Rail to Digital automated up to autonomous train operation

D38.2 – Results of GoA1 remote controlled stabling and bringing a train to the station

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REPORT CONTRIBUTORS

Name	Company	Details of Contribution
Jeroen Braakman	NS	Author, Task Lead
Lotte Lammers	NS	Author
Patrick de Ruiter	NS	Author
Ellemieke van Doorn	NS	Author (HMI topics)
Stan Albers	NS	Author (HMI topics)
Jon Mikel Olmos Serna	CAF	Author
Mikel Labayen Esneola	CAF	Author
Simon Funke	DB	Review
Benjamin Wyss	SBB	Review
Beat Rappo	SBB	Review
Ronald Helder	PR	Review

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EXECUTIVE SUMMARY

This document describes the results of the remote driving demonstrator that was applied during remote stabling operations in the railway region of Twente, The Netherlands. A total of 92 runs were performed remotely, featuring mainly stabling operations performed between Hengelo's station and Enschede's shunting yard. This high-traffic route has a length of eight kilometres, featuring mixed traffic, one intermittent station and an operating speed of 125km/h. The train was remotely driven from the Remote Operation Centre (ROC) located in Utrecht, ~120km away from the physical location of the train.

The tests were performed using a technical implementation of RTO technology developed by CAF, retrofitted into an existing Sprinter New Generation (SNG) regional trainset. This solution has been aligned to match the logical architecture of X2RAIL4 (EU Rail baseline), with adjustments based on technical and homologation constraints. Two information transmission streams were developed allowing low-latency streaming of videos, live parameters and commands for both Train-to-Ground and Ground-to-Train communication. In addition to the onboard modifications, the ROC front- and back-end applications were implemented.

A study was conducted in which train drivers of NS acted in the role of remote driver, performing realistic stabling and driving operations. While they were operating the system, several studies were being performed: (1) a human-factors study with questionnaires investigating the topics of motion sickness, workload, safety and information need, (2) a performance study investigating the ability of the driver to perform basic tasks while operating remotely and (3) a technical study into the (network) performance of the RTO solution in the operational environment. In addition to the studies, observations were made by human-factor experts and the research leaders.

All the drivers were quickly able to use the remote driving solution and perform the basic driving functions of applying tractive or braking effort. More precise manoeuvres such as stopping at a reference location or estimating braking curves turned out to be more difficult when they were relatively unfamiliar with the system, causing them to adopt a more defensive driving strategy. During the duration of the study, only one safety-related intervention was performed by the onboard safety driver, related to the recognition of lineside signals. The technical solution and network coverage proved to be functioning well for most runs with measured latency between the capturing of the camera lens to the displaying on the ROC screens (glass-to-glass) in the range of 150-200ms. The only network issues that made it unable to operate the train remotely occurred when a music festival, with 17500 visitors, was taking place next to the test location, causing bad network connections making it impossible to operate the train remotely. This underlines the importance of a prioritized bandwidth for remote applications.

The results of the human factors study indicate difficulties the remote drivers encountered during their first day of driving remotely such as (A) symptoms of motion sickness, (B) increased workload, (3) speed, distance and braking curve estimations (D) correctly recognizing and distinguishing signal aspects. The researchers believe that the design of the ROC and video streams, the short training, and short duration of the study have contributed to these effects. It is unclear if these issues are also applicable to a target solution, also depending on the operational concept in which the technology is applied. Future improvements to cameras, image quality, screens and the ergonomic design of the ROC may (partially) mitigate these effects, this should be further investigated in future, more mature RTO solutions.

ABBREVIATIONS AND ACRONYMS

ADM	Automatic Driving Module
APM	Automatic Processing Module
ATB	Automatische Treinbeïnvloeding (Automatic Train Protection)
ATO	Automatic Train Operation
BTW	Bureau Tijdelijk Werk (Temporary Employment Agency)
CBG	Centrally Controlled Area
CMOS	Complementary Metal-Oxide-Semiconductor
DMI	Driver Machine Interface
ECN	Ethernet Consist Network
EEA	European Economic Area
ES	Enschede
ETCS	European Train Control System
FOV	Field of View
GDPR	General Data Protection Regulation
GoA	Grade of Automation
HGL	Hengelo
HMI	Human Machine Interaction
HSCB	High-Speed Circuit Breaker
ISP	Internet Service Provider
LOZ/LZ	Localization System
OB	On Board
PER	Perception System
R2DATO	Rail to Digital automated up to autonomous train operation
RBC	Radio Block Centre
RD	Remote Driver
RD-OB	Remote Driving On Board
RD-TS	Remote Driving Track Side
RGB	Red Green Blue
ROC	Remote Operation Centre
RTO	Remote Train Operation

S&O	Service & Operatie
SD	Safety Driver
SNG	Sprinter New Generation
SSL	Secure Socket Layer
STM-ATB	Specific Transition Module – Automatische Treinbeïnvloeding
TCMS	Train Control and Management System
TE	Technical Enabler
Telecomm	Telecommand Manager
TM/TMS	Traffic Management System
TP	Train Protection
TRDP	Train Real-Time Data Protocol
TRL	Technical Readiness Level
TRN	Train Running Number
TS	TrackSide
TTC	TrainTestCentre (of NS)

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1 INTRODUCTION

Task 38.2 "Stabling a train and bringing a train to the station by remote control (GoA1)" 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 has been done into the use of remote control for performing shunting and stabling operations, including the testing of moving a passenger train from a platform track to the depot/yard and back by a remote operator.

The technology of remote driving can function as an enabler for future technologies such as ATO-GoA4, serving as a fall-back method for autonomous trains unable to continue their journey. If this scenario occurs, a human remote operator would be able to connect to the train remotely, assess the situation and attempt to take over control until the Automatic Train Operation (ATO) system is able to resume driving or until the next station.

Remote driving can also be applied as a stand-alone feature for stabling and shunting operations. When a train enters service, the driver usually must go to the shunting yard, prepare the train, and then drives it to the station where the passenger service will begin. The yard's location and layout often require significant buffer times in the timetable to account for walking distances. Additionally, some yards are inconveniently situated, resulting in considerable time and money being spent to transport drivers to the site to start service. By implementing remote control in the stabling process, it will no longer be needed for drivers to physically relocate in between stabling operations, allowing for increased productivity and efficiency of stabling operations.

1.1 PROJECT RELATIONS

1.1.1 Internal WP-relations

This task has a strong relation with the other tasks of WP38, while the remote-control technology incorporated in the NS demonstrator as described in this deliverable is also applied within tasks:

- Task 38.3 *"Stabling a train and bringing a train to the station with remote supervision (GoA2)"*
- Task 38.4 *"GoA4 stabling and shunting, including non-commercial runs, with Remote Control Centre as backup"*
- Task 38.6 *"Remotely controlled coupling and uncoupling"*

Considering that the technical solution and most of the research environment for the remote-control demonstrator of NS is the same in the aforementioned tasks, it will only be described once as part of deliverable D38.2. The other deliverables will not duplicate these chapters but instead refer to D38.2 and mention any differences if applicable.

A pre-requisite for the execution of the remote driving demonstrator of NS is the development of training materials and operational guidelines. This work is performed as part of:

- Task 38.1 *"Training of involved staff"*

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

- Task 38.9 *"Monitoring, analysis, and reporting"*

Within WP38 another demonstrator took place at SBB in which the technology of remote driving is applied in a shunting environment. The results of this study are not part of this document but are included as part of the deliverable D38.7.

1.1.2 R2DATO relations

The demonstrator as described in this study is the result of years of work that was performed as part of R2DATO and Shift2Rail. The work on remote driving within R2DATO started with the establishment of use-cases for remote driving as part of Task 5.4 (M3-M12), the non-functional and functional-requirements of remote driving in Task 6.7 (M13-M25), the definition of architecture and interfaces of remote driving in Task 6.8 (M20-M36) and the development of a functional prototype in Task 12.2 (M1-M42). 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 technology of remote driving is still relatively new to the railway sector; it is expected to reach TRL6 by the end of the R2DATO first project (2026). Operating a train remotely introduces a fundamentally different way of working compared to traditional train driving methods that were used in the past. This shift introduces new roles, responsibilities, and workflows for all stakeholders involved, including drivers and dispatchers. Due to these profound changes, it is essential to thoroughly investigate the implications of RTO on both technical and human factors.

The studies as performed in this demonstrator focus on applying the technology of remote driving in a relevant environment, testing both the technical feasibility of the concept as well as the HMI implications for train drivers who first experience remote driving. The goals include:

- Testing the performance of the remote driving technical enabler incorporated in the demonstrator.
- Providing feedback to the TE-developer, to improve the functioning of the TE, or to enhance/improve/modify the specifications.
- Performing measurements to show the improvement of the new (sub)system over the existing system, to contribute to the realisation of the KPIs defined in the call.
- Providing implementation recommendations on the HMI-related aspects of remote driving.

2 RESEARCH METHODOLOGY

The design of this study is based on applying the remote driving technology in a relevant environment and evaluating three research themes: (1) the human factor impact on the end user (remote driver), (2) the ability of the user to perform tasks when applying this technology and (3) the abilities and performance of the remove driving technical solution. This chapter describes the research method for each of the three study topics.

As this project is researching a technical proof-of-concept for RTO, the solution developed for this test campaign has been limited in scope in order to focus on the most important elements of RTO, demonstrating basic functionalities (i.e. driving controls, camera streams) needed for shunting and stabling in the "happy flow" use cases. This means that scenarios in which the RD and/or system are intentionally confronted with degraded situations (e.g., infrastructure malfunctions, train system failures, or emergency situations) are not included. The preparation of the train (i.e. daily brake tests) is also not included in the scope and is instead performed by the safety driver prior to testing.

2.1 HMI METHODOLOGY

This research adopts a comprehensive methodology to assess the performance of the RD, focusing on multiple aspects of Human Machine Interaction (HMI). In an earlier NS study [1], the validity of the RTO concept from a human machine interaction perspective was investigated using simulation studies. This culminated in a validated proof of concept, with identification of human needs that need to be addressed and insight in limitations of the RTO concept. The aim of the current research as described in this study is to assess the findings from these earlier studies for the first time with representative users in the actual environment.

In addition to the fact that earlier research has contributed to the further development of the RTO workplace and working method, it identified the points of attention and human-centred requirements to support human performance and human technology interactions in case of RTO. For those human factor constructs that turned out to be important, the same research resources were used in this study as in the earlier research phases. Namely:

- **Simulation sickness**: The study monitors and evaluates the extent to which users experience symptoms of simulation sickness during the operation of the RD system. (Appendix B)
- **Workload**: The research measures the cognitive and physical workload on the RD to understand how demanding the system is to operate (see Appendix C).
- **Questionnaire:** A questionnaire investigating the driver's experiences on the topics of situational awareness, latency and safety. (see Appendix D).
- **Eye tracking**: This tool is employed to gain deeper insight into the cognitive processes of train drivers, particularly in situations where they fail to correctly respond to signals or signs.
- **Observations**: An expert in HMI closely observes the test runs to provide qualitative assessments and identify potential issues.

All study participants were asked to fill an informed consent form which can be found in Appendix A.

2.2 ANALYSIS METHODOLOGY

To evaluate the ability of the end user – in this case the remote driver – to perform basic tasks when operating a train remotely, an analysis methodology was developed based on three data sources: task observations from an observer on the train, from an observer in the Remote Operation Centre (ROC) and a combination of both. The selected tasks on which this study focused are:

- The task of driving the train on the route of Hengelo – Enschede while adhering to the rules of the Dutch lineside protection.
- The task of stopping the train at a target location alongside the track.

It was specifically decided to not investigate the aspects of punctuality while the design of the test environment included non-regular timetables, featuring different margins compared to regular operations. Punctuality in NS is only measured for passenger timetable operations, not for shunting operations.

Additionally, after the test runs an interview with the crew on the train and the RD has been conducted to obtain knowledge regarding their experience with remotely controlled stabling and bringing a train to the station.

An observer positioned on the train conducted detailed observations during each test run. These notes offered real-time insight into the operational context and any issues encountered. The data collected includes:

- **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.
- **Scheduled and Actual Departure and Arrival Times:** Data from key stations such as Enschede, Kennispark, and Hengelo were recorded to assess punctuality.
- **Stopping Accuracy:** Measurement of how precisely the train stopped at designated points at Kennispark station as well as Enschede and Hengelo.
- **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.
- **Event Documentation:** Comprehensive logs of all notable occurrences during the test run, including software updates, interruptions by external factors, unexpected stops, and significant changes in weather conditions.

The exact topics that were analysed for each of the test runs may differ based on the actual timetable and operational conditions. I.e. in some scenarios it was not possible to make a stop at Kennispark, therefore making it impossible to perform stopping accuracy measurements.

Parallel to the onboard observations, an observer in the ROC made detailed notes during the test runs. These observers focused on the following factors:

- **Technical Difficulties**: Documentation of any faults, system errors, or malfunctions encountered that could be of impact.
- **Comments** or concerns that were made by the remote driver related to their remote driving experience and performance.

2.3 TECHNICAL METHODOLOGY

Before implementation phase and testing, a proof of concept was deployed in laboratory environment to test integration of different parts of Train to Ground communication. In a parallel way, camera characteristics were also tested during several runs under different lighting conditions (dawn, mid-day, sunset, night) to achieve the optimal camera configuration that fits all situations.

During implementation most important technical matters are latency on video and command transmission and integrity transmitted video over non-reliable physical network layer. To measure these aspects quantitative/qualitative mixed methodology is used.

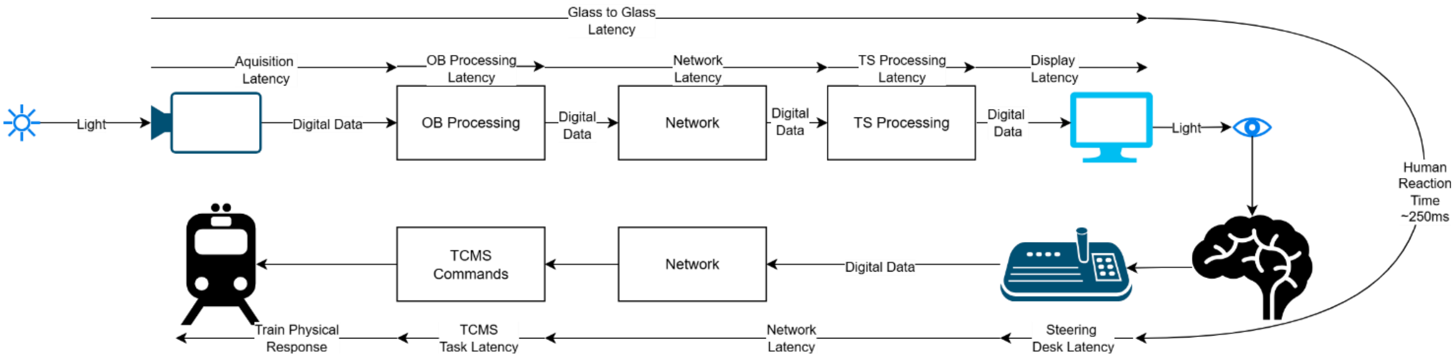


Figure 1a: Latency model for RTO Solution

- **Latency Testing:** Measurement of the video delay between the train and the ROC, which is a key factor in control responsiveness and overall system safety. The latency model for developed system is presented on Figure 1a. Two methods are used to measure this aspect.
    - End to End latency: Latency from optical input of light on train cameras to optical output on ROC displays. This is the most representative measure for latency, and it is also called glass-to-glass latency. Measurement is done by either recording screen with camera producing a loop where a time reference can be seen in all iterations or by recording an atomic clock reference time with camera and checking same time reference on the display side if physical location is different. This method is shown on Figure 1b, where a picture is taken containing atomic clock reference on ROC and atomic clock reference on train seen through streaming system. Difference between both measurements is the actual end to end latency as the reference is common.

