Rail to Digital automated up to autonomous train operation

D38.4 – Results of automatically stabling a train and bringing a train to the station in GoA4

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EXECUTIVE SUMMARY

This deliverable reports on a field trial that demonstrates, in an operational railway environment, an ATO-GoA4 solution based on the technical design developed in Shift2Rail and R2DATO. The demonstrator builds directly on the R2DATO GoA3/4 work of use-cases, non-functional and functional requirements and the prototype developed as part of WP10. The results are now taken from lab prototype level into a full-scale implementation on a retrofitted NS train, providing feedback for future developments on the standardisation, migration and deployment of ATO-GoA4 technologies.

In the field trial, an SNG passenger train was retrofitted to perform fully autonomous ATO-GoA4 operations over Dutch ATB lineside signalling (via ETCS/STM-ATB), with remote supervision and a remote-driving fallback. The train was operated in real mixed-traffic conditions between Hengelo and Enschede, including their adjacent shunting yards, to test automatic stabling, shunting and non-commercial runs (no passengers) on centrally controlled infrastructure. The demonstrator executed complete mission profiles such as moving between yard and platforms, running over the main line, and performing coupling/decoupling and post-run procedures.

The technical solution extends earlier GoA2 work and integrates several GoA4 enablers: mission profile management in the Automatic Processing Module (APM) to execute task sequences; a “location from start-up” localization (LZ) function that provides a valid reference balise and position from the beginning of a mission; a perception (PER) system using stereo cameras and LiDAR for signal and obstacle detection; and a Collision Avoidance System (CAS) that combines perception, mission management, train protection and train control to prevent collisions. A Remote Operation Centre (ROC) in Utrecht provides remote monitoring and remote driving as fallback if GoA4 conditions are lost or if intervention is required.

The research methodology centres on validating the full ATO-GoA4 operational chain in a real-world context. A retrofitted SNG was operated between June and September 2025 on the Hengelo–Enschede line, a double-track corridor with a 125 km/h line speed and intermediate station Enschede Kennispark. Forty-nine autonomous GoA4 runs were completed (around 392 km and 9 hours 45 minutes of GoA4 operation), mostly under daylight, dry or mildly wet conditions. Each run was monitored on board by a safety driver and test staff; for specific scenarios, remote drivers participated to test remote fallback. Observations and quantitative data covered mission execution, localization behaviour, obstacle and signal detection, CAS performance, and remote intervention.

Mission profile execution proved largely successful once system maturity was reached. After an initial debugging phase, the system stabilised and was able to perform a full day of GoA4 operation on the test route. The train could automatically execute journey profiles, perform coupling and decoupling and transition to standby and shutdown. Cabin enabling worked as intended, with the remaining limitation that the Train Running Number still had to be entered manually after automatic cabin activation. Train wake-up and detailed preparation procedures were deliberately kept out of scope.

The application of the CAS system for obstacle detection has been demonstrated on different type of obstacles. In several dynamic scenarios, potential obstacles were encountered such as buffer stops or other trains (for coupling). These obstacles were recognized by the CAS and the train consistently stopped at or beyond the predefined 15 m safety distance. People close to platform edges triggered temporary speed restrictions in station areas, demonstrating correct use of “Track”, “Near Track” and “Protection” zones. Static tests in Amersfoort showed that a person standing in the

protection zone leads to speed reductions, while a person in or very near the track area causes a stop. Safety procedures for loss of GoA4 operational conditions (e.g. PER faults) were also validated: the system applied Full Service Brake and prevented further movement until conditions recovered.

The perception system, based primarily on stereo cameras during dynamic tests, achieved consistent detection ranges in static trials in a shunting yard environment: approximately 50–70 m for people and 70–90 m for trains and buffer stops under daytime, good-visibility conditions. Distance errors from the stereo camera were kept below roughly 10% up to 100 m, while LiDAR-based distance estimates in static scenarios were within 1 m over the same range. An AI-based obstacle detection model, trained on labelled images from static and dynamic tests, correctly identified persons, trains, buffer stops and road vehicles; remaining false negatives were mainly distant or crowded scenes, and the most relevant obstacles in the operational test scenarios were detected. False positives were mostly conservative: people behind platform safety lines and trains on adjacent tracks in curves.

Overall, the demonstrator advances the ATO-GoA4 solution from lab validation (around TRL4) to field validation in a mixed-traffic operational environment (around TRL6 for the core remote-driving and GoA4 functions), albeit under controlled “happy-flow” conditions and with safety drivers on board. The results confirm that autonomous GoA4 stabling, shunting and non-commercial runs over ATB are technically feasible, and that key enablers—mission profile management, start-up localization, perception-based obstacle detection, collision avoidance and remote fallback—can work together coherently on a real NS train and infrastructure. At the same time, the trial underlines the importance of high-quality data and conservative safety margins, and it identifies priority areas for future work: handling degraded modes and failures, extending to a wider range of environmental conditions (night-time, severe weather), adapting the solution to ETCS-based infrastructures, and feeding the lessons learned back into interoperable GoA4 standards and future R2DATO / Europe’s Rail activities.

ABBREVIATIONS AND ACRONYMS

ADM	Automatic Driving Module
APM	Automatic Processing Module
ATB	Automatische Treinbeïnvloeding (Automatic Train Protection)
ATO	Automatic Train Operation
AV	Available (APM state)
CAS	Collision Avoidance System
CBG	Centrally Controlled Area
DM	Digital Map
DMI	Driver Machine Interface
EG	Engage (APM state)
EOJ	End of Journey
ES	Enschede
ETCS	European Train Control System
FA	Failure (APM state)
FSB	Full Service Brake
GoA	Grade of Automation
HGL	Hengelo
JP	Journey Profile
LOZ/LZ	Localization System
MP	Mission Profile
MRSP	Most Restrictive Speed Profile
OB	On Board
OD	Obstacle Detection
PER	Perception System
R2DATO	Rail to Digital automated up to autonomous train operation
RGB	Red Green Blue
ROC	Remote Operation Centre
RTO	Remote Train Operation
SCV	Signal ConVerter
SD	Safety Driver
SR	Short Range
SNG	Sprinter New Generation

SOM	Start of Mission
STM-ATB	Specific Transition Module – Automatische Treinbeïnvloeding
TCMS	Train Control and Management System
TE	Technical Enabler
TM/TMS	Traffic Management System
TP	Train Protection
TRL	Technical Readiness Level
TRN	Train Running Number
TS	TrackSide
TSR	Temporary Speed Restriction
TTC	TreinTestCentrum

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1 INTRODUCTION

Task 38.4 “GoA4 stabling and shunting, including non-commercial runs, with Remote Control Centre as backup” is part of R2DATO WP38 titled “Automatic Stabling, Shunting, and Non-commercial runs Demonstrator”. The aim of this work package is to test the different technical enablers for automatic stabling, shunting and non-commercial runs. This deliverable discusses the research that was done on operating a train autonomously between the stations and yards of Enschede & Hengelo.

The purpose of this study is to automatically and non-supervised move a train in different settings, this includes bringing stations from the station platform track to the yard, as well as non-commercial runs moving trains from one location to another via the mainline, without passengers onboard. The results of performing these tasks, combined with the quantitative analysis into the performance of the ATO-system are reported in this deliverable.

1.1 Project Relations

1.1.1 Internal WP-relations

The majority of the technologies used in this task – specifically related to the GoA4-functionality – are new and have not previously been applied in WP38. However, the remote driving functionality that is used to support the remote fallback feature is based on the same technology that was applied during the demonstrators of:

- Task 38.2 *“Stabling a train and bringing a train to the station by remote control (GoA1)”*
- Task 38.3 *“Stabling a train and bringing a train to the station with remote supervision (GoA2)”*

For the development of KPI’s and the monitoring, analysis and reporting there is a relation with:

- Task 38.9 *“Monitoring, analysis, and reporting”*

1.1.2 R2DATO relations

The demonstrator described in this study is the result of years of work that was performed as part of R2DATO and Shift2Rail. The work on ATO-GoA4 within R2DATO started with the establishment of use-cases as part of WP5, the non-functional and functional-requirements of ATO-GoA4 in WP6, and the development of a functional prototype in WP10. Considering that the finalization of the technical prototype took place from M25, it was based on the available knowledge and deliverables at that moment in time. Some of the developments within ERJU after this month may not have been integrated into this demonstrator.

The output of this demonstrator will be distributed to Task 12.1 (Analysis of migration and deployment strategies) and Task 33.1 (Research on state-of-the-art lessons learned and analysis of FP2-R2DATO demonstrations). It is also expected to be used as input for the second wave continuation of R2DATO.

1.2 Objectives

The objectives of this deliverable are to gain experience from the application of ATO-GoA4 technology in a real-world environment. It seeks to gain insight into the performance of the technical enablers that are incorporated in the demonstrator, to provide feedback to the TE-developers, improve the functioning of the TE and to enhance, improve and modify the specifications.

2 RESEARCH METHODOLOGY

The research on the ATO-GoA4 functionality is based on applying the technology in a real-world railway environment using a retrofitted trainset, while observing the performance, issues and strengths of the technical solution. This chapter describes the applied research methodology and the test environment in which the research has been conducted.

2.1 Analysis methodology

The design of this study is based on applying the ATO-GoA4 technology in a real-world environment and evaluating the performance of the technology and the ability to perform certain tasks. The methodology focuses on validating the complete ATO GoA4 operational chain by assessing the behaviour of all functions required for fully autonomous operation. The plan includes verifying the transition from GoA2 to GoA4, ensuring correct execution of each Mission Profile, and confirming system stability under controlled incremental updates. Additionally, the methodology incorporates the validation of train localization from start-up to ensure that the ATO system receives reliable and accurate position data from the beginning of each mission. Through the following structured tests, the methodology ensures comprehensive coverage of all key elements required for safe and reliable GoA4 operation.

An observer stationed on the train carried out detailed observations during each test run. These notes provided real-time insights into the operational context and any challenges encountered. The collected data included:

- **Train Running Number (TRN)**: Unique identification for each train journey to track and cross-reference observations.
- **Route Driven**: Specification of the exact route taken during each test to identify location-specific factors or variances.
- **Weather Conditions**: Recording weather data is critical since environmental factors can influence train operations and test outcomes.
- **Number of Interventions**: Number of manual or system interventions required during the test, providing a metric for automation reliability and safety implications.
- **Technical Difficulties**: Documentation of any faults, system errors, or malfunctions encountered that could be of impact.
- **Comments** or concerns that were observed related to the performance and ability.

In addition, the execution of specific tasks is tested and monitored during the test runs. The tasks performed include:

- **Mission profile performance**: Executing basic driving tasks, such as stopping at the correct location and maintaining punctual driving. Next to that, the
- Performing the **coupling** and **decoupling** task.
- Performing the **standby** and **shutdown procedures.**
- **Automatic cabin enabling:** Activation of the cabin, but not the performing of cabin checks, preparations and confirmation of the SOM. This is done by the local driver.

