Rail to Digital automated up to autonomous train operation

D12.1 – Migration scenarios for Remote Driving

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EXECUTIVE SUMMARY

This deliverable defines migration scenarios for Remote Driving in the European railway system. Remote Driving is positioned both as a stand-alone operational capability and as a fallback for Automatic Train Operation Grade of Automation 4 (ATO GoA4). The work supports Europe's Rail objectives by focusing on feasibility, interoperability, safety and economic viability across passenger, freight and other railway operations.

Strategic context

The European railway landscape combines ETCS with a wide range of legacy train control systems, particularly in yards and depots. This diversity makes a single migration approach unrealistic. The central conclusion of this deliverable is that Remote Driving must be introduced incrementally, with each step delivering clear operational or economic value and avoiding proprietary solutions that increase cost and complexity.

Remote Driving addresses key sector challenges, including high personnel costs in shunting, limited operational flexibility due to workforce constraints, safety risks in yard environments, and the need for robust degraded-mode operation in future GoA4 scenarios.

Migration approach

Instead of a fixed roadmap, the document proposes a flexible migration framework that stakeholders can tailor to their context. Two complementary approaches are presented:

- Functional clustering based on stakeholder pain points and complexity, enabling phased deployment of Remote Driving functions.
- Clustering by area of application and risk, starting in controlled depot environments and gradually extending to mainline and passenger operations.

Both approaches support early value creation and controlled risk growth.

Passenger and Freight Perspectives

From a passenger Railway Undertaking perspective, the experiments carried out by WP38 need an extension of the scope in the future to become a minimum viable solution. The limited scope chosen lead to a situation in which a second driver on the train was still needed. To achieve an economical viable solution, a Minimum Viable Product (MVP) is defined, focused on remote driving from A to B without an on-board driver, enabled by remote safety voice communication, remote start of mission and harmonised ETCS-DMI, TCMS and perception interfaces.

For freight, Remote Driving is primarily positioned as a fallback for GoA4 autonomous operation. Freight-specific challenges related to train dynamics, braking behaviour and legacy fleets require dedicated migration strategies that cannot be directly derived from passenger use cases.

Voice communication

A critical enabler across all scenarios is reliable safety voice communication. Dispatcher calls and emergency alerts must always reach and be answered by a responsible remote operator. Without this, the removal of the local driver is not acceptable.

Conclusions

Overall, the deliverable demonstrates that Remote Driving is strategically and technically viable if migration is value-driven, incremental and based on harmonised interfaces, with early deployment in controlled environments to de-risk the transition towards higher levels of automation.

Different migration scenarios will be presented, depending on the objectives and viewpoints of different stakeholders in the area.

ABBREVIATIONS AND ACRONYMS

AHABV	Alarmoproep GSM-R uitzenden; Herroepen van seinen; ARI uitzetten; Buurtreindienstleider informeren; Veiligheidsmaatregelen nemen
ARI	Automatische Rijweginstelling (English: Automatic Route Setting)
ATO	Automatic Train Operation
ATO-OB	Automatic Train Operation On-Board
CAB	Driver's cabine
DMI	Driver Machine Interface
EDB	Electro-Dynamic Brake
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation
GoA1 / GoA2 / GoA4	Grades of Automation 1, 2 and 4
GSM-R	Global System for Mobile Communications – Railway
IM	Infrastructure Manager
MVP	Minimum Viable Product
NTP	National Train Protection
OPE	Railway Operating Rules (Operations)
R2DATO	Rail to Digital automated up to autonomous train operation
RD	Remote Driving
RTO	Remote Train Operation
RUP	Railway Undertaking Passenger
RUF	Railway Undertaking Freight
RU	Railway Undertaking
SoM	Start of Mission
SWOT	Strenghts, Weaknesses, Opportunities and Threats
TCMS	Train Control Management System
TSI	Technical Specifications for Interoperability
UIC	International Union of Railways

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1 INTRODUCTION

The European railway sector is undergoing a major transformation aimed at increasing capacity, improving operational efficiency and safety, and addressing long-term workforce challenges. Digitalisation and automation are key enablers of this transition. Within this context, **Remote Driving** is emerging as an important capability, both as a stand-alone operational concept and as a supporting or fallback function for **Automatic Train Operation Grade of Automation 4 (ATO GoA4)**.

Remote Driving allows trains to be controlled from a Remote Operation Centre without a driver physically present in the cab. Potential use cases include shunting and depot operations, empty train movements, inspection vehicles, freight services and tramways, as well as degraded-mode operation for highly automated or autonomous trains. While technical feasibility has been demonstrated in pilots, large-scale deployment remains challenging due to system heterogeneity, safety requirements, regulatory constraints and economic considerations.

The European railway landscape combines ETCS with multiple national train protection systems, particularly in yards and depots. This diversity means that a single, uniform migration strategy is not realistic. Passenger and freight Railway Undertakings and Infrastructure Managers operate in different contexts and face distinct operational challenges and priorities.

The objective of this deliverable is to define **migration scenarios for Remote Driving** that support a gradual, economically viable and technically feasible transition. Building on earlier Innovation Pillar work, the document proposes a methodological framework that enables stakeholders to structure and tailor their own migration strategies, with emphasis on phased implementation, risk reduction and interface harmonisation, in line with the broader Europe’s Rail system approach.

The structure of this document is as follows:
Chapter 2 starts with a generic methodological approach based on the work done by WP33.
Chapter 3 is based on the lessons learned from WP38 in which remote driving for shunting passenger trains is demonstrated. A migration scenario starting with a minimum viable product to a full solution for remote driving of shunting passenger trains is proposed.
Chapter 4 is an evaluation of the challenges for the remote driving of freight trains in case of ATO GoA4 fall back.
Chapter 5 evaluates the requirements for safe train communication which is needed for all railway scenarios.
Chapter 6 evaluates the migration strategy for tramways, based on the publications for tramways made by work packages 6 and 42.
Chapter 7 sums up the conclusions and the proposals for the follow-up.

2 MIGRATION STRATEGIES BASED ON FUNCTIONAL CLUSTERING

The railway industry is undergoing a transformative period, driven by the imperative for enhanced operational efficiency, increased capacity, and improved safety. Remote driving technology represents a pivotal advancement in this evolution, offering the potential to redefine operational paradigms across various railway domains. This strategic paper evaluates comprehensive migration strategies for the implementation of remote driving solutions, a critical area currently under standardization efforts by the Europe’s Rail Joint Undertaking (ERJU).

The European railway landscape is characterized by the coexistence of the standardized European Train Control System (ETCS) and numerous legacy national train control systems, particularly prevalent in critical operational areas such as yards and depots. This heterogeneity presents significant challenges and opportunities for the seamless integration of remote driving capabilities. This paper aims to delineate a structured approach to technology migration, drawing insights from foundational work packages within the ERJU program, specifically leveraging functional definitions from Work Package 6 (WP6) and identifying operational pain points and strategic methodologies inspired by Work Package 33 (WP33).