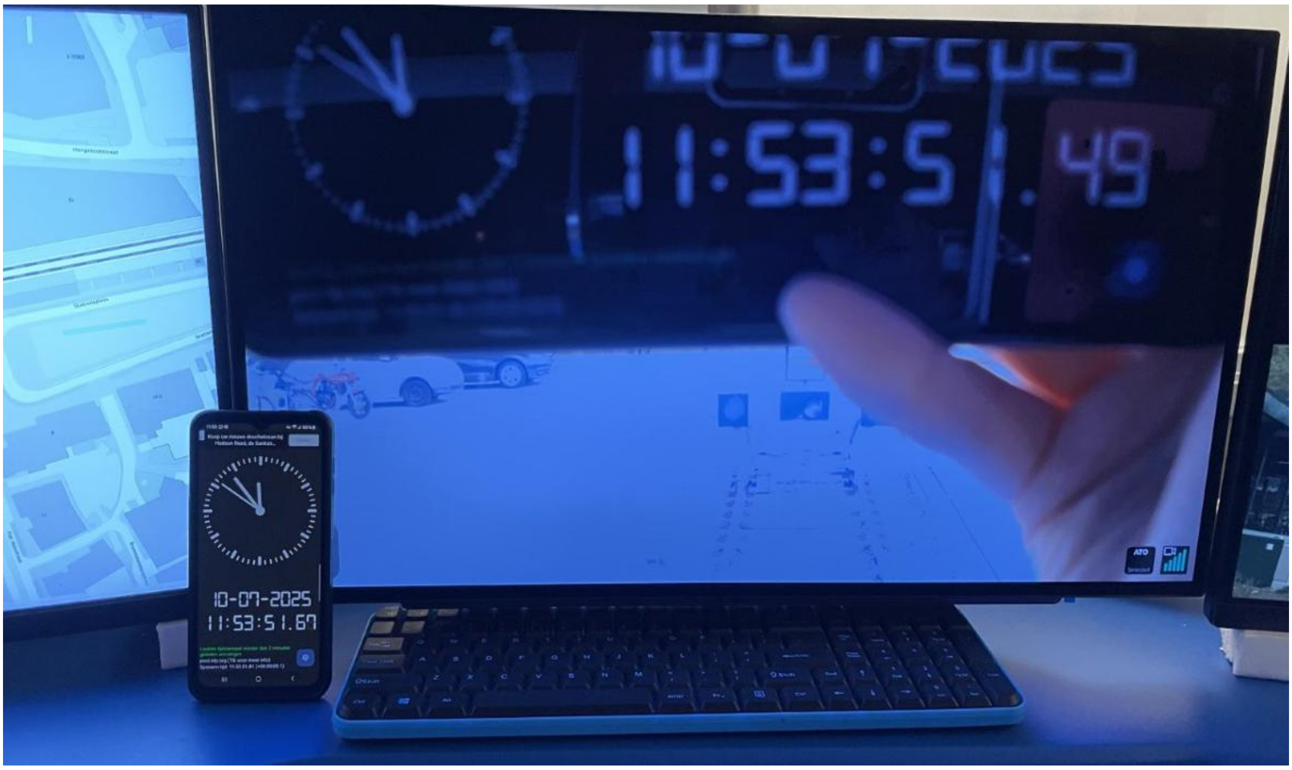


Figure 1b: Measurement using glass to glass method.

- Network Latency: Time that takes for data to be transmitted from train to ROC. It has hard dependency on ISP coverage and band type availability. Measurement for network latency is done by introducing a reference timestamp on train side and reading it on the ROC side. Reference is added on streaming protocol.
- Processing Latency: Time required for executing operation with frames (encoding, decoding, mixing, demosaicing etc.).

- **Image quality:** Image quality is also a key point for video transmission; it is measured qualitatively and quantitatively to fine tune encoding and transmission parameters to enharden stream against information loss.
  - Qualitative image quality control: If packets are lost when transmitted over network blurry blocks can be seen on the image on regions with quickly changing objects due to lack of information when decoding image. This visual control allows to reduce compression rate and technics as much as possible, so relevant information has lower loss rate and not as much, so bandwidth gets heavily affected.
  - Quantitative image quality control: Information loss on streaming can be measured by measuring the packet loss rate counting packets by incremental reference IDs.
- **Latency on command application:** Apart from video feed, command application is the other half of the control loop. It can be measured detecting events on ROC data from traction brake request to application feedback.

The results of the measurements are shown in chapter 4.2.4 and Figure 23.

2.4 TEST ENVIRONMENT

The research as described in this deliverable takes place in two physical environments, which are the ROC in Utrecht and the railway environment between Hengelo and Enschede central stations. The locations of the test environments are displayed in Figure 2. This chapter further describes the characteristics related to the test environments.

Figure 2: The location of the ROC and test environment

2.4.1 Remote Operation Centre

The ROC is located in the head office of NS (Laan van Puntenburg) and is situated in a dedicated room in the IT/OT test laboratory of NS. This room of approximately 35 m² features customizable lighting conditions (i.e. dimming in multiple sectors) and is protected using a badge reader only allowing selected employees to enter. All windows were blocked using opaque foil to prevent interference with passing office workers. Due to the location of the ROC being in the middle of the office building, there are no indications of outside (day)light and weather conditions.

Situated in the ROC is the steering desk, visible in Figure 3, that is used to operate the train remotely during this study. It features control elements similar to the onboard controls and a livestream to the train.

The ROC also has multiple working desks and computer setups that are used by the research leader and human factors researcher during the experiment.

Figure 3: The ROC Steering Desk

2.4.2 Railway Environment Hengelo-Enschede

During this study, the remotely operated 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.

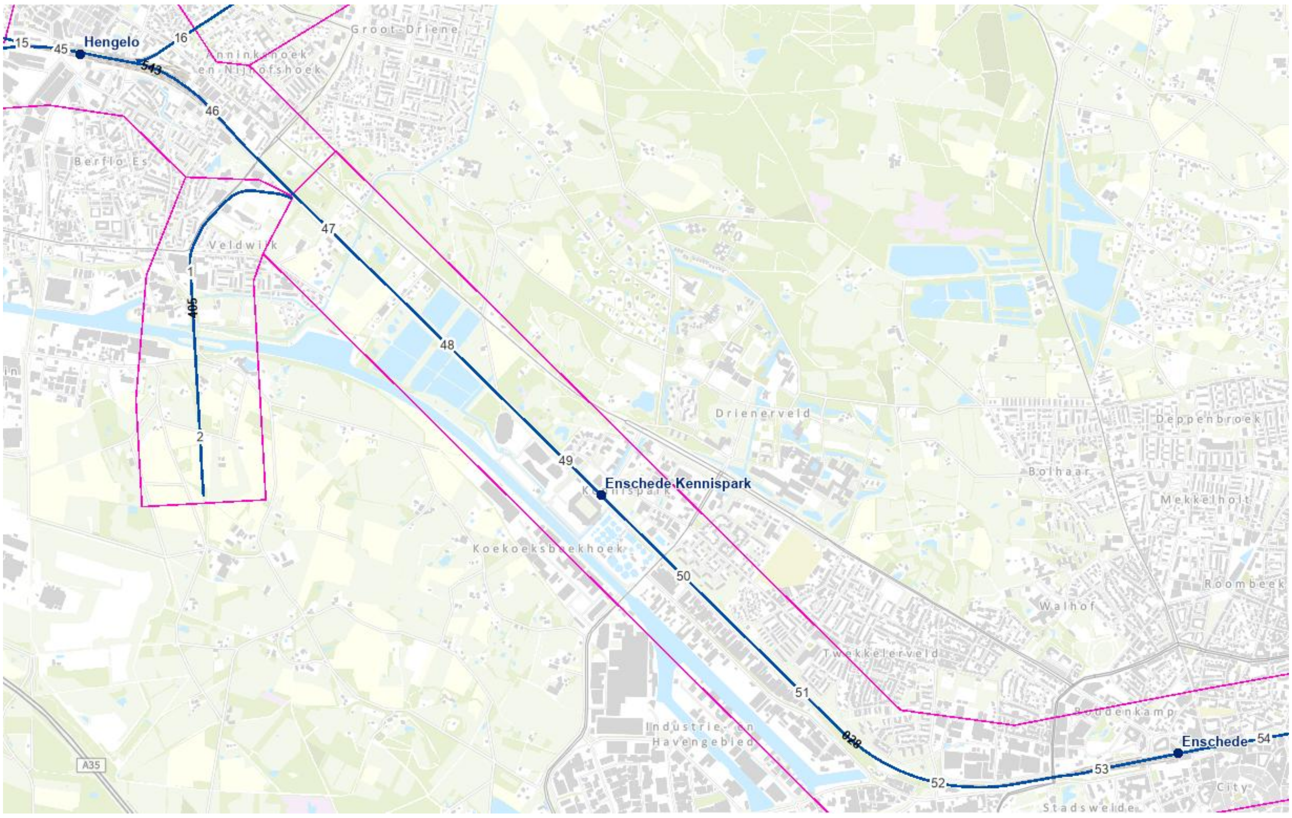


Figure 4: Segment Hengelo-Enschede (BasisBeheerKaart Prorail)

The tests during this study were conducted on tracks that are equipped with line side signalling and a class B ATP (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 5 shows the station and shunting yard of Hengelo. The most common position for the train to be situated at when starting or ending the remote journey is shown as "Train", this position is also shown in Figure 5 & 6.

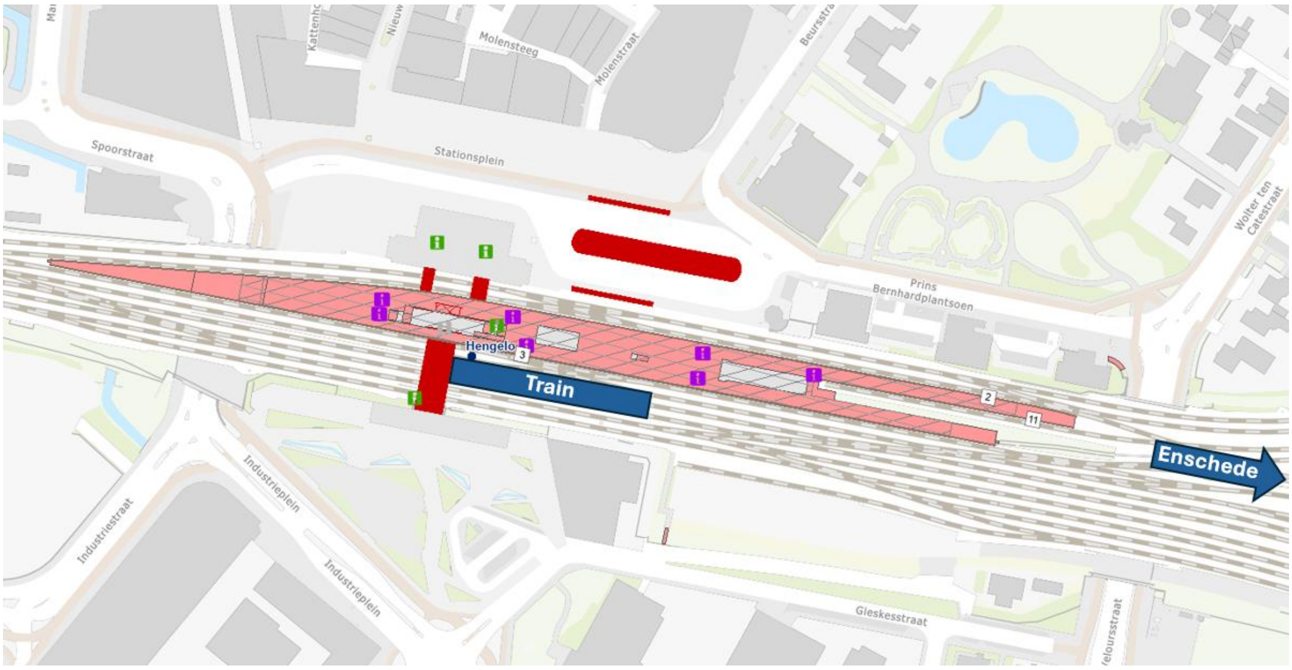


Figure 5: Station area of Hengelo (BasisBeheerKaart Prorail)

Figure 6: 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 4.

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 7.

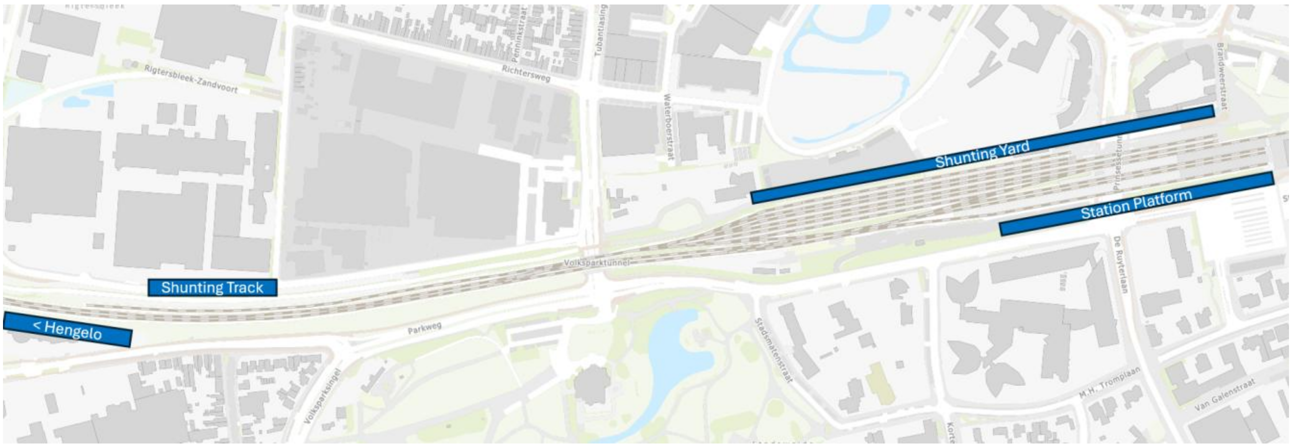


Figure 7: Enschede Station area (BasisBeheerKaart Prorail)

2.5 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 8, 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).