- **Obstacle detection**: Assessment of the performance of the Collision Avoidance System and the Obstacle Detection module under both static and dynamic conditions. By positioning a mannequin on the shunting tracks, the detection ranges for people, trains, and buffer stops using stereo cameras and LiDAR, verifying distance-measurement accuracy, and analysing system response times to confirm compliance with safety margins for braking is tested.
- **Remote monitoring and remote GoA1 fall-back**

The plan also includes scenarios to test the safety driver intervention and the confirmation of remote-operation fallback procedures. The decision has been made to focus on demonstrating basic functionalities needed for shunting at each Grade of Automation, the “happy flow” use cases. This means that scenarios in which the system is intentionally confronted with degraded situations (e.g., infrastructure malfunctions, train system failures, or emergency situations) are not included.

2.2 Test Environment

In the early stage of the technical development process, tests have been performed in a privately-owned shunting yard of NS in Amersfoort. These tests served the purpose of validating the system, the integrations with the trackside and testing and improving the perception systems prior to testing on the mainline. The Amersfoort tests were mainly performed when the train was static, while some specific dynamic tests were performed (i.e. driving towards an obstacle).

The majority of the research described in this deliverable takes place in the physical railway environment between Hengelo and Enschede central stations where all the GoA4 tests take place. For some specific use-cases, a connection is made to the ROC in Utrecht. This chapter further describes the characteristics related to the test environments.

The physical test environment of the ROC is the same environment used during the dedicated RTO-tests that were performed in D38.2 Remote Stabling, and D38.3 Remote Supervision tests. Detailed information on the ROC test environment can be found in these documents.

2.2.1 Railway Environment Hengelo-Enschede

During this study, the autonomous train is driving on the railway segment of Hengelo-Enschede, located at a 116km distance from the ROC in Utrecht. Both the Hengelo and Enschede areas feature a mainline station with at least four platforms, and an adjacent shunting yard.

The tests during this study were conducted on tracks that are equipped with line side signalling and a class B TP (ATB “Verbeterde Versie”). There are no shunting yards in the Netherlands equipped with ETCS, hence the need to perform this study over lineside signalling. This study was entirely performed over centrally controlled tracks with automated switches, located in the Centrally Controlled Area (CBG). Figure 2 shows the station and shunting yard of Hengelo. The most common position for the train to be situated at when starting or ending the autonomous journey is shown as “Train”, this position is also shown in Figure 2.

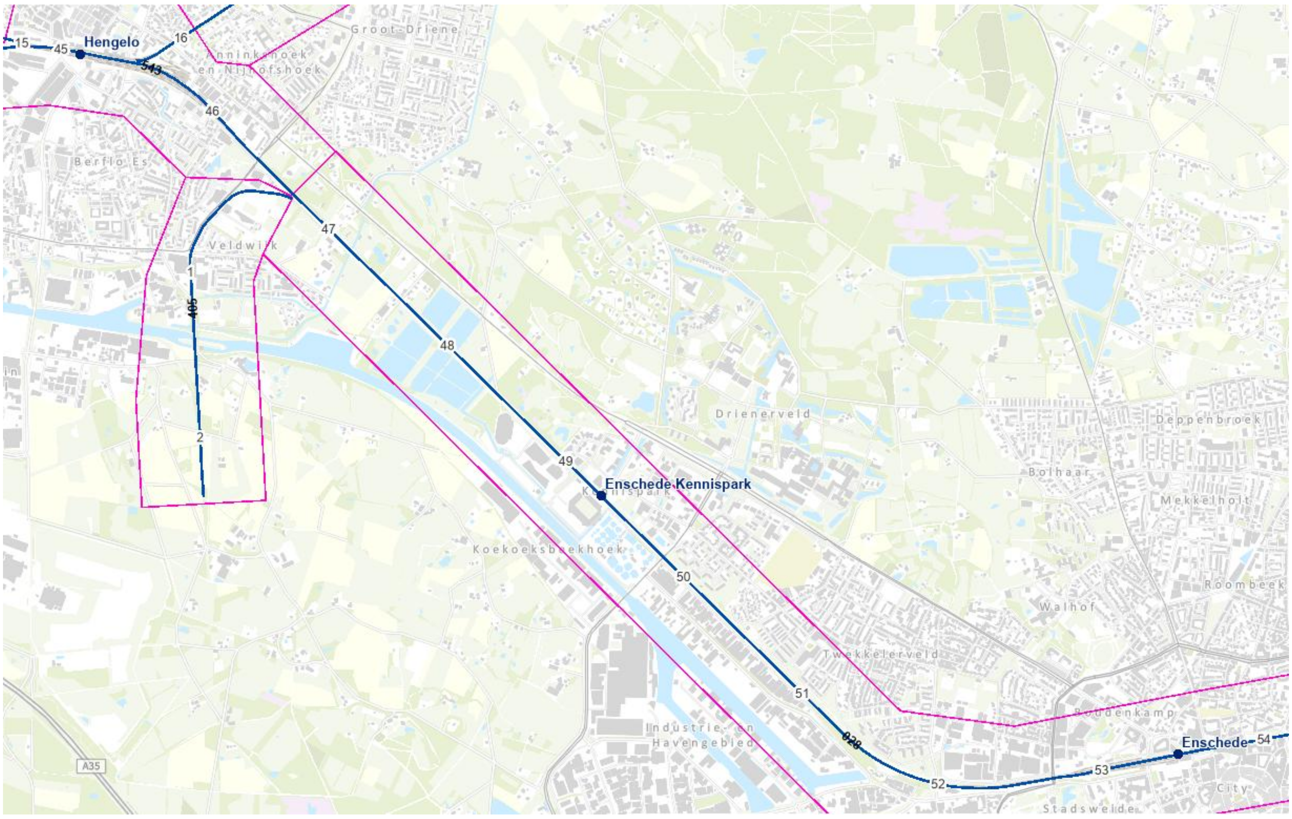

Figure 1: Segment Hengelo-Enschede (BasisBeheerKaart Prorail)

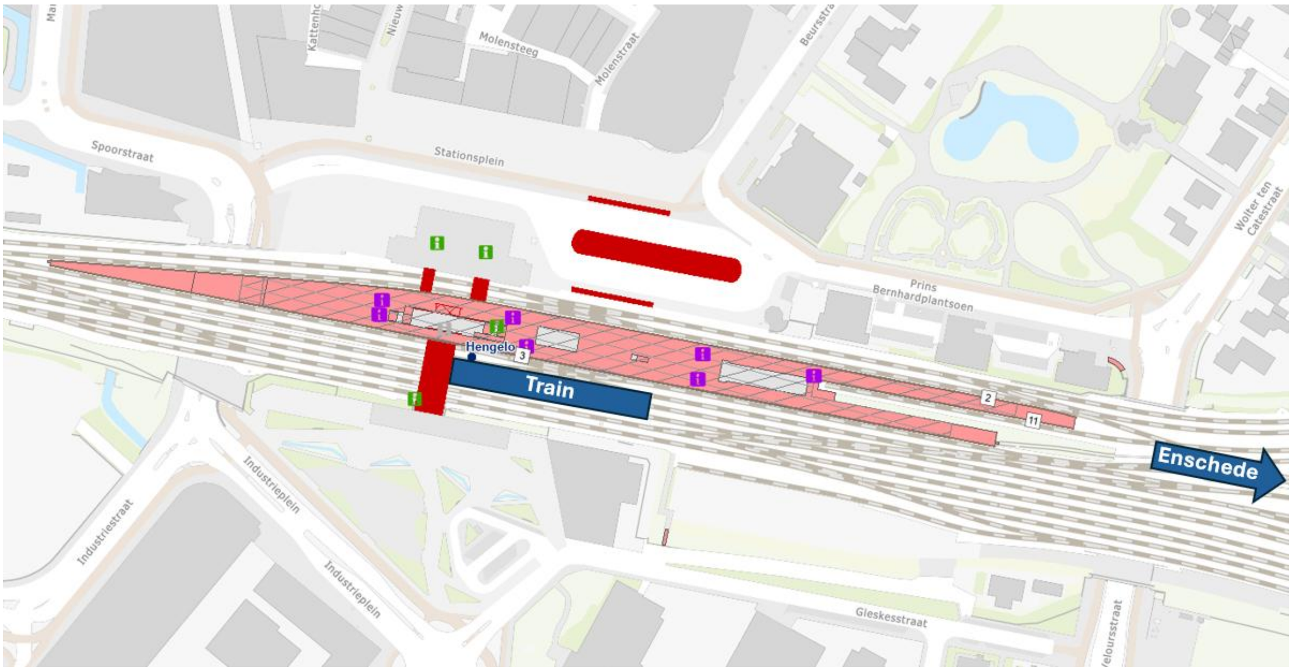

Figure 2: Station area of Hengelo (BasisBeheerKaart Prorail)

Figure 3: The SNG3002 located alongside Hengelo station (De-Amersfoortse-spotter)

The area between Hengelo and Enschede consists of an 8 km railway segment, with double tracks and one intermittent station Enschede Kennispark. This segment has an operating speed of 125 km/h, with gradual speed reductions on both the Hengelo and Enschede approach. There are three protected level crossings, which operate autonomously and are not protected by signals, between the stations of Hengelo and Kennispark. An overview of the track between Hengelo and Enschede can be found in Figure 1.

Enschede is an end-station, featuring buffer stops at the end of both the passenger and shunting tracks. The shunting tracks are located alongside the station, so shunting operations require changing direction at a dedicated shunting track, this track also contains the washing installation. All of the passenger and shunting yard tracks can be reached when approaching from Hengelo. An overview of the Enschede area can be found in Figure 4.

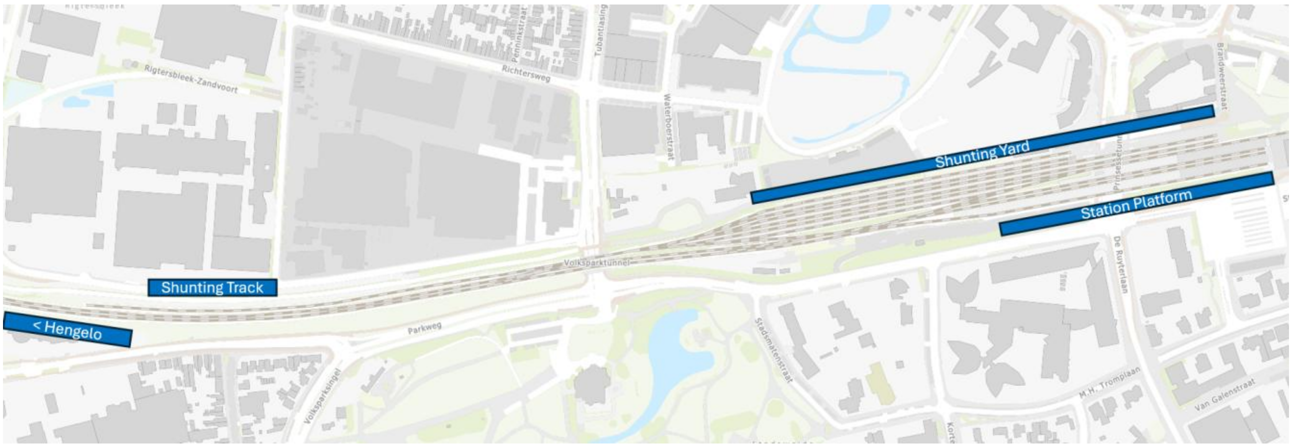

Figure 4: Enschede Station area (BasisBeheerKaart Prorail)

2.3 Obstacle Detection Tests

One of the important features of the ATO-GoA4 technology is the automatic detection and response to obstacles that are on or near the track. The testing of obstacle detection in the scope of this study has been strictly limited to static tests in the Amersfoort private shunting yard and dynamic tests on dedicated tracks in the live shunting yard of Enschede. This was done with special test procedures and safety guidelines under supervision of the safety drivers

A testcase was designed for testing obstacle detection using a mannequin, as shown in Figure 5, placed in the track on the shunting yard of Enschede, within the movement authority and mission profile of the train. It is then observed if the train detects and responds to the mannequin. Tests were performed under daytime conditions with dry weather at the local operating speed of 20km/h. Additional tests were performed without any deliberately placed obstacles, detecting the presence of railway buffers indicating the end of the track or the specific location of other trainsets (i.e. for mission profiles with coupling tasks).