The strategic impetus for remote driving is multifaceted. Foremost, it addresses the logistical inefficiencies associated with staff transportation between train sets, thereby optimizing personnel deployment and reducing operational downtime. Furthermore, remote driving serves as a robust backup mechanism for degraded Grade of Automation 4 (GoA4) operations, enhancing system resilience and maintaining service continuity under challenging circumstances. This chapter will systematically analyse stakeholder segments, operational pain points, functional requirements, and potential migration pathways to facilitate the strategic adoption of remote driving technologies.

The purpose of chapter 3.1 and 3.2 is to give a possible methodology for a market player or stakeholder to cluster functions defined in WP6 in order to achieve their own objectives. Since each stakeholder operates in a different environment and has their own challenges and boundary conditions, it is not realistic to create one strategy-fits-all stakeholders. The following approach to migration planning is only exemplary and must be interpreted as a methodological proposal for a specific use case.

2.1 CLUSTERING BASED ON STAKEHOLDER PAIN POINTS AND COMPLEXITY

2.1.1 Stakeholder Segmentation

For the purpose of developing targeted migration strategies, the primary stakeholders in the railway industry are categorized into three distinct customer segments, each possessing unique operational characteristics and strategic priorities. This list of stakeholders is not exhaustive, since many more stakeholders are relevant and have high influence on the technological adoption for remote train operations and driving. However, these stakeholders are primarily identified for the purposes of this task.

- **Railway Undertaking Passengers (RUP):** This segment encompasses operators primarily engaged in passenger transport services. Their priorities typically revolve around passenger safety, service punctuality, comfort, and efficient turnaround times at stations and depots.
- **Railway Undertaking Freight (RUF):** This segment includes operators focused on freight transport. Their core concerns involve optimizing logistics chains, maximizing payload capacity, reducing operational costs, and ensuring timely delivery of goods. Efficiency in mainline operation, shunting and yard operations is particularly critical for this segment.

- **Infrastructure Managers (IM):** This segment is responsible for the maintenance, operation, and development of railway infrastructure, including tracks, signaling systems, and power supply. Their priorities include network availability, safety of operations, efficient traffic management, and cost-effective infrastructure maintenance.

2.1.2 Stakeholder Pain Points and Importance Mapping

Following the Deployment Strategies and Roadmapping Framework as well as lessons learned summarized in WP33 and reflecting on inputs from [1] and [2], stakeholder pain points can be derived from a stakeholder's SWOT analysis by extracting the Threats and Weaknesses of the stakeholder. As an example following pain points are identified as an initial step, in order to structure the solution adoption centred around the specific pain point.

The successful adoption of remote driving technologies is contingent upon their ability to effectively address existing operational challenges. Since retrofitting an existing vehicle fleet with an entirely new technology is cost intensive, the approach highlighted here gives a possibility for stakeholders to focus the solution on their actual pain points to increase their return on investment.

Drawing inspiration from the methodologies outlined in WP33, the following key customer pain points have been identified, with their importance mapped across the defined customer segments:

- **High Operational Costs Associated with Personnel Deployment:** The necessity of physically transporting drivers to and from trains, particularly for shunting, coupling, and depot movements, incurs substantial labor costs, travel time, and logistical overhead. This is exacerbated in large yards or when trains are frequently moved short distances.
- **Inefficient Shunting and Depot Operations:** Manual shunting processes are often time-consuming, labor-intensive, and prone to delays. The need for a driver in each locomotive for every movement limits throughput and operational flexibility in yards and depots, impacting overall network capacity and turnaround times.
- **Limited Operational Flexibility and Driver Availability:** The reliance on on-board drivers restricts the ability to quickly reconfigure train sets, respond to unexpected operational changes, or manage operations in remote or challenging environments. Driver shortages or limitations in working hours can further constrain operational flexibility. In addition, the aging workforce among train drivers and the upcoming retirement rates constitute a relevant demographic risk to stakeholders.
- **Safety Risks in Manual Shunting and Depot Environments:** Operations in yards and depots, characterized by frequent train movements, coupling/uncoupling, and close proximity of personnel, inherently carry higher safety risks compared to mainline operations. The presence of personnel on the ground or in cabs during these maneuvers increases exposure to potential hazards.
- **Future operational risk for GoA4 Operations:** While GoA4 (highest grade of automation) aims for driverless operation, unforeseen system failures or external events can necessitate human intervention. The absence of an on-board driver in such scenarios requires robust remote intervention capabilities to manage degraded modes effectively and safely, preventing service disruptions.

2.1.3 Prioritization of Functions per Pain Point towards a Migration Roadmap

The functions essential for remote driving operations, as defined in WP6, vary significantly in their technical complexity and safety criticality. A comprehensive evaluation of these functions is crucial for developing a phased migration strategy. In the following evaluation, the technical implementation complexity is used as criteria as an example. A first assessment of the implementation complexity was conducted to help bundle the functions, which in turn allows the creation of a phased migration approach, prioritizing functions based on the estimated implementation complexity.

It is important to note that other factors and criteria are important for the evaluation, one example is the impact of the functions or solution on already integrated systems on the vehicles to be retrofitted (e.g. ETCS, TCMS).

This roadmap outlines an exemplary logical progression for each pain point, which gives the possibility for any stakeholder to consider a stepwise approach to adopt the technology.

2.1.3.1 Clustered Functions for addressing the High Operational Costs Associated with Personnel Deployment

- **Basic Bundle: Foundational Remote Access and Basic Monitoring**
  - T6.7-Funct-008 Command remote wake-up
  - T6.7-Funct-009 Manage components power-on
  - T6.7-Funct-069 Initiate wake-up
  - T6.7-Funct-097 Manage shutting down request
  - T6.7-Funct-070 Provide access to remote driving functions
  - T6.7-Funct-033 Request monitoring access by the RD
  - T6.7-Funct-056 Manage RD user profiles
- **Add-on Bundle: Secure Control Transfer and Cab Occupancy**
  - T6.7-Funct-057 Control RD Monitoring State
  - T6.7-Funct-063 Allow control by different actors
  - T6.7-Funct-064 Validate control request
  - T6.7-Funct-065 Grant control
  - T6.7-Funct-066 Refuse control
  - T6.7-Funct-068 Occupy cab

2.1.3.2 Clustered Functions for addressing the Inefficient Shunting and Depot Operations

- **Basic Bundle: Basic Information and Auxiliary Control**
  - T6.7-Funct-006 Display (national shunting) speed limitation
  - T6.7-Funct-046 Control headlight
  - T6.7-Funct-108 Control visibility
- **Add-on Bundle 1: Core Movement and Operational Controls**
  - T6.7-Funct-039 Select direction
  - T6.7-Funct-040 Preset and monitor speed
  - T6.7-Funct-050 Control holding brake
  - T6.7-Funct-096 Control parking brake
  - T6.7-Funct-045 Control pantograph
  - T6.7-Funct-007 Manage coupling of trains
  - T6.7-Funct-091 Uncouple train
  - T6.7-Funct-073 Confirm length of train consist
  - T6.7-Funct-075 Train Data Entry and Confirmation
- **Add-on Bundle 2: Advanced Environmental Perception and Safety Procedures**
  - T6.7-Funct-048 Observe track surroundings
  - T6.7-Funct-049 Observe track
  - T6.7-Funct-074 Carry out operational brake test