Most of the tests were performed during daytime, either in an early (i.e. 9-15) or late (15-21) shift, with also one test session occurring during the night.

```
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 8: Hengelo – Enschede timetable

2.6 Research Participants & Roles

During the test program with remote driving, several key stakeholders were actively involved to ensure the experiment ran smoothly and safely. Within the Remote Operations Center (ROC), the following roles participated:

- The **instructor/research leader**, who manages overall coordination and guidance of the study in the ROC, as well as training the remote driver.
- the **remote driver**, who operated the train remotely during the tests.
- and the **human factors researcher**, who primarily conducts surveys and operates the eye tracker to analyse behaviour and interactions.

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 the tests, **technical support** is offered remotely by system experts of CAF. During some test days the technical experts are also 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.

The remote driver is the focus of this research and is different for each day of testing. Each of the assigned remote drivers have no earlier experience of performing in the role of remote driver. Personnel taking part in the experiments as a remote driver are assigned from one of the following three departments:

- **TreinTestCentrum (TTC):** Drivers from NS's department for test activities with trains. These drivers are used to operating in unusual scenario's and handling new systems.
- **Bureau Tijdelijk Werk (BTW):** An internal NS department that provides work for train drivers temporarily unable to perform their regular duties due to personal physical or mental circumstances.
- **Service & Operatie (S&O):** The department responsible for the regular day-to-day train operations of NS.

The train drivers of TTC have been assigned by the planning department without specific selection criteria, while the train drivers of BTW and S&O enrolled themselves voluntarily for this experiment. All train drivers involved in the experiment were qualified train drivers, holding specific qualifications for the used train asset as well as the necessary certificates for operating in the test environment. No additional criteria or randomizations were applied in the selection process.

Before being involved in the test runs as described in this document, the participants acting in the role of RD are first trained using the training materials, procedures and operational guidelines as described in Deliverable 38.1. The first three runs of each test day are dedicated to training runs, while the rest of the runs are assigned as research runs. The number of research runs varies between the different days depending on the timetable possibilities, ranging from 4 to 7 runs per test-day.

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 and the ROC.

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 Remote GoA1 stage will be described as planned within the scope. The other stages will be discussed in deliverable D38.3 and 38.4.

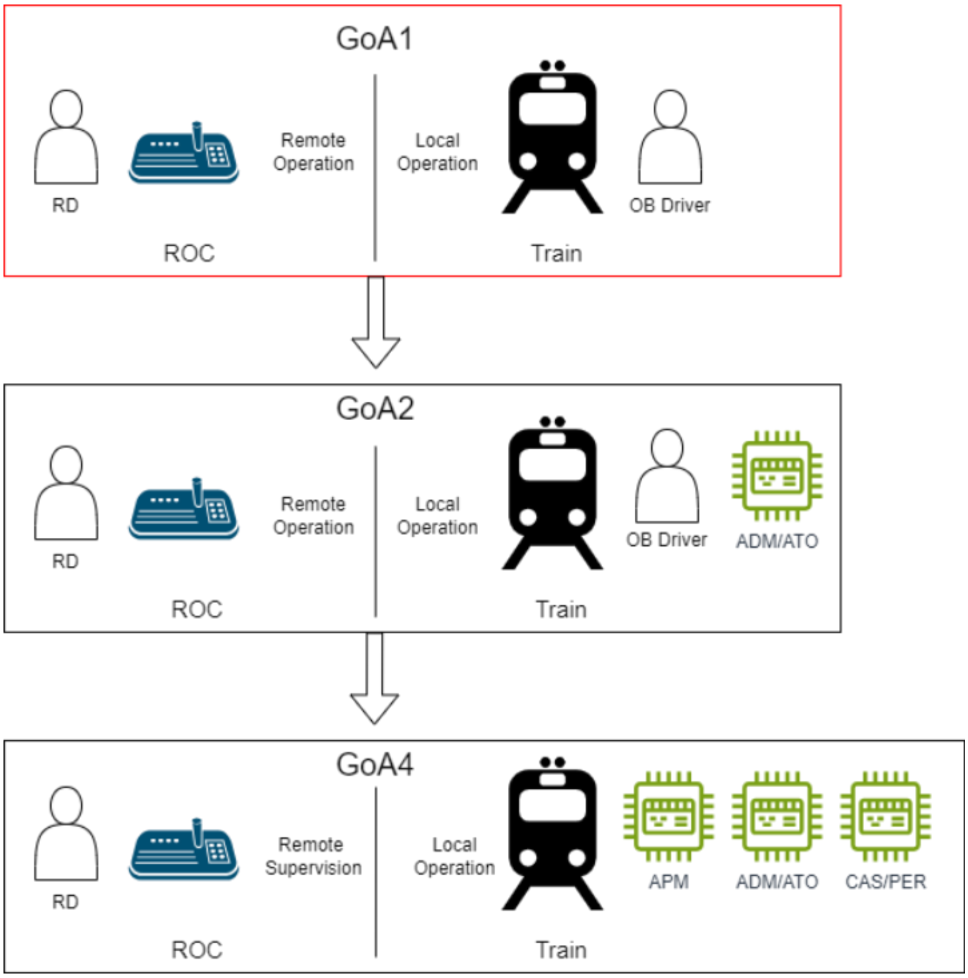


Figure 9: Incremental actors along GoA stages.

3.1 REMOTE DRIVING ONBOARD SOLUTION

The remote GoA1 Solution is intended to let a remote operator manage trains in a non-disruptive way in case of unexpected situation. For that purpose, local train controls are to be recreated in a remote operation facility with a high-fidelity similarity to local train operation environment.

3.1.1 Main Functions

With the RTO GoA1 functionality, a remote operator/driver can ask to telecommand a particular train for shunting and stabling operations. The operator will control remotely the usual driver's commands supervising the front-view of the train and the cab status. Secured communications and low-latency video streaming with different FOV cameras are in scope.

These are the main high-level functions that are available in developed solution:

- Train start-up operations: Start of Mission. (Functionality only proved in depot testing, not applied during field tests).
- Drive the vehicle inside depot.
- Drive the vehicle from/to last/first station to/from depot.
- Shunting operations: (de)coupling.
- Manage train modes: washing and cleaning.
- Stabling manoeuvres.
- Modify streaming parameters to adapt brightness, view angle and image quality to each driver's preferences.

3.1.2 Functional Exchange

All the relevant information for driving and remote operating train is sent from train to ground:

- ETCS/STM-ATB Information: ETCS DMI indicators, Speed limit, Current train speed, ATB Code.
- Train TCMS Information: Operational mode, traction/brake, brake status, door status. HMI info, alarms.
- Positioning information: Current GPS position.
- Low Latency Video stream: Front camera, front zoom camera, coupler camera, pantograph camera.

Next to that, the following controls for relevant commands of the given functionalities are allocated:

- Enter/Leave Coupling mode.
- Command Front Lights.
- Activate Cabin.
- Apply traction and brake.
- Command horn sound.

- Trigger driver vitality device (deadman device).
- Command wipers.
- Operate pantograph.
- Command High-Speed Circuit Breaker (HSCB).
- Command parking brake.
- ATB intervention recovery.
- ETCS Start of mission.
- Video controls, stream selection for main screen and brightness control for main front streams.

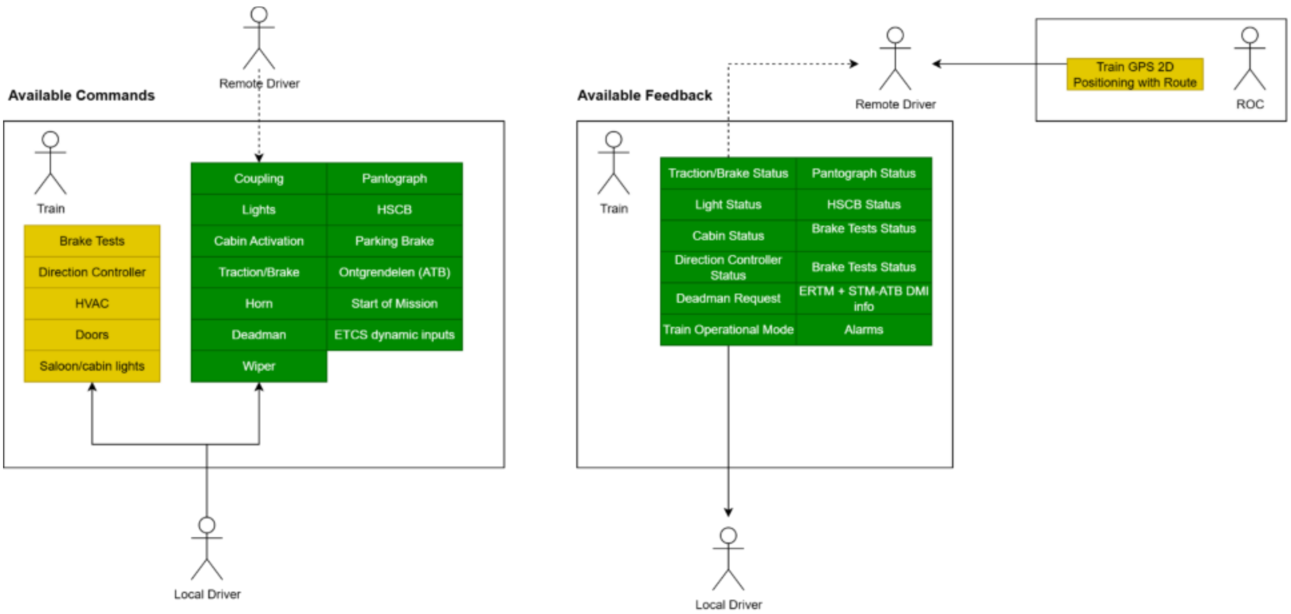


Figure 10: Functional exchange between train GoA1 System and local/remote driver.

3.1.3 Logical Architecture

Figure 11, shows the logical modules, aligned with the EURAIL defined architecture, which are implemented for the demonstrator. The white modules are already installed on the train or part of TrackSide (TS). The red modules are newly introduced for RTO GoA1 solution. The ETCS Train Protection (TP) was not changed from official train baseline due to derogation constraints. Therefore, an adaptor was implemented for covering required integration. Implemented logical modules for GoA1 are:

- ETCS Adaptor as TP module.
- LZ module for localization (GPS coordinates used for 2D map).
- TCMS Extended to support commands from remote operation centre and manage control sources and handovers.
- Telecomm module as Remote Driving – On Board (RD-OB) to act as gateway from train to ground exchanging information securely.

- Perception system (PER) module with dedicated low-latency cameras for streaming video feed to Remote Operation Centre.
- ROC Backend as RD-TS establishing secure Train to Ground connection.
- ROC Frontend as RD-TS displaying video feed and managing steering desk controls.

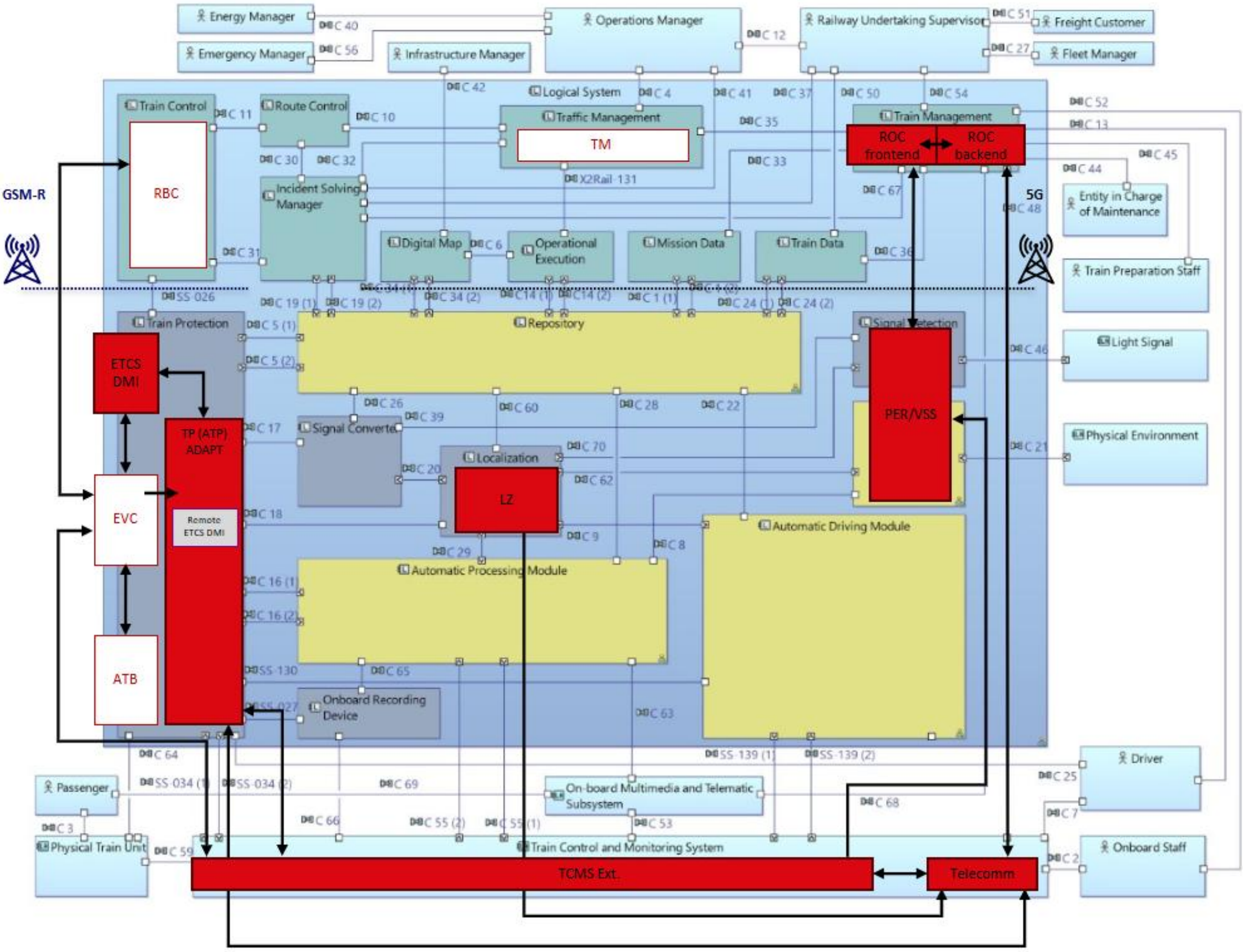


Figure 11: Logical architecture for Remote Driving GoA1 based on X2RAIL4 (EU Rail baseline) architecture.

3.1.4 Physical Architecture

The On-Board Side physical architecture introduces some modifications over previous TCMS and ETCS installation without ETCS modifications due to derogation constraints. To avoid ETCS modifications a TP-adaptor is installed which reads information from ETCS through ethernet debug interfaces.

The new TCMS control unit is installed alongside legacy ones to allocate all new functionalities and interfaces, as well as new Input/Output peripherals to allow required feedback readings and required actions over subsystems from the remote operation centre. A telecommand manager is also installed on railway grade hardware and communicated with TCMS through ethernet using the Ethernet Consist Network (ECN)/Train Real-Time Data Protocol (TRDP) interface.

To generate low latency video streaming, four cameras are installed for each cabin and dedicated high-performance low-latency hardware for encoding streams. Streaming is also integrated with TCMS to switch active camera in terms of active cabin and direction.

Finally, for enhanced communications with remote facilities, a secured 5G router is installed with a respective 5G antenna.

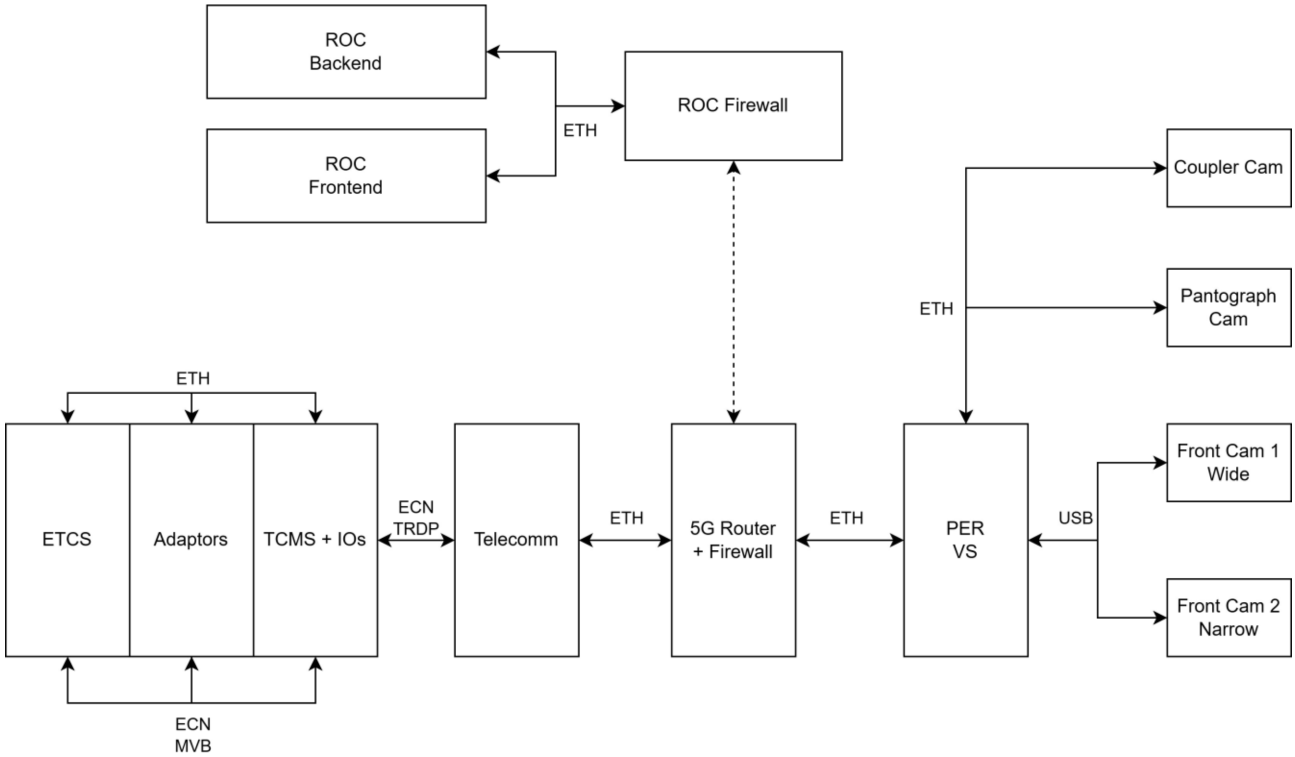


Figure 12: Physical Architecture of full GoA1 Solution.

Figure 13: Physical location of RD Cameras.

3.1.5 Control Handovers

The local train operation and remote train operation must be seamlessly compatible to avoid disruptions in both local and remote driver actions. For this specific scenario, where local supervision is required, control handovers between a local safety driver and remote driver may differ from regular established handovers with requests. This demands some logical level extension in the train's TCMS operational modes and their transitions. Therefore, two additional modes are introduced: Remote Control and Remote Driving. See Appendix E, for a flow chart for handovers and interactions between Train, Local Driver and Remote Driver.

The control is transferred between the local and remote operator using the rules of:

- Local Driver can introduce the cabin activation key and take control over the RD.
- Remote operator can request control which is granted if:
    - ROC is authenticated and authorised for given driver profile.
    - No local driver has control.
    - Connection status is healthy.
- Local Driver takes brake control with any of the levers in the train overriding any action from Remote Operator at any time for prototype supervision purposes.
- Automatic braking is performed if Remote Operator is driving and connection is lost for a given time margin. This margin was set at 2 seconds during this study. Safe reaction is also triggered if there is network degradation producing latency increase over same time margin. System recovers automatically if connection is recovered and no traction is applied.

The control priority is designed based on R2DATO mechanisms defined in addition to specific considerations for operational safety in prototype testing. The following criteria principles are applied:

1. Until Video/Control transmission channels from train to ground are fully end-to-end validated, local driver has either highest-fidelity visual and train feedback and has the most-immediate ability to control train to intervene in case of disruption. Therefore, local control shall be predominant over all other controls apart from train protection's safe intervention.
2. Connectivity is not reliable enough to assume that transmission channels cannot be broken. Based on that potential risk, connection health status during remote operation shall be monitored and safe reaction shall be defined in case of disruption of connection or significant delay on data transmission.

3.1.6 Developed Technologies

3.1.6.1 PER Low Latency Video Streaming

A low latency video streaming was developed to provide a real-time video feed from front view, coupler and pantograph for the remote driver. Next to that, the video streaming system was integrated with train operational variables (TCMS) to change the streaming cameras in terms of active cabin and reduce data rate. This four-stream solution is highly optimized to fit in available bandwidth and is tuned to be the best encoding quality possible within the provided bandwidth limitation. Additionally, the camera configuration is also tuned to be optimal for expected mutable lighting conditions, such as night, dawn, day, tunnel or fog. Transmission details are fine-tuned to cope with information loss avoiding the appearance of video artifacts. To measure transmission latency a specific protocol was added at network level in both train source and ROC destination.

In addition, since the brightness level is driver-dependent, two control knobs are added to the remote table to change the brightness level while driving, allowing the driver to change the brightness based on the current lighting and weather conditions. Telecommand Manager: TCMS-Telecomm / RD-OB.

For remote operation the information transmission is vital for both the directions Train-to-Ground and Ground-to-Train. For this purpose, a service has been developed that permits this connectivity to mirror variables in both ways. The developed service operates on a Telecommand Manager system on board and connects to a listening-server in the ROC. After connection is established, variables coming from ROC control sources are transmitted to the train for periodic control and variables coming from several On-Board subsystems are transmitted to the ROC for periodic control.

In short, the TCMS incorporates a new logic sub-module that interfaces for the management of the interaction with ROC:

- To apply telecommands coming from the ground are received and executed directly by the TCMS. Although coming from different channels, such as the physical cabin, Automatic Driving Module (ADM) or ROC, the TCMS will manage the same actions.
- To collect all the information coming from the remaining modules and that is of interest for display in the ROC.

3.1.6.2 Train Control and Management System: TCMS

The TCMS has been upgraded to allow for interaction with new logic signalling modules. For instance, the TP-Adapter (GoA2+GoA4) and the Automatic Processing Module (APM) (GoA4), as well as required interface with telecommand manager (RD-OB). The TCMS is also responsible to deploy all the logic that guarantee the control priority over the train and manage coexistence of all GoA levels in their local and remote variants.

3.1.7 Security Considerations

During the design phase, cybersecurity considerations were analysed. Performing the operation over a public network carrier also implies the need for measures to avoid external intrusions in both the ROC and the train. The implementation is based on key points for secure communications:

- **Encryption:** In publicly available communication media information must be coded to avoid the risk of confidential train information and commands being handled by external agents. This is achieved by implementing an Internet Protocol Security (IPSEC) VPN service from train to ground.
- **Authentication:** Even in an encrypted channel identity of peers must be verified to prevent fake controller from controlling the train. This Authentication is implemented by using Secure Socket Layer (SSL).
- **Segmentation:** By design, the train-ROC link is isolated from On-Board control network to avoid lateral damage in case of intrusion. On ROC different networks are also segmented to avoid lateral intrusions.
- **Private Access Point:** ISP provides a private access point where no other peers can join. From this point of view, despite the use of public 4G/5G Carrier, there is no reachable network route to train router but from ROC.
- **Firewall on both endpoints:** Application of firewall rules in both ROC and Train gateways guarantee that no unmanaged intrusion path is enabled.

3.1.8 Safety Considerations

The project scope focuses on functionality development, however, safety consideration must be integrated into the solution design phase to minimize the risk of incidents during testing.

During the RTO tests, a local safety driver is always on board of the train and can intervene if necessary. The following implementations are needed to ensure this:

- Emergency brake push-button must remain unaltered after the solution implementation. Wiring of the emergency brake is not altered and is checked after every change on circuits and TCMS software.
- Local brake lever must be considered over any other control but emergency brake during remote train operation. Train software implementation enforces this requirement allowing local driver to be able to brake always with the local manipulator overriding remote manipulator command.

A disconnection procedure is implemented in the train software to respond in the case of severe connection loss between the train and the ROC. This procedure ensures that:

- If life word coming from ROC is not updated after 2 seconds, the connection is considered lost, and procedure must be triggered.

- If connection is lost, the remote control/driving status must be removed and therefore all previous ROC commands.
- If connection is lost, full-service brake must be applied until train is in safe state (stopped, parking brake engaged and no active cabin).
- Safe state must be recoverable if:
    - Local safety driver inserts the train key to take local control.
    - ROC connection is recovered, and traction/brake lever is at 0 position to avoid unexpected sudden traction effort.

3.2 REMOTE OPERATION CENTRE

The ROC consists of frontend and backend systems that enable Remote Operations. The frontend consists of a modified SNG driver desk, which the RO interacts with to control and monitor the test train from a distance. This includes sending commands to the train and receiving data and video from the train, which is managed by the ROC backend application and displayed by the ROC frontend application. A dedicated VPN (further described in 3.1.7) provides a secure connection between the train and the ROC and firewalls on the train and in the ROC further protect the connection.

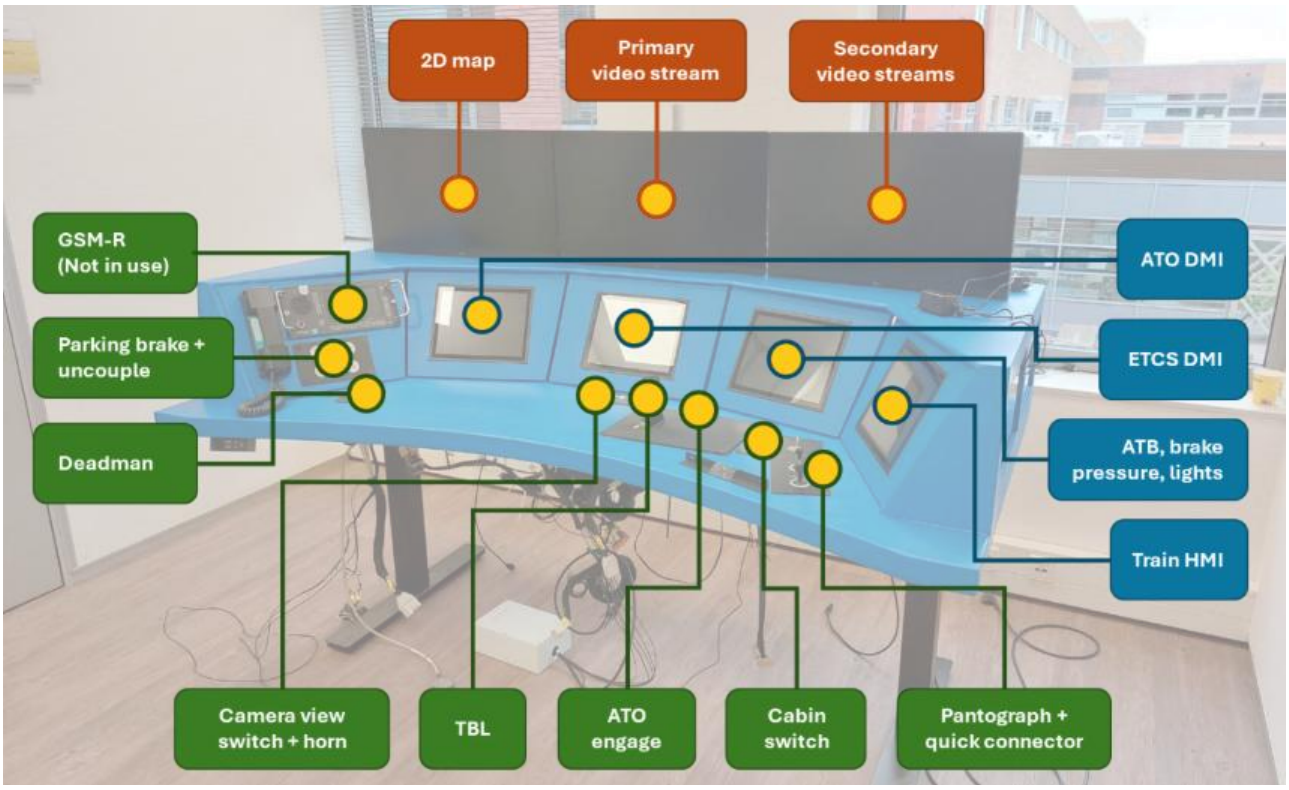


Figure 14: Steering desk functionalities

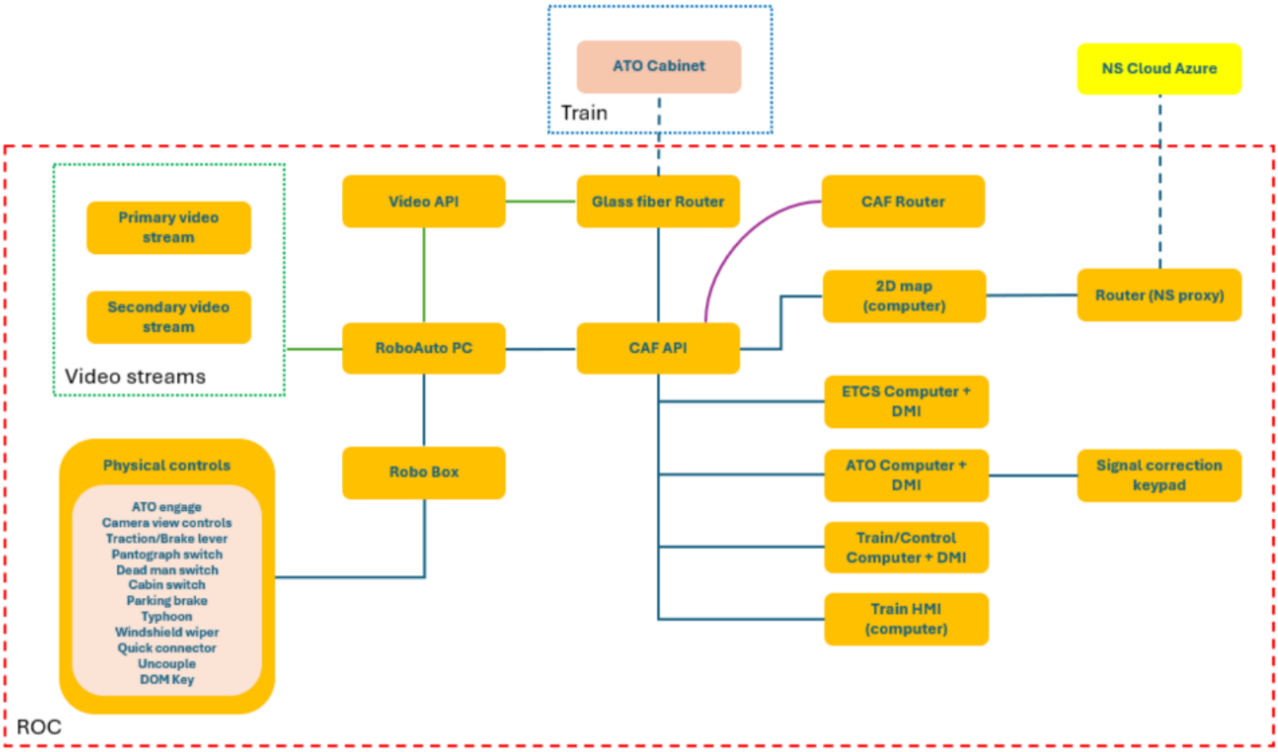


Figure 15: Graphic representation of ROC components

3.2.1 2D Map

The 2D map shows the real-time location of the vehicle selected in the ROC with surrounding tracks and objects. It overlays the planned route for the train (i.e. switches and tracks) and updates throughout the journey.

There is no interaction with the remote driver, it only provides additional information to the driver, for situational awareness.

Figure 16: 2D-Map

3.2.2 Primary video stream

The primary video stream shows the selected view from one of the cameras. The front perspective (normal zoom and enhanced zoom) can be switched to other views by using the video controls. The speed of the train limits the view of the pantograph and coupling camera, which are deactivated above 15km/h. The remote driver can influence what he sees, pending on the desired primary focus. The purpose is to highlight the focus to the remote operator.

3.2.3 Secondary video stream

The secondary video stream shows the three video streams other than the one selected on the main video stream. All video streams currently show the outside view of the train, front perspective (normal zoom and enhanced zoom) as well as a pantograph and coupling focus camera. Note pantograph and couple camera will be shut down above a speed of 15 km/h.

3.2.4 ETCS DMI

The ETCS DMI shows information to the remote operator, identical to what is presented to the driver in the train. The information contains the train speed, ETCS level or current ATB code. Furthermore, it provides an indicator for an ATB brake intervention, an indicator that the brake criterium is satisfied and an indicator showing that ATB is not in service. Example picture:

Figure 17: ETCS-DMI

3.2.5 ATO DMI

This component is not applicable for this Task.

3.2.6 Control DMI

The control DMI is the visual interface of the ROC to be able to connect to the train remotely. After startup of the ROC, a login screen and vehicle selection screen is visible. When logged in, the train information is presented which is normally visible on the active cabin by means of physical buttons, lights, gauges. It shows the brake pipe pressure meter, brake cylinder pressure meter, the fault indicator lights and Deadman switch warning light.

Figure 18: Control-DMI

3.2.7 HMI

The HMI is a representation of the train HMI, where the majority of the functionality is included. Not all regular features are included due to the prototype nature of this solution, i.e. the brake test is not included. It provides the remote operator with different types of information depending on which screen is selected in the train HMI. The screen that is active during driving is the "driver screen". This screen shows the rolling stock ID, service ID and train clock (local time) in the header line. Next, it shows the active cabin and train set status. Finally, this screen also shows information regarding the brake/traction demand, battery/catenary voltage, operational mode, driving mode, main pipe pressure and total distance driven. Another commonly used screen is the "station screen" providing information regarding the door/ramp status, also shows the active cabin and provides a list of actual A/B/C category alarms.

Figure 19: HMI

3.2.8 Controls

The ROC has the relevant train controls embedded within the desk, see Figure. The purpose is to recreate the train cabin as good as is possible.

1	ATO engage button (n/a for this Task)
2	Camera view controls
3	Traction / Brake lever
4	Pantograph Switch
5	Dead man switch
6	Cabin selection switch
7	DOM key
8	Signal correction numpad (n/a for this Task)
9	Windshield wiper
10	Quick connector
11	Parking brake
12	Couple / uncouple
13	Horn

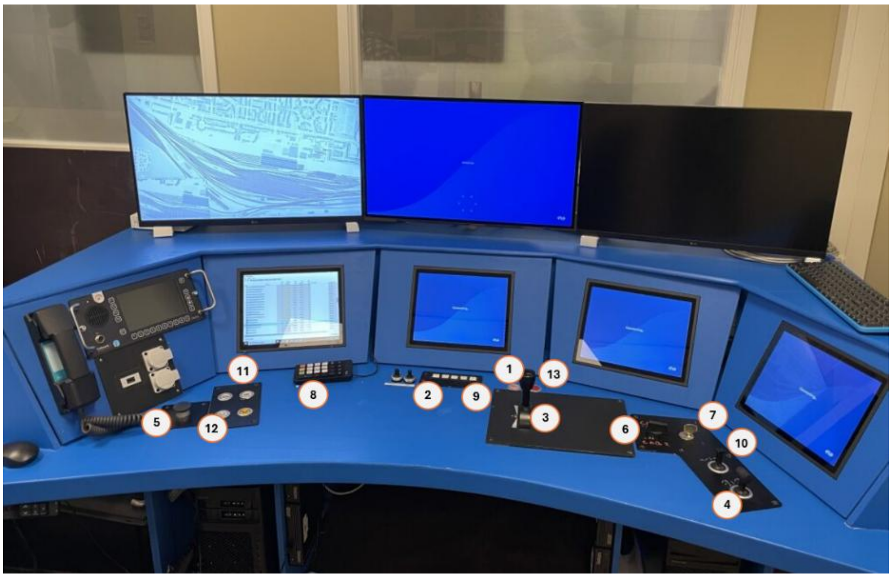


Figure 20: ROC control elements

4 RESULTS

The test campaign took place with a total of 92 remotely 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 750km was driven remotely, with a total driving time of 18 hours and 10 minutes. Tests were conducted during the summer, featuring mainly dry conditions and cloudy or sunny skies, most tests were performed during the day, but some test runs were performed at night. 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.

This section presents a comprehensive overview of the findings including a generic evaluation of the experiments, and both quantitative and qualitative analyses. The quantitative analysis covers key performance aspects such as stopping accuracy, punctuality, number of interventions, technical difficulties, and potential challenges. Complementing this, the qualitative analysis offers insights into the performance of the RD, focusing on the results of the HMI questionnaires and incorporating observations made by the HMI expert. Additionally, the section explores various use cases and evaluates the technical feasibility of the system. Finally, it determines the TRL level of the demonstrated technological solution and provides justification for the selected KPI’s, ensuring a well-rounded assessment of the RTO operational effectiveness.

4.1 GENERAL OBSERVATIONS

Once the remote driving capability was functional, remote control of the train was quite smooth. All of the drivers were able to utilize the remote driving solution quickly, performing the basic driving functions of operating the traction and braking installation and monitoring the outside world, all while adhering to the movement authorities of lineside signalling. The remote driving solution proved to be capable of enabling the driver to operate the train under happy flow conditions, both on the mainline with speeds up to 125km/h, as well as on shunting yards. This includes specific procedures commonly performed during shunting operations such as coupling/uncoupling or driving in nighttime conditions. In addition, the test personnel aboard the train felt that the RD was able to safely operate the train remotely. While it was possible to drive remotely, it is important to note that the current ROC setup is not a fully mature solution yet. Several functionalities are not yet included in this setup, for instance filling in the start of mission or the deadman foot pedal. Additionally, the system isn’t a standalone solution, since support was necessary from CAF to allow the ROC to contact the train and reset the connection at times.

The tests performed during this phase indicate that, from a technical standpoint, the conclusion is that it is technically feasible to operate a train under RTO between Hengelo and Enschede. In the context of this proof-of-concept phase, “technical feasibility” has been scoped to only include demonstration of basic functionalities of shunting movements performed remotely. The conclusions drawn here are only meant to say whether a function is possible to execute and not whether it is ready to be used in an operational environment. Certain functions may only be possible with additional interventions (i.e. cleaning of cameras), making them technically feasible, but not operationally feasible.

4.2 Quantitative Analysis

4.2.1 Stopping accuracy

To evaluate the stopping position accuracy of the RD, it was instructed to halt the train precisely at the stop sign at station Kennispark during each test run Figure , illustrates the stopping point at station Kennispark which is a diamond shaped blue sign with a 4. This is the same sign that would indicate a stopping location for this train’s length in regular passenger operations. The tests were performed using regular operating speeds.

This task presents a significant challenge for the RD due to the limited viewing angles of the current cameras, which do not cover the right front side of the train, making accurate judgment difficult. During the training runs, the RD received feedback on the stopping accuracy, allowing the creation of a reference framework. This led to a learning effect, with performance improving steadily. During the research runs the driver would no longer receive feedback on their performance. In Figure , the stopping accuracy results of all test runs are shown, where the positive numbers indicate the meters before the stopping point and the negative numbers the meters past. The first three test runs, which were used for training, are excluded from these results.