Figure 5: Obstacle Detection Tests

2.4 Research Timetable Design

This study is performed on a high-density railway line used for regional, intercity, international and freight operations. The planned traffic on this line is treated with a higher priority compared to the research runs; it is therefore not possible to have a consistent timetable for all test days. The run duration, intervals and number of runs therefore differ between the research days.

The generic timetable design tried to perform mainly stabling runs, using a basic timetable template of:

1. Depart from Hengelo shunting track.
2. Short stop at Enschede Kennispark station.
3. Arrive at Enschede station.

4. Change driving direction (min 10 minutes).
5. Depart from Enschede station.
6. Short stop at Enschede Kennispark station.
7. Arrive at Hengelo shunting track.

An example timetable is shown in Figure 6, featuring two runs from Hengelo (HGL) to Enschede (ES) and vice-versa. The total journey time is between 9 to 13 minutes, all runs were performed at the maximum operating speed (up to 125km/h).

All of the tests were performed during daytime, either in an early (i.e. 9-15) or late (15-21) shift.

```
LM    93235            SNG  3
(Hgl    V 12:59 - Es      A 13:09)
  ATO
 Hgl      306A  V  12:59 306A,339,HE [175A-R] 140   (0)
 Esk      2     K  13:03
 Es       3     A  13:09 HE,411,3
________________________________________________________

LM    93236            SNG  3
(Es     V 13:21 - Hgl     A 13:34)
  ATO
 Es       3     V  13:21 3,412,EH             140   (0)
 Esk      1     A  13:26
          1     V  13:29
 Hgl      306A  A  13:34 EH,338,306A [213B-R]
```

Figure 6: Hengelo – Enschede timetable

2.5 Research Participants & Roles

During the test program with ATO-GoA4, several key stakeholders were actively involved to ensure the experiment ran smoothly and safely. Onboard the train, three individuals have specific responsibilities:

- The **safety driver (SD)** manages the safe execution of the test run as a backup and would intervene whenever the situation requires it. The SD is authorized to stop the test run or take over control if safety is compromised.
- The **test ride supervisor** is also a qualified train driver or has received specific training and is responsible for implementing safety measures under the ultimate responsibility of the test driver, including giving briefings before and debriefings after the test run. The test ride supervisor was also authorized to stop the test run if safety was at risk.
- Lastly, the **test leader** is responsible for carrying out the test plan and discusses it during the briefing, they do not have specific authority regarding the safe execution of the test run. The test leader on the train is in charge of the overall study amongst the different test locations.

During dedicated tests the remote fallback functionality was also studied. In that case, participants were also located in the ROC in Utrecht. Within the Remote Operations Center (ROC), the following roles participated:

- The **research leader**, who manages overall coordination and guidance of the study in the ROC.
- the **remote driver**, who operated the train remotely during the tests. These drivers previously completed the remote driving training described in Task 38.1, and participated in the RTO tests of Task 38.2

During the tests, **technical support** is offered by system experts of CAF, physically present onboard of the train. A digital video connection (Microsoft Teams) is used to connect all participants at the various locations and communicate during the experiments.

The test- and research leaders are actively involved in the project; this small group of operational experts and researchers were trained by experts that have operated in similar roles during earlier remote driving studies of NS. The SD and test ride supervisor are supplied by TreinTestCentrum (TTC) and have special qualifications for performing test work. They have different levels of experience with remote driving and Automatic Train Operation (ATO). Some TTC drivers involved in this experiment have previously been involved in remote driving tests in the role of safety driver.

3 TECHNICAL SOLUTION

This chapter describes the technical solutions that are applied as part of this study, it specifically involves the modifications of the existing train asset. The technical solution for this demonstrator is integrated into an existing train asset called the Sprinter New Generation (SNG), of the CAF Civity class. The SNG unit is equipped with ETCS and STM-ATB signalling system. The technical solution, integrated into the existing train, is divided into three stages based on Grade of Automation, with an incremental number of logical components and actors in each stage:

- **Remote GoA1 (RTO):** Driving from remote facilities with ETCS/STM-ATB supervising driver.
- **Remote GoA2:** Driving from remote facilities with operative ATO technologies over ETCS/STM-ATB transitioning seamlessly between ETCS and ATB equipped lines.
- **Autonomous GoA4:** Self driving and operating with the possibility to supervise and fallback operation from remote facilities.

For this deliverable, only the GoA4 stage is described as planned within the scope. The other stages are described in deliverable D38.2 and 38.3.

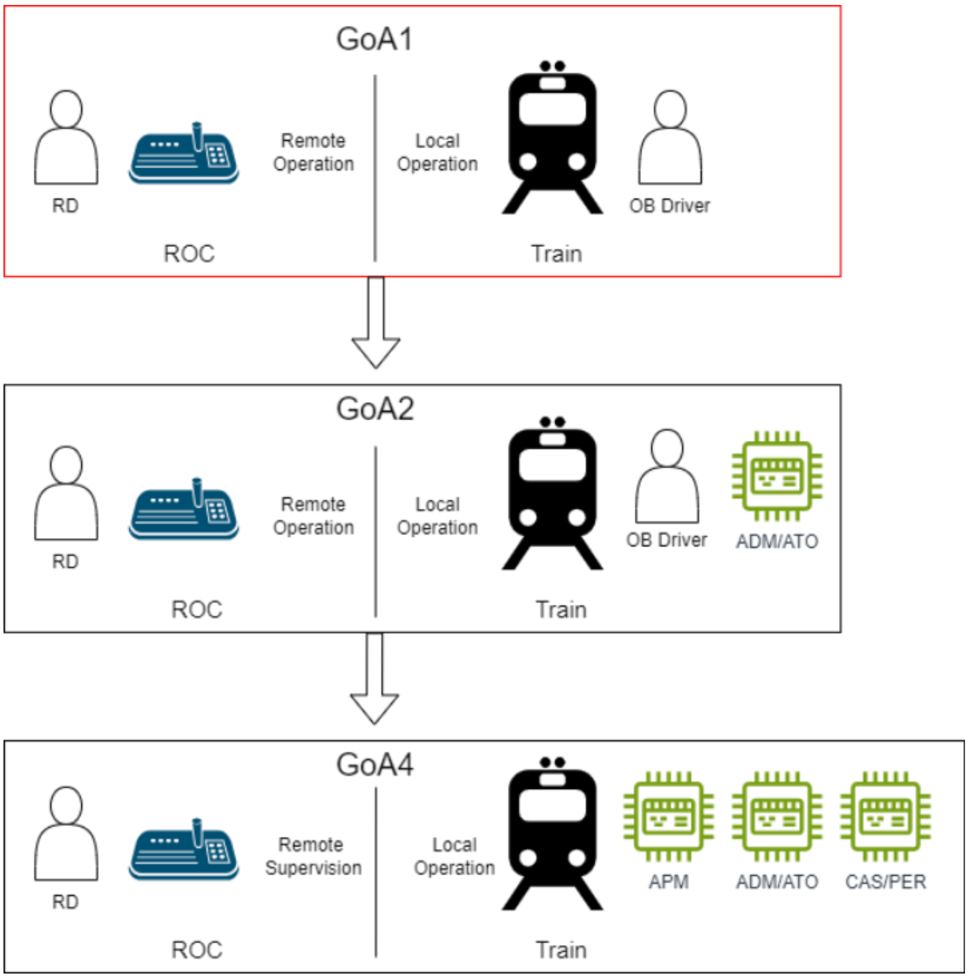

Figure 7: Incremental actors along GoA stages.

3.1 ATO Onboard Solution

The ATO onboard solution replicates all shunting and stabling functionalities autonomously (over ETCS and STM-ATB). The vehicle shall be ready to execute mission profile (concept defined for future standard for ATO GoA3/4), react in front of obstacle and enable cabins, change them, switch travel direction and other task.

Reliability / Safety: the train will operate simulating unattended movements. The reliability to protect the vehicle against overspeed and rebase of movement authority when operating in non-ETCS environment shall be high. Diversity of sensor (visual and thermal camera, and LiDAR) and diversity of algorithms (AI + classic visual computing) will be in place. Everything integrated with the vehicle.

3.2 Main Functions

The system is based on an ATO-GoA2 solution that has been extended with additional functions required for ATO-GoA4 operation. Each of these implemented functions are based on R2DATO WP6 Deliverable 6.5, SRS version 1.1.1 functions and WP5 Deliverable 5.1 Use Cases. The relationship between the implemented functions and both documents is represented in Table 1, where the applicable functions and use cases are indicated, not representing the full set of functions and use cases defined in the reference documents.

Table 1: Implemented functions

Implemented function	Related T6.5 functions	Related TP5.1 use cases
Wake-up and switch-on the train	12.3.10 Manage mission execution	UC5.1-001 UC5.1-002 UC5.1-003 UC5.1-004
Manage mission profile	12.3.10 Manage mission execution 12.3.8 Define consist leadership	UC5.1-010 UC5.1-011 UC5.1-014
Operate driver actions for shunting operations	12.3.4 Emulate action from driver 12.3.6 Start coupling 12.3.7 Start splitting 12.3.3 Deactivate driver activity control	UC5.1-012 UC5.1-013 UC5.1-027
Manage incidents and obstacle during mission	12.3.11 Monitor System status 12.3.12 Check departure conditions except signalling	UC5.1-019 UC5.1-027

execution and collision avoidance system.	12.3.13 Define evaluated reaction depending on incident 12.3.14 Define reflexive reaction depending on incident	
Perform cabin change	12.3.1 Determine running direction 12.3.10 Manage mission execution	UC5.1-005
Switch-off and put the train in stand-by mode	12.3.10 Manage mission execution	UC5.1-011 UC5.1-012 UC5.1-013
Location from start-up	12.3.1 Determine running direction	UC5.1-005 UC5.1-027
Non-ERTMS environment protection		UC5.1-027

3.3 System Architecture

This section summarizes graphically the logical architectures of the solution and how it matches to architecture defined in R2DATO Deliverable 6.5 version 1.1.1.

