and a final concept is synthesized under practical constraints [26]. In ScaTERS, this logic is applied to a scaled railway automation laboratory. The result is not a single component, but a coordinated test environment including track geometry, vehicle platforms, infrastructure elements, supervision interfaces, and a synchronized digital twin that supports extended reality methods.

The derivation follows five steps, shown in Figure 1. First, the operational scope is defined using relevant on-sight ATO scenarios. Second, these scenarios are translated into laboratory design requirements. Third, required laboratory functions are derived. Fourth, solution principles are selected for vehicle, infrastructure, scenario, supervision, and digital-twin layers. Fifth, these principles are implemented in the spatial design of the ScaTERS laboratory.

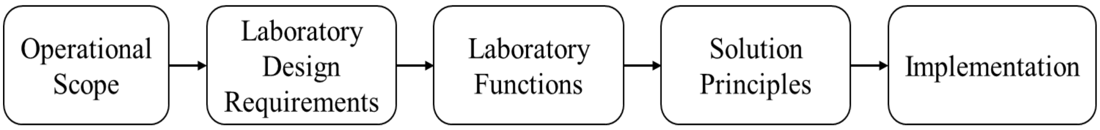

Figure 1: ScaTERS design process

The first step, operational scope definition, restricts the design space to use cases relevant for perception-based low-speed railway operation that can be meaningfully investigated at model scale. Rather than addressing railway automation in general, the selected scope focuses on a compact set of operational situations with distinct experimental requirements. These include shunting movements, depot and siding operations, station-related stopping and transition manoeuvres, infrastructure-supported perception, hybrid physical–virtual testing, and selected mixed-environment scenarios.

In the second step, this operational scope is translated into laboratory design requirements. These requirements specify what the laboratory must provide physically, digitally, and procedurally to support the selected use cases. They include track geometry, defined approach and stopping situations, observable obstacle and clearance conditions, reconfigurable scene elements, infrastructure states, supervision interfaces, repeatable scenario execution, and consistent representation within a digital twin. This step connects operational needs with the structural design of the laboratory.

The third step derives the laboratory functions needed to satisfy these requirements. These are grouped by their role. Vehicle-side functions include perception, localization, low-speed control, safety monitoring, and communication. Infrastructure-side functions include switch and route state representation, zone monitoring, occupancy or clearance detection, and state exchange with vehicles. Scenario functions define obstacle positions, configurable elements, and repeatable test setups. Digital-twin functions include synchronization of vehicle, infrastructure, and scenario states, virtual sensor rendering, replay, and hybrid scenario augmentation. Supervision functions include experiment configuration, mission control, monitoring, logging, and intervention.

In the fourth step, solution principles are assigned to each function group. Vehicle-side functions are realized through modular scaled vehicles with onboard sensing, computing, and communication capabilities. Infrastructure-side functions are supported by actuated switches, defined route and zone states, and fixed sensing infrastructure. Scenario functions rely on configurable and reproducible objects with documented positions. Digital-twin functions require a synchronized virtual counterpart rather than a purely visual representation. Supervision functions require interfaces for setup, execution, monitoring, and data collection.

The fifth step translates these principles into the ScaTERS implementation. Track geometry, switches, stopping points, sensor coverage, scene elements, infrastructure interfaces, supervision access, and digital-twin reference points are integrated into a coherent physical and digital laboratory. The result is a traceable design chain that connects the operational motivation, derived laboratory functions, selected technical principles, and spatial implementation decisions, leading to the ScaTERS layout and system concept presented in the following section.

4 Resulting ScaTERS Laboratory Design

Applying the methodological process results in a set of laboratory design requirements, function groups, solution principles, and implementation decisions for ScaTERS. Due to the limited scope of this conference paper, the complete requirements-to-layout matrix is not reproduced in full. Instead, the following section illustrates the derivation using three representative design decisions that are decisive for the ScaTERS layout: the shunting-oriented track area, infrastructure-supported perception zones, and the digital-twin-compatible implementation of the physical laboratory.