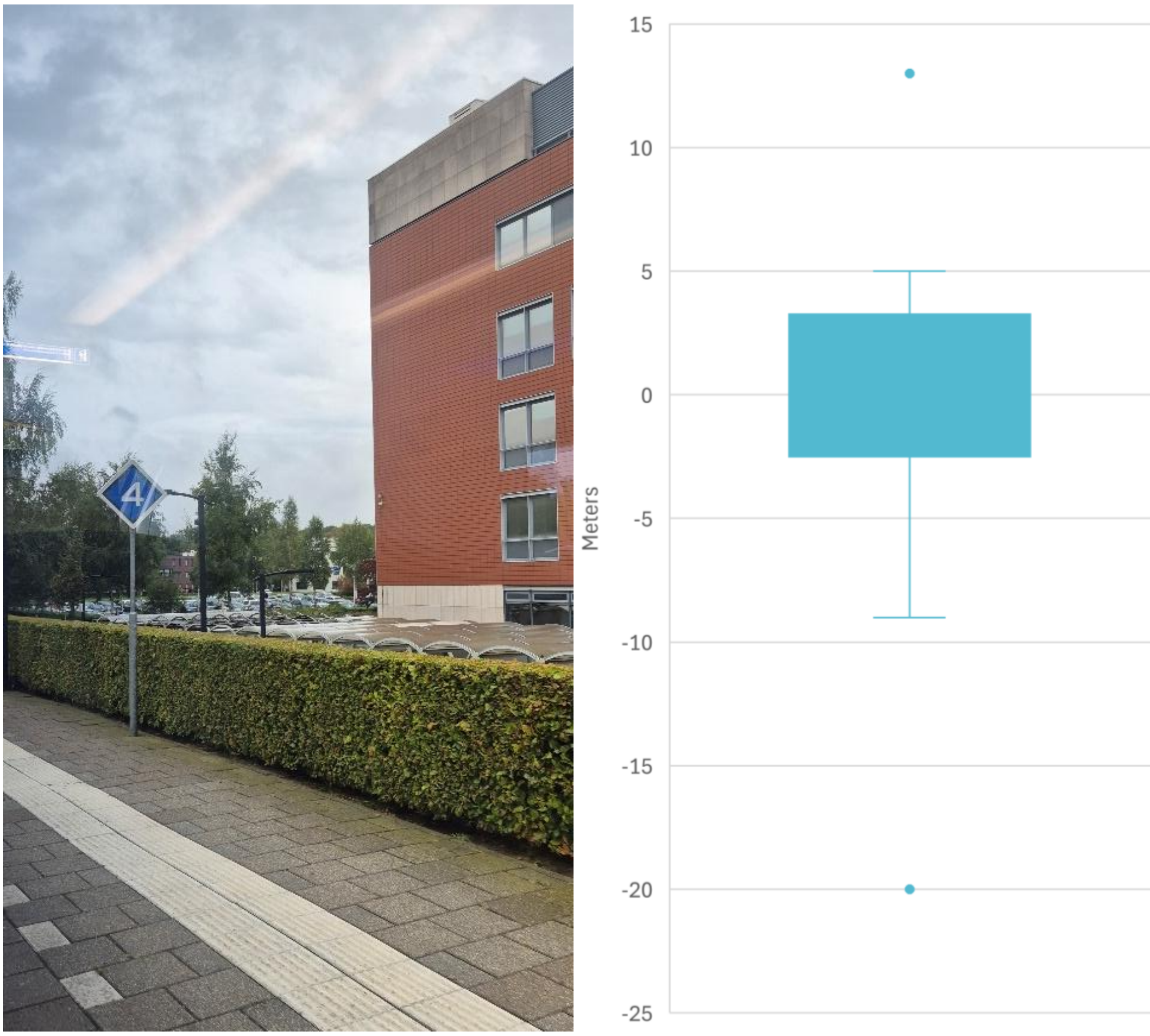


Figure 21: Stopping point and stopping accuracy (in meters) at station Kennispark

While most drivers managed to stop within a short distance of the target location, there have been outliers including some being 20+ meters away from the target location. The average distance from the stopping point is 0.3 meters.

Furthermore, the RD was instructed to stop the train precisely at station Enschede and Hengelo. The stopping point in Hengelo was near the signal of the track situated on the lefthand side (so not the signal for the track on which the driver was operating). In Enschede the stopping instruction could vary depending on the incoming track. Either near the buffer stop of the track situated on the lefthand side or 5 meters in front of the buffer stop on the current track. Estimating the stopping distance before an object on the track is observed as challenging. The RD frequently overestimated their proximity to the buffer stop. In **Fout! Verwijzingsbron niet gevonden.**22, an example of the stopping points at Hengelo and Enschede can be seen.

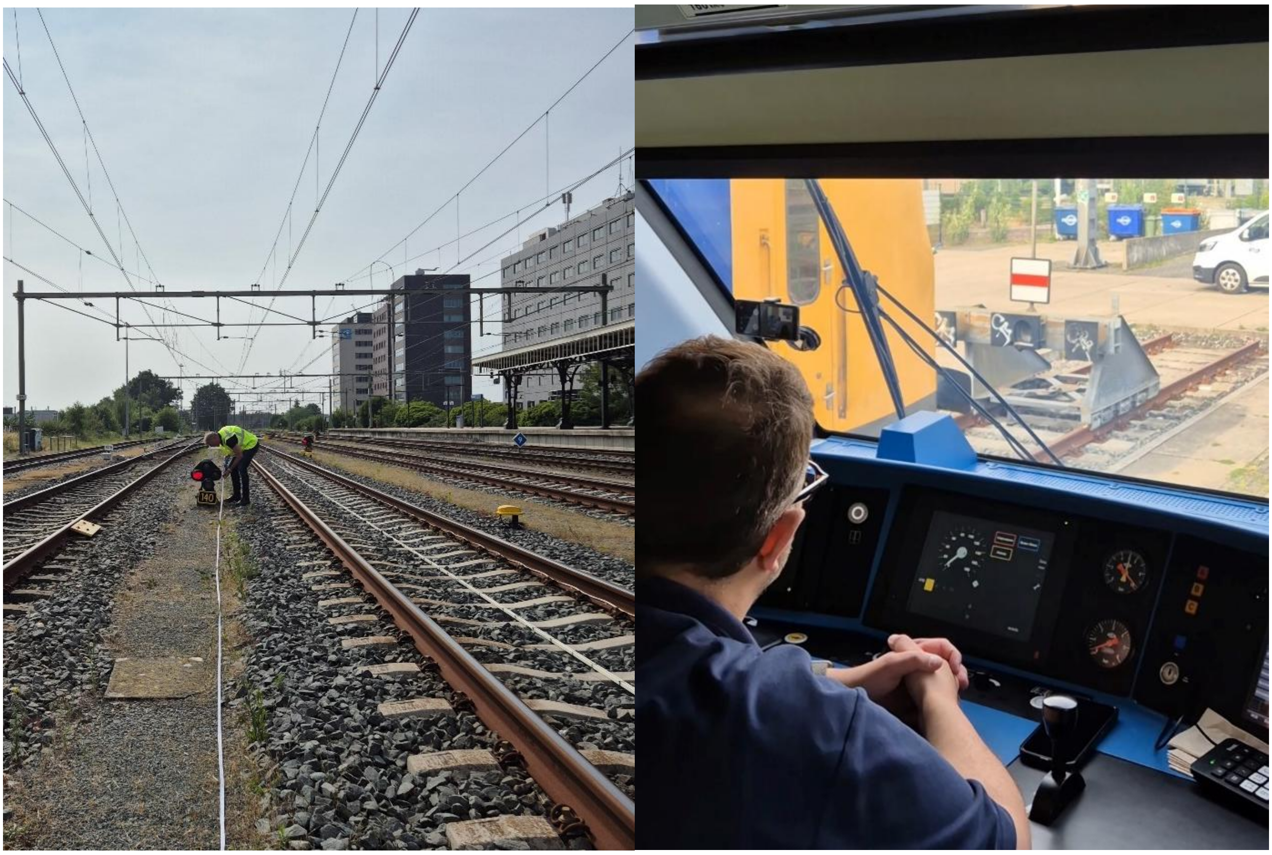


Figure 22: Stopping points Hengelo & Enschede

4.2.2 Punctuality

Punctuality has been examined during the test runs, although it is less critical for shunting compared to regular operation. Nonetheless, assessing punctuality provides valuable insights into the system's performance and the behaviour of drivers during shunting operations.

The tests show that, under ideal conditions the RD's are able to the perform the tasks on time. However, several important factors influenced the punctuality. First, the departure times frequently deviate from the schedule due to other trains having higher priority, leading to delayed departures and disrupted operating times. As a result, punctuality becomes a less relevant measure of success in this context. Additionally, during the training and testing phase, the RD's primary focus is not on adherence to strict timekeeping, but rather on learning and mastering the new technology. This learning process affects their driving behaviour and the extent to which they prioritize punctuality. Furthermore, it has been observed that drivers tend to adopt a more cautious driving style compared to regular operations. This cautiousness may stem from the need to manage safety risks carefully when working with the new technology. Such a defensive approach can result in slightly increased driving time, which also impacts the punctuality.

4.2.3 Number of interventions

During the initial RD test runs, the dead-man's device was triggered frequently. Unlike the traditional foot-operated system, the test setup used a button on the control panel to operate the dead-man's device. This design choice was made to simplify the prototype design, however, this new method of operation, posed a significant challenge for the RD. As a result, the device often activated unexpectedly, causing emergency braking. After the first day, it was decided to hand over control of the dead-man's device to the SD on board to reduce the number of unintended interventions.

During the tests in the ROC, it was observed that several drivers accidentally exceeded the allowed speed, driving at 132 km/h instead of the permitted 125 km/h. This was quickly adjusted when the remote driver took notice themselves or was informed by their trainer/safety driver. Drivers explain this to be caused by the lack of perceivable g-forces and other physical cues that they would normally apply to estimate their speed when operating the train from the physical cabin.

NS has a safety system called ORBIT that can alert the driver when their current speed and braking effort results may be inefficient to stop prior to an approaching red signal. This system, which was only installed on the onboard cabin of the train, has raised a total of two alerts during this study for different remote drivers. In one instance, a safety driver intervention was triggered to prevent a potential passing of a red signal. This case is further elaborated on in the next section. Additionally, there was one intervention of the safety driver because of failure to recognize the yellow flashing signal (which indicates potential track occupancy and requires driving on-sight).

4.2.3.1 Deep dive: Safety Driver intervention for red signal approach

In one occurrence, a remote driver did not timely recognize and perform sufficient braking effort when approaching a red signal. This triggered a safety driver intervention, stopping the train at a safe distance before the signal.

Before this situation occurred, the remote driver had completed several training and research runs and was about to head to their lunch break. Before the start of the run, they received a compliment from the test leader on how well they were getting accustomed to the test solution. The first half of the journey started in an unusual manner; the dispatcher allowed the train to depart 10 minutes ahead of schedule. The research leader opted to use this additional time to make an unplanned stop at Kennispark which was not possible with the original departure time. The driving from Enschede to Enschede Kennispark went uneventful.

Upon departure from Kennispark, the second encountered signal indicated a yellow aspect which is very unusual for this route. The driver did initiate a small braking effort as required by ATB, but later mentioned that he did not consciously register this yellow signal. When approaching the next signal, the driver mentions to be confused on the colour of the signal, hesitating between a yellow or red signal. He concluded it to be yellow and announced this to the safety personnel onboard of the train.

Once the remote driver realized the signal was instead displaying a red signal, the safety driver already intervened and increased the braking effort.

After this event, the remote driver was visibly upset. They mentioned that they had not at any point realized the approaching risk of the red signal and the preceding yellow signal. They also mentioned being overconfident in their ability of operating the remote system after receiving a compliment, aiming to drive closer to their regular (less defensive) driving strategy.

The researchers believe this event to be caused due to a combination of circumstances; including the difficulty of distinguish different colour aspect of the signal (red vs yellow), tiredness, expectations based on previous experience and system unfamiliarity. It is recommended to specifically address the topics of colour differentiation for any further studies or applications of remote driving technology in lineside signalling environments or shunting yards without lineside signalling.

4.2.4 Technical difficulties

A critical element of the technical feasibility of the RTO concept is the remote connection; without a stable remote connection, it is not possible for the RD to safely drive the train. During testing, it was demonstrated that, in general, the remote connection was sufficient to allow uninterrupted remote operation of the train. That is not to say that it was perfect, but the issues encountered were generally not severe enough to prevent the RD from safely carrying out their tasks.

During this study, the measured glass-to-glass latency was on range 150ms – 200ms with sporadic peaks up to 1.2s due to network saturation. Network latency and stability is vital for stability of full solution and is highly affected by number of users in nearby area using same network physical access. As an example, during a weekend test day, it became clear that there were multiple instances of connection loss at the same location. It was eventually discovered that a festival, with 17500 visitors, was taking place near the station in Enschede, which caused the connection issues. This fact requires further investigation on new technologies, such as network slicing, for guaranteeing availability of dedicated network or enhanced techniques for detecting network degradation on real time and apply mitigations as temporal speed limits. In this demonstrator safe reaction to connected losses higher than 2s were implemented using a full service break stop.

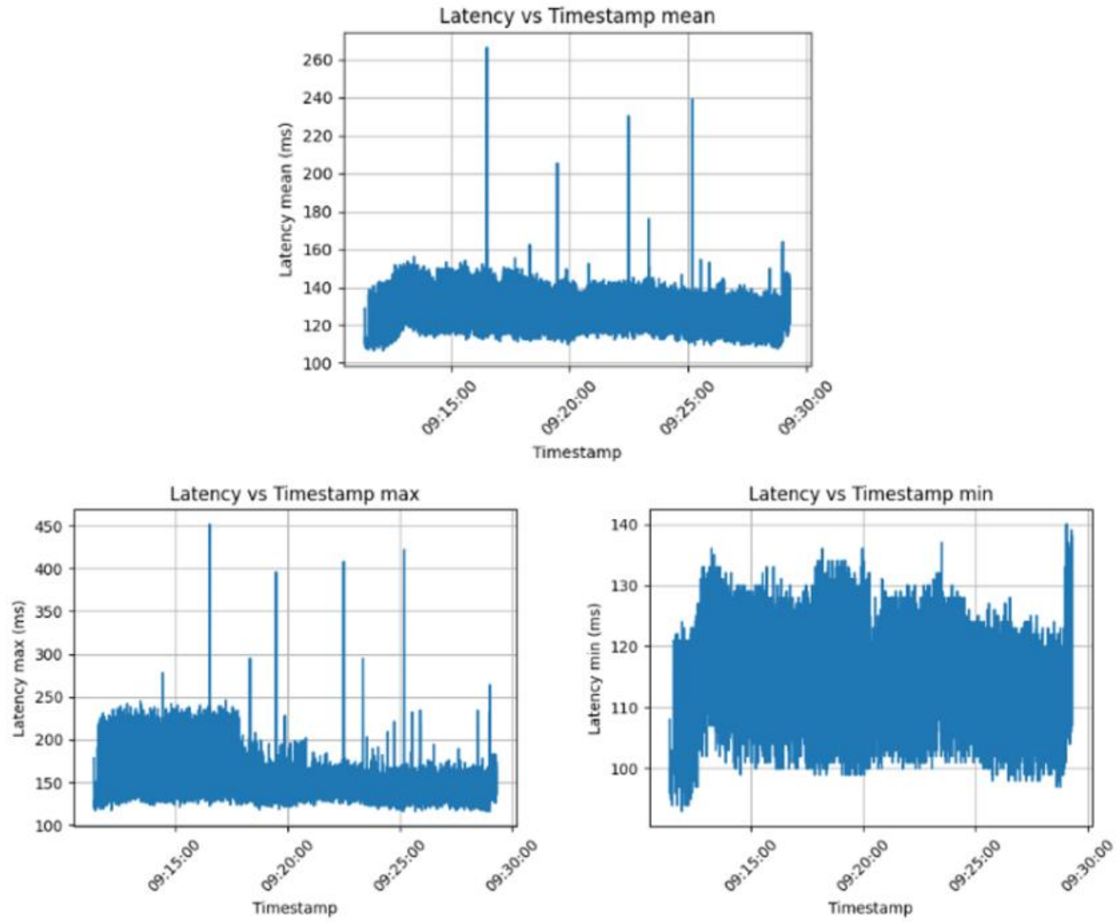


Figure 23: Network latency mean, maximum and minimum during a test run between Hengelo and Enschede

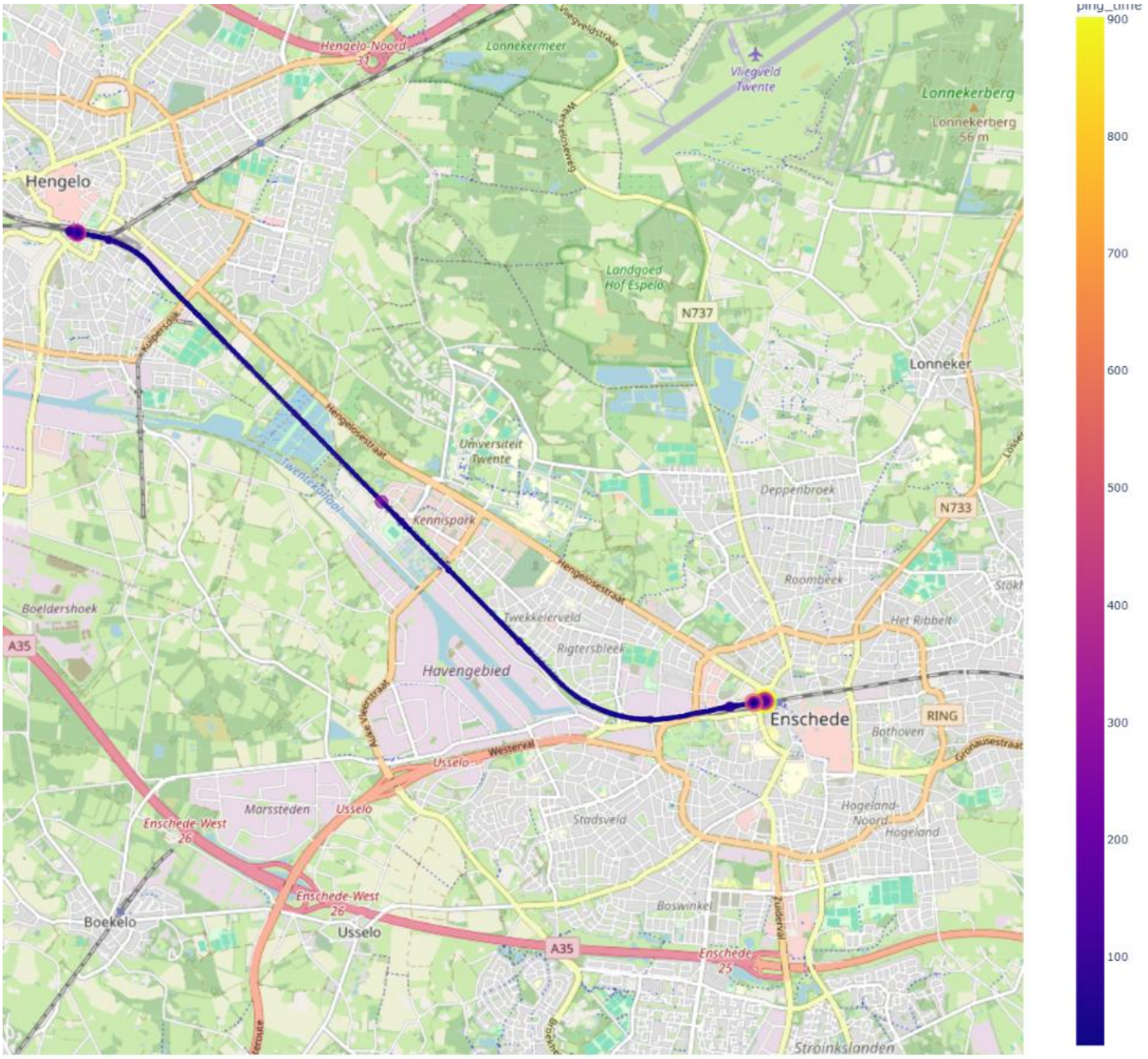


Figure 24: Network latency heatmap on Enschede-Hengelo line with scale in milliseconds

Technology basis for cameras used can evolve with new models. Industrial grade cameras with USB access were used because of their faster response to reduce glass to glass latency but these devices tend to have lower dynamic range as the Complementary Metal-Oxide-Semiconductor (CMOS) sensor is smaller than in external cameras. There is also a trade off on exposure time configuration, suitable configuration for night conditions requires high exposure times which are not suitable for day conditions and produce saturation if dynamic range is not high enough. During day, if exposure time analogue frequency lowers down below 30Hz half power grid frequency, some light signals, which seem to be powered by half-wave rectifier, present an aliasing effect seeming to be switched off for an envelope period. Colour definition is also a challenge on fast response cameras as a slightly difference on one of Red Green Blue (RGB) channels produce a non-linear decompensation between colour channels and, therefore, colour differentiation on light signals is harder, mostly on Red-Yellow differentiation.

Lens selection is another key point of the solution, selected lens of focal lengths 6mm and 25mm have proven to not show a significant area perception that provides comfort to drivers. Further investigation may focus on testing alternative camera sets that improve environment representation fidelity.

Sound transmission was not initially planned as video transmission was expected to be enough, and sounds could be replicated when needed on ROC taking digital alarms as inputs. However, sounds provide additional information about environment and integration of sound feedback from cabin should be furtherly evaluated.

4.2.5 Potential challenges

During the uncoupling test, see Task 38.6, a mechanical issue occurred with the coupling. This problem had to be resolved on-site by the SD. In the future, however, there will be no one physically present on the train to address such issues, as the driver will be operating from a remote location. It is therefore crucial to consider how this type of mechanical problem will be effectively and efficiently resolved in the future when no one is on board of the train.

Another important aspect to consider when there is no one on board the train is the maintenance and cleaning of the cameras. As the train moves, environmental factors such as dust, dirt, rain, and debris can quickly accumulate on the camera lenses, leading to reduced visibility. Since there will be no personnel present to clean or inspect the cameras during operation, it is essential to find effective solutions to keep them clear and functional. One potential approach is to equip the cameras with windscreen wipers, which could help clean the lenses.

4.3 Qualitative Analysis

In this section, the qualitative findings are discussed, focusing on topics such as signal recognition, the results obtained from the Human Machine Interaction (HMI) questionnaires and observations and insights provided by the HMI expert. Together, these qualitative findings offer a comprehensive view of how users engage with the system and highlight areas for potential improvement.

4.3.1 Signal recognition

The observers noticed that the distance from which the driver can identify the signal aspect of oncoming signals differed between the SD onboard of the train, compared to the RD. This was further tested in a mini experiment where both drivers were asked to announce the aspect of oncoming signals as soon as they became confident on the aspect. During this experiment, the involved drivers could not hear each other's input. The research leader observed that the SD was able to identify the oncoming signals at an earlier moment compared to the RD.

