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Rail to Digital automated up to autonomous train operation

D42.2 – Autonomous movements of trams in depot

Approach to demonstration for autonomous movements in controlled areas.

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EXECUTIVE SUMMARY

This document presents the framework, objectives, implementation approach, and validation strategy for the autonomous depot movement demonstrator developed under WP42 of the R2DATO programme. The demonstrator represents a key project milestone, consolidating the technological developments and validation activities previously conducted in WP40 and WP41 into a fully integrated operational demonstration.

The demonstrator aims to validate autonomous tram movements within a depot environment using two prototype vehicles from the SL18 fleet operated by Sporveien in Oslo. These vehicles, manufactured by CAF, were modified and approved during WP40 to operate as experimental tram-labs capable of supporting advanced automation functionalities while maintaining compliance with operational safety requirements.

The demonstration focuses on three key capabilities: the remote command and execution of mission profiles from ground-based supervisory systems, including the CERES platform; the autonomous regulation of vehicle speed according to operational and safety constraints; and the detection and avoidance of potential collisions with vehicles, infrastructure elements, and obstacles within the operational envelope.

Testing activities are conducted at the Holtet Depot, a facility prepared to support automated movement testing under controlled yet operationally representative conditions. The testing programme includes typical depot manoeuvres such as parking operations, workshop access movements, and vehicle repositioning tasks, with operational speeds validated progressively up to 15 km/h.

The prototype vehicles incorporate modular automation architectures operating alongside original vehicle systems and supporting multiple operational modes, allowing safe transitions between commercial service, passive data acquisition, and supervised autonomous testing. Enhanced communication infrastructure, including redundant Wi-Fi and 5G connectivity, ensures reliable interaction between onboard and ground-based systems.

Development activities during 2025 focused on subsystem maturation through laboratory and test bench validation, culminating in the first onboard integration milestone achieved in Week 51 of 2025. The validation methodology follows lifecycle-oriented principles derived from CENELEC processes, particularly the EN 50126 framework, ensuring structured and traceable system validation.

The demonstration programme is structured through progressive testing campaigns aimed at delivering a fully functional demonstrator aligned with the project's technological and dissemination objectives. Overall, WP42 confirms the feasibility and maturity of autonomous depot movement concepts and supports the development of scalable automation solutions for future railway operations.

TABLE OF CONTENTS

Report Contributors **2**
Executive Summary **3**
Table of Contents **4**
List of Figures **4**
1 INTRODUCTION **5**
1.1 Context and Objectives 5
1.2 Document structure 6
2 AUTONOMOUS MOVEMENT DEMONSTRATION **7**
2.1 Demonstrator Objectives 7
2.2 Testing environment 8
2.3 tram topology an modification 9
2.4 Testing plan and metodology 12
3 CONCLUSIONS **14**
References **16**

LIST OF FIGURES

Figure 1: Holtet depot at Oslo 8
Figure 2: Key-based selector installed in existing cabinets 9
Figure 3: PERception System detail (Lidars) 11
Figure 4: PERception System detail II (Radar installation) 11
Figure 5: Cameras installation at driver's cab 11
Figure 6: Detail of the external adhesive labels 12

1 INTRODUCTION

This deliverable aims to provide a structured and qualitative description of the demonstration phase currently being carried out under Work Package 42 (WP42). The document establishes a common framework to describe the overall objectives, scope, and implementation strategy of the demonstration activities. In particular, it defines the testing scenarios, identifies the vehicles and assets involved, and outlines the validation methodologies that will be applied throughout the demonstration campaign.

1.1 CONTEXT AND OBJECTIVES

WP42 represents a key milestone within the R2DATO project, as it consolidates the technical developments and system integration efforts performed in previous work packages into real operational demonstrations. The primary purpose of this phase is to assess the performance, robustness, and operational feasibility of the developed solutions under representative tramway operating conditions, ensuring alignment with the project's overall goals of advancing automation, digitalization, and remote operational capabilities within the rail sector, specifically in urban operations.

