Introducing Scaled Model Development to on-Sight Automatic Train Operation

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Abstract: Rail systems are often not an economic option in terms of flexibility and cost in intermodal competition. To address this issue, there is a push towards implementing automation and digitalization components. In recent years, there has been a strong focus on on-sight automated train operation systems. As the applications move beyond protected areas such as metro systems, to complex on-sight driving scenarios, the demands on system development, verification, and validation increase. Methods from the automotive industry are well known for overcoming these challenges with virtual development and final field testing. Fundamentally different operating conditions prevent sufficient field testing, as rail infrastructure and vehicles are difficult to procure for development and testing purposes. In science and research, scaled models are being promoted for similar problems. These models allow for simulations to be verified and favorable estimates to be made. This paper demonstrates the possibility of using scaled model methods for the development of on-sight automatic train operation (ATO) functions. A demonstrator of a highly automated shunting locomotive is being built as a scaled model and equipped with sensors for environment detection and localization as well as communication interfaces. The feasibility of ATO functions in the scaled model is demonstrated using defined use cases.

1 INTRODUCTION

The climate policy framework for the coming decades requires a shift in traffic volumes from road transport to more environmentally friendly alternatives, with rail being one of the preferred solutions (Kaack et al., 2018).

In order to create a competitive rail-based alternative to road transport, it is necessary to analyze the existing disadvantages of rail transport in passenger and freight transport.

According to (Trepáčová et al., 2020) the common disadvantages of passenger rail transport are crowding; organization of the rail system; financial cost; low number of trains; delays; train route, boarding and exiting the train as well as luggage transportation and safety issues.

In rail freight transport, a fundamental distinction must be made between full train and single wagonload transport. In full train transport, large quantities of general cargo or bulk goods are predominantly transported with the same origin and destination, whereas in single wagonload transport, trains with different load types, origins and destinations of each wagon are transported. The more flexible single wagon load transport competes with road transport. Disadvantages against road transport are less flexibility on the last mile, poor predictability and high costs. The costs for the shunting process account for a significant proportion of the total costs of single wagonload transport, without any direct value added (Guglielminetti et al., 2015).

Consequently, shunting processes offer potential for optimizing rail freight transport.

Automation and digitalization are seen as driving factors for increasing predictability, which has a positive impact on both passenger and freight transport and secondarily increases economic efficiency and performance of railway systems (Pourian, 2023), (European Union, 2019).

Based on this expectation, several automation projects in passenger and freight transport have already been successfully implemented. As automated railway systems become more widespread, these systems also need to be developed for use in critical environments. Current methods do not guarantee sufficient testing and development possibilities to reliably bring systems to market

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maturity. The following paper presents the potential of scaled models for the problems involved in the development of on-sight automatic train operation (ATO) functions.

2 AUTOMATIC TRAIN OPERATION

As already mentioned, several automation projects are already successfully in operation. The grade of automation (GoA) is defined in (IEC, 2006) and describes the ascending takeover of tasks by an automated system, ranging from on-sight driving operation GoA0 to unattended operation GoA4.
To examine the influence on systems currently under development, the operating conditions of some example systems are described below.
The first GoA4 system was already in use in Kobe, Japan in 1981 (Powell et al., 2016) and represents a sealed off system. Subsequently, the underground railways in European cities became increasingly automated. Another milestone was the launch of the U2 and U3 underground lines in Nuremberg, which was the first to ensure mixed operation with automated and non-automated lines since 2008 (Zasiadko, 2019). The closed and mostly intersection-free system, with few clearly defined interfaces to the outside world, means that subways can be automated simply by monitoring the infrastructure at critical locations.

A further step in the automation of rail vehicles is the S-Bahn in Hamburg, where ATO over European Train Control System (ETCS) is demonstrated. Passenger operation is carried out with GoA2 (automated operation with driver monitoring) and depot operation is carried out according to GoA4 (fully automated) (DB Systemtechnik, 2021).
Rio Tinto also operates highly automated rail vehicles in Australia with its auto haul project. The automation is realized via a radio remote control as a fallback level. Safe operation is realized through the extra protection of critical points such as level crossings and inhabited areas. Collisions with wild or grazing animals pose the greatest risk on most of the route. The train detects impacts on the locomotive and provides the supervisor with data to evaluate the impact. The supervisor can decide remotely whether the journey must be interrupted or can be continued (Rio Tinto, 2017).

The systems listed here are located in more or less protected environments and are operated fully automatically if human or economic damage can be ruled out. For the further spread of automated rail systems, solutions must be developed that also work in critical areas of application. This process is explained below.