3.3.1 Logical architecture

Figure 8 shows the logical architecture used for the design of the solution. As can be seen in the figure, the architecture defined in D6.5 version 1.1.1 of the R2DATO project—the latest version agreed at the European level and intended to become standardised—has been followed as closely as possible.

Since there are no depots in the Netherlands equipped with ETCS to carry out the tests, the system includes an adapter that allows it to operate over the national ATB train protection system. Moreover, because the tests are performed in an open environment with mixed traffic, the testing permits do not allow any modifications to the onboard EVC, which makes the use of adapters necessary in this solution.

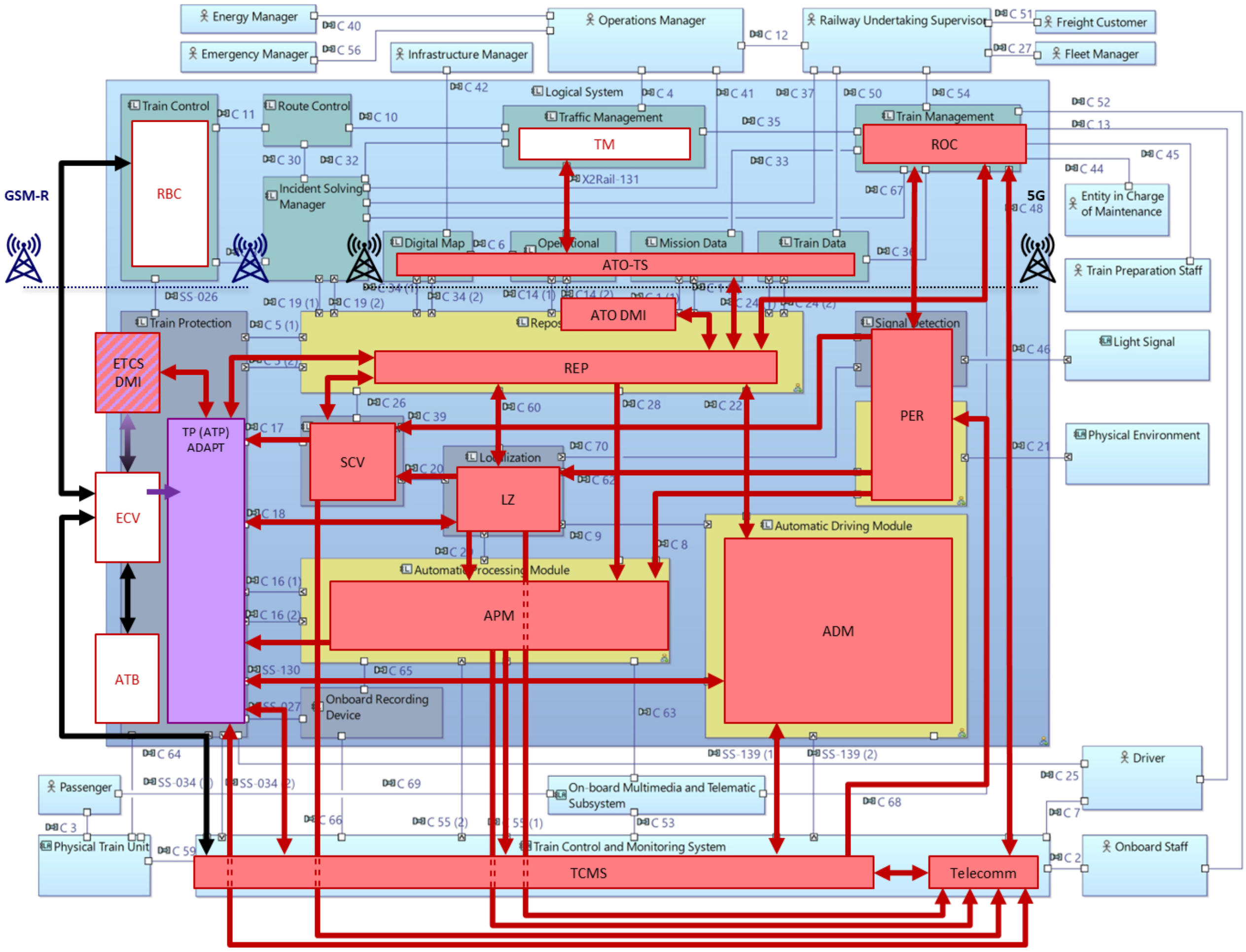

Figure 8: ATO GoA4 logical architecture match to R2DATO (EU Rail baseline) architecture.

3.4 Developed Technologies

3.4.1 APM – Mission Profile management

When operating under ATO GoA2, the train only performs one task (a movement from point A to point B) for each JP received from trackside. However, in ATO GoA4 mode, the train has the capability to execute a task list that combines different JPs with tasks that in ATO GoA2 are executed by the driver, such as coupling.

Table 2 contains a list of the tasks names including their acronyms used for the current version of APM supports. Note that the interface defined between REP and APM includes more tasks that future GoA4 train should do in operations with passenger.

Table 2: Task names and description

Task ID	Task Name	Description
TJP	Journey Profile	The train goes from location A to B, driving automatically.
TCP	Coupling	The train goes to coupling mode and perform coupling operation.

TUP	Decoupling	The train goes to decoupling mode and perform decoupling operation.
TSB	Standby	The train goes to standby mode. Open disjunctor.
TSD	Shutdown	The train shuts down. Panto down. Minimum energy consumption mode.
TTA	Train Awakening	Train wake-up and preparations were out-of-scope for this study.
TC1	Enable Cabin A1	Enables cabin A1.
TC2	Enable Cabin A2	Enables cabin A2.

3.4.2 Remote Supervision

Actual GoA4 operation and Remote Operation Centre integration allows a remote operator to monitor GoA4 operation by receiving low latency video and train data feed and by having the ability to pull the brake lever to intervene if remote control mode is selected in the ROC. This operation mode is called Supervised GoA4 but it is indeed the intermediate step from GoA2 to GoA4, a kind of "remotely supervised GoA3".

3.4.3 Collision Avoidance System

For Autonomous Train Operations, a Collision Avoidance System is needed to preserve safety when an obstacle is present. This system's functionality goes beyond detecting obstacles, as it also needs to process them, react to them, and correctly handle their disappearance. Because of that, the proposed solution includes (parts of) many sub-systems; most notably, PER, APM, TP Adaptor, ATO & TCMS.

In few words, PER detects objects as potential obstacles, APM processes them and assesses their risk, TP Adaptor sends them to ATO while also supervising the braking with the possibility of directly requesting brake from TCMS. Details about the solution can be found in this section.

3.4.3.1 APM Collision Avoidance Functionality

As the central part to the system, APM handles GoA states and decides when and how to perform CAS duties.

In GoA4 state, it is responsible for safely stopping the train, so before and during any task in the MP involving train movements (TJP, TCP) the operational conditions are constantly checked:

- There is connection to PER.
- There is connection to LZ.
- LZ is located with a reference balise.
- No manual override is taking place (local or remote cabin activated by driver).

Should any of those operational conditions fail, APM transitions to AV (Available) or FA (Failure) state, which results in the TCMS applying EB (Emergency Brake) directly unless a manual override is taking place.

APM can also actively request FSB (Full Service Brake) to be applied by sending TP Adaptor an FSB request which will directly send a Full Service Brake command to TCMS . These situations can trigger a brake:

- The current task is a TJP, the train is moving and ATO is not in EG (Engage) state.
- TJP just finished. The brake is used to disengage ATO.
- An obstacle is detected inside the pre-defined safety zone of 15m.
- PER Operational State is not ACTIVE. This means that there is still connection to PER, but it is not able to correctly carry out its duties.
- A LZ or PER packet reception error was found.

In the rest of the cases, normal operations can be resumed. PER is responsible for environment perception, detecting different kinds of objects in the sensor data it collects. That information is shared with APM, including relevant characteristics such as the type of object, the 3D position and a unique ID provided by the trackers.

Note that an important design decision for this solution was to abstract PER from Train Operations: apart from receiving basic data such as the active cabin and the train speed from the TCMS, PER performs independently from the rest of the sub-systems. It uses an internal reference-frame, placing objects in relative positions to the train, and it is APM who translates that to the format expected by TP Adaptor: position relative to the reference balise.

APM filters the received objects to select potential obstacles by applying previously agreed upon and configured risk zones (Figure 9: PER zones definition

): Track Zone (inside the tracks), Near Track Zone (up to 0.5m from the tracks) and Protection Zone (up to 1.5m from the tracks). Information about the closest object in these zones will be sent to TP Adaptor as EoA to stop the train (Track Zone, Near Track Zone) or as TSR (Temporary Speed Restriction) to reduce the train's speed (Protection Zone).

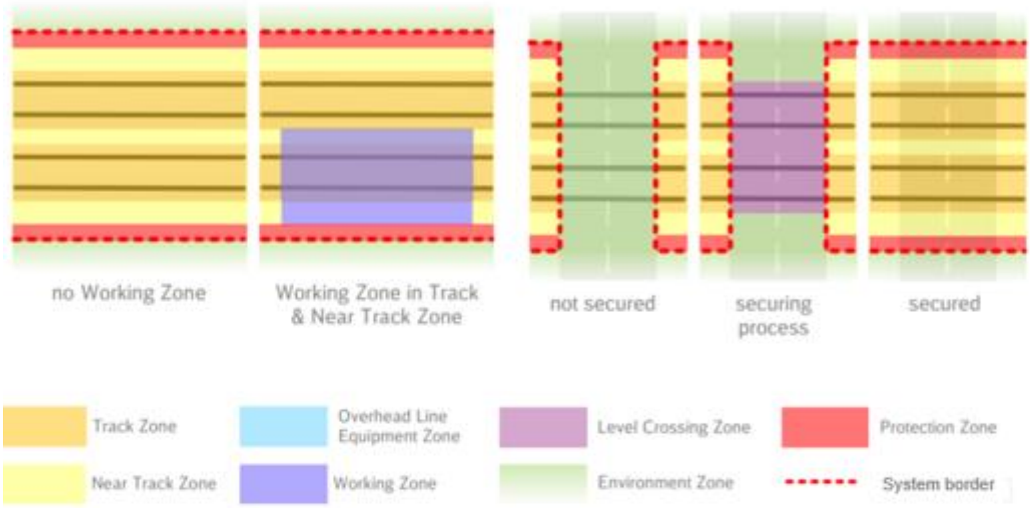

Figure 9: PER zones definition

TSR restrictions can be leveraged to get a smoother behaviour by the train:

- The desired speed can be indicated in TSR-s; this way, during the first seconds this limit can be progressively lowered to avoid rough braking.
- Even when sending an EoA due to an obstacle being in tracks, a TSR from the actual position to the obstacle is also sent.