The demonstration activities conducted in WP42 are the culmination of the preparatory and validation work performed in WP40 and WP41. In WP40, two representative vehicles were prepared, instrumented and approved to serve as the core experimental platforms for the entire R2DATO project and future extensions. This preparation included the integration of enabling technologies, the installation of monitoring and communication systems, and the adaptation of onboard and trackside interfaces required to support advanced operational functionalities. The work carried out in WP40 ensured that the selected vehicles provide a flexible, safe, and reliable environment to host and test the technologies developed throughout the project.

Building on this foundation, WP41 focused on the development and validation of the remote driving functionalities. The work performed in this phase addressed both the technological and operational aspects required to enable remote operation, including communication architectures, human-machine interfaces, operational procedures, and safety-related considerations. The results of these activities are documented in the corresponding WP41 deliverables, which describe the system architecture, functional validation results, and performance assessments obtained during controlled validation campaigns. These outcomes demonstrated the technical feasibility of remote driving concepts and provided the necessary confidence to progress towards large-scale demonstration under more representative operational environments.

Within this context, WP42 aims to move from controlled validation towards integrated system demonstration in realistic operational scenarios. The objective is not only to verify the correct functioning of individual subsystems, but also to evaluate their interaction, interoperability, and overall system performance when deployed in real-life conditions. The demonstration activities therefore focus on validating end-to-end operational concepts, including interactions between onboard systems, remote operation centers, communication infrastructures, and operational staff.

To achieve these objectives, this deliverable defines a structured approach to the demonstration campaign. It identifies the testing scenarios selected to represent a broad range of operational situations, considering both nominal and non-nominal conditions. These scenarios are designed to progressively evaluate system capabilities, starting from basic functionality verification and advancing towards more complex operational use cases. The document also describes the vehicles and supporting assets that will be used during the demonstration phase, including the technical roles they fulfil within the overall testing framework.

Furthermore, this deliverable establishes the validation strategy and testing methodologies that will be applied to assess system performance. The validation approach is designed to ensure traceability between project requirements, implemented functionalities, and demonstration results. It defines the criteria for success, the metrics to be monitored, and the data collection and analysis procedures that will support the evaluation process. The methodologies are aligned with best practices in railway system validation and aim to guarantee reproducibility, transparency, and consistency across the different demonstration activities.

Beyond its technical role, WP42 also supports the broader dissemination and impact objectives of the R2DATO project. Demonstration activities provide tangible evidence of the project's achievements and contribute to building stakeholder confidence in the proposed solutions. By validating the developed technologies in realistic environments, WP42 facilitates knowledge transfer, supports standardization efforts, and promotes the future adoption of advanced automation and remote operation concepts within the European rail ecosystem.

In summary, this deliverable serves as the reference framework for the WP42 demonstration phase. It provides a comprehensive overview of the demonstration objectives, defines the testing scope, describes the assets involved, and establishes the validation methodologies that will guide the execution and evaluation of the demonstration campaign. Through this structured approach, WP42 aims to demonstrate the maturity, reliability, and operational value of the solutions developed within the R2DATO project, paving the way for their future deployment in real railway operations.

1.2 DOCUMENT STRUCTURE

The deliverable D42.2 has been structured as follows:

- Chapter 1: Introduction (the current chapter).
- Chapter 2: Autonomous movement demonstration
    - 2.1 Testing environment
    - 2.2 Tram topology and modification
    - 2.3 Testing plan and metodology
- Chapter 3: Conclusions

2 AUTONOMOUS MOVEMENT DEMONSTRATION

2.1 DEMONSTRATOR OBJECTIVES

The autonomous movement demonstrator aims to validate the capability of tram vehicles to safely and reliably perform autonomous movements within a depot operational environment. The demonstration focuses on the use of two prototype units equipped with autonomy-enabling technologies[2] that have been developed and integrated throughout the previous project phases.

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.

Overall, the demonstrator seeks to validate the feasibility, safety, and operational value of autonomous depot movements, providing evidence of system maturity and supporting the potential future implementation of automated operational concepts within depot environments.