2.1.3.3 Clustered Functions for addressing the Limited Operational Flexibility and Driver Availability

- **Basic Bundle: Basic Communication and System Status**
  - T6.7-Funct-001 Manage communication between drivers
  - T6.7-Funct-037 Operational communication
  - T6.7-Funct-038 Provide operation relevant information
  - T6.7-Funct-058 Register at network
  - T6.7-Funct-059 Request train registration
  - T6.7-Funct-060 Register train
  - T6.7-Funct-061 Refuse train registration
  - T6.7-Funct-062 Report train registration request status
  - T6.7-Funct-067 Report control request status
  - T6.7-Funct-071 Provide status of operationally relevant subsystems
  - T6.7-Funct-072 Provide operational failure information
  - T6.7-Funct-101 Manage diagnostic information
  - T6.7-Funct-102 Manage Remote Driver functionality
  - T6.7-Funct-104 Set preparation time
- **Add-on Bundle: Operational Mode Management and Emergency Communications**
  - T6.7-Funct-003 Manage handover between drivers
  - T6.7-Funct-011 Facilitate change in train operational mode
  - T6.7-Funct-020 Manage Handover request from Driver
  - T6.7-Funct-043 Dispatch train radio emergency call
  - T6.7-Funct-044 Receive train radio emergency call
  - T6.7-Funct-051 Release control

2.1.3.4 Clustered Functions for addressing the Safety Risks in Manual Shunting and Depot Environments

- **Basic Bundle: Auxiliary Safety and Monitoring**
  - T6.7-Funct-042 Control horn
- **Add-on Bundle 1: Critical Control and Safety System Integration**
  - T6.7-Funct-002 Manage control of the driver speed limitations
  - T6.7-Funct-036 Manage high voltage circuit breaker
- **Add-on Bundle 2: Immediate Safety Intervention and Human Factors Monitoring**
  - T6.7-Funct-034 Perform safety relevant action
  - T6.7-Funct-041 Control emergency brake
  - T6.7-Funct-048 Observe track surroundings
  - T6.7-Funct-049 Observe track
  - T6.7-Funct-074 Carry out operational brake test
  - T6.7-Funct-100 Manage remote driver vitality

2.1.3.5 Clustered Functions for addressing the Future operational risk for GoA4 Operations

- **Basic Bundle: Basic ETCS/ATO Access and Data Provision**
  - T6.7-Funct-088 Input ETCS-OB Train Data
  - T6.7-Funct-079 Provide information for position and orientation consistency check
  - T6.7-Funct-092 Select ETCS mode
  - T6.7-Funct-099 Manage demote from monitoring to observing
  - T6.7-Funct-105 Allow access to ETCS
  - T6.7-Funct-106 Allow access to ATO
  - T6.7-Funct-107 Control doors
- **Add-on Bundle: Safety-Critical Handover and Command Execution**
  - T6.7-Funct-021 Monitor conditions for handover to autonomous train

- T6.7-Funct-022 Manage Handover from autonomous train
- T6.7-Funct-090 Command ETCS SoM

2.2 Clustering Based on Operating Environment of the Remote Controlled Vehicle

An alternative, complementary migration strategy involves phasing the implementation of remote driving functions based on the operational environment. This approach allows for a gradual introduction of technology, starting in controlled environments and progressively expanding to more complex scenarios. The categories below describe the operating environment and state of the vehicle under consideration, e.g. “Depot Stand-Still” means the train is in the Depot and at stand-still, “Mainline Operations Without Passengers” means a passenger train is moving on the mainline tracks but without any passengers inside, etc.

- **Depot Stand-Still:** This initial phase focuses on trains that are stationary within a depot.
    - T6.7-Funct-008 Command remote wake-up
    - T6.7-Funct-009 Manage components power-on
    - T6.7-Funct-010 Manage components self-test
    - T6.7-Funct-036 Manage high voltage circuit breaker
    - T6.7-Funct-045 Control pantograph
    - T6.7-Funct-046 Control headlight
    - T6.7-Funct-069 Initiate wake-up
    - T6.7-Funct-071 Provide status of operationally relevant subsystems
    - T6.7-Funct-072 Provide operational failure information
    - T6.7-Funct-097 Manage shutting down request
    - T6.7-Funct-101 Manage diagnostic information
    - T6.7-Funct-108 Control visibility
- **Depot with Movement:** This phase extends to trains moving within the controlled environment of a depot, typically at low speeds.
    - All functions from "Depot Stand-Still"
    - T6.7-Funct-006 Display (national shunting) speed limitation
    - T6.7-Funct-007 Manage coupling of trains
    - T6.7-Funct-039 Select direction
    - T6.7-Funct-040 Preset and monitor speed
    - T6.7-Funct-041 Control emergency brake
    - T6.7-Funct-042 Control horn
    - T6.7-Funct-048 Observe track surroundings
    - T6.7-Funct-049 Observe track
    - T6.7-Funct-050 Control holding brake
    - T6.7-Funct-073 Confirm length of train consist
    - T6.7-Funct-074 Carry out operational brake test
    - T6.7-Funct-075 Train Data Entry and Confirmation
    - T6.7-Funct-091 Uncouple train
    - T6.7-Funct-096 Control parking brake
- **Train Movement to the First Platform (No Passengers Onboard):** This involves movements from the depot to a passenger platform or an initial staging area, prior to passenger boarding.
    - All functions from "Depot with Movement"

    - T6.7-Funct-002 Manage control of the driver speed limitations
    - T6.7-Funct-011 Facilitate change in train operational mode
    - T6.7-Funct-020 Manage Handover request from Driver
    - T6.7-Funct-034 Perform safety relevant action
    - T6.7-Funct-037 Operational communication
    - T6.7-Funct-038 Provide operation relevant information
    - T6.7-Funct-043 Dispatch train radio emergency call
    - T6.7-Funct-044 Receive train radio emergency call
    - T6.7-Funct-051 Release control
    - T6.7-Funct-057 Control RD Monitoring State
    - T6.7-Funct-058 Register at network
    - T6.7-Funct-059 Request train registration
    - T6.7-Funct-060 Register train
    - T6.7-Funct-061 Refuse train registration
    - T6.7-Funct-062 Report train registration request status
    - T6.7-Funct-063 Allow control by different actors
    - T6.7-Funct-064 Validate control request
    - T6.7-Funct-065 Grant control
    - T6.7-Funct-066 Refuse control
    - T6.7-Funct-067 Report control request status
    - T6.7-Funct-068 Occupy cab
    - T6.7-Funct-070 Provide access to remote driving functions
    - T6.7-Funct-079 Provide information for position and orientation consistency check
    - T6.7-Funct-088 Input ETCS-OB Train Data
    - T6.7-Funct-092 Select ETCS mode
    - T6.7-Funct-099 Manage demote from monitoring to observing
    - T6.7-Funct-100 Manage remote driver vitality
    - T6.7-Funct-105 Allow access to ETCS
    - T6.7-Funct-106 Allow access to ATO
- **Mainline Operations Without Passengers:** This phase focuses on empty passenger trains operating on the mainline.
    - All functions from "Train Movement to the First Platform"
    - T6.7-Funct-001 Manage communication between drivers
    - T6.7-Funct-003 Manage handover between drivers
    - T6.7-Funct-021 Monitor conditions for handover to autonomous train
    - T6.7-Funct-022 Manage Handover from autonomous train
    - T6.7-Funct-090 Command ETCS SoM
    - T6.7-Funct-107 Control doors (to ensure that doors stay closed and no passengers enter the train)
- **Mainline Operations for Freight:**
    - All functions from "Train Movement to the First Platform"
    - T6.7-Funct-001 Manage communication between drivers
    - T6.7-Funct-003 Manage handover between drivers
    - T6.7-Funct-021 Monitor conditions for handover to autonomous train
    - T6.7-Funct-022 Manage Handover from autonomous train
    - T6.7-Funct-090 Command ETCS SoM
    - Additional relevant function: Visual/Audible external Train Departure Warning (similar to train door closing for passenger trains)
- **Mainline Operations With Passengers:** This represents the highest level of complexity and risk, involving passenger trains in revenue service.
    - All functions from "Mainline Operations Without Passengers"
    - T6.7-Funct-107 Control doors (critical for passenger safety)