Other implementation details are as follows:

- APM applies a delay correction to the distances reported by PER.
- On top of that correction, a pre-configured offset is used for safety reasons, considering objects to be closer than they actually are.
- APM can cross-check the positions of Buffer Stops in the DM.
- APM maintains detected obstacle EOAs for some time for safety reasons to prevent early moving of the train.
- APM uses the information about the object type (Person, Train, Buffer Stop…) of obstacles to trigger different behaviours apart from stopping the train. For instance, stopping in front of another train is a pre-requisite for TCP; or the train stopping in front of a Buffer Stop in a TJP can mean that the task is done, even if ATO did not reach its intended EOJ.

The TP Adaptor receives this information and merges it with the incoming data from SCV: another EoA (such as a Red Light) and the MRSP (Most Restrictive Speed Profile) profile from signs and signals. If the obstacle is closer than the previous EoA, it is updated. For speed limits, the most restrictive MRSP profile is calculated, updating the signals-related one with possible TSR-s from APM.

During the TJP task, both EoA-s and the updated MRSP profile are sent to ATO so it can calculate a valid braking curve. Note that it is not necessary to modify ATO in order to integrate it into the CAS functionality – it needs no context about the reason behind EoA and speed limits.

EoA and TSR-s are constantly updated with information provided by PER. This means that when an obstacle is no longer present, restrictions will be calculated using the others; and when no obstacle is present anymore, those limits will be lifted without treating this situation as an edge-case. This approach is also robust to possible errors in assigning unique ID-s to objects.

3.4.3.2 Obstacle Detection – PER

The PER prototype developed for a previous "ATO GoA2 over ETCS and ATB" project (Elaborated in D38.3) was extended with Obstacle Detection functionality. This new version implements Sensor Management (sensor reading, synchronization, fusion, recording), Signal Detection, Obstacle Detection and communications with other systems. In the next sections, PER acronym is used to identify the Obstacle Detection functionality of the general perception prototype.

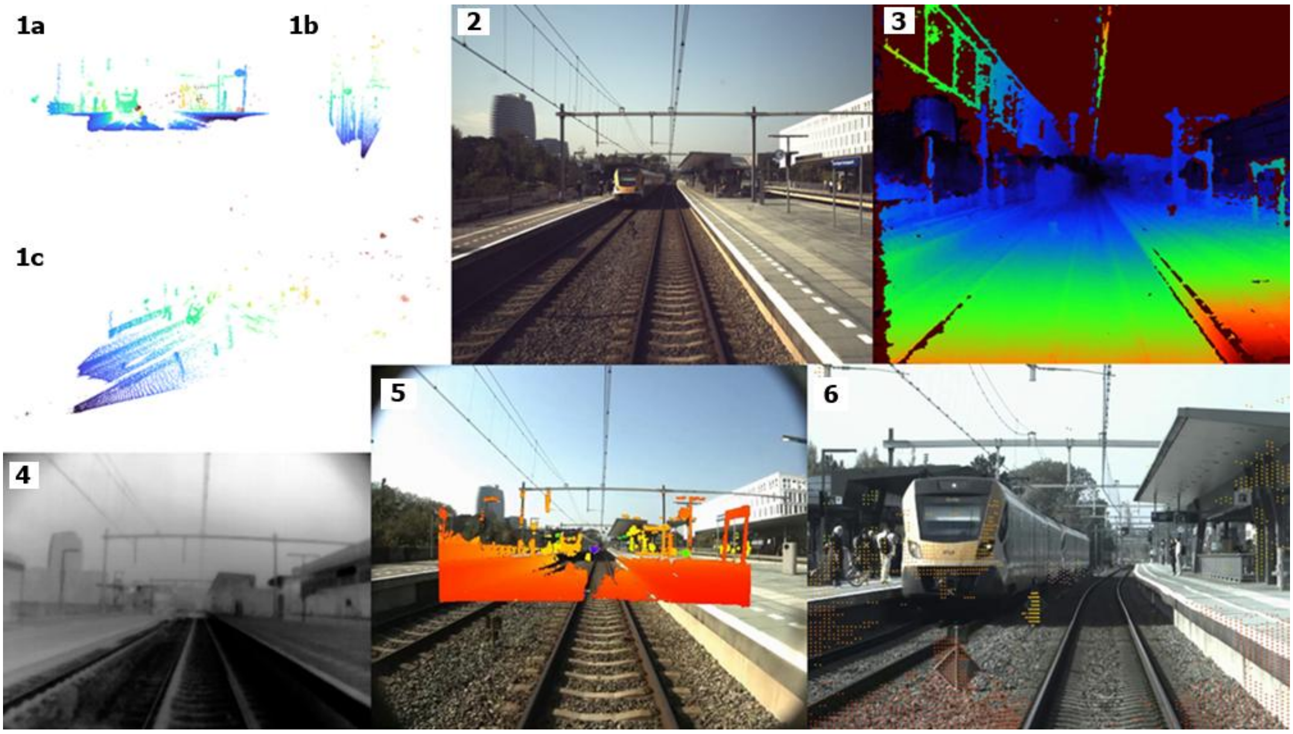

Figure 10: PER sensors example when positioned at a station platform: (1) LiDAR frontal (a), top (b) and side (c) views; (2) stereo camera's RGB output; (3) stereo camera's disparity map; (4) Thermal camera; (5) Short Range camera with LiDAR depth map on top; (6) Long Range camera

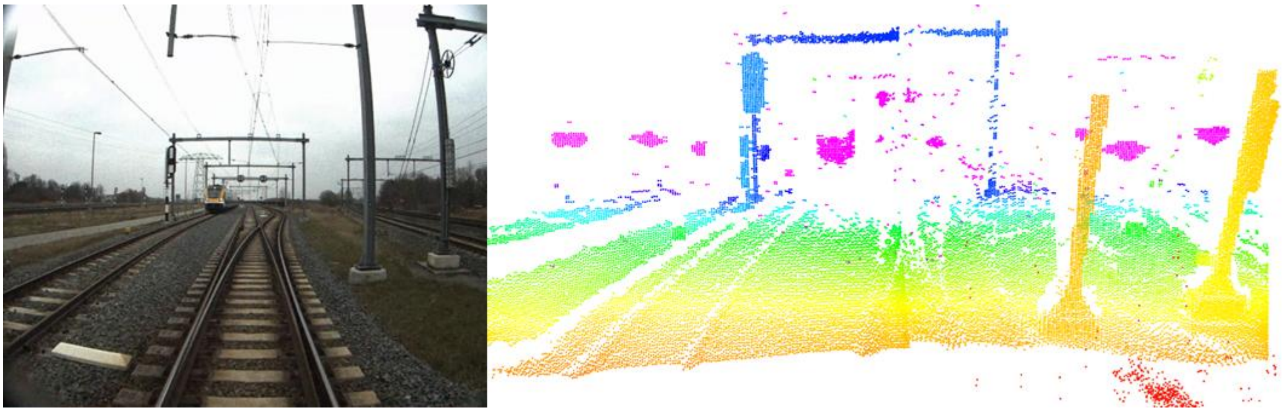

Figure 11: Camera vs LiDAR view example.

PER system's sensor setup for this project consists of two sensor boxes: stereo camera and LiDAR-box.

Stereo camera, with two Short Range (SR) RGB cameras with 8mm focal length, aligned and pre-calibrated against each other. Inside the sensor both images are processed and matched pixel-to-pixel resulting in a disparity map (image 3 in Figure 10) and output together with the left image (image 2 in Figure 10). For each pixel in the image, this map codifies the horizontal difference in pixel between the cameras. Knowing the intrinsic and extrinsic calibrations of the sensors, this disparity can be translated into distance and used to estimate 3D positions.

LiDAR-box, consisting of a LiDAR (images 1a, 1b, 1c of Figure 10), SR camera with 6mm focal length (image 5 of Figure 10), a Long Range camera with 35mm focal length (image 6 of Figure 10) and a thermal camera.

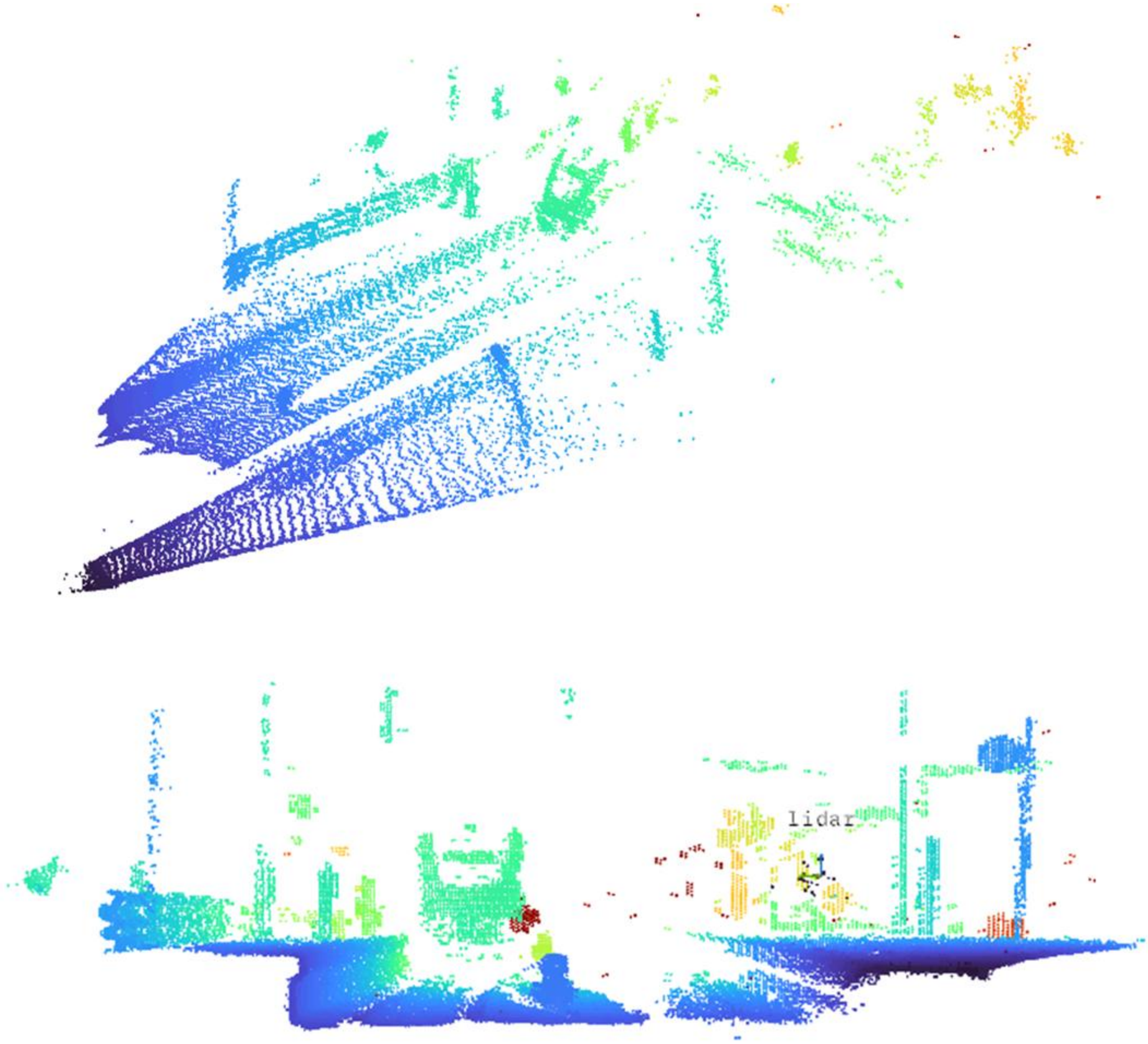

Figure 12: LiDAR view examples at a station platform (lateral and front).