2.1 Developing ATO Systems

The examples show that the automation of railroad systems is used in a wide range of applications. In terms of railroad technology, the areas of application can be divided into main line and on-sight operation. In order to promote their automation, it is necessary to work out the differences.

On the mainline trains are mainly operated using train control systems featuring signals. Due to their mechanical properties, the trains have very long braking distances, meaning that the stopping distance cannot be monitored by the vehicle. The signals are used to divide the line into individual blocks to ensure that trains stop in good time. The signal either blocks the following block or releases it and transmits the permitted speed. In manual mode, the driver reacts to the signal position. this process must be taken over by the system in automated mode (Pachl, 2020).

In Europe, ETCS is being introduced to automate main lines. From equipment level 2, it transmits the permitted speeds by radio, receives position information and monitors the information generated. At ETCS level 3, it will be possible to operate without "fixed block" signals in order to increase line utilization by means of dynamic virtual blocks. (Schnieder, 2021).

ECTS already provides a functional automation basis for the mainline. However, significant investment in the infrastructure is still required for the rollout across the entire rail system (European Commission, 2023).

The 'driving-on-sight' includes more complex operations such as depot trains, shunting, approaching stops or mixed tram and road traffic. Due to the significantly lower speeds, it is possible to monitor the stopping distance from the vehicle.

When the vehicle is automated, it is therefore necessary to replace the driver's visual, (acoustic and sensory) perception with an automated system. This step is accomplished by merging several sensor data. Depending on the application, color cameras, infrared cameras, LiDAR, radar or ultrasonic sensors are used to replace the driver's visual capabilities (Tagiew et al., 2022). In addition, it is necessary to locate the locomotive in the track plan with high accuracy in order to distinguish between obstacles in the clearance gauge or objects by merging with the data from the environment detection system. Since the installed balises do not provide the necessary accuracy, positioning systems consisting of GPS/GNSS, IMU and odometry sensors are used.

The basic problems and the sensor setup used are similar to autonomous driving in the automotive sector. Therefore, it is advisable to examine closely the development and testing methods used in the automotive industry.

With the increasing complexity, not only the development but also the adequate testing of automated systems is becoming more and more important. In the automotive industry, the scenario-based test approach developed in (Pegasus, 2019) is a common practice to support the development process and bring the automated system to market.

In the early stages of the project, systems are developed and tested in simulation environments; as development progresses, the system is tested in the real environment.

This approach seems appropriate for rail technology. However, due to the fundamental differences between road and rail vehicles in terms of masses, friction coefficients, track characteristics and operating environments, it is necessary to adapt the approach for use in rail technology.

A correspondingly derived method for railroad technology is described in (Greiner-Fuchs et al., 2022). Due to the lack of general measurement data with ATO reference in railway technology, the methodology is driven by a knowledge database derived from operational regulations, observations in the field and self-generated data. Similar to the automotive industry, the methodology propagates the performance of simulative tests and final verification and validation in the field.

In (Schäfer et al., 2023), the application of a virtual environment for the development of highly-automated rail vehicles is demonstrated. At the level of research questions, it is therefore feasible to use virtual environments to pre-develop systems. To date, these simulations have not been sufficiently verified and validated, so there is no commercially available platform for on-sight ATO functions. The development of field tests using the above-mentioned method is also still under development and has not yet been sufficiently validated.

It should therefore be noted that the fundamental problems of highly automated rail vehicles are known and the first solutions derived from the automotive industry are available. The sensor concepts and system topologies have been concretized, but unfortunately the test and development standards do not yet correspond to the desired target image. The problems still to be solved are discussed below.

2.2 Challenges for Development and Testing of on-sight ATO Functions

Based on the research group's experience in the field of automated on-sight rail systems, some remaining problems for simulative and field testing can be identified.

On the simulation side, there is the problem of the dynamic development of new or other sensor technologies for which adequate sensor models must first be developed. Due to a long period of low demand for simulation environments for rail vehicles, the number of commercial participants is still very low, which means that it is not always possible to adapt the simulation environments in step with sensor development. State-of-the-art development must therefore often be carried out with non-validated sensor models. With sufficient prior knowledge, the basic sensor simulations can be considered reliable, although they may not always provide a solid foundation.