The first design decision concerns the representation of on-sight low-speed operation beyond supervised line running. While railway automation on protected or signalling-supervised lines is already comparatively mature and increasingly entering operational deployment, automation in non-mainline on-sight domains remains less clearly defined. This includes shunting yards, depots, stabling and preparation areas, industrial sidings, and tram-like environments, where movements are often slow, local, perception-dependent, and only partially covered by infrastructure-based protection.

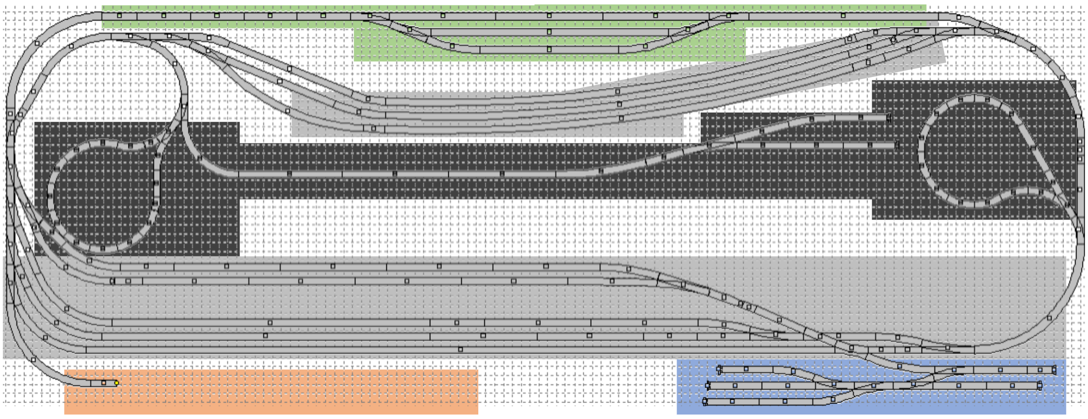

Figure 2: Track plan with functional zoning

Figure 2 shows the resulting functional zoning of the ScaTERS layout, divided into several on-sight operation areas instead of reproducing a generic model railway or a full marshalling yard, while respecting financial and spatial constraints. The shunting-oriented region, shown in light grey, is derived from a known track layout of a project-related marshalling yard. It provides a recognizable operational reference while reducing the geometry to the elements required for repeatable laboratory experiments. The area includes straight and curved tracks with realistic radii of approximately 480 m, as well as sections with a high density of switches. This reference to a real yard layout also supports later alignment between the physical scaled environment, the virtual representation, and potential real-world data.

To enable realistic marshalling operations, the layout includes a hump and direction tracks, marked in green. This section supports automated marshalling research by combining hump locomotive operation with infrastructure-based sensing and automated switch control for wagon sorting. The blue area represents a depot-style section used to investigate automated preparation and servicing procedures before operational deployment. The dark grey area represents tram-like infrastructure with tight radii and turning loops, enabling studies of mixed traffic interactions with road users. Finally, the orange area provides access to a flexible experimental zone, where additional scenarios can be implemented using modular track elements and a chamber for controlled lighting and fog experiments.

The second design decision concerns the integration of infrastructure-supported perception. In on-sight low-speed operation, the sensor perspective of the vehicle is not always sufficient to observe the complete operationally relevant area. This is particularly critical for pushed movements, depot and siding tracks, switch areas, clearance monitoring, and tram-like sections with road crossings or mixed traffic. In these situations, obstacles, persons, or other traffic participants may be outside the vehicle sensor field of view or temporarily occluded by wagons, infrastructure, road vehicles, or track geometry. For ScaTERS, this leads to the requirement that selected areas of the laboratory must be observable from fixed external perspectives in addition to onboard sensing.