Sensor		Resolution (pixels)	FoV (º)	Focal Length (mm)	Frame Rate (Hz)
Stereo cameras		1216x1024	48x40	8.0	10
LiDAR-box	Short Range	1232x1028	69x60	6.0	20
	Long Range	2064x1544	16x12	25.0	20
	LWIR	320x240	56x42	4.0	10

Table 3: Technical specs of RGB and LWIR (thermal) cameras.

Sensor	Point Rate	Resolution	FoV (º)	Frame Rate (Hz)

	(kb/s)	(º/reading)		
LiDAR	500	0.13x0.13	60x20	10

Table 4: Technical specs of LiDAR.

Table 3 and Table 4 summarize some of the relevant technical specifications of the selected model: imaging cameras (RGB and thermal) and LiDAR, respectively.

Two different Visual Obstacle Detection solutions were developed and integrated in the train, one for each group of sensors (stereo camera and LiDAR-box). In both cases, the pipelines are similar:

- Object Detection. A Convolutional Neural Network is used as AI model for Object Detection with types Person, Train, Buffer Stop and Road Vehicle. This set of classes was chosen based on examples found in recordings. As decision-making was simplified not to react differently based on attributes, no distinction was made for sub-classes (such as children or workers wearing safety vests for Person; different kinds of vehicles for Road Vehicle).
- Bounding Box Tracking. A tracker based on Kalman Filters is applied to the detections, to filter False Positives and False Negatives and to assign unique ID-s to the detections.
- 3D Positioning. Regions defined by the Bounding Boxes are analysed in disparity or depth maps provided by the sensors. Using known calibrations and geometry, tri-dimensional position relative to the train front can be estimated, together with physical width and height attributes.
- Track positioning. 3D position is translated into distance over the predicted path of the train, and the distance from the object to the middle of the tracks. This step could have different inputs in the generic solution (a Digital Map, visual segmentation of tracks…); for this prototype, a visual AI model was developed to estimate the track topology up to the first switch using RGB images. For small distances, the whole front of the train is monitored, regardless of the estimated track curve.
- Top-view tracking. Another Kalman-based tracking step smoothens object trajectories in time.
- Filters & interface with APM. Custom filters can be used to adapt the internal information used in PER to the format and specification of the interface with APM.

Additionally, LiDAR-based 3D detection algorithms were tested in static test days inside the depot. Without using RGB cameras nor Deep Learning techniques, traditional Point-Cloud post-processing, filtering and 3D clustering of points showed potential for an alternative detector.

Nevertheless, for the sake of simplicity and correct global operation, only the visual solution based on stereo camera is active during Dynamic testing, as challenges related to the reliability of the LiDAR box and uncertainty added by more advanced but less tested pipelines could become distraction from the real focus of the tests. Consistent detection of pre-stablished Person, Train and Buffer Stop classes in a robust system works better for the purpose of this project, as the focus was not PER but overall GoA4 Operations. The benefits of including LiDAR should be further analysed in future projects.

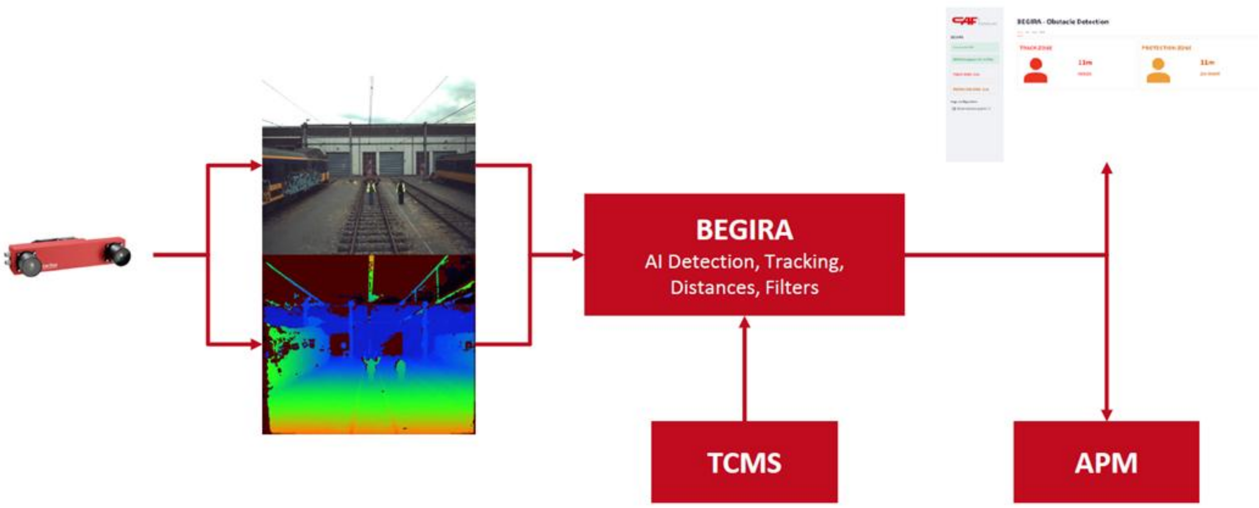

Figure 13: PER OD pipeline used for Dynamic testing, integrated with APM.

As seen in Figure 13, the stereo-based pipeline is integrated with both TCMS and APM, receiving and sending relevant information to these subsystems. For informative purposes, a basic GUI was implemented to give test staff and drivers live knowledge about how the OD system is performing.

Other implementation details:

- PER reads basic information such as active cabin and train speed from the TCMS.
- PER only turns on sensors in the active cabin.
- PER records active cabin's stereo camera data as video whenever the train is moving (and PER powered on) synchronized with TCMS data.
- PER fits inside a 100ms cycle between receiving a new image from the sensor and sending it to APM.
- After a cycle without new sensor data and/or obstacle detection result, PER Operational State will be reported as FAILURE.

3.4.3.3 AI Object Detection Model

The obstacle detection task is performed with a deep learning-based model. As for the signals detection task data collection, choosing an architectural model and definition and validation of KPIs is needed.

The train and validation sets used to train and evaluate the deep learning-based obstacle detection model has 8835 and 600 images respectively, recorded during the static and dynamic tests in the train and collected iteratively. The set of labels defined for the model contains 4 classes, "Train", "Person", "Road Vehicle" and "Buffer Stop". The distribution of these classes in the most updated training and validation sets is shown in Figure 14.

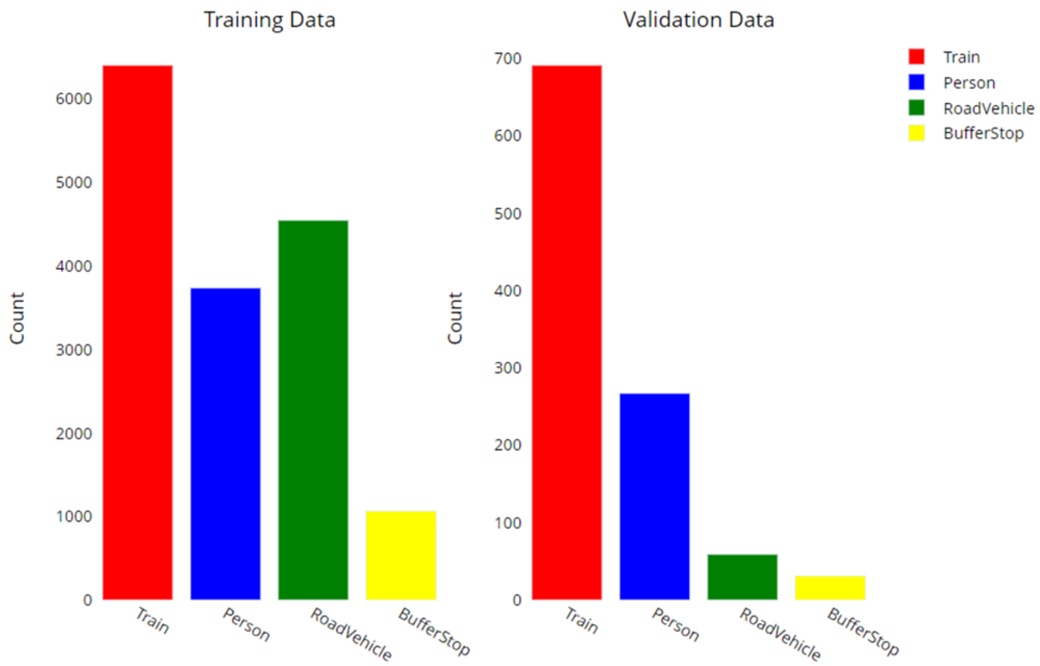

Figure 14: Distribution of the obstacle labels in training and validation sets.

3.4.4 Location from start-up

For the ATO Automatic Shunting tests, a new feature was implemented in LZ that made it possible to have train localization from start-up. The high-level description of the algorithm in which this feature was based is described next:

If LZ module does not have a reference balise and a new DM is received, the two closer balises to the train are found by means of the haversine formula and saved for future calculations, together with their distance to the train and the distance between them. Apart of this, and considering that all the balises in the DM are sorted by their absolute position, LZ also saves the balise prior to the closest one.

If the distance between the two closest balises is greater than the distance from the train to the second closest balise, it means that the train is between the two closest balises. To know which of the two closest balises is the actual reference balise, the ID of the balise prior to the closest balise is compared with the ID of the second closest balise. If these IDs happen to be the same, the second closest balise is chosen as reference balise. Otherwise, the closest balise is the one selected as reference balise

If the distance between the two closest balises is not greater than the distance from the train to the second closest balise, the train might be before or after both of the two closest balises. To know which of these is the actual case, the ID of the balise prior to the closest balise is compared with the ID of the second closest balise. If these IDs happen to be the same, it means that the train is after both of the two closest balises and, therefore, the closest balise is chosen as reference balise (see Figure 16). If the ID of the balise prior to the closest balise is not the same as the ID of the second closest balise, the train lays before both of the two closest balises and, therefore, the balise prior to the closest balise is the one chosen as reference balise.

In all these cases, the odometry value that the train would have had when crossing the reference balise is calculated by subtracting the distance from the train to this balise from the current odometry value of the train.

3.5 Trackside

At the moment of testing, no TMS or ATO-Trackside functionality exists in the Netherlands. Therefore, NS has developed the required Traffic management and Train management functions as defined in the logical architecture (Figure 8) with its own development teams.