[2] Given that the objective of the demonstrator, and indeed the related work packages, is to research and demonstrate progress towards future autonomous mobility, the authors consider it appropriate to use the term 'autonomy-enabling technologies', since the trams have been instrumented and equipped far beyond what the eventual final product may be.

2.2 TESTING ENVIRONMENT

The testing activities are conducted exclusively within the Holtet depot, operated by Sporveien and located in Oslo. The Holtet depot has been specifically prepared and operationally procedurised to support testing activities involving autonomous and remotely supervised vehicle movements. The depot provides a controlled operational environment that allows the safe execution of experimental testing while maintaining representative depot operational conditions.

This depot is ideal for this type of activity since during the daytime it is almost always empty or has low occupancy. For this purpose, Sporveien defined, already for work package WP41, a safety case for each test batch (e.g., remote driving or autonomous operation), detailing which switches remain closed and locked, the mandatory markings on the ground to trigger emergency braking should the onboard operator need to take control, the personnel required at each point either onboard or outside the train, etc. These procedures are designed to closely resemble those used in the daily operation of a depot, including the variable of an autonomous or remotely operated vehicle.

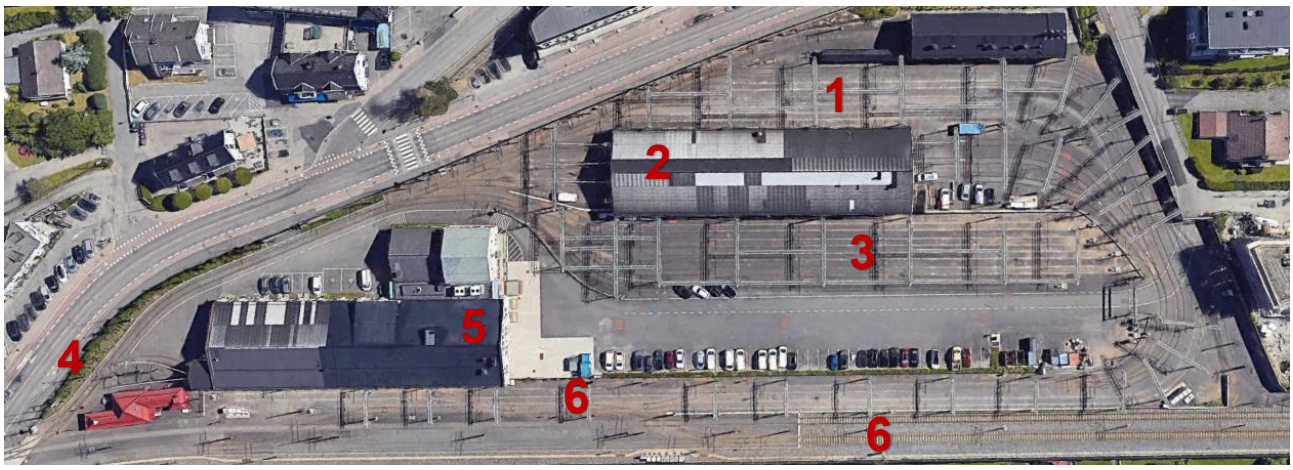


Figure 1: Holtet depot at Oslo

Where

1. Parking area (I)
2. Workshop
3. Parking area (II)
4. Entrance
5. Main building
6. Testing track
7. Main line

The depot infrastructure includes multiple parking tracks, workshop access tracks, and internal routing possibilities that allow the execution of a wide range of operational manoeuvres. The facility supports integration with depot management and signalling systems, enabling coordination between vehicle movements and infrastructure routing elements. Where functionally available, testing activities leverage the automated depot interlocking system to support route setting and movement authorisation processes, ensuring alignment with realistic depot operational workflows.

Operational testing is performed under predefined safety and operational procedures established jointly with the depot operator. These procedures define movement authorisation protocols, supervision requirements, and emergency intervention mechanisms, ensuring that testing activities can be performed safely while maintaining operational realism.