Additional relevant function: Communication between passengers and remote train driver.

3 MIGRATION STRATEGY FOR REMOTE DRIVING FOR SHUNTING FROM A RU PASSENGER PERSPECTIVE

3.1 INTRODUCTION

Objective

Shunting operations for passenger trains are characterised by relatively short task durations, relatively long transfer times for shunting staff between station and shunting yard, and a lot of waiting time. The utilisation rates for the shunting staff duty schedules are estimated to be very low. Besides the low utilisation rate the availability of drivers for shunting operations is becoming more and more challenging due to the overall scarcity of personnel.

With the upcoming opportunities for automating functions for trains the objective is to look for possibilities to reach a higher productivity in shunting operations by optimising the utilisation rate for shunting staff, reduce the need for shunting staff and reduce the cost for shunting operations.

Looking from the current opportunities within the Innovation Pillar there are two main migration scenarios to achieve the objective for improving the shunting operations for passenger trains:

1) Remote Driving by a train driver from a remote operations centre, with sub-scenarios:
    a. Remote Driving at level ATO GoA1, and
    b. Remote Driving at level ATO GoA2, where the remote driver monitors and controls the ATO-On Board.
2) Fully automated driving at level ATO GoA4, with sub-scenarios:
    a. No fall-back, and
    b. Remote Driving as a fall-back.

The scope of this deliverable is Remote Driving for shunting of passenger trains, so the focus will be on defining migration steps for migration scenario 1 and a limited evaluation of the use of Remote Driving as a fall-back for fully automated driving at level ATO GoA4.

Approach

The approach is to define migration steps in which every step has an added business value. The structure of this chapter is as follows:

1) Lessons learned from the experiments on Remote Driving for shunting passenger trains done by WP38.
2) Definition of a minimum viable product for Remote Driving for shunting passenger trains with a minimum added value for a Railway Undertaking as a first migration step.
3) Definition of additional migration steps to a full solution for Remote Driving for shunting passenger trains.
4) Evaluation of the Remote Driving for shunting passenger trains as a fall-back for automated driving of shunting passenger trains at the level of ATO GoA4.

There are two main differences in approach in this chapter and the approach in the previous chapter:

1) The approach in this chapter is mainly based on re-using current system functions in the cabin of the controlled train, instead of defining all functions needed from scratch. The main idea behind this is that if you want to drive a train remotely, then you ideally like to have the same functionalities that a local driver on the train has available for operation. This approach is in line with the approach in the WP38 experiments which mainly aims at the remote reuse of existing system functionalities (ATB, ETCS, TCMS, controls, etc.) on the train, only extended with extra functionalities for handover of control between remote and local driver.

2) Defining a minimum set of (system) functions which delivers a minimum business value towards the mentioned objective for a Railway Undertaking. In this case the RU passenger objective to achieve a higher productivity for shunting passenger trains within a station and via mainlines.

3.2 Lessons learned from WP38 Remote driving for shunting (passengers)

Within the work package 38 NS together with CAF has executed an experiment with remote driving for shunting (passengers) movements. Shunting movements in this experiment were not limited to depots and stations, but also included train movements via mainlines. This experiment was carried out for the level GoA1 and for the level GoA2 in which the remote driver monitors the ATO on board of the train.

The Innovation Pillar Work Package 38 has published their results for the experiment on Remote driving for shunting (passengers). For this evaluation of the lessons learned mainly the Deliverable D38.2 was used.

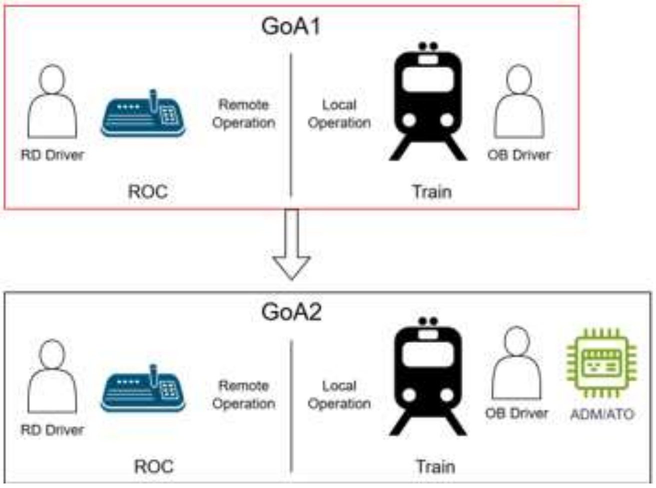
Scope

There were several limitations in the scope of the experiment compared to a full solution for Remote Driving:

1) No remote preparation of the train for departure was available.
2) Limited testing on remote coupling/uncoupling (D38.7)
3) No safety voice communication (GSM-R) was available on the Remote Operation Centre.
4) The use of the national train protection system (ATB), instead of the ETCS-DMI.

Results

Due to the limted scope in the experiments a local driver was still needed on the train next to the remote driver in the Remote Operating Centre.



Lessons learned

The lessons that can be learned after the experiments done by WP38 are the following:

1) The experiment on remote driving looks promising from a technical perspective (latency, remote cameras, etc.).
2) The need for a local driver on the train during the driving (apart from the remote driver) leads to a non-viable product from a Railway Undertaking perspective, mainly because of an increase on the number of shunting staff needed to drive a train and the investment in remote operating functionalities on board and on the trackside.
In the next paragraphs we will define a minimum viable product to reach a profitable solution for a railway undertaking which avoids to need an extra driver on the train next to the remote driver.
3) The proprietary solutions as used in the experiment will have a negative impact on the cost and will slow down migration steps. Examples of these proprietary solutions are the use of the national train protection system, and proprietary solutions for remote driving for one type of train with a corresponding proprietary remote cabin desk.
This lesson learned will be used to look for standardised instead of proprietary solutions which can reduce the cost of migration.