This observation was made based on the current state of the technology, which does not fully reflect a target solution. It is expected that improvements on the camera configurations, video quality and design of the ROC will improve the ability of the RD to perceive the outside world. It is suggested to further investigate the recognition of points of interest at longer-distances in future RTO projects.

4.3.2 Human Machine Interaction

4.3.2.1 Motion Sickness

The HMI questionnaires addressed topics such as simulation sickness, workload, and latency. The results of the simulation sickness questionnaire reveals that some train drivers experienced symptoms potentially indicative of mild simulation or motion sickness. Two drivers reported no discomfort, while three reported some discomfort that might have other causes. Additionally, two drivers noted minor complaints across 8 to 10 different symptoms, suggesting a case of mild motion sickness. Additionally, one of the research leaders in the ROC experienced symptoms related to motion sickness while being involved in the study.

The topic of motion sickness has not been addressed during the design of the ROC. Research shows that the design of the technical solution can contribute to the occurrence and severity of motion sickness, indicating potential room for improvement on mitigating or reducing the effects of motion sickness compared to the remote operation environment used in this study [2]. The lessons learned from the motion sickness questionnaire indicate the need to address this topic both in the design of future RTO technical solutions and in future human factors studies on the topic of remote driving.

4.3.2.2 Workload

Three RD's experienced an increased workload in the field of information processing. Consequently, these operators also face greater demands in knowledge retrieval and decision-making. Notably, the workload does not decrease over the course of the day, indicating it is unlikely to be due to a lack of familiarity with the system. The primary cause appears to be the more challenging perception of signal aspects (colour and displayed number). Additionally, estimating distance and speed remotely adds to the workload. Differences in perceived speed between the two camera views contributes to this strain. Furthermore, four operators report increased demands on fine motor skills and physical effort during remote operation. While this can partly be attributed to the dead man being positioned in an ergonomically unfavourable location, this factor alone does not fully explain the increased physical load.

The topic of workload should be further addressed in the design of the technical solution (i.e. improving the camera quality may improve the ability of drivers to interpret signal aspects). The topic of workload should be further investigated in future research programs with a high TRL ROC solution, investigating the implications on the design of training programs and operational concepts.

4.3.2.3 Latency, Situation Awareness & Safety

The latency, situation awareness, and safety questionnaire reveals that drivers experience several challenges in estimating speed, position, the timing of braking, and the location where the train will stop. Drivers report that these difficulties hinder their ability to perform timely and accurate actions, particularly when executing braking. Although some improvement is observed over the course of the day, it indicates that three brief training trips were insufficient for adequate learning. Even by the end of the day, there remains significant room for improvement.

4.3.2.4 Information Needs

The evaluation of the information needs questionnaire shows that all operators consider the camera images from the 6 mm lens as the most important source of information, followed by those from the 25 mm lens. Having both lenses available is regarded as essential. The clutch view is particularly important during specific manoeuvres. However, several drivers report insufficient support from the camera images when it comes to determining the train's position and stopping location. Additionally, multiple train drivers rate the camera image quality as inadequate, especially concerning sharpness, prevention of flickering caused by non-flashing external signal aspects, and colour accuracy. The 2D map is considered irrelevant in the context of this study, where the driver continuously operates the same train and thus is familiar with its location and direction. However, if drivers have to switch trains and cabins regularly, the 2D map may become useful for situational awareness.

4.3.3 Observation of HMI expert

Next to the questionnaires, an expert in HMI closely observes the test runs to provide qualitative assessments and identify potential issues. The following observations are identified:

- The RD's are able to perform the basic actions for driving under ATB from the ROC without much of a learning curve.
- However, actions depending on the estimation of distance to objects (stopping at signals, buffer stop, stopping at dwelling location) are considerably more difficult when driving remotely. This leads to larger deviations, more play with controls and longer execution times. Camera positioning and framing are crucial aspects in this. The disappearance of important objects from the image (especially stop location signs) is problematic. During the tests it has been observed that drivers show some improvement in performance, but still there remains a gap with normal operation. Feedback on distance deviations from the test crew on the train helped drivers to get a better position reference, however this information is not available outside of a test setting.
- Speed perception and acceleration perception are reduced. The RD checks more frequently and experiences braking force and acceleration less distinctly. This increases the workload and demands greater attention.
- Drivers use their route familiarity more extensively than in normal operation, by viewing the (position of) objects and scenery next to the track more frequently and comparing that with their route knowledge. During driving, this provides information to the driver about their general position on the route. During the halting brake, objects on the platform are used to identify the start of the brake and correctly brake towards the stopping location. It is possible that the reduced perception of train location, distance to objects, speed and acceleration contributes to drivers relying more on route familiarity.
- Night conditions make track visibility difficult without track lighting. The RD must rely more on signalling and route familiarity. Signals were generally clearly visible, but sometimes ambiguous between yellow and red. There was also "flickering" in the zoom camera at signal lamps, which is undesirable since this could be interpreted as a different signal aspect.
- The 2D map was little used but may become more important in the future in more complex scenarios.
- The 'coupling-view' is useful for docking and stopping, but pantograph view hardly relevant. The latter is only used for preparation of service and in case of degraded modes, no such situations were tested as part of this task.
- The remote cabin changes are faster than in normal operation.

- The absence of a dead man's foot pedal leads to unnecessary ergonomic discomfort and reduced execution of the automated behaviour of operation of the dead man. This hinders fully autonomous operation, without proactive interaction with the safety driver on the train.

The above observations require attention from two perspectives. First of all, technical improvements in the provision of information can be examined. Further research is necessary to test if changes in positioning and type of cameras facilitate better depth perception, improved speed/distance information, preventing flicker, and improve colours. The test campaign setup was not suitable for investigating potential impact of RTO on driver alertness, it remains unclear if this is a topic for the RTO concept that needs to be addressed. Further investigation is crucial in the next phase of implementation, particularly for RTO operations lasting longer than 10 minutes.

4.4 USE-CASES & TECHNICAL FEASIBILITY

The current architecture, specifications and requirements of RTO as developed within Europe's Rail R2DATO are indirectly based on the use-cases described in deliverable D5.4. It was decided to perform specific test runs to validate use case UC5.4.024 which was considered most representable for the study environment of this demonstrator. Another use-case has been tested using the same demonstrator technology for the purpose of coupling and uncoupling which is described in D38.6. While other use-cases were encountered during the duration of this study, they were not specifically investigated or registered as part of this deliverable.

To verify the applicability of use-case 5.4.024 in a relevant environment, it has been applied using the demonstrator technology by an unexperienced remote driver in an operational setting. The results of this application can be found underneath.

4.4.1 Use-case Description:

"UC5.4-024 Perform routine driving by remote driver.

This use case details remote train control operation by a person in the ROC. The RD should be able to drive the train remotely as if on the train itself. It is crucial that there is a working communication between the train and the ROC and that the RD has functioning sensors and real time camera images on which the RD drives and also access to warning sound devices."

Two remote control variations can be used when controlling a train remotely from a control centre. Variant A: Controlling. In this option, the RD controls all train control elements and is guided by the sensors and the data sent. Variant B: Monitoring. With this option, the RD controls only the emergency brake button, plus warning devices such as the horn. Otherwise, the train runs autonomously according to the sensors and is monitored. In the RTO tests of this study, variant A: Controlling is used.

The following chapter describes each of the steps from the original use-case, followed by a description of the steps being performed in the D38.2 demonstrator:

4.4.2 Performing of use-case 5.4-024 using RD-demonstrator:

- Step 1: The RD checks the functionality of individual parts of a stationary train.

The inspection of individual components falls under preparing a train for departure. Examples of this are brake tests, vigilance device tests, and checking the front and rear signals. The technical functionality to have these tests performed by the RD were not available. Therefore, all tests were carried out by the driver on the train and not tested by the RD on this functionality.

- Step 2: The train starts. The RD attends the train motion.

From the ROC, the train is set in motion, and the RD closely monitors the train movement using the availability of real-time camera images. This step was successfully tested without any failures.

- Step 3: The RD monitors the train motion without influence most of the time.

With the help of the available cameras that provide live images from various perspectives to the ROC, the RD is able to monitor the train motion and accurately assess the situation on the track and control the train. The latency and camera quality is sufficient for the train driver to operate the train. In one specific situation, communication with the train was lost for a few seconds, and an emergency brake applied to the train. Furthermore, a continuous but muted communication connection via Teams is used as an additional safety measure for the RD and the safety driver on the train.

- Step 3.1 The RD decreases the train's speed: controls the train's brakes lever.

The safety driver on the train handed over the operation of the traction and brakes to the RD before starting the test runs. During the tests, it was demonstrated that the remote driver has full control over the train and can adjust the speed and operate the brakes accurately from the ROC.

- Step 3.2 The RD uses the emergency brake button to stop the train in a potential danger situation.

On the control panel at the ROC, the emergency brake button function is available for the remote driver. Immediately after the RD presses the emergency brake from the ROC, the train initiates the emergency break functionality, resulting in a full stop. With this, the step has been successfully tested.

- Step 3.3 The RD uses warning sound devices: sounds the horn.