Railroad test sites are not public areas. Consequently, clearly defined operational and regulatory conditions apply on the available test sites. This means that an operational and technical test manager must be present in addition to the train driver for the actual test and development personnel. The high utilization of railway infrastructure also makes it difficult to provide temporary routes for test and development purposes without retrospective impact. Maintenance backlogs for locomotives coupled with the general availability of railway vehicles also make field operations more difficult.

Prices for the use of a shunting area e.g. in Germany are listed in (RLC Wustermark, 2023). A locomotive including a shunting driver and diesel are required for testing. This process can be considered a shunting service for rough calculation purposes. Additionally, costs are incurred for infrastructure, such as track utilization. It is important to note that the locomotive may lose its license when upgraded, so costs for upgrading, disassembly, and certification must be factored into the test. Accordingly, it is advisable to plan test and development runs in the field for extended periods to reduce the expenses and labour involved in conversion and transportation. Taking into account the daily rates for operational and technical test managers, as well as the test and development staff, the cost of a single test day can amount to several thousand euros.

The high cost and inadequate availability of test facilities and personnel ensure a high degree of transferability of simulation results to the field.

However, this is often not the case due to the aforementioned non-validated simulation data, non-simulated interfaces and unforeseen hardware effects.

In order to optimize the test time in the field, the leap in technology maturity between simulation and the real environment must be reduced. One possible solution appears to be the use of scaled models, this option is presented and discussed below.

Interface technologies such as WiFi, Ethernet or radio and protocols such as TCP/IP, UDP, I²C, etc. can still be used in their original form even at very large downscaling due to their small size. This allows interface problems, faulty data, bit shifts or similar connectivity issues to be resolved realistically in the model.

3 SCALED MODELS

Scaled models are commonly used in the literature when real test objects are expensive or difficult to obtain. They are also utilized to verify simulation models. The reasons described are similar to the problems observed during on-sight ATO-function development and testing. The following section shows how scale models are adapted in technology and science to identify conditions and limits.

3.1 Scaled Models in Science

A large number of scaled models are known in science and in engineering applications. These are presented below as examples and analyzed with regard to synergies with the problems discussed in the paper.

The investigation of air flows in wind tunnels is one of the best-known applications of scaled models. Large objects such as airplanes (Aerospace Engineering, 2022) or buildings (Geurts & Van Bentum, 2007) cannot be tested economically in their original size. Consequently, the wind tunnel (test site) and test object are scaled until a satisfactory relationship between cost and gain in knowledge is achieved. The measurement results are scaled to the real application using physical correlations, such as the Reynolds number. The scaled models are also applied to verify simulation approaches.

Furthermore, scaled models are utilized for the design of buildings for special cases such as earthquakes. Various approaches are explored to determine the scaling factors by which the results and effects can be transferred to reality (Atar, 2022).

The research and development of autonomous ships is more closely related to the topic of automated train operation, because these entail even higher individual costs for test vehicles and a comparable availability and utilization of test sites as in railway technology. Scaled ships are used as test vehicles, the length of which is chosen to allow for a lighter regulatory framework is possible in terms of driving licenses and operation. Due to the large initial size of ships, it is still possible to use original LiDAR, camera and radar sensors even after scaling. (Kolewe & Tietz, 2023).

In the automotive industry, the use of scaled models for the development and testing of autonomous driving functions is unknown. It is assumed that the costs for test vehicles and test sites are too low to consider investing in scaled models.

3.2 Scaled Models in Railways

In the field of rail vehicles, the use of scaled models is already in use in teaching and research.

(Aceituno et al., 2017) shows the use of a scaled vehicle with a 5-in track gauge for the validation of dynamic simulations.

In the railway operations laboratory (ger. “Eisenbahnbetrieblabor”) of TU Dresden a model layout in H0 gauge (16.5 mm) is provided for, teaching and research focused on safety technology and signal box technology, with the possibility of establishing a link to real systems such as the Dresden suburban railway (TU Dresden, n.d.).

RWTH Aachen University also operates an H0-scale environment featuring different realistic signal box technologies, with the ability to simulate real switch towers, as well as different kinds of safety technologies up to ETCS simulation, and an extensive track network to elaborate solutions for dispatch optimization (RWTH Aachen, n.d.).

In the literature, scaled models are utilized in railway technology for research, development and demonstration of safety and interlocking technology, timetable optimization and validation method for dynamic simulation. An approach to establish scaled model methods for on-sight ATO is described below.