3.3 MINIMUM VIABLE PRODUCT FOR REMOTE DRIVING FOR SHUNTING (PASSENGERS)

In this first migration step we try to define a minimum viable product for Remote Driving with a minimum added value for a Railway Undertaking as a first migration step.

Scope
If we make the assumption that a full solution for Remote Driving consists of:

1) Remote preparation to initialise the train for departure (wake-up, self-testing, etc.)
2) Remote Driving from A to B, and
3) Remote coupling/uncoupling.

Starting from the objective for improving the shunting operations the minimum scope should be to choose the Remote Driving from A to B to avoid inefficiencies due to transfer times. By doing so there is still a need for local train staff to do the preparation for departure and the coupling/uncoupling.

Functionalities
To achieve a profitable business case the Remote Driving from A to B needs to be without a Driver on the train.

This implies that the high level functionalities as used in the WP38 experiments are needed, extended with functionalities that avoid the need for a local driver on the train.

The high-level functionalities for Remote Driving as used in the WP38 experiment:

1) Remote ATB-DMI (national train protection Netherlands).
2) Remote TCMS-controls for traction and braking.
3) Remote Localisation for Train Position.
4) Remote camera images for cabin views.
5) Remote communication between local and remote driver.

To avoid the need for a local driver on the train at least the two mentioned limitations in the scope for the WP38 experiment should be solved leading to the following two extra functionalities:

6) Safety voice communication between the remote operator and the signaller (GSM-R/FRMCS).
7) Remote control of the ETCS-DMI for the remote driver. Not only for driving on ERTMS-trajectories, but also for:

    a. Driving in national train protection areas (shunting areas, stations without ERTMS, etc.). To avoid remote control versions of a wide variety of national train protection systems (like ATB in the WP38 experiment).
    b. Driving in different levels of ATO; GoA1 and GoA2.

8) Safe data communication between Remote control centre and train. Safe and reliable data communication between the Remote Control Centre and the train is essential for safe operation. In the event of a loss of communication during train movement, the remote driver would be unable to issue commands, including a command to stop the train. This could lead to a hazardous situation, such as train overspeed. To mitigate this risk, the system shall be designed to automatically trigger the emergency brake upon detection of a communication loss. This fail-safe function ensures that the train is brought to a safe stop without reliance on remote intervention. As a result, continuous onboard driver presence is not required for managing this specific failure scenario.

Minimum Viable Product for migration step 1.1

Minimum scope: Remote driving for shunting (passengers) from A to B

Out of scope: remote preparation, remote coupling/uncoupling.

Minimum Functionalities: the above mentioned functionalities 1 to 8

3.4 MIGRATION STEPS TO A FULL SOLUTION FOR REMOTE DRIVING FOR SHUNTING (PASSENGERS)

Migration steps to a full solution

After defining a Minimum Viable Product for "Remote Driving from A to B" as a first migration step we now try to define further migration steps for a full solution for Remote Driving.

Looking at the full scope as defined in the previous paragraph the next migration steps could be:

1.2 Remote preparation to initialise the train for departure (wake-up, self-testing, etc.), and
1.3 Remote coupling/uncoupling

Overall optimisation of the migration steps

Looking at the lesson learned number 3 the cost of the total implementation and the migration steps can be optimised by the following harmonisation of interfaces with the Remote Operating Centre:

- Remote use of the ETCS-DMI as mentioned in paragraph 3.3 (point 7).
- Remote control of traction and brakes via re-use of SUBSET-139 (as proposed by IP12.1).

These harmonised interfaces help to standardise the cabin desk in the remote operating centre and avoid the need for proprietary cabin desks per rolling stock type in the Remote Operation Centre..

3.5 REMOTE DRIVING FOR SHUNTING PASSENGER TRAINS, AS A FALL-BACK FOR ATO GOA4

In the previous paragraph we have built a migration strategy for remote driving for shunting (passengers) starting from the lessons learned from the experiments done by WP38. The main characteristics of the shunting movements was that they were train movements over the mainline and within the depot, but always without passengers.

In this paragraph we evaluate the former results for migration scenario 2b Remote Driving as a fall-back for automated shunting of passenger trains at the level ATO GoA4.

In the previous paragraphs we have defined three migration steps for the migration scenario 1 for Remote Driving of shunting movements for passenger trains:

1) Remote Driving from A to B (migration step 1.1)
2) Remote Preparation of the train (migration step 1.2)
3) Remote Coupling/Uncoupling (migration step 1.3)

When we compare these migration steps with the migration scenario 2b for the use of Remote Driving as a fall-back for automated driving of shunting movements for passenger trains at the level of ATO GoA4, then the following differences can be noted:

1) When shunting movements for passenger trains are automated at the level ATO GoA4, then there will most likely be a need for monitoring these automated shunting movements, combined with the need for an automatic alert in case of degradation.
2) In case of degradation a minimum fall-back for ATO GoA4 train movements for shunting EMU passenger trains could be limited to get the train back to the nearest train station or depot where local shunting staff can take over. This requires a minimum set of functionalities as already defined for the migration steps 1.1 and 1.2:
    a. Remote Preparation (in case of changing the active cabins for reverse movement)
    b. Remote Driving from A to B
3) In case of degradation for ATO GoA4 train movements for shunting passenger trains with locomotives the functionalities for Remote Coupling/Uncoupling (migration step 1.3) might also be needed.

Conclusion
In the case of automated driving of shunting movements for passenger trains at the level of ATO GoA4 the fall-back with Remote Driving requires the same three migration steps as needed for Remote Driving as a separate function, combined with the extension of the monitoring function of automated shunting movements.

4 FREIGHT PERSPECTIVE ON MIGRATION CHALLENGES

Freight rail presents a distinct set of operational, technical, and regulatory challenges that fundamentally shape the migration path to Automatic Train operation (ATO) and to Remote Train Operation (RTO) as a fallback to fully autonomous operation under Grade of Automation 4 (GoA4). Unlike passenger services, freight trains exhibit highly diverse configurations, significantly different braking architectures, extreme variability in train dynamics, and a complex legacy fleet that must be retrofitted for automated functions. For these reasons, the concept of migration for freight cannot simply mirror passenger-sector strategies but must incorporate freight-specific constraints, hazards, and functional requirements from the outset. The following explanations focus on some of the most important aspects for freight in the given context of the deliverable. Therefore, no claim to completeness is made, especially since some aspects (e.g. adhesion management) needed to be deliberately left out.

Since for freight trains, no personnel is onboard for GoA4, remote driving is an important fallback solution in case of degraded mode of one of the train systems to evacuate the infrastructure. Accordingly, the remote driving fall-back as well as the GoA4 systems need to be developed for freight trains in parallel to be available at the same time. That means, that while remote driving will have limited operational conditions as a fallback in degraded mode – for example limited speed with which the train is brought to the next depot that makes handling of train dynamics somewhat easier than in full speed –, GoA4 as a primary system needs to be fully available on the same migration path.

The following chapter focuses on mainline operation in the European context with ETCS. In shunting yards, ETCS is generally not available and in addition, the case of solving degraded situations is less complex. Accordingly, shunting operations of freight trains are out of scope.