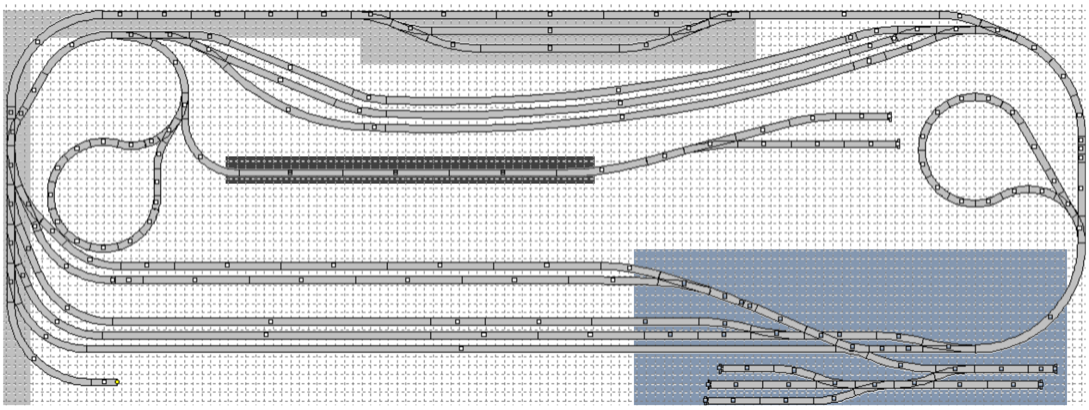

Figure 3: Infrastructure sensing concept

Figure 3 illustrates how infrastructure sensing is integrated into the track plan to handle the mentioned challenges. Three different areas are equipped with hardware to enable monitoring of the surrounding infrastructure. While specific functionalities were considered during the design process, the use of this hardware is not limited to these applications. The blue area represents a complex switching zone. External observation of the tracks can be used to validate whether the route of a locomotive has been set correctly. The light grey area represents the path used by a hump locomotive to push wagons over the hump. Additional trackside infrastructure must be applied here to determine whether sections of the route outside the locomotive's field of view are free of obstacles. Finally, the dark grey-marked area within the tram-style section can be used to investigate increased safety through redundant monitoring from both infrastructure-side and vehicle-side sensing in mixed-traffic scenarios.

The third design decision concerns the digital-twin-compatible implementation of the laboratory. ScaTERS is not intended to provide only a physical scaled track layout, but a physical environment that can be synchronized with a virtual representation and, where available, related to real-world reference data.

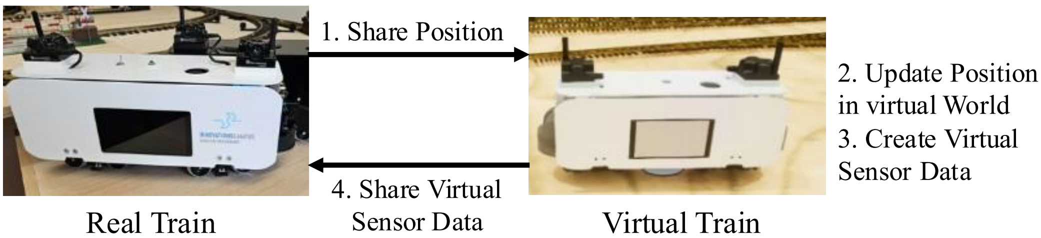

Figure 4: Concept for coupling the physical and virtual laboratory

Figure 4 illustrates the concept of coupling the virtual laboratory with the physical laboratory environment, adapted from [24]. In this approach, the real world defines the positioning of all physical objects and the track geometry, while the virtual environment mirrors and remains synchronized with it. During a test run, a corresponding virtual locomotive aligns with the real train position. Based on this synchronization, virtual data can be generated and exchanged with the physical system, augmenting real sensor information. This enables the execution of scenarios that are difficult to reproduce in the scaled physical setup, such as moving humans or animals. To support this, vehicle states, infrastructure states, and sensor data are continuously logged and exchanged through defined interfaces. As a result, the digital twin acts not only as a visualization layer but as an integral component of the experimental architecture.

Together, the three design decisions illustrate how the methodological process is applied without reproducing the full requirements-to-layout matrix in this paper. The resulting ScaTERS concept is shaped by three principles: a scaled but operationally recognizable railway layout, infrastructure-supported perception zones, and a physical structure synchronized with a virtual representation. The final laboratory is therefore not a generic model railway or a full replica of a railway site. Instead, it condenses operationally relevant elements into a controllable test environment where vehicle perception, infrastructure interaction, repeatable scenario execution, and physical–virtual synchronization can be investigated jointly.