The operational speed in the depot is limited to a maximum of 15 km/h, reflecting typical depot operational speed limits and ensuring safe manoeuvring conditions. In order to progressively validate system performance and reliability, a significant portion of the tests is initially conducted at reduced speeds, typically starting from 5 km/h. This progressive speed validation approach allows the verification of perception, control, and braking performance under controlled conditions before advancing towards higher operational speeds.

The testing campaign includes a variety of movement scenarios representative of typical depot operations. These scenarios include automated parking manoeuvres, movements between parking positions, transitions between parking tracks and workshop entry tracks, and preparation movements associated with vehicle operational deployment. The diversity of manoeuvres allows comprehensive validation of autonomous movement capabilities across different routing configurations, infrastructure layouts, and operational contexts.

The Holtet depot environment therefore provides a safe, representative, and operationally relevant testing platform that supports the systematic validation of autonomous depot movement functionalities while enabling close coordination with depot infrastructure systems and operational personnel.

2.3 TRAM TOPOLOGY AN MODIFICATION

The modification, integration, and approval of the demonstration vehicles were performed during WP40, where the two prototype units used across the R2DATO project were prepared as experimental platforms. The vehicles selected for the demonstration correspond to units 455 and 456 of the SL18 fleet operated by Sporveien. These vehicles are based on the Urbos 100 tram platform manufactured by CAF and represent a modern light rail architecture suitable for the integration of advanced automation technologies.

The two vehicles have been adapted to operate under different operational modes through a dedicated key-based selection mechanism that enables switching between homologated and experimental configurations. This concept ensures that the vehicles can safely operate both in regular passenger service and in testing scenarios while maintaining strict separation between operational states.



Figure 2: Key-based selector installed in existing cabinets

- Mode 0 corresponds to the fully homologated configuration, allowing the vehicles to operate in normal commercial service without any interference from experimental automation functionalities. In this mode, all systems operate according to their approved operational configuration, ensuring compliance with existing regulatory and safety requirements.
- Mode 1 enables operation in real service while activating additional data recording capabilities associated with the onboard perception systems. This configuration allows the system to collect operational data seamlessly during regular driving without introducing any additional workload or operational changes for the driver neither the operator. The objective of this mode is to support system validation and performance monitoring under real operational conditions while maintaining standard vehicle behaviour.
- Mode 2 is a dedicated testing configuration that can only be activated under controlled testing environments and specific safety measures. In this mode, the vehicles are enabled to perform autonomous movements. The activation of Mode 2 requires the presence of an onboard safety driver responsible for supervising vehicle behaviour and capable of taking immediate control if required. This operational mode is exclusively used for the autonomous movement demonstrator described in WP42.

Both vehicles have been equipped with autonomous-enabling systems that are implemented as an additional architecture installed alongside the original vehicle systems. This architecture has been designed to remain functionally separated from the baseline vehicle control systems while allowing safe and controlled interaction through defined interfaces. Except for the perception system components, which may incorporate vehicle-specific sensor installation adaptations, both prototype vehicles share identical system architectures, ensuring consistency in testing results and facilitating cross-validation of system performance.

The onboard perception system provides environmental awareness by detecting obstacles, infrastructure elements, and other vehicles within the tram's operational envelope. These systems are complemented by localisation and control modules that enable autonomous movement execution while maintaining compatibility with existing vehicle control logic.



Figure 3: PERception System detail (Lidars)



Figure 4: PERception System detail II (Radar installation)

Communication capabilities have been enhanced through the installation of new onboard routing equipment incorporating redundant Wi-Fi and 5G communication modules. This communication architecture increases data transmission reliability and availability, supporting continuous connectivity between the vehicles and ground-based supervisory systems. The redundancy strategy ensures improved resilience against communication disruptions and supports the safe execution of remote command and monitoring functionalities.