These functions are effectively:

- Trackside service to deliver subset 125/subset 126 compliant journey profile and segment profile data. This service is based on the existing journey profile / segment profile services for the NS C-DAS system and has a live connection with the ProRail production traffic management system to receive real time journey profile updates. The service ensures the data consistency requirements as specified in subset 125 and subset 126.
- Trackside service to deliver mission profile data in a pre-TSI subset like binary data format. The mission profile service is not connected to any production planning system. Scenarios can be defined in readable text as a sequence of tasks (as defined in paragraph 3.4.1) and the mission profile service converts these to binary subset messages to provide to APM. In this way the various tests can be accommodated in a very flexible way.

The figure below shows an overview of the components involved in traffic and train management.

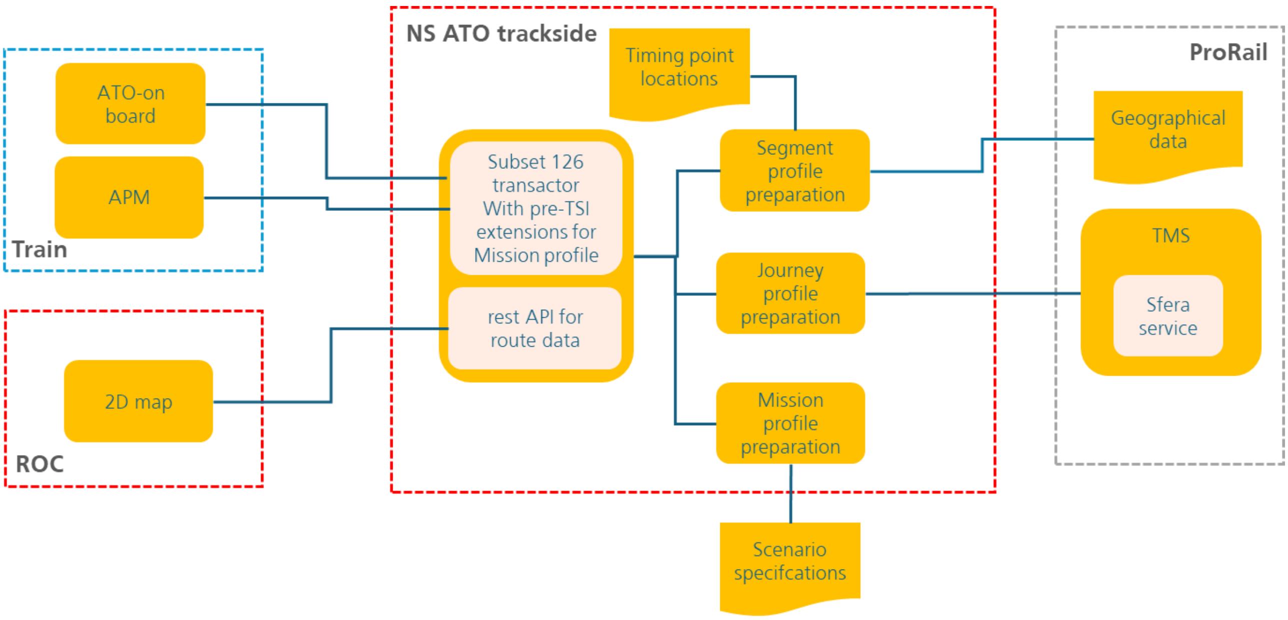

Figure 15: ATO trackside architecture

4 RESULTS

The test campaign took place with a total of 49 autonomously operated test runs during the period of June until September 2025. This excludes additional test runs that were performed for the purpose of system validation, driven manually due to technical or operational restrictions and tests for demonstration purposes. During this timeframe, an approximate 392km was driven autonomously, with a total driving time of 9 hours and 45 minutes. Tests were conducted during the summer, featuring mainly dry conditions and cloudy or sunny skies, all tests were performed under daylight conditions. A couple instances of light to moderate rainfall were encountered during the study. There have been no instances of severe weather conditions and snow, and slippery track conditions were minimal.

4.1 General Observations

Throughout the test runs, observations were made by the people involved in the research on the technical feasibility of the specific driving features and generic findings related to driving under ATO-GoA4. This chapter will describe the findings for the different topics.

4.1.1 Task feasibility

As anticipated, the first week of ATO GoA4 dynamic testing proved to be challenging. The transition from GoA2 to GoA4 required multiple system updates to work together, which made it difficult to pinpoint the causes of issues encountered. It also took some time to validate and improve the data of the local infrastructure, especially due to ongoing maintenance in the test environment during the test period resulting in infrastructure changes. Nevertheless, significant progress was made, and by the start of the second and final week of testing, a reasonably stable GoA4 version was established. From that point onward, the focus shifted to postponing major fixes and applying only minor updates to ensure a stable GoA4 system.

Overall, the fundamental tasks, such as stopping at the correct location and maintaining timely operations, were executed effectively. However, the successful completion of these tasks largely depended on the accuracy of the input data for the stopping positions and the passenger timetable coordination with other trains to ensure on-time driving.

During testing, several manual interventions were necessary, especially in the early days of testing. For instance, when discrepancies arose in the passenger timetable of other trains, the safety driver had to take manual control to maintain proper timing. Additionally, if the system encountered localization issues or difficulties in resuming automatic operation after stopping at station Kennispark, the safety driver manually moved the train before allowing it to continue automatically. Lastly, in cases where the run could not be completed at the intended end location, the system failed to conclude the run properly and was unable to perform cabin switching.

Table 5 summarizes the final status of the GoA4 system on the different tasks that were in the scope of these tests.

Table 5: Mission Profile task identifiers, names and performance when executing them.

Task ID	Task Name	Performance
TJP	Journey Profile	Successfully performed. The train showed conservative behaviour on stations, where temporary speed restrictions were often triggered.

TCP	Coupling	Successfully performed.
TUP	Decoupling	Successfully performed. After decoupling brake tests must be done (manually).
TSB	Standby	Successfully performed.
TSD	Shutdown	Successfully performed.
TTA	Train Awakening	Train wake-up and preparations were out-of-scope for this study.
TC1	Enable Cabin A1	Successfully performed. Had the limitation that the TRN had to be inserted manually after the automatic cabin activation.
TC2	Enable Cabin A2	Successfully performed. Had the limitation that the TRN had to be inserted manually after the automatic cabin activation.

4.1.2 Start-up location

After some initial tweaking, the algorithm designed for localizing the train from start-up resulted to be successful. During all the dynamic GoA4 testing days, it was possible to provide ATO with reliable location data from the beginning. Figure 16 shows the train's location status as soon as one of the runs from Enschede to Hengelo commenced on 23 June 2025. The highlighted balise (ID 313) was selected by the designed algorithm and provided ATO with ERTMS positioning data until the next balise was passed, after which the LZ resumed normal operation.

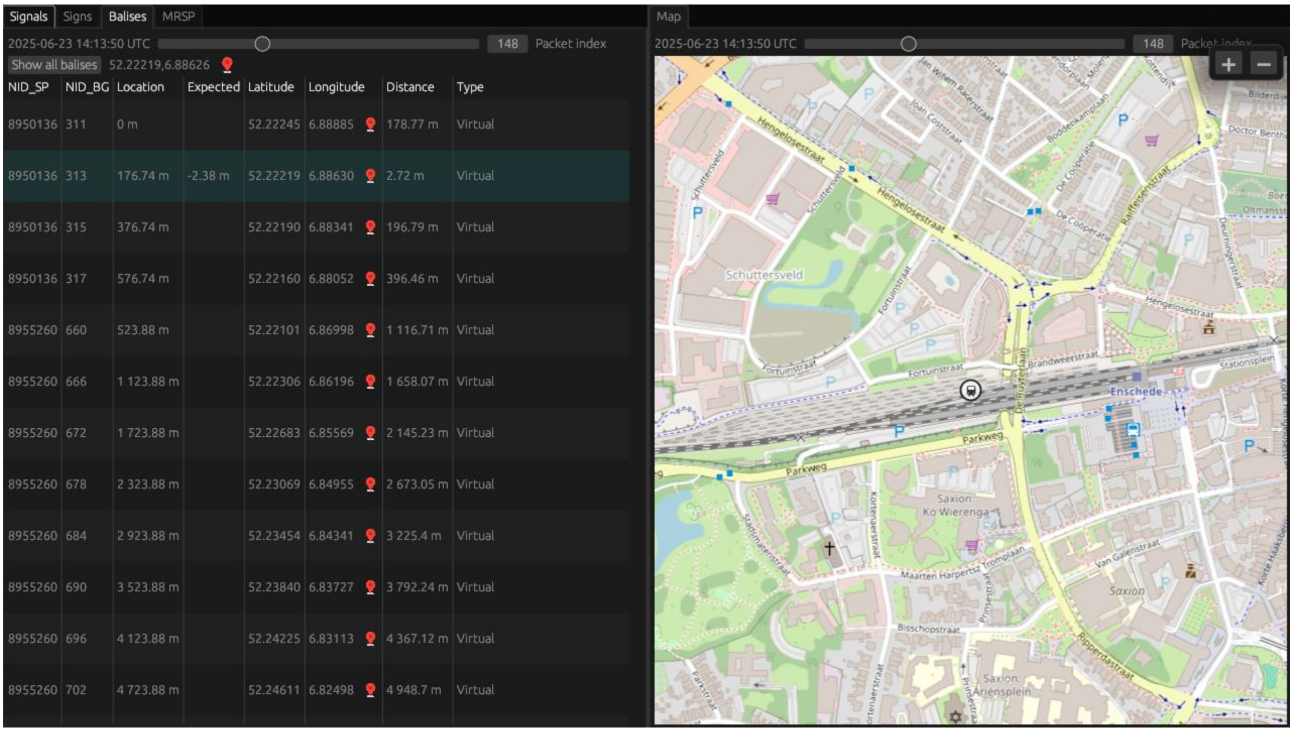

Figure 16: Location from start-up.

4.2 Collision Avoidance System (CAS)

During the initial phase of testing, some issues were encountered with the Collision Avoidance System (CAS) and the integration in the full ATO-solution, resulting in safety driver interventions when approaching obstacles. However, upon resolving of these issues and achieving system maturity and stability, the CAS performed really well. This is under low operating speed (20km/h) and good weather conditions. Most of the scenarios involved a Buffer Stop or another train for coupling, in both cases before the nominal EOJ location for ATO, and the train safely stopped at the pre-defined 15m distance (at least). People standing close to the edge of platforms also triggered speed restrictions in Enschede and Hengelo stations.

No False Negative was reported during the tests (a real obstacle not detected by the system). False Positives included people close to the platform edge but still behind the security line in the floor, and other trains crossed in adjacent tracks while in curves. See PER results section for more explanations.

During static testing in Amersfoort, Person detection was also tried in the following ways:

- A person stands in front of the train while it is stopped. The train is not able to move.
- A person stands in the protection zone. The train detects it and lowers the speed until passing the person's location. Then accelerates again.
- A person stands in Near Track Zone (0.5m outside the tracks), and the train stops.

Safety procedure for APM Operational Conditions loss was also tested, with the train applying FSB when PER Processing Unit experienced a fault or LZ positioning error, as an error in positioning could also lead to an incorrect stop in obstacle, and not being able to move until LZ reported a valid position to APM.