At the request from the safety driver, the RD was asked to test the horn at an agreed time and in the rural area. This test was successfully carried out several times. A point of attention is that, due to the absence of microphones, the Remote Driver could only hear the horn via the open communication channel.

- Step 4 The RD controls the train remotely by performing all along the drive, successively or in parallel.

During the test runs, between Hengelo and Enschede (8 km), the RD had full control over the train and operated it remotely from the ROC in Utrecht. There was a continuous connection (key) between the train and the ROC without technical problems.

- Step 4.1 At Standstill, select / revert the driving direction: showing video and sensors of an extremity cabin or the other.

When the train is at a standstill the RD must select the active cabin and the driving direction by displaying the video and sensor views from the active cabin. This allows the RD to see the perspective and sensor information from the chosen cabin when changing the driving direction.

- Step 4.2 The RD engages or disengages ATO.

The RD can select the train operation mode from the ROC and engages and disengages the ATO functionality on and off from the ROC before driving the train.

Note: This functionality was tested as part of the RTO-GoA2 tests as described in D38.3.

- Step 4.3 The RD corrects the train's speed (controls the train's traction and brakes).

Via the control elements, the RD can adjust the speed according to the current speed restrictions of lineside signalling. The traction controller responds immediately to the driver's input, after which the train slows down or accelerates.

- Step 4.4 The RD confirms its vitality while driving by pressing the vitality button.

While the functionality of the driver vitality monitoring has been proved in the ROC, the current design proved to be unergonomic and difficult for the train drivers due to the lack of a foot pedal. Resulting in additional workload, and unplanned interventions. After proving of the correct functionality (i.e. handling driver input, interventions due to lack of input), it has been disabled on the ROC's side for the remainder of this study and was instead handled on-board. This highlights the importance of an ergonomic design but does not reflect a target solution.

- Step 4.5 The RD manages doors.

This functionality was not available and controlled by the RD on the ROC train and not tested.

- Step 4.6 The RD manages external lights.

This functionality was not available and controlled by the RD on the ROC train and not tested.

- Step 4.7 The RD manages pantographs.

"Up" and "down" of the pantograph mean respectively raising and lowering the pantograph. Pantograph up: The pantograph is raised and makes contact with the overhead line to draw power. Pantograph down: The pantograph is lowered, breaking contact with the overhead line and stopping the power supply. This is an important action when starting and stopping the train. The function and operation of the pantograph were available on the RD's control panel. When pressing this button, the pantograph on the train responded immediately, allowing the remote driver to operate the pantograph remotely. During the tests, it is demonstrated that the functionality and operation from the ROC worked successfully.

- Step 4.8 The RD wipe and wash front window and sensors, also defrost and demist front window and sensors.

During the test runs, various weather conditions where it was necessary to operate the windshield wipers, were encountered. This improves the visibility for the onboard driver in the train and the visibility of the inside camera images in the train to the ROC. However, the RD operates the train using also cameras outside of the train, it is essential for the future, for reliable images and information, that the lenses of the cameras and sensors on the front of the train are kept clean for clear sight.

- Step 4.9 The RD provides Energy for traction and auxiliaries.

The RD provides energy for traction and has control from the ROC over switching on and managing the power flows needed to drive the train (traction). Traction energy is the electric current used to power the train's propulsion, enabling it to accelerate and run. Supporting systems on board the train, such as power for lighting, heating, ventilation, air conditioning, and other electrical devices essential for comfort, were not available and controlled by the RD on the ROC and not tested.

- Step 5.0 The RD closes High Voltage Circuit Braker.

The high voltage breaker was not available from the ROC and was operated by the safety driver from the cabin in the train.

- Step 5.1 The RD engages the train holding brake and step 5.2 The RD stops the train at a safe place.

After bringing the train to a stop in the shunting yard at a safety place, the remote driver is able to engage the parking brake.

To conclude, the main findings from this use case are:

- Demonstrably successful use case-test in which the RD can control the train from a distance and drive the train remotely. During the tests, it was demonstrated that the remote driver has full control over the train and can adjust the speed and operate the brakes accurately from the ROC.
- The monitors provide good information for a controlled and safe ride by clear sight. While difficulties were observed during other tests, it was possible for the RD to correctly observe the signals during the testing of this use case.
- The latency and camera quality is sufficient for the train driver to operate the train. The effect of latency / network issues did not disrupt the driving.
- Well-functioning sensors and clean camera lenses outside of the train are essential to provide the remote drivers with accurate information to operate the train safely and reliably.

- To control the vigilance device was quite intensive for some drivers, with the manual button and distinct audio-visual signals.
- During the journeys, there is a continuous communication connection with the driver on the train. In one specific situation, communication with the train was lost for a few seconds, and an emergency brake applied to the train.
- The feedback from the safety driver onboard of the train helped the RD on improving the stopping accuracy and their distance estimations.
- The key functionalities to operate a train remotely were available during the tests. A number of functions are not available on the test train and therefore were not tested. For instance, remote preparation of the train, managing external lights, RD managing the doors.

4.5 ACHIEVED TECHNOLOGY READINESS LEVEL

It is important to note that the definition of an interoperable standard for remote driving technology is still in the early stages of development. However, during the conducted tests, the technology, based on available definition in D6.7 of R2DATO, was successfully implemented and the correct operation was demonstrated across various trials. The demonstrator was performed using a proprietary remote driving solution that was presented as a standard candidate by CAF for R2DATO.

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 ROC and Train using simulators for logic testing and simulated delays for video transmission. An additional step to reach TRL 5, technology validated in relevant environment, is achieved by deploying the final network configuration for the video transmission technology and measuring delays and data loss rates [3].

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 92 trips between Hengelo and Enschede with maximum speed 125km/h and covering a total distance of 750km. Total time driven is 18 hours and 10 minutes, with an average trip duration of 12 minutes. 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 remote driving has been tested in an operational environment (TRL6). However, it is important to mention that the tests were performed without any degraded modes and under supervision of safety drivers and technical experts.

The strongest evidence for this is the public demonstrations held in Utrecht in September 2025 [4], which clearly showcased the system's capabilities and maturity to key industry stakeholders. Additionally, D12.2 of R2DATO provides a detailed account of the development of the remote driving solution 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 study described in this demonstrator is one of the first applications of R2DATO's RTO architecture, applying the remote driving technology in a real-world environment with operating speeds up to 125km/h. It has effectively addressed the objective of advancing remote train driving technology, not only testing the technical feasibility but also the human-machine interface (HMI) implications for train drivers newly introduced to remote train operation (RTO).

The study demonstrated that all participating drivers were quickly able to operate the remote driving solution and perform fundamental driving functions such as applying tractive or braking effort. More precise manoeuvres, including stopping at reference locations and estimating braking curves, proved to be more challenging initially, leading drivers to adopt a cautious, defensive driving strategy. Importantly, only one safety-related intervention by the onboard safety driver was necessary during the entire study, underscoring the robustness and safety of the system.

From a technical perspective, the solution, including network infrastructure, performed reliably in most test runs, with glass-to-glass latency consistently measured between 150 and 200 milliseconds. The only notable exception was during a local event hosting 17,500 visitors near the test site, which severely impacted network connectivity and temporarily prevented remote operation of the train. This shows the need for prioritized and secured bandwidth.

These results provide valuable confirmation of the technical feasibility and user acceptability of RTO, while also highlighting specific challenges related to precision control and network reliability under exceptional conditions. Feedback collected throughout the study has enabled targeted improvements in the technical enabler and informed practical recommendations for HMI design.

In conclusion, this deliverable represents a significant milestone in pioneering remote driving technology, blending technical innovation with human-centric design considerations. The progress documented here confirms the promise of remote driving to transform rail operations safely and effectively, aligning with and advancing Europe's Rail strategic objectives.

6 FUTURE WORK

The RTO test setup was a limited version of the driver experience in a SNG train. The RD was able to control the traction and braking of the train, switch the active cabin, and perform coupling/uncoupling actions. The test setup in the ROC was not a full replica of the driver experience in a train. Key functionalities such as degraded modes and performing brake tests were not possible from the ROC and had to be completed by the test driver in the train. Additionally, several warning lights and aural signals were not sent to the ROC from the train and the RD relied on feedback from the test driver in the train to know the exact state of the train. While these functions were not included in this demonstrator, this was the result of a scope restriction, not a technical restriction. Future developments should carefully consider what specific tasks should be performed during RTO operation and ensure that the functionalities and information available in the ROC align with those tasks.

While the study has proved most of the basic driving functions in a relevant environment, it has only touched the surface of degraded operating modes. These degraded situations are crucial for the future successful implementation of RTO, especially when there are no capable drivers onboard of the train. It is suggested for future demonstrators to further apply the remote driving technology under degraded operating conditions to gain additional insight are required for future commercial applications.

The HMI-topics that are described in this document provide relevant topics to be addressed in the design of future RTO solutions but should also be further investigated in future demonstrators applying higher TRL-solutions in representable environments. Additional topics to investigate include the need for haptic, audio and similar types of feedback. As well as optimizations on the configuration of cameras such as distinguishing of colours, field of views and image quality.