4.1 OPERATIONAL: REMOTE DRIVING AS FALLBACK FOR GOA4 FREIGHT

An important aspect is to distinguish the use case for remote driving. For the freight use case described here, the operational philosophy is that remote driving is not a primary mode of operation. Instead, RTO is designed as a degraded-mode fallback for GoA4 autonomous driving. Under nominal conditions, trains operate under the ATO-OB, whereas RTO is invoked when the autonomous system becomes unable to perform safe or reliable driving—e.g., degraded perception, exceptional operational scenarios, infrastructure incidents, or train-specific emergencies. During ATO operation, a remote supervisor can supervise multiple trains, whereas during remote driving of a train one specific remote driver is in control. The Remote Supervision and driving will be a new work environment with a new role for the remote supervisors and drivers. Accordingly, the driver´s job description needs to be adapted as well as the organizational structure within the railway undertaking.

Resulting requirements for Remote Driving

This principle has several implications on technical systems supporting the operational process:

- Remote-control functions must mirror the driver's authority without requiring permanent human involvement, supporting short, targeted interventions.
- The RTO workspace must be optimised for intermittent use, enabling operators to take over quickly—with full situational awareness—when an autonomous mission cannot continue.
- Fallback transitions require clearly defined, safe handover conditions, ensuring ETCS maintains safety supervision while control authority shifts, e.g. between ATO, RTO, and, personnel on or near the train as well as between remote supervisor and remote driver.,.

Remote driving as a fallback option implies two important aspects: 1) The aspect of remote driving needs to be solved for ATO GOA4 can be applied to ensure safe ATO GoA4 operation including all possible operational scenarios, e.g. in degraded modes. 2) Freight specific challenges and gaps in regulation / standardization for freight ATO GoA4 directly impact RTO as its fallback option. Accordingly, the following explanations describe freight specific challenges in general for ATO and RTO operation.

More details on remote driving as fallback for ATO GoA4 mainline operation can be found in FP2-R2DATO deliverable D5.5 "Documentation of Freight specific user requirements for automation process".Operational Conditions for ATO GoA4: Freigh-specific dynamic behaviour and operational constraints

4.2 GoA4 Freight specifications

Freight trains differ from passenger trains not just in weight and length but in their complex internal force propagation, sensitivity to gradients, and highly heterogeneous wagon characteristics. Automated driving must therefore incorporate functionality that is not required in passenger ATO deployments.

Traction and Train-Force Management

Freight operations depend on careful regulation of in-train forces to avoid violating mechanical coupler limits (typically 450 kN for UIC screw couplers). The automated system must:

- Apply traction gradually to stretch couplers without causing shocks.
- Reduce traction with a precisely shaped decay curve to avoid slack-run-in.
- Dynamically manage adhesion, especially under low-friction conditions.
- Avoid unnecessary power modulation to ensure energy-efficient, low-wear operation.

Unlike passenger EMUs—where traction is distributed and coupler forces are minimal—freight locomotives must manage forces across wagon configurations several hundred meters long. These requirements must be embedded in both autonomous behaviour and remote-driving control.

Braking Systems and Blended Braking Requirements

Freight operates with multiple braking systems that behave fundamentally differently:

- Electro-dynamic brake (EDB) as the preferred deceleration source.
- Pneumatic train brake, propagating with significant delay through the brake pipe.
- Locomotive brake, typically used only for standstill holding.

Automated systems must apply blended braking considering:

- EDB limits at high and low speed.
- The need for pneumatic support near End of Authority (EOA) due to possible loss of electrical supply.
- Variations in braking performance caused by train length, load distribution, brake valve settings, and environmental conditions.
- The impossibility of relying on fixed brake-release times.

This complexity is largely absent in passenger use cases, where multiple-unit braking is faster, more homogeneous, and more predictable. For example, in today's freight trains a continuous power and data line throughout the whole train composition cannot be assumed.

Special Considerations for Tanker Trains

Freight trains may include tanker wagons exhibiting fluid-induced sloshing. Sudden reductions in traction or the application of braking forces can amplify internal fluid movement and destabilise the consist. Current driver advisory systems cannot manage this. With regard to a migration perspective, these critical cases will be probably not the first use cases to be implemented for GoA4 and remote driving.

Resulting requirements for Remote Driving

The above-mentioned challenges neeed to be solved for GoA4 systems in parallel to the development of remote driving to be available at the same time.

4.3 Specification: Challenges of Retrofitting the Freight Locomotive Fleet

The challenge of retrofitting locomitives bring the requirement of necessary standardization not only for newly designed trains, but also solutions for already locomitives in operation. A critical factor in freight automation is the nature of the legacy fleet. Europe's freight locomotives vary widely by:

- Age (some 40+ years old)
- Braking technology
- Power-electronic architecture
- Cab layout and access equipment
- Interface maturity with TCMS and ETCS

Retrofitting them for GoA4 and RTO poses several challenges.

Functional Interfaces Not Designed for Automation

Many locomotives lack:

- Standardised access to brake control circuits
- Reliable traction command interfaces
- Pantograph and circuit breaker control logic suitable for automation
- Sanding interfaces compatible with automated control
- TCMS functionalities needed to expose train state or locomotive health data

Modern ATO specifications (Subset-125/126/139) do not fully cover these freight-specific requirements, leaving gaps to be addressed in the migration architecture.

Cab and Access-Related Requirements

GoA4 freight locomotives require:

- External status indication (system active, secured, imminent departure)
- A consistent override and boarding mechanism enabling safe human access
- Movement warning systems (lights + audible signals)
- Interoperable RTO camera and sensory equipment

Passenger trains almost always provide safe platform environments. In addition, access for passengers can be managed via door controls; freight locomotives operate in yards and industrial sidings, where shunters, inspectors, and other staff work in close proximity. This necessitates additional layers of human-factor safety technology.

Mixed Fleet and Multi-Locomotive Consists

Freight operations often involve:

- Multiple locomotives in distributed or double-traction configuration
- Variable brake modes (P/G)
- International operation with different pantographs or national systems

ATO and RTO must therefore support:

- Multi-locomotive coordination of traction, braking, and pantograph control
- Calculation and execution of pantograph-raise/lower timing without relying solely on ETCS balise information
- Dynamic consist updates performed remotely by the RU

These requirements exceed those typically encountered in passenger ATO deployments.

4.4 Implications for Migration Planning

To introduce RTO as a fallback for GoA4 freight operation safely and efficiently, the migration strategy must be built around the freight-specific requirements above. Key implications include:

1. New specifications for remote operation and degraded-mode management. Existing TSI and UNISIG subsets are insufficient for freight unattended operation beyond GoA2. Missing functions must be harmonised across ETCS, ATO, and RTO layers.
2. Progressive retrofitting roadmap. Retrofitting must be prioritised based on locomotive type, operational value, and upgrade complexity.
3. Operational rulebook transformation. Today's OPE framework assumes a driver on board. Freight GoA4 migration requires new rules for European Instructions, degraded mode, SR handling, emergency processes, and communication flows.
4. Parallel development of RTO centres and procedures. RTO must become a fully defined operational concept.

Human-machine collaboration for yards and sidings. Automation must seamlessly integrate with manual operations during shunting, inspection, and maintenance.