5 Initial Realization and Discussion

The initial realization of ScaTERS marks the transition from the methodological laboratory design to a physically implemented research environment.

5.1 Overview

The ScaTERS laboratory is currently in a functional but partially completed state. The fixed track and switch infrastructure is fully installed and can already be operated remotely via ESP32-based relay modules, enabling automated and repeatable route configurations. Existing modular ATO vehicles from previous work are reused due to their onboard computing capabilities and expandable sensor interfaces, while infrastructure-side cameras and logging systems are still under development.

Figure 5 Initial Implementation

Figure 5 shows the initial implementation of the laboratory. The setup is based on a modular table substructure with screwed OSB boards, forming a walkable surface for vehicle recovery, maintenance, sensor installation, and temporary experiments.

Maintenance openings ensure accessibility throughout the layout. The fixed ScaTERS area covers about 72 m² and contains the installed track and switch system, while an additional 20 m² remain free for temporary scenarios, algorithm experiments, and flexible sensor or obstacle configurations. A separate chamber on the right side of the setup is used for controlled environmental experiments with configurable LED lighting and fog generation.

5.2 Technical Implementation of the Physical Laboratory

This section describes the current control implementation of the physical ScaTERS laboratory, including route configuration, switch actuation, vehicle-state visualization, and experiment supervision.

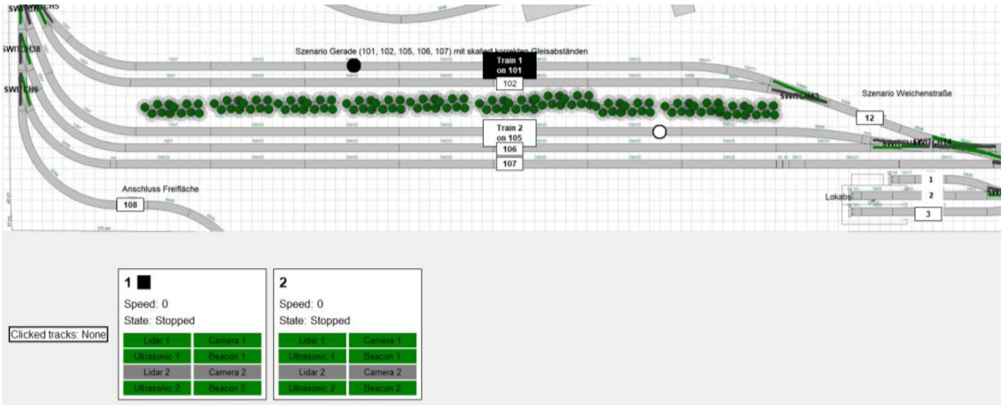

Figure 6 ScaTERS Control Center

Figure 6 shows a section of the ScaTERS Control Center, which is used to initialize and operate experiments on the system. All switches can be controlled manually or automatically. Their current states are visualized, with the active direction highlighted in green. Train positions are displayed as colored dots corresponding to each train, while the current operating and sensing status of every train is shown at the bottom of the interface. The figure also provides an initial illustration of the integration of real and virtual data, which is discussed in more detail later in this section.

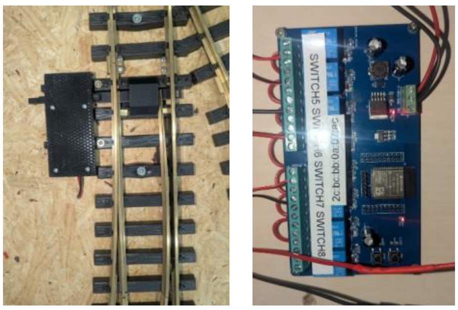

Figure 7 Technical Implementation of the Switch Control

Figure 7 illustrates the implementation of the switch control system. Each switch is connected to an analog actuator controlled by an ESP32 relay board. The relay board regulates the direction of current pulses through the switch mechanism, thereby determining its position. To achieve this, the ESP32 receives control signals from the Control Center.