APPENDIX

A. INFORMED CONSENT FORM

Disclaimer: This document was originally in Dutch which is the native language of the remote drivers involved in this study. It has been translated to English using generative AI, this translation was verified by the authors of this document.

Consent Form for Participation in the ERJU Remote Shunting Study with Eye Tracking and Surveys among NS Employees

Title of the Study: ERJU Remote Shunting

Principal Investigator: <Redacted>

Dear participant,

You are kindly requested to read and complete this consent form before participating in the ERJU remote shunting study being conducted. This consent form contains important information about the study, your rights as a participant, and how your data will be handled. Please take the time to carefully review this information and ask any questions before deciding to participate.

Why consent?

By signing this consent form, you give NS permission to process your personal data for the Human Factors Study involving surveys and Eye Tracking.

You may, of course, choose not to give your consent. Without your consent, personal data will not be collected. Refusal to consent will never have any negative consequences for you. Your choice not to consent will not be recorded or included in your personnel file.

Purpose of the study:

The purpose of the Human Factors study is to investigate how various factors influence the performance of NS employees in their working environment. We aim to gain insight into the human factors that may affect efficiency, productivity, and safety during task execution. The results of this study may contribute to improving working conditions and developing effective tools for NS employees.
The specific goal of this study is to gain insight into how a train driver experiences remotely controlling a train. These experiences will be used to better tailor the technology behind remote shunting to the driver's needs in the future. We will also share these experiences with European partners. Insights may be applied to future training materials.

Which personal data do we collect?

The personal data we collect for this study are as follows (the Data):

1. Prior to the start of the study and upon selection for participation, the following data will be collected:

- First and last name
- Job position

- Work e-mail address
- Work phone number
- Signature
- Whether your eyeglass prescription falls within the set of lenses provided for the eye tracker. The set consists of (single) lenses with diopter strengths between +3 and -5 in steps of 0.5 [yes/no]
- Eye condition (cataract/astigmatism/nystagmus) [yes/no]
- Experience with the technology under study [yes/no]

These personal data are necessary because characteristics like work experience may influence behaviour during the study. Your data on eyeglass prescription and eye conditions are collected to properly adjust the equipment.

Via the eye tracker, the following data will be collected:

- Voice audio
- Ambient noise including system noises from equipment (audio)
- Gaze direction (video)
- Pupil size
- Position of left and right eye

By signing this consent form, you agree that this personal data will be retained for the duration of the study for which it was collected. This means the data will be stored for a maximum period of one year.
Your personal data will not be shared with third parties nor transferred to countries and/or organizations outside the European Economic Area (EEA).

Risks and benefits:

Wearing the eye tracking glasses may cause mild discomfort, similar to wearing (sunglasses). This discomfort is generally minimal. The benefits of participation are that your input may contribute to improving working conditions, ergonomic design, and safe implementation of innovative workplace technologies.

Confidentiality and privacy:

All collected data, including eye tracking data, will be treated with strict confidentiality and anonymized as soon as the personal data have been collected. Your personal data will only be used for research purposes and will not be shared with third parties without your explicit consent. The data will be analysed at group level, and individual results will be reported anonymously.

Rights:
Under the General Data Protection Regulation (GDPR), you have several rights. A complete overview of these rights and how to exercise them can be found in the Personnel Personal Data Privacy Regulation (see here – from page 10). If you wish to exercise any of your rights regarding the processing of your data, you can submit your request by emailing <Redacted>

You have the right to withdraw your consent for the use of your personal data (in whole or in part) at any time, without giving a reason and without any adverse consequences. Your supervisor will not be informed of this, and ending your participation will not affect your relationship with the project team or the researchers involved. You can do this by sending an email to <Redacted>

Consent and agreement:

By signing below, you confirm that you:

- Are 18 years or older;
- Are employed by NS;
- Have read and understood the information in this letter and have had sufficient time to ask questions;
- Your eyeglass prescription falls within the range of lenses provided for the eye tracker, which consists of (single) lenses with strengths between +3 and –5 diopters in steps of 0.5; and
- Do not have an eye condition.

You voluntarily agree to participate in the Human Factors Study with Eye Tracking as described above. More specifically, this means you consent to the processing of your personal data in accordance with this consent form and for the following purposes:

• Providing relevant demographic information such as age, gender, and experience level so that the study can be tailored to you. This information will be treated confidentially and used solely for research purposes.

• Wearing an eye tracking device during the Human Factors study. The device records your eye movements, such as fixations and saccades, to map attention processes. An audio recording will also be made. The device can be safely and comfortably worn like glasses according to the researcher's instructions.

• Participating in observation sessions where your work activities will be observed while eye tracking data are recorded. This may involve performing specific tasks, interacting with equipment, or communicating with colleagues.

• Participating in interviews, surveys or questionnaires where you are asked about your experiences, perceptions, and feedback regarding your work and work environment.

You understand that your participation is your personal choice and that you can decide to end your participation at any time.

Signature section:

B. Motion Sickness Questionnaire

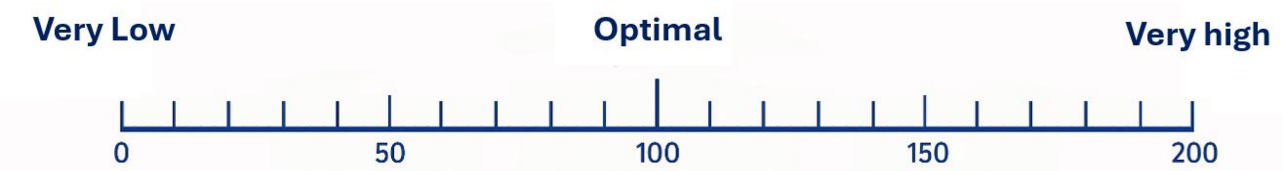
This questionnaire consists of 16 symptoms associated with motion sickness. By watching moving images without physically moving yourself, you may become dizzy or become nauseous. For each symptom, please indicate to what extent you are experiencing it on a scale from 0 to 3.

Symptom	0=absent	1=mild	2=moderate	3=severe
Nausea	☐	☐	☐	☐
General discomfort	☐	☐	☐	☐
Increased awareness of the stomach	☐	☐	☐	☐
Sweating	☐	☐	☐	☐
Increased saliva production	☐	☐	☐	☐
Difficulty concentrating	☐	☐	☐	☐
Vertigo or spinning dizziness	☐	☐	☐	☐
Burping	☐	☐	☐	☐
Dizziness with eyes open	☐	☐	☐	☐
Dizziness with eyes closed	☐	☐	☐	☐
Fullness in the head	☐	☐	☐	☐
Difficulty focusing	☐	☐	☐	☐
Headache	☐	☐	☐	☐
Blurred vision	☐	☐	☐	☐
Fatigue	☐	☐	☐	☐
Eye strain	☐	☐	☐	☐

C. Workload Questionnaire

Disclaimer: This document was originally in Dutch which is the native language of the remote drivers involved in this study. It has been translated to English using generative AI, this translation was verified by the authors of this document.

In this list, we ask you to assess your workload on various aspects for **remote shunting**. The centre of the scale (Optimal) represents your personal optimum regarding workload. This is the workload at which you feel good. For each aspect, we ask you to choose how you rate your effort in relation to this personal optimum.



Information processing: How much effort did it take you to find relevant information in the environment while performing the task? Did gathering information require too little effort for you personally (underload), was it just right (optimal), or did it require too much effort (were you overloaded)?

Score:

Memory retrieval: How much effort did it take to retrieve relevant knowledge from your memory while performing the task? Was recalling information from your memory too little effort (underload), just enough (optimal), or too much effort (overload) for you personally?

Score:

Decision making: How much effort did it take to decide which action(s) to take during the task? Was decision making too little effort (underload), just enough (optimal), or too much effort (overload) for you personally?

Score:

Fine motor skills (motor) and physical effort (strength): How much motor or physical effort did it take to perform the task? Did you have to move or exert yourself physically too little (underload), just enough (optimal), or too much (overload) for you personally?

Score:

Time pressure: How much time pressure did you experience during the execution of the task?

Score:

Effort: How much mental and physical effort did it take to deliver the task with the desired performance? Did you experience the effort required as too little, optimal, or too much?

Score:

Would you like to provide any further explanation regarding the above answers related to workload?
.....

D. Latency, Situation Awareness & Safety Questionnaire (Dutch)

Disclaimer: This document was originally in Dutch which is the native language of the remote drivers involved in this study. It has been translated to English using generative AI, this translation was verified by the authors of this document.

Please indicate your experience during the recent trips.

1. The way the trips went I experienced as:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very bad *Very good*

2. Estimating the speed of the train during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very difficult *Very easy*

3. Determining the position of the train on the track during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very difficult *Very easy*

4. Determining the moment to brake during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very difficult *Very easy*

5. Determining the moment to give traction during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very difficult *Very easy*

6. How the train behaved during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very unpredictable *Very predictable*

7. The place where the train would stop when braking during these trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very unpredictable *Very predictable*

8. The moment the train would reach the required speed at a speed restriction was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very unpredictable *Very predictable*

9. About the decisions I made during these trips I am:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very dissatisfied *Very satisfied*

10. The extent to which during the trips I was able to perform the correct action upon seeing the stop signal was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very poor *Very good*

11. The moment I came to a stop for a stop signal during the trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Much too late *Much too early*

12. The brakings I performed during these trips were:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very uncontrolled *Very controlled*

13. The amount of time I had to perform braking was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Far too limited *More than enough*

14. Achieving the correct speed at a speed restriction during the trips was:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very difficult *Very easy*

15. The way of remote driving during these trips I consider:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very uncomfortable *Very comfortable*

16. Remote driving during these trips gave me:

☐ ☐ ☐ ☐ ☐ ☐ ☐

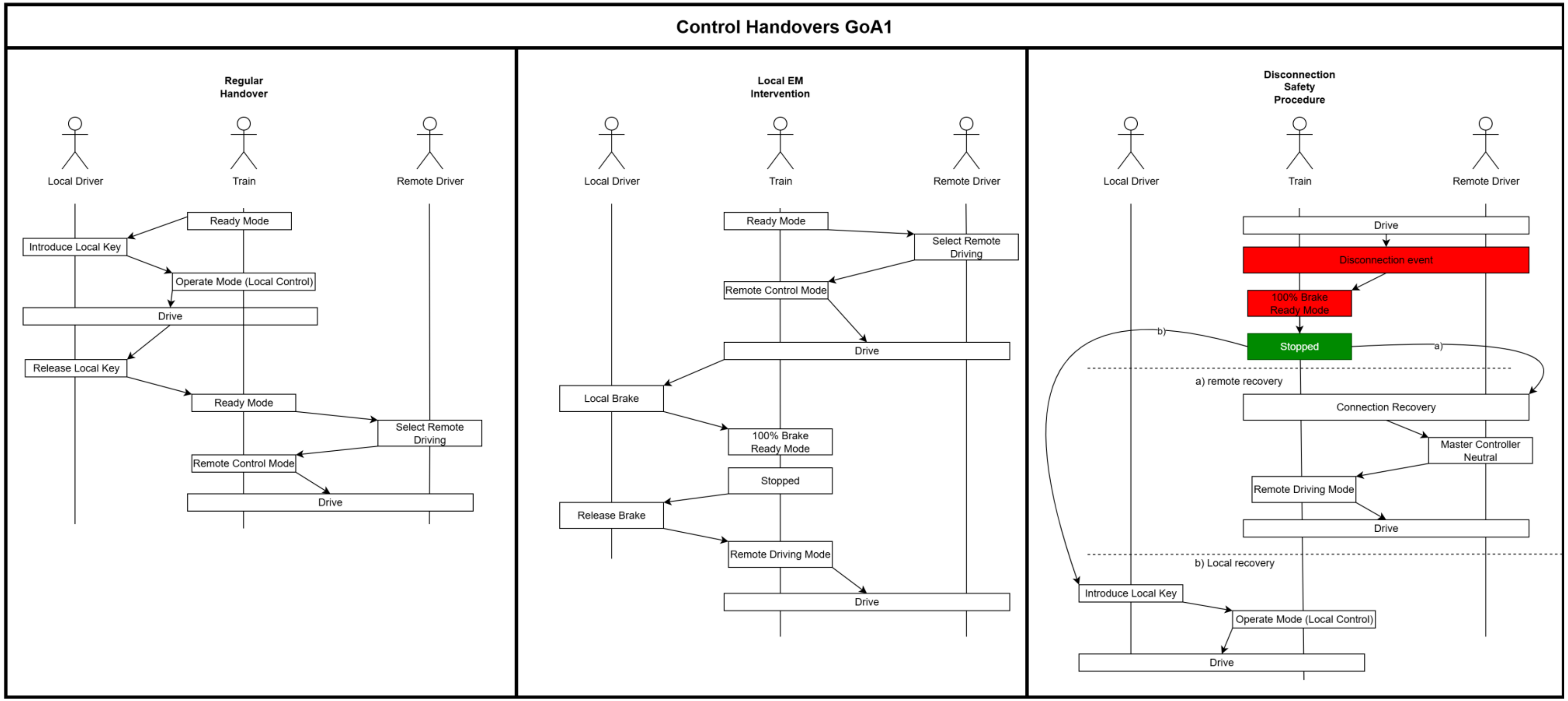
Very little confidence *Very much confidence*

17. Remote driving during these trips I experienced as:

☐ ☐ ☐ ☐ ☐ ☐ ☐

Very unsafe *Very safe*

E. Flow chart for handover interactions



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