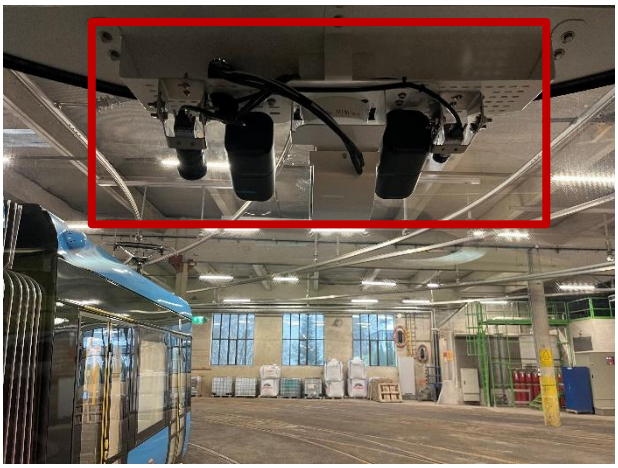


Figure 5: Cameras installation at driver's cab

The modified vehicles can be considered "tram-labs", serving as experimental platforms designed to validate innovative automation concepts under controlled conditions. However, despite their experimental nature, the solutions implemented within these vehicles have been developed following recognised railway engineering principles. Particular attention has been given to safety, cybersecurity, system segregation, and compliance with applicable regulatory frameworks.

As a result, while the vehicles themselves are configured as testing platforms, the architectural concepts, safety strategies, cybersecurity measures, and operational approaches implemented during this demonstrator are designed to be directly transferable to future commercial implementations. This ensures that the knowledge generated during the demonstration phase contributes not only to technological validation but also to the development of scalable and deployable automation solutions for real-world tram operations.



Figure 6: Detail of the external adhesive labels

2.4 TESTING PLAN AND METODOLOGY

Throughout 2025, development activities were primarily focused on subsystem design, implementation, and validation in laboratory environments and dedicated test benches. These activities covered perception technologies, control algorithms, communication architectures, remote supervision functionalities, and safety-related mechanisms. The development strategy followed an agile and iterative approach, allowing progressive refinement of system functionalities while ensuring early detection and resolution of integration challenges.

The overall planning strategy established 2025 as a development and subsystem validation phase, with the objective of reaching initial onboard integration testing by Week 51 of 2025. This milestone was successfully achieved, enabling the first integrated demonstrations of the autonomous movement functionalities onboard the prototype vehicles, unit 455 in this case. These initial integration tests validated the correct interaction between onboard subsystems, communication infrastructures, and ground-based supervisory platforms, confirming the readiness of the system to progress towards full demonstration activities.

A detailed description of test cases, validation results, and performance assessments will be provided in Deliverable D42.3. Within WP42, the primary objective of the testing campaign is to validate complete end-to-end operational use cases, ensuring that all elements of the functional chain operate coherently. This includes the generation of mission profiles, command transmission from ground-based systems, onboard execution of autonomous movement functions, obstacle detection and response, communication supervision, and human-machine interaction.

The validation methodology follows principles derived from the CENELEC standard EN 50126, particularly regarding early validation strategies and lifecycle-oriented system assurance. This approach supports progressive system validation through staged testing activities, ensuring that integration testing is performed with sufficient maturity of individual subsystems. The methodology

emphasises traceability between system requirements, implemented functionalities, and validation evidence, supporting a structured and auditable validation process.

The ground-based CERES platform follows an independent software development lifecycle, incorporating iterative releases and functional expansions. Multiple software versions have been developed and validated throughout 2025, culminating in the deployment of a first fully functional version during the Week 51 integration milestone. This version enabled the execution of initial remote mission profile management and supervisory functionalities, forming the basis for further refinement during the demonstration phase.

Looking forward, the demonstration programme is structured around a series of progressive testing campaigns aimed at achieving a fully functional and publicly demonstrable solution by InnoTrans 2026. To support this objective, several intermediate milestones have been defined:

- Week 17, 2026 – Holtet Testing Campaign:

  First large-scale integrated demonstration campaign focusing on validating representative operational use cases under realistic depot conditions. The objective is to verify system stability, communication performance, and autonomous movement reliability.