4 SCALED MODEL DEVELOPMENT FOR ONSIGHT AUTOMATED TRAIN OPERATION

To map on-sight ATO functions in the scaled model, it is necessary to develop and set up an appropriate test field and a demonstrator vehicle. The first step is to clarify which functions are to be tested with the development and testing platform. With reference to a parallel project in which a shunting locomotive is being automated, the test field and the demonstrator are to be adapted to the needs of automated shunting operations in order to improve the comparability of the results. Due to the increasing complexity and development effort required for GoA4 functions, it is expected that scaled models can contribute to development, especially for highly automated vehicles, due to the advantages already described. Accordingly, the scaled model should be planned in a modular way, so that functions up to GoA4 can be developed.

4.1 Scaled Test Environment and Demonstrator Locomotive

A marshalling yard usually contains arrival tracks, a hump, directional tracks and classification tracks. The tasks of a (automated) shunting locomotive are divided into use cases for testing and development purposes. These are “check, move, approach, attach, pressing-up, push-loose, follow, closing gap, retrieve wagon, clear track, emergency brake, buffing, humping and move-up” (Hofmeier et al., 2022). For an initial exploration of the possibilities of scaled models for the development of ATO functions, the focus will be limited to a reduced range of functions of the shunting locomotive. For the experiment, the use cases will include "move," where the locomotive switches the track by moving via the dead-end track; "approach" and "attach," where the locomotive approaches an obstacle or wagon at a safe distance or attaches to it; and "check," where the locomotive verifies the functionality of the sensors. These use cases are primarily performed in the area of the arrival tracks and the hump; consequently, these must be considered at least in the test field setup.

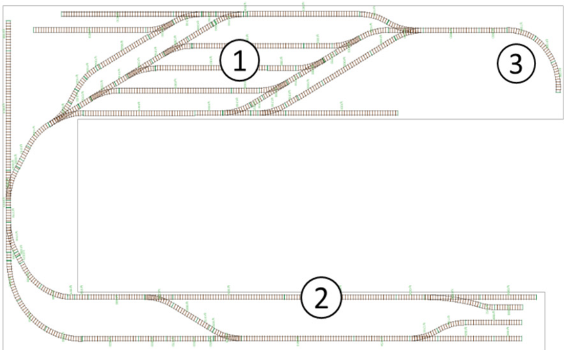

Figure 1: Track layout with arrival tracks (1), hump (2) and dead-end track (3).

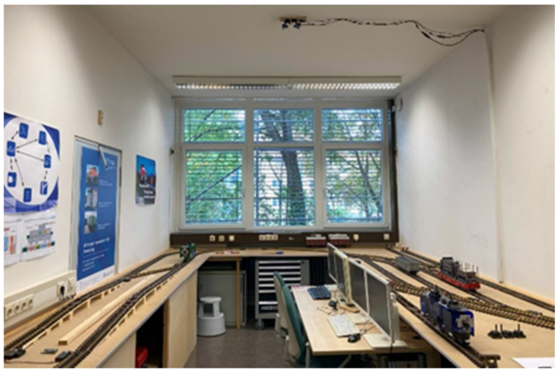

Figure 2: Overview of test area.

The test environment (Figure 1) is constructed on a u-shaped plate with external dimensions of 6.2 m x 3.6 m, constrained by the room size (Figure. 2) and features approximately 34 m of track length, incorporating 17 switches and two three-way switches, with a track gauge of 45 mm.

The test area consists a track harp as arrival tracks (1), a hump with two parallel tracks (2) and a dead-end track (3) used for switching between the tracks.

A range of rail vehicles are also available for testing, including flat wagons, container wagons, timber wagons and vehicle transporters.

In order to implement automated driving, appropriate sensors must be positioned, data analyzed and actuators controlled. In terms of sensor data, this primarily requires data for environment detection and localization. A comparatively high level of computing power is expected to be required to analyze environmental data. A Raspberry Pi appears to be a sensible solution, as it also provides a large number of interfaces. State-of-the-art ATO systems mainly use LiDAR sensors for obstacle detection. Accordingly, a LiDAR sensor should also be used in the scaled model. It is possible to estimate the installation space for a demonstrator from the minimum requirements for computing power, sensors and interfaces. The G or 1 gauge with 45mm (scale 1:32 to standard gauge) offers the possibility of a sufficiently large demonstrator to accommodate all the required components and keeps the effort and costs for infrastructure construction to a minimum compared to larger model railway gauges.

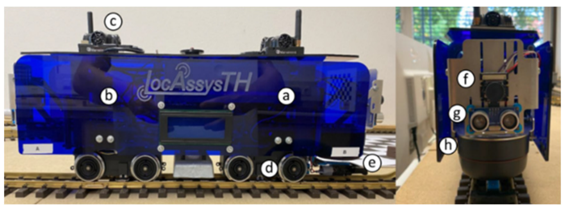

Figure 3: Demonstrator setup.