5 SAFETY VOICE COMMUNICATION FOR ALL RAILWAY SCENARIOS

Introduction

One of the reasons for the need of a local driver on the train in the WP38 experiments was the safety communication via GSM-R. The safety communication services were not redirected to the remote driver desk. To avoid the need for a local driver on the train this issue needs to be solved for all the previous railway scenarios.

<u>Special attention is needed for the broadcast of emergency alerts based on the train position.</u>

[D6.8-Sys.Arch.Spec and Interface Spec. for remote driving, 11.2 CAB-Radio Interface] states: The cab radio interface was discussed during task 6.7 as part of the broader system architecture. The cab radio functions still need an analysis in order to define the subset of service useful for remote driver like for example the communication with passenger or train attendant while voice services enabling dispatcher communications could be reallocated to the remote desk without using the on board cab radio (see open point D6.8-OP07).

This open point on safety voice communication needs to be solved for all scenarios.

Requirements for communication between driver and dispatcher
As the title of this paragraph already indicates, safe voice communication is required in all scenarios. This stems from the fact that at any time, when the dispatcher calls the train(driver), he expects that the call is answered. This is required for cases where a specific train is contacted, but also for instance, where trains are contacted based on their location. This is an important requirement (R1):

> R1a: When the dispatcher calls the train(driver), the call is always answered.
>
> R1b: When the dispatcher alerts the train(driver) based on the train position (AHABV), the train (driver) always responds consistently.
>
> R1c: R1a/b shall also be guaranteed in case a remote driver controls more than one train (probably not going to happen).

*AHABV: **A**larmoproep GSM-R uitzenden; **H**erroepen van seinen (indien noodzakelijk); **A**RI uitzetten voor betreffende planregels (indien noodzakelijk); **B**uurtreindienstleider informeren (indien noodzakelijk); **V**eiligheidsmaatregelen nemen, verhinderen van rijweginstelling.*

Any technical/procedural solution to implement requirements R1a/b shall address the issue that a call whether train selection based, or position based is always relayed to a responder that is able to act. This responder is, presumably, the remote driver.

The assumption is that GOA4 is out of scope. In this case, there is no remote driver, perhaps a supervisor. The scope of the current document is limited to the situation where the train is actually in remote driving mode.

The assumption is that the dispatcher uses conventional means to connect to trains by phone or to initiate alerts. This leads to requirement R2.

> R2a: The dispatcher calls the train (driver) in the usual way

R2b: The dispatcher initiates an alert (AHABV) in the usual way

A technical solution to implement the above requirements may result in delays in communication or a delayed response to an alert. The technical solution shall be analyzed to assess signal quality and existence and impact of delay (R3):

R3: Any technical solution to establish voice communication, or to communicate alerts (AHABV) to the train (driver) shall be analyzed to assess signal quality and existence and impact of delay.

In case of a calamity, the remote driver shall also be able to contact the dispatcher. This is not technically challenging, but for completeness: R4.

R4: The driver shall always be able to contact the dispatcher.

Requirements for communication between driver and attendant

There is also communication required between the driver and the attendant. This may concern simple procedural communication, but in case of a calamity, this may also concern important directions, or alerts.

R5a: When the remote driver calls the train(attendant), the call is always answered.

R5b: When the attendant calls the remote driver, the call is always answered.

R5c: R5a/b shall also be guaranteed in case a remote driver controls more than one train (probably not going to happen).

Requirements for communication between driver and passengers

It may be required to also communicate with passengers. This may concern simple procedural communication, but in case of a calamity, this may also concern important directions, or alerts. It is assumed that passengers will have the option to control an emergency brake and the Remote driver should be able to control the doors.

R6: The remote driver shall be able to communicate to the train (passengers/intercom), as the passenger shall also be able to communicate to the remote driver.

Conclusion summary

To establish effective/safe means of communication between train and tracksidel, the following requirements apply:

R1a: When the dispatcher calls the train(driver), the call is always answered.

R1b: When the dispatcher alerts the train(driver) based on the train position (AHABV), the train (driver) always responds consistently.

R1c: R1a/b shall also be guaranteed in case a remote driver controls more than one train (probably not going to happen).

R2a: The dispatcher calls the train (driver) in the usual way

R2b: The dispatcher initiates an alert (AHABV) in the usual way

R3: Any technical solution to establish voice communication, or to communicate alerts (AHABV) to the train (driver) shall be analyzed to assess signal quality and existence and impact of delay.

R4: The driver shall always be able to contact the dispatcher.

R5a: In case of a train with passengers, when the remote driver calls the train(attendant), the call is always answered.

R5b: In case of a train with passengers, when the attendant calls the remote driver, the call is always answered.

R5c: R5a/b shall also be guaranteed in case a remote driver controls more than one train (probably not going to happen).

R6: The remote driver shall be able to communicate to the train (passengers/intercom).

6 MIGRATION STRATEGY FOR TRAMWAYS

Introduction

The migration strategy for tramways is derived from the complete evolution path investigated within R2DATO. In particular, D41.2 – Testing Reports & Assessment [8], produced within WP41 – Remote Driving and Telecommand Demonstrator, documented the successful validation of a remote driving solution for tramways up to TRL7 through real operational demonstrations performed at the Holtet depot in Oslo. The demonstrator validated remote control, telecommand functionalities, communication architecture, operational procedures and associated performance indicators, demonstrating the feasibility of remote driving for depot operations and establishing the first practical step towards higher levels of automation.
Building on these results, D6.6 – Documentation of Use cases, requirements & Specification autonomous operations for tramways [5] defined the operational use cases and requirements for autonomous tramway operation, while D42.2 – Autonomous movements of trams in depot [6] and D42.3 – Testing reports & assessment [7] extended the concept towards supervised autonomous operations and mission-based depot automation. Therefore, the migration strategy presented in this chapter is based on both the demonstrated remote driving capabilities validated in WP41 and the subsequent autonomous operation concepts developed in WP42, representing successive steps towards increasing levels of automation.

Objectives

The objective for tramways as stated by reference [7], chapter 7: "*Improve depot productivity by reducing manual intervention, improving vehicle availability, accelerating vehicle preparation and enabling more flexible sequencing of depot tasks.*"

Reference [5] describes the following functional use cases for autonomous operations for tramways:

- *Remote parking in a depot*
- *Remote washing*
- *Pre-departure tram check*
- *Autonomous shunting (from indoor to outdoor)*
- *Autonomous shunting of several vehicles simultaneously using V2X*
- *Wheel profile examination*

Reference [6] describes the following demonstrator objectives:

- *A primary objective of the demonstrator is to validate the capability to command and execute mission profiles remotely. These mission profiles represent predefined operational tasks that the vehicles must perform autonomously, such as moving between parking positions, accessing maintenance areas, or preparing vehicles for operational service. The demonstrator evaluates the ability to generate, transmit, and execute these commands from ground-based supervisory systems, including the CERES remote operation center platform, ensuring seamless coordination between remote operational control and onboard vehicle systems.*
- *Additionally, the demonstrator aims to validate the capability of the vehicles to autonomously manage their movement while maintaining safe operational behaviour. This includes verifying the vehicles' ability to regulate speed in accordance with operational constraints and environmental conditions, ensuring compliance with depot operational safety requirements.*
- *Another key objective is to assess the vehicles' capability to detect and avoid potential collisions with other vehicles, infrastructure elements, or any obstacles that may be present within the vehicle's movement envelope. The demonstrator therefore evaluates onboard*

perception, obstacle detection, and autonomous response functionalities that contribute to safe autonomous manoeuvring within the depot environment.