5.3 Coupling of the Physical and Virtual Laboratory

This section describes the coupling between the physical laboratory and its virtual counterpart for synchronized sensor-data generation and augmentation.

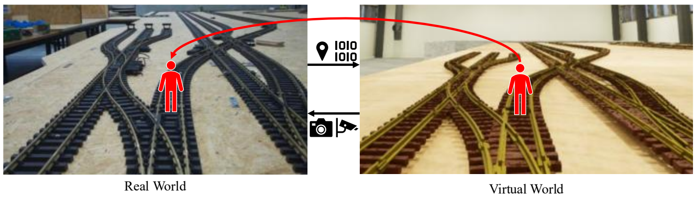

Figure 8: Implementation of physical–virtual laboratory coupling

Figure 8 illustrates the coupling of the physical and virtual laboratory environments. The image presents both the real train camera view and the corresponding virtual train camera perspective. The position of the virtual train is continuously synchronized with the real train, enabling virtual sensors to reproduce a comparable viewpoint. The resulting virtual sensor data can then be forwarded to the real train to augment its physical sensor inputs. This approach enables the testing of scenarios that would otherwise be difficult or impossible to represent within the constraints of the scaled laboratory environment.

5.4 Current Limitations and Next Steps

The current implementation demonstrates that the ScaTERS concept can be materialized as a large scaled physical–digital test environment, but it also reveals practical challenges. The most relevant limitation is the alignment between planning data, the digital model, and the constructed layout. For cost and construction efficiency, the laboratory uses flexible track elements. While this enables the large geometry to be realized economically, it introduces deviations, especially in curved sections. These deviations must be measured and compensated before precise physical–virtual synchronization, replay, and hybrid scenario augmentation become possible.

The initial realization provides a stable basis for repeatable on-sight ATO experiments with controllable route states and reusable vehicle platforms, while the flexible test area and environmental chamber preserve room for scenario-specific extensions. The next implementation steps are the measurement of the as-built track geometry, installation and calibration of infrastructure sensors, integration of logging and supervision interfaces, and synchronization of the physical laboratory with the digital representation.

6 Conclusion and Contribution

This paper presents the methodological design and initial realization of ScaTERS, a Scaled Test Environment for Railway Systems. Motivated by challenges in on-sight

Automatic Train Operation (ATO), ScaTERS bridges the gap between purely virtual simulation and full-scale field testing. The main contribution is not the idea of scaled testing itself, but the systematic translation of predefined laboratory boundary conditions into a traceable design process and a first physical implementation.

The proposed methodology links representative ATO scenarios to laboratory requirements, functional decomposition, solution principles, and implementation decisions. Automated shunting, depot and siding operations, infrastructure-supported perception, hybrid physical–virtual testing, and selected tram-like conditions act as primary design drivers. Due to space limitations, the full requirements-to-layout derivation is not presented in detail. Instead, the approach is illustrated through three representative design decisions: a shunting-oriented reference geometry, perception zones supported by infrastructure, and a digital-twin-compatible system architecture.

The current implementation demonstrates the feasibility of the concept. It includes a modular laboratory substructure, a fixed track layout covering approximately 72 m², remotely controllable switches, reusable modular ATO vehicle platforms, and an initial digital representation. An additional 20 m² remain free of permanent track installation for temporary scenarios, sensor configurations, and algorithm-specific experiments. A separate chamber enables controlled environmental testing using configurable LED lighting and fog generation. However, key components are still under development, including infrastructure-side camera systems, logging and supervision interfaces, and precise synchronization between design data, as-built geometry, and the digital model.

ScaTERS therefore functions as an intermediate experimental layer enabling early testing with real sensors, controllable infrastructure, repeatable low-speed scenarios, and hybrid physical–virtual representations, without replacing full-scale validation. Current limitations include scale effects, geometric deviations, incomplete sensing infrastructure, and ongoing calibration of the physical–digital link. Future work will address these aspects through improved geometry acquisition, sensor integration, digital twin synchronization, and systematic experiments on perception, localization, control, and infrastructure-supported ATO functions.