- Week 25, 2026 (starting 15 June 2026) – Holtet Testing Campaign:

  Second integration campaign focused on expanding operational coverage, validating additional use cases, and consolidating system performance. This campaign will incorporate lessons learned from the previous testing phase and target improved robustness and operational readiness.

- InnoTrans 2026 – Final Demonstrator:

  Delivery of a fully functional demonstrator capable of showcasing end-to-end autonomous depot movement functionalities under representative operational scenarios.

Both intermediate testing campaigns at Holtet are designed to act as realistic operational rehearsals of the targeted demonstration use cases. The periods between campaigns will be used for system refinement, performance optimisation, bug fixing, and validation of incremental software and system updates. This iterative testing and improvement strategy ensures continuous system maturation and reduces integration risks prior to the final demonstration milestone.

Overall, the testing plan combines structured validation methodologies with agile development principles, enabling progressive system maturation while maintaining alignment with railway safety and reliability requirements. This approach ensures that the autonomous movement demonstrator evolves through controlled validation stages towards a robust and operationally credible demonstration platform.

3 CONCLUSIONS

The autonomous movement demonstrator developed within WP42 represents a significant milestone in the progressive validation of automated tram operations within depot environments. By integrating technological developments from previous project phases into a realistic operational testing framework, the demonstrator has enabled the execution of a comprehensive set of preliminary validation activities, laying the foundations for the final assessment to be reported in D42.3.

The demonstration activities have provided early evidence of the technical feasibility of executing remotely commanded mission profiles through coordinated interaction between ground-based supervisory systems and onboard vehicle control architectures. These results should be understood as part of an ongoing validation process, with further analysis and consolidation required to reach final conclusions.

Initial testing has also shown promising capabilities of the prototype vehicles to autonomously regulate movement speed in accordance with operational safety requirements and infrastructure constraints. The progressive validation approach, including testing across different operational speeds and manoeuvre types, has contributed to building confidence in system behaviour, while additional validation steps remain necessary to fully characterise performance and robustness.

Similarly, preliminary validation of onboard perception and obstacle avoidance functionalities has been achieved. The vehicles have demonstrated the ability to detect and react to potential collision risks within controlled scenarios. These outcomes represent early-stage confirmation of key functional building blocks, which will be further assessed and quantified in subsequent activities.

The integration strategy adopted for the prototype vehicles has proven effective in enabling advanced automation functionalities while maintaining compatibility with existing vehicle architectures. The modular and segregated system design allows experimental technologies to coexist with baseline vehicle systems without compromising safety principles. While the vehicles serve as experimental tram-labs, the architectural approach, safety strategies, and cybersecurity concepts developed constitute a solid basis for future commercialisation, pending final validation.

The structured testing methodology applied throughout WP42, based on lifecycle-oriented validation principles, has ensured traceability between system requirements, implemented functionalities, and preliminary validation outcomes. The combination of iterative development cycles with formal railway validation practices has supported progressive system maturation, although the validation process remains ongoing.

Beyond the technical aspects, the demonstrator has generated valuable initial insights into human-machine interaction, supervision strategies, and the integration of automated functionalities into existing depot workflows. These insights contribute to shaping the operational framework for automation, while further refinement is expected as the project progresses.

From a strategic perspective, the WP42 demonstrator contributes to the overarching objectives of the R2DATO programme by providing early, tangible evidence of the potential of autonomous and remotely supervised rail operations. At this stage, the results should be considered as intermediate outcomes that support continued development, knowledge consolidation, and alignment with future standardisation and regulatory evolution.

In conclusion, WP42 has successfully delivered a comprehensive set of demonstrator activities and preliminary validation results, confirming the viability of key technological concepts and integration approaches. However, the work presented here does not constitute the final validation of the system.

The consolidation of results, final performance assessment, and definitive conclusions will be presented in Deliverable D42.3, which will provide the complete evaluation of the autonomous depot movement capabilities.

REFERENCES

[1] D42.1 – Collection of test cases and validation criteria