Figure 3 shows the structure of the demonstrator vehicle. The central unit is a *Raspberry Pi 4B 8GB* (a). Two *Arduino Nano* (b) are used to read out sensor data. The localization is implemented with an ultrasound-based *Marvelmind Indoor Positioning System* with mobile hedges on the vehicle (c) and fixed beacons at the labs walls. To record odometry data, an incremental encoder (d) is attached to the engine shaft. A strain gauge is installed in (e), which can be used to measure the trailer load. An RGB camera *RPI WWCAM* (f), an ultrasonic sensor *HC-SR04* (g) and a LiDAR sensor *RPLIDAR M2A8* (h) are used as sensors for environment detection.

The sensor data from the strain gauge and ultrasonic sensor are read out on Arduino 1, and data can also be visualized on the LCD display via Arduino 1. The incremental encoder is processed with Arduino 2. Both Arduinos are connected to the Raspberry Pi via I²C. The hedges of the indoor positioning system are connected to the Raspberry Pi via USB.

In the next step, an ATO system is set up with these components.

4.2 Developing a Scaled ATO Shunting System

To fulfil the use cases defined at the beginning, the first step is to derive the position of the locomotive on the route or in the track plan using reliable positioning in combination with the route data transmitted externally to the locomotive (X-coordinates, Y-coordinates, additional information). Additional information includes, for example, speed specifications between two waypoints and expected obstacles such as a wagon on the track. The Indoor Position System offers a 100 Hz protocol in which, among other data, the X and Y coordinates of the hedges are transmitted via USB. The ultrasonic beacons use an IMU to interpolate between the sampling rate of the actual ultrasonic system to increase the data rate up to 100 Hz.

The localization data is read out via USB on the Raspberry Pi and the route data is transferred via TCP/IP.

The hardware support of *Simulink* for Raspberry Pi is used for programming. The development process here is analogue to the development on a *dSPACE MicroAutoBox II* used in the real locomotive application.

Figure 4 describes the procedure for determining the position. Data is transferred to Simulink via WiFi, USB and I²C interfaces. There, the position data is checked for plausibility (verification of coordinates in the laboratory), then the measurement data is

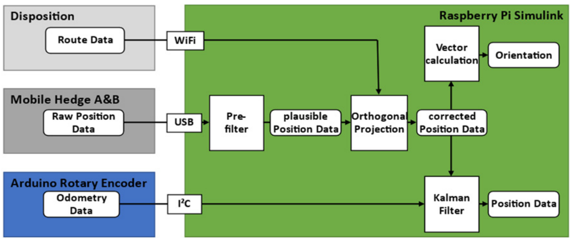

Figure 4: Interfaces, process and components of positioning.

projected onto the distance data in order to eliminate the lateral deviation. The actual position is estimated using the odometry data and a Kalman filter. It is also possible to determine the locos orientation from the positions of the hedges A & B.

This process enables the determination of the locomotive's position on the route with sufficient accuracy, sampling rate, and reproducibility.

The next step is to set up the environment monitoring system. In the first approach, the ultrasonic sensor is used to detect obstacles in order to reduce complexity. This makes it possible to enable platooning between two demonstrator vehicles in a straight line. As it is not possible to clearly determine where the object detected by the ultrasonic sensor is located, this system cannot be used to ensure safe movement in the track curve.

The LiDAR sensor is integrated into the system for fully functional environment detection. For this purpose, Robot Operating System (ROS) is installed as a framework to provide LiDAR sensor data.

To make a driving decision based on the LiDAR data, the raw data is transferred to Simulink via the ROS topic and processed there in X/Y format coordinates. In addition, the position of the sensor in the world coordinate system is calculated using the position of the beacons and the position of the LiDAR on the locomotive (see Figure 5). By adding the sensor position to the point cloud, the detected objects are available in world coordinates.

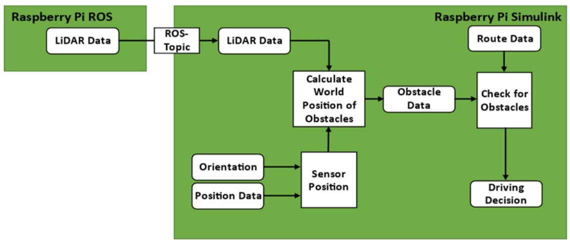

Figure 5: Decision-making obstacle detection.