Author Contributions

Raphael Kling contributed to the planning of the physical ScaTERS layout and to the implementation of the physical laboratory setup. Tobias Hofmeier contributed to the requirements analysis, functional derivation, methodological concept, and implementation of the physical laboratory setup. Martin Cichon provided academic supervision, conceptual guidance, and critical review.

Acknowledgements

This work was partly accomplished within the project VAL, FKZ 53T200008KT, EBA Ref. 8fd/003-1255#008-VAL, funded by the German Federal Ministry of Transport.

References

[1] European Union, ‘Digitalisation in railway transport’, 2019, Accessed: May. 27, 2026 [Online]. Available: https://www.europarl.europa.eu/RegData /etudes /BRIE/2019/635528/EPRS_BRI(2019)635528_EN.pdf

[2] IEC, IEC 62290-1:2014 Railway applications – urban guided transport management and command/control systems – part 1: system principles and fundamental concepts, IEC 62290–1, 2014.

[3] D. Leinhos, H. Flatt, and S. Witte, ‘Sensorik als technische Voraussetzung für ATO-Funktionen’, Deutsches Zentrum für Schienenverkehrsforschung beim Eisenbahn-Bundesamt, 2022. doi: 10.48755/DZSF.220015.01.

[4] L. Schnieder, European Train Control System (ETCS). Berlin, Heidelberg: Springer Berlin Heidelberg, 2021. doi: 10.1007/978-3-662-62878-2.

[5] J. Pachl, Railway Signalling Principles. Universitätsbibliothek Braunschweig, 2020. doi: 10.24355/DBBS.084-202006161443-0.

[6] R. Tagiew et al., ‘Sensor system for development of perception systems for ATO’, Discover Artificial Intelligence, vol. 3, no. 1, p. 22, Jun. 2023, doi: 10.1007/s44163-023-00066-4.

[7] Pegasus, ‘Projekt zur Etablierung von generell akzeptierten Gütekriterien, Werkzeugen und Methoden sowie Szenarien und Situationen zur Freigabe hochautomatisierter Fahrfunktionen’, Schlussbericht – Gesamtprojekt, Feb. 2020. Accessed: May. 27, 2026. [Online]. Available: https://www.pegasusprojekt.de

[8] L. Greiner-Fuchs, S. Schäfer, T. Hofmeier, and M. Cichon, ‘Database-supported methodical approach for the development of a toolchain for the evaluation of ATO functions using a scenario-based test methodology’, in Proceedings of the Fifth International Conference on Railway Technology: Research, Development and Maintenance, in Paper 13.4. Montpellier: Civil-Comp Press, 2022. doi: 10.4203/ccc.1.13.4.

[9] G. D’Amico et al., ‘TrainSim: A Railway Simulation Framework for LiDAR and Camera Dataset Generation’, IEEE Trans. Intell. Transp. Syst., vol. 24, no. 12, pp. 15006–15017, 2023, doi: 10.1109/TITS.2023.3297728.

[10] T. Hofmeier and M. Cichon, Vir2Rail – Modular LiDAR Simulation Framework for ATO Research in Railway Environments. (Mar. 04, 2026). Zenodo. doi: 10.5281/zenodo.18769047.

[11] T. Hofmeier and M. G. Cichon, ‘Introducing Scaled Model Development to on-Sight Automatic Train Operation’, in Proceedings of the 10th International Conference on Vehicle Technology and Intelligent Transport Systems, SciTePress, 2024, pp. 378–385. doi: 10.5220/0012691500003702.

[12] T. Hofmeier and M. Cichon, ‘A Scaled Lab Proposal for Development and Testing of On-Sight Automatic Train Operation’, in 2025 IEEE International Automated Vehicle Validation Conference (IAVVC), Baden-Baden, Germany, Sep. 30–Oct. 2, 2025, doi: 10.1109/IAVVC61942.2025.11219509.