In addition to the autonomous operation objectives described above, D41.2 – Testing Reports & Assessment [8] introduced complementary objectives focused on the validation of Remote Driving and Telecommand functionalities for tramways in a real operational environment.

- *A primary objective of the WP41 demonstrator was to validate a remote driving concept up to TRL7 by demonstrating the capability of a remote operator to establish communication with the vehicle, monitor onboard cameras, execute remote commands, remotely prepare the vehicle for operation and perform driving movements under controlled depot conditions. The objective was not only to verify the correct implementation of the technological solution, but also to assess its operational feasibility, safety, reliability and potential value for future deployment scenarios.*
- *Additionally, the demonstrator aimed to establish and validate an operational framework for remote driving activities, including test methodologies, operational procedures, safety roles, risk control measures, communication management and configuration management processes. Functional verification was performed through auxiliary circuit tests, static functional tests and dynamic functional tests, covering remote wake-up, remote control acquisition, video monitoring, communication management, braking functions and remote driving operations. All test protocols were successfully completed, providing evidence of the maturity of the solution.*
- *Another important objective was to evaluate the operational and technical performance of the remote driving solution through a set of Key Performance Indicators, including image quality, communication latency, system availability, operator usability, productivity improvement and reaction time reduction. The assessment aimed to demonstrate that remote driving could generate measurable operational benefits in depot activities while providing a realistic and operationally validated migration step between conventional depot operations and higher levels of automation.*

Conclusions

The R2DATO activities for tramways demonstrate a progressive migration path from remote driving towards increasingly autonomous depot operations. WP41 successfully validated Remote Driving and Telecommand functionalities up to TRL7 in a real operational environment, demonstrating the feasibility of remotely controlling tram movements, executing remote commands, ensuring reliable communications and supporting depot operations through a remote operation centre. The results also showed measurable benefits in terms of operational efficiency, productivity improvement and reaction time reduction, establishing Remote Driving as a viable operational concept for depot environments.

Building on this validated foundation, the subsequent work carried out in WP42 expanded the operational concept towards autonomous execution of mission profiles, where predefined depot tasks can be generated by supervisory systems and executed autonomously by the vehicle. These developments introduced higher levels of automation, including autonomous vehicle movements, supervised mission execution and obstacle detection capabilities within depot environments.

Therefore, the migration strategy for tramways should not be considered as a direct transition towards mission-based autonomous operation. Instead, Remote Driving represents a practical and operationally validated intermediate step that enables the gradual introduction of automation while delivering immediate operational benefits. As automation capabilities mature, the role of the operator can progressively evolve from direct vehicle control towards supervision and management of autonomous missions. Consequently, the preferred long-term evolution for tram depots is based on autonomous mission execution under remote supervision, while Remote Driving remains an important enabling technology and migration step towards higher levels of automation.

Comparison between tramways and passenger railways

The general objective of improving productivity in shunting, parking, vehicle preparation and maintenance processes is largely the same for both tramways and passenger railways.

For both passenger railways and tramways, the long-term vision is the progressive automation of shunting and maintenance processes through ATO GoA3/GoA4 functionalities supported by remote supervision capabilities. For passenger railways, achieving this vision may require a full implementation of ERTMS in stations and shunting areas, together with remotely operated switches and a higher degree of infrastructure digitalisation. Since this final situation might be further away for railways than for tramways, Remote Driving for passenger railways can be considered a practical migration step towards higher levels of automation, allowing operational benefits to be achieved while progressively introducing the technologies and procedures required for future ATO GoA3/GoA4 operation.

A similar migration logic can be identified for tramways. WP41 demonstrated that Remote Driving and Telecommand functionalities can be successfully deployed in a real depot environment, achieving TRL7 validation and demonstrating measurable improvements in productivity, reaction time and operational flexibility. Remote Driving therefore represents an operationally validated capability rather than merely a fallback function.

Building on these capabilities, WP42 extended the concept towards autonomous execution of mission profiles, including autonomous shunting, parking and depot movements under remote supervision. Since tramway autonomous operations are currently restricted to depot environments, characterised by low operating speeds and controlled operational conditions, the transition towards mission-based autonomous operation can be achieved more rapidly than in mainline railway applications. Nevertheless, the WP41 results indicate that Remote Driving remains an important enabling technology, providing operational benefits in its own right while also constituting a practical migration step towards autonomous depot operation.

Consequently, the migration strategy for tramways can be described as a progressive evolution from conventional depot processes towards Remote Driving and Telecommand capabilities, followed by increasing levels of supervised automation and ultimately autonomous mission execution.

7 CONCLUSIONS

Fulfilment of the goal

The goal of this deliverable was to define migration scenarios for Remote Driving from different perspectives.

To achieve this, chapter 2 started with a methodological framework for what migration strategies based on functional clustering might look like. This methodological framework was inspired by Work Package 33 (WP33). It therefore attempted to identify operational pain points. In the end, the third chapter offers two ways in which pain points can be clustered. The first way is that there is clustering based on stakeholder pain points and complexity. The second way is that there is clustering based on area of application.

Chapter 3 describes migration scenarios for remote driving of shunting movements for passenger trains from a railway undertaking perspective. For the objective of achieving a higher productivity for the shunting operations on passenger trains two migration scenarios with migration steps are defined, based on clustering system functionalities around minimum added business values and thus also avoiding the need for a second local driver on the train as in the experiments in WP38.

Chapter 4 describes a freight perspective on the migration challenges for remote driving as a fall-back for the automated driving at the level of ATO GoA4.

Chapter 5 describes the requirements for safety voice communication in case of Remote Driving for all railway scenarios when the driver is not on the train but in a remote operations centre. These requirements are valid for all railway scenarios.

Chapter 6 describes the migration scenario for tramways for automating the shunting and maintenance processes for tramways within a depot.

Proposals

1) Redefine Remote Driving into Remote Train Operation.

   As already defined in chapter 3 it is proposed to redefine Remote Driving as Remote Train Operation with at least three sub-functions which are used for the different migration steps:

   a. Remote preparation, to initialise the train for departure (wake-up, self-testing, etc.)
   b. Remote Driving, from A to B, and
   c. Remote Coupling/Uncoupling.

      This is a first proposal for redefinition and is driven by the splits already used in the WP38 experiments (D38.2 Remote Driving [3], from A to B and D38.6 Coupling/Uncoupling [4]) and the three proposed migration steps for Remote Driving for shunting passenger trains.

2) Take Safety Voice Communication in scope for Remote Driving.

      Without a solution for Safety Voice Communication we will always need a second driver on the train, as experienced in the work done WP38, and we will never reach a positive business case.

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