4.2.1 Overall performance and detection range

Given that the proposed solution is based on visual information for detection with AI models, weather, lighting, and visibility conditions can severely affect the performance of the system.

Table 6: Consistent detection range for different types of potential obstacles, from measurements by CAF & NS staff during static testing in Amersfoort.

Obstacle Type	Detection Range (m)	
	Stereo camera	LiDAR box
Person	50	70
Other Train	70	90
Buffer Stop	70	90

Table 6 shows the conclusions drawn from various static test days in Amersfoort, with consistent detections up to the specified range in meters under standard circumstances: daytime, good visibility, no sensor malfunction. The test days included changing weather (cloudy, light rain, sunny days), different hours of the day (morning, afternoon) and both cabin setups. Performance is quite stable across the sessions and the pre-defined Track, Near Track and Protection Zones. In case of person detection, the tests were carried out only with a mannequin wearing an adult-size reflective vest, as this would be the target to detect in a real shunting operation. At least 10 test runs were performed with mannequins in the demo operating environment.

Figure 17 is an example scene where PER is able to successfully detect Person type obstacles in front of the train. A person walks across the front of the train, 12-13m away from it, and another one is standing 50m away. The one crossing tracks is painted in orange (Protection Zone) and red (Track Zone), while the detected person that is not an obstacle is white. Figure 17 is from a static test day in Amersfoort where a Train inside Track Zone and a person outside zones are detected (left) before coupling, and a Buffer Stop's physical elements are detected (right).

Using LiDAR box more range was achieved mostly thanks to the long-range zoom camera (35mm focal length). Just for the detection step, its potential is even better, and the AI model could detect obstacles even further than the reported 90 meters. However, beyond that distance the LiDAR points are too scarce or non-existent, so objects cannot be placed in the 3D world.

Nighttime detection was left out of scope for this analysis, but preliminary conclusions from Endurance recordings and CAF internal tests show that: AI models should perform OK in short range if artificial light is added (such as stations); LiDAR range should increase, and noise-level should be smaller; obstacles with reflective surfaces (Buffer Stop or people with safety vests) should be easier to detect.

Figure 17: PER output example in Amersfoort shunting area. Person outside (left, white) and Train (left) and Buffer Stop (right) in Track Zone (red).

4.2.2 Obstacle detection AI Model performance

Table 7 shows the confusion matrix with the errors of the model in the validation set. It describes the error types for the labels the model detects. The goal is to maximize the values in the main diagonal (True Positives). The last column contains the False Negatives (nothing is detected where an actual label stands), and the last row the False Positives (a label is detected where there is not any). The errors are coloured based on the severity of the error. The errors with the highest severity are when the obstacle is not detected, and it has an impact in the integrity of the train. Not detecting a person also has a high impact, but in this case the integrity of the train is not affected. We consider an error with a medium impact when the model detects an obstacle, but there is not any because the operational process is affected, but there is not any party hurt.

The model misses some of the obstacles in the set, but these errors are because the obstacle is far away from the train or for cases when there are crowds of people or group of road vehicles parked at some distance of the railroads.

Table 7: Errors for the obstacles in the validation set

		predicted				
		train	person	road vehicle	buffers top	FN
actual	train	659	0	0	0	32
	person	0	206	0	0	61
	road vehicle	0	0	33	0	26
	buffer stop	0	0	0	28	3
	FP	23	26	13	1	
Very high impact						
High impact						
Medium impact						
No risk						
Impossible						

4.2.3 Distance measurements and accuracy

Another important aspect for successful obstacle detection is distance estimation. After the corrections applied to the stereo camera, the error for the first 100m was below 10%. That is enough for safe operations, considering additional offsets introduced by APM and ATO.

For LiDAR distance measurements, all distances were exact to below 1m error for the tested objects up to 100m, according to measurements with a 50m metric tape and other tools such as GPS positioning. Note that the surface material, sun interference and noise can affect this, and that for each object a cluster of points is present, each of those with a particular distance that varies a few centimetres.

4.2.4 Braking distance

For the critical systems that were introduced for this project, their maximum cycles are known, adding up to 418ms between them: 100ms for PER; 100ms for APM; 100ms for TP Adaptor; and 128ms for TCMS. After TCMS requests a service brake, that information is sent to Brake Control Unit and then a physical reaction happens. Given the unknowns before and after the implemented systems (sensor capture time, network latency and electrical/pneumatic reaction), a safe margin of 1 second was used to estimate braking distances for the train.

These estimations are analysed in Table 8. For each reference speed, reaction delay specifies the previously mentioned upper bound for the delay of the systems after PER sensor capture in processing the obstacle's presence and applying brake. By the time this request is done, "distance to reaction" meters will be travelled. From that point on, assuming that the train is braking at 100% of its braking capacity, time and distance needed to fully stop the train is calculated. Finally, both are combined to estimate the minimum distance needed to halt the train after PER sensors have captured an obstacle.

Table 8: Minimum braking distance for the train after detecting an obstacle.

Speed (km/h)	Speed (m/s)	Reaction delay (s)	Distance to reaction (m)	Maximum deceleration (m/s^2)	Time to halt since reaction (s)	Distance to halt since reaction (m)	Distance to halt TOTAL (m) (ceil)
5	1.39	1	1.39	1.1	1.26	0.88	3
10	2.78		2.78		2.53	3.51	7
20	5.56		5.56		5.05	14.03	20
34	9.44		9.44		8.59	40.44	50
40	11.11		11.11		10.10	56.12	68
80	22.22		22.22		20.20	224.47	247

This high-level analysis of the braking distances makes certain assumptions:

- The 1s reaction time is a rough estimate based on field experience.
- The halting distances were estimated assuming a direct FSB request by TP Adaptor. In real scenarios, ATO could use a smoother curve if it has more space.
- These estimations are based on static objects. Obstacles moving towards the train or moving away from it radically change the values.

And preliminary conclusions can be drawn from it:

- With the current range of PER system, speeds up to 34km/h would be covered by CAS in good visibility conditions.
- Even though the maximum speed during dynamic tests was 80km/h, in those places where obstacle is most likely to appear the train goes much slower: the static limit inside the shunting yard is 20km/h, and in stations 40km/h. Moreover, near Stopping Points and EOJ locations, ATO is already in a braking curve even without obstacle detection.
- For the rest of the route, lowering the maximum speed to 30km/h could be evaluated, reducing the efficiency of operations, but improving safety.
- In a hypothetical scenario where the system is not able to fully halt and avoid collision, reducing its speed as much as possible reduces the impact and the risk of the collision.

Trackside-based obstacle detection can be used to complement the on-board PER in case of curves obstructing the vision, for level crossings and to increase the detection range.

4.3 Remote monitoring and remote GoA1 fall-back

During test execution Remote driver was able to brake interrupting GoA4 mission execution stopping the train. With train stopped, remote driver was able to change the controlling mode from remote control to remote driving enabling the Remote GoA1 mode and was able to carry on train operation. This operation was also successfully performed after a safe break caused by APM loss of GoA4 operational conditions.

4.4 Technology Readiness level

It is important to note that the definition of an interoperable standard for GoA4 driving technology is still in the early stages of development. However, during the conducted tests, the technology, based on available definition in D6.2 of R2DATO, was successfully implemented and the correct operation was demonstrated across various trials. The demonstrator operates over ATB, and although the system has been developed to work over ETCS, it incorporates adapters to operate with the Dutch national signalling system.

The actual solution was initially validated in the laboratory up to Technology Readiness Level (TRL) 4, technology validated in lab, before being deployment on the Train.

Finally, the system was tested in field trials to validate its performance under real operational conditions. It is important to highlight that these tests were conducted in a real mixed-traffic environment, both within the depot and on the mainline, covering the route from the depot to the first passenger station. The tests replicated real operational conditions in terms of both physical location and operational dynamics. They were conducted on different trips between Hengelo and Enschede with maximum speed 125km/h. In addition to track tests and use case demonstrations involving stabling and shunting, demonstration sessions were also conducted.

Within this operational context, the core functionality of ATO-GoA4 were tested in an operational environment (TRL6) under “happy flow” conditions and under strict supervision of safety drivers and technical experts. However, ATO-GoA4 comprises many additional functions (i.e. degraded mode handling, automatic preparation, extended environmental conditions) that were out of scope for this study. Tests related to obstacle detection were only performed in good conditions with a long shunting track, good weather and a low operating speed (20km/h). The demonstrator is therefore not a stand-alone, complete or operationally deployable GoA4 solution, and no conclusions can be drawn about the overall TRL of a full-scope ATO-GoA4 system.

The evidence on the GoA4-solution’s performance was demonstrated during a live event in Utrecht in September 2025, showcasing the system’s capabilities and maturity to key industry stakeholders. This demo also showcased some of the challenges that still exist, for example unexpected updates to the JP that interfered with the train schedule. Additionally, D10.1 and D11.2 of R2DATO provides a detailed account of the development of the different solutions tested within the WP38 demonstrator. This description can be considered further evidence of the system’s compliance with the design requirements validated during testing.

5 CONCLUSION

The demonstrator has shown that – after an initially difficult integration of all subsystems – it was possible to perform the basic ATO-GoA4 operations such as driving according to a timetable, coupling, decoupling, standby, shutdown and cabin enabling in a real-world environment under "happy flow" conditions and while supervised by human safety drivers and technicians. The scope of the tests verified some of the ATO-GoA4 functions, but several functions (i.e. degraded mode, train preparations) were not integrated on the train.

Train localization from start-up showed consistently positive results. The algorithm designed for initial positioning reliably provided accurate location data to ATO from the beginning of each run. Collision Avoidance System (CAS) performance was also satisfactory, with no driver interventions needed once system maturity was reached. The system correctly reacted to buffer stops, other trains, and people near platform edges, producing only minor false positives and no false negatives when operating at low speeds (<20km/h) in a shunting yard track. Static tests confirmed the system's behaviour when detecting people in different zones and its ability to trigger appropriate speed restrictions or braking when necessary.

Obstacle detection capabilities were evaluated and measured during static testing using both stereo camera and LiDAR inputs. Under normal visibility conditions, detection ranges observed during static tests were consistent, reaching up to 50–70 m for people and 70–90 m for large objects like trains and buffer stops – and in line with the. The AI model generally performed well, although it occasionally missed distant obstacles or those in crowded scenes. Distance-measurement accuracy was within acceptable limits, with stereo camera errors below 10% and LiDAR measurements accurate to within 1 m. Braking-distance calculations, which incorporated system reaction times and maximum deceleration, showed that the current CAS could support operations up to approximately 34 km/h, with reduced speed recommended in more complex environments.

Finally, remote monitoring and fallback procedures were validated during the tests. Remote operators were able to interrupt GoA4 operations, stop the train, and transition to Remote GoA1 mode without issues. This capability was also confirmed following safe stops caused by APM loss of operational conditions. Overall, the test campaign demonstrated solid progress toward reliable GoA4 operation, with successful validation of key functions such as localization, obstacle detection, collision avoidance, and remote fallback control.