[13] International Association of Public Transport (UITP), ‘Statistics Brief: Metro Automation’, UITP, Brussels, 2018. Accessed: May. 27, 2026. [Online]. Available: cms.uitp.org/wp/wp-content/uploads/2020/06/Statistics-Brief-Metro-automation_final_web03.pdf

[14] Department for Transport, Thameslink Programme Evaluation: Baseline Report. London, UK: Department for Transport, 2018. Accessed: May. 27, 2026. [Online]. Available: https://www.gov.uk/government/publications/thameslink-programme-evaluation-baseline-report

[15] DB Systemtechnik, 'Digitale S-Bahn Hamburg - A safety concept to operate ATO over ETCS'. Accessed: May. 27, 2026. [Online]. Available: www.era.europa.eu/system/files/2022-11/control_major_risks_-_marc.pdf

[16] A. Bonacchi, A. Fantechi, S. Bacherini, and M. Tempestini, 'Validation process for railway interlocking systems', Sci. Comput. Program., vol. 128, pp. 2–21, Oct. 2016, doi: 10.1016/j.scico.2016.04.004.

[17] A. E. Haxthausen, 'Automated Generation of Safety Requirements from Railway Interlocking Tables', in Leveraging Applications of Formal Methods, Verification and Validation. Applications and Case Studies, T. Margaria and B. Steffen, Eds., Berlin, Heidelberg: Springer, 2012, pp. 261–275. doi: 10.1007/978-3-642-34032-1_25.

[18] D. Macko, Ľ. Hrmo, J. Hrbček, and P. Nagy, 'Real-Time Control System for Model Railway Based on SIMIS W Interlocking System', Appl. Sci., vol. 15, no. 1, p. 180, Jan. 2025, doi: 10.3390/app15010180.

[19] M. Rahimi, H. Liu, I. D. Cardenas, A. Starr, A. Hall, and R. Anderson, 'A Review on Technologies for Localisation and Navigation in Autonomous Railway Maintenance Systems', Sensors, vol. 22, no. 11, p. 4185, Jan. 2022, doi: 10.3390/s22114185.

[20] F. Yan, Y. Gu, and Y. Sun, 'Deep Learning-Based Train Obstacle Detection Technology: Application and Testing in Metros', Electronics, vol. 14, no. 7, p. 1318, Jan. 2025, doi: 10.3390/electronics14071318.

[21] RWTH Aachen, 'Die Eisenbahntechnische Lehr- Versuchsanlage der RWTH Aachen'. Accessed: May. 27, 2026. [Online]. Available: www.via.rwth-aachen.de/elva.php

[22] TU Dresden, 'The Laboratory', TU Dresden. Accessed: May. 27, 2026. [Online]. Available: https://tu-dresden.de/bu/verkehr/ibv/ebl

[23] T. Hofmeier, M. Kleinlein, and M. Cichon, 'Development of Positioning Methods for ATO in a Scaled Model Environment', in Proceedings of the Sixth International Conference on Railway Technology Research, Development and Maintenance, J. Pombo, Ed., in Online volume CCC 7. Edinburgh, UK: Civil-Comp Press, 2024, p. Paper 21.1. doi: 10.4203ccc.7.21.1.

[24] T. Hofmeier and M. Cichon, 'Scaled Model Development and Testing for Automatic Train Operation: Creating a Digital Twin', SN Computer Science, 2025, doi: 10.1007/s42979-025-04529-6.

[25] T. Hofmeier, K. Otto, Y. Cao, and M. G. Cichon, 'Vorentwicklung kamerabasierter on-sight-ATO-Funktionen – Schienenkopf- und Weichenlagendetektion sowie infrastrukturseitige Unterstützung der Lichtraumprofilüberwachung bei geschobenen Einheiten im skalierten Modell', in Proceedings of the 5th International Railway Symposium Aachen (IRSA 2025), 2026, pp. 256–271, doi: 10.18154/rwth-2026-00357

[26] Verein Deutscher Ingenieure (VDI), ‘VDI 2221 Part 1: Design of Technical Products and Systems – Model of Product Design’. Düsseldorf, Germany, Nov. 2019.