The distances of the objects to the track are calculated taking the route data into account. If the distance falls below a defined nominal value (e.g.

clearance profile), the object is classified as an obstacle. If the distance to obstacles approaches the stopping distance, braking is initiated.

Figure 6 shows the LiDAR point cloud after the locomotive has approached. The sensor is installed in such a way that the buffer level of the wagon is intersected. Buffer and wagon front can be clearly distinguished at a short distance.

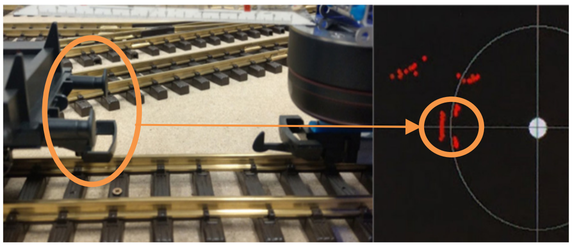

Figure 6: Point cloud after approaching.

Figure 7 visualizes the ATO system in action. The decision making is able to guide the loco along the route. During the journey, the system checks the sensor data for plausibility and executes the use cases check, move, approach and attach with sufficient reliability. Consequently, the implementation of ATO functions in the model has been successfully completed.

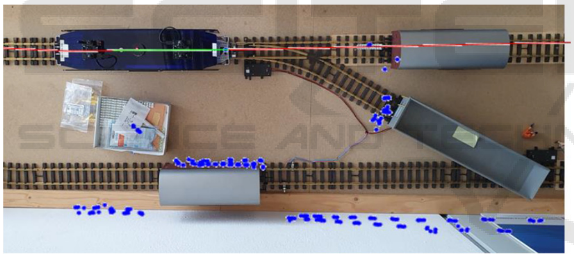

Figure 7: Visualization LiDAR-position, route data and point cloud data.

For the test runs of the “move” use case, target positions are defined on the track to be approached by the demonstrator. The system always determines the correct orientation and therefore moves in the right direction. The distance to the target point can be determined at the time of measurement with a maximum deviation of ±15 mm. In addition, the error increases with speed (approx. 50 mm/s and effective sampling rate (approx. 75 - 85 Hz) to the next measurement point.

For the “approach” case, the system is able to reliably determine the distance to obstacles within the clearance gauge. The deviation of the distance measurement is lower than that of the localization system and therefore depends heavily on the local localization accuracy. During the investigations, borderline cases such as objects at the clearance gauge boundary were excluded. It is expected that further software (and hardware) improvements to the system will be necessary in order to be able to maintain tight tolerances (<10 mm) around the boundary of the clearance gauge.

“move” and “approach” have in common that a (defined) braking curve must be maintained, for which precise speed information is required. The tests show that the installed incremental encoder works unreliably at times and that controlled braking is intolerably often (>40 %) not possible. Furthermore, it is not possible to model the realistic control behavior of a real locomotive with this setup. A revision of the speed sensor is necessary to increase the functionality of the demonstrator.

The distances to be covered in the "attached" case are short and can, in principle, be achieved with the system stand. However, it is not possible to implement a realistic approach speed behavior depending on the load or other factors.

5 CONCLUSION

The test setup demonstrates that it is possible to develop an ATO system in a scaled model in a cost- and time-efficient manner. The sensors used in reality can either also be scaled or have to be mapped using corresponding substitution technologies (e.g. GPS → ultrasonic positioning). Also, the processes and programming languages used in reality can be transferred directly to the model. The problems and hurdles with regard to different interfaces and latencies are analogous to reality. Accordingly, it is expected that it will be possible to transfer the knowledge gained to the real application.

The most important step is to demonstrate scalability into the real system. Various hurdles are expected here that could limit the usability of scaled models. For instance, the effects caused by masses are primarily distorted through scaling. Mechanical processes may, in certain cases, fail to depict reality with sufficient accuracy for estimating loads or similar factors. Nevertheless, alternative solutions are already delineated in the literature regarding this matter. Moreover, it is anticipated that processes and structures for environment detection and localization, as well as interfaces and software architectures, can be effectively developed within the demonstrated scaled model approach. However, it is essential to identify and determine dimensionless quantities for scaling the individual system components to achieve this.

To this end, it is planned to expand the test field structure in order to be able to consider further application areas of driving on-sight and to generate a more flexible and versatile test environment that requires increased performance in the system. Additionally, the vehicle will be equipped with enhanced sensors to address the described issues.

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