Rail to Digital automated up to autonomous train operation

D9.1 – Concept of migration and deployment for “automating functions” based on Input from TE20

Due date of deliverable: 31/05/2026

Actual submission date: 31/05/2026

Leader/Responsible of this Deliverable: Jad Haber, SMO

Reviewed: <u>Y</u>/N

Document status		
Revision	Date	Description
01	02/03/2026	First issue ready for internal review.
02	20/03/2026	Incorporation of comments after final internal review. Ready for TMT review.
03	09/04/2026	Incorporation of comments after TMT review. Ready for SteCo review.

Project funded from the European Union’s Horizon Europe research and innovation programme		
Dissemination Level		
PU	Public	X
SEN	Sensitiv – limited under the conditions of the Grant Agreement	

Start date: 01/12/2022 Duration: 42 months

ACKNOWLEDGEMENTS

This project has received funding from the Europe's Rail Joint Undertaking (ERJU) under the Grant Agreement no. 101102001. The JU receives support from the European Union's Horizon Europe research and innovation programme and the Europe's Rail JU members other than the Union.

REPORT CONTRIBUTORS

Name	Company	Details of Contribution
Jad Haber	SMO	Co-author and reviewer of contribution
Markus Korb	SMO	Co-author and reviewer of contribution
Dominik Kevický	AZD	Co-author and reviewer of contribution
Michele Bruzzo	STS	Co-author and reviewer of contribution
Pierre-françois Jauquet	ATSA	Co-author and reviewer of contribution
William Busuttil	ATSA	Co-author and reviewer of contribution
Diego García Vaquero	ADIF	Author of executive summary and reviewer of contribution

Disclaimer

Funded by the European Union. Views and opinion expressed are however those of the author(s) only and do not necessarily reflect those of the European union. Neither the European Union nor the granting authority can be held responsible for them. The project FP2-R2DATO is supported by the Europe’s Rail Joint Undertaking and its members.

EXECUTIVE SUMMARY

This deliverable synthesizes a stakeholder-driven methodology to plan the migration and deployment of automating functions across the railway value chain. It recognizes the coexistence of ETCS/ERTMS and numerous national control systems—particularly in yards and depots—and proposes a pragmatic, phased path that clusters use cases by complexity and impact. The approach builds on functional definitions developed in WP6 and on deployment strategy lessons captured in WP33, and is intended as a reusable method that stakeholders can tailor to their context.

Objectives: The report aims to (i) map key stakeholder pain points, (ii) cluster related automating functions into implementable packages, and (iii) provide area-based migration options—from depots to mainline—culminating in higher Grades of Automation (GoA3/4) with remote driving as a fallback for degraded operations.

Method: Stakeholders are segmented into passenger RUs, freight RUs, and Infrastructure Managers; pain points are identified (costs, capacity, punctuality, safety, workforce, shunting efficiency); and, for each, there is a proposal of an initial cluster plus add-on clusters of use cases. In parallel, an area-based view distinguishes Depot stand-still, Depot with movement, Train movement to first platform, Mainline without passengers, and Mainline with passengers.

Key results: The clustering yields low-barrier initial packages—e.g., automated preparation, configuration, and tests—that reduce costs and staff workload. Add-on clusters progressively introduce automated yard driving and shunting, optimized mission execution, and cross-border operations, improving capacity and punctuality while maintaining safety. An area-based sequence enables early wins in controlled environments and de-risks mainline deployment.

Recommendations: Use of a multi-criteria decision analysis (MCDA) to prioritize use cases (e.g., based on technical complexity, safety impact, benefits, dependencies, regulatory readiness, cost). Plan remote driving capability in lockstep with GoA4 to support degraded modes. Advance harmonized standards, robust cybersecurity, and safety certification to scale beyond pilots.

Limitations: The roadmap is stakeholder-agnostic by design and must be tailored through engagement with specific market players, local regulation, and fleet/infrastructure constraints.

ABBREVIATIONS AND ACRONYMS

AoC	Area of control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CBG	Centrally controlled area
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
GoAx	Grade of Automation, Level X
MCDA	Multi-Criteria Decision Analysis
NCBG	Non-centrally controlled area
R2DATO	Rail to Digital automated up to autonomous train operation
SWOT	"Strengths, Weaknesses, Opportunities, Threats" Framework
WPx	Work Package X

TABLE OF CONTENTS

LIST OF FIGURES

No figures are in this document.

LIST OF TABLES

No tables are in this document.

2 INTRODUCTION

The railway sector is undergoing a transformative period, driven by the imperative to enhance operational efficiency, increase capacity, improve safety, and reduce environmental impact. Central to this evolution is the progressive automation of railway operations, encompassing a spectrum of functions from discrete tasks to fully autonomous train operation. This strategic paper examines technology migration strategies for automating functions and automated driving, acknowledging the complex interplay of existing national control systems and the overarching European Rail Traffic Management System (ERTMS), specifically the European Train Control System (ETCS). While ETCS represents a significant step towards standardization in mainline operations, a multitude of national systems persist, particularly in yards and depots, presenting unique challenges for automation deployment.

The European Rail Joint Undertaking (ERJU) plays a pivotal role in harmonizing these efforts, with various WPs contributing to a unified vision. This analysis draws upon the functional definitions established in WP6 and leverages insights into pain points and strategic methodologies inspired from WP33 to construct robust migration frameworks. The objective is to delineate actionable strategies for the phased implementation of automating functions, paving the way for advanced grades of automation, including full autonomous driving. This includes considering the role of complementary technologies such as remote driving, which is increasingly recognized as a crucial fallback mechanism for degraded GoA4 operations, thereby influencing the availability requirements within migration pathways.

The purpose of this document 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.

3 STAKEHOLDER SEGMENTATION AND PAIN POINT ANALYSIS

Effective migration strategies necessitate a thorough understanding of the diverse needs and challenges faced by key stakeholders within the railway ecosystem. This section segments these stakeholders and identifies their primary pain points, assessing the relevance of each pain point to specific groups.

3.1 STAKEHOLDER SEGMENTS

For the purpose of developing targeted migration strategies, the primary stakeholders in the railway industry are categorized into three distinct stakeholder segments, each possessing unique operational characteristics and strategic priorities. Among many stakeholders in the industry (e.g., Suppliers, ERA, etc.) whose involvement in the standardization is key for a harmonized and interoperable solution, these stakeholders are considered as primary focus for this deliverable.

- **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 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, signalling systems, and power supply. Their priorities include network availability, safety of operations, efficient traffic management, and cost-effective infrastructure maintenance.

3.2 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], a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of a stakeholder allows to identify weaknesses and threats facing a stakeholder. A SWOT analysis is a strategic planning framework used to evaluate a business by identifying its (internal) strength (S) and weaknesses (W) as well as (external) opportunities (O) and threats (T). The identified weaknesses and threats translate into stakeholder pain points, which will be used as basis for this methodology.

Following key pain points have been identified for the different stakeholder segments. These pain points are exemplary and differ in their weight per stakeholder segment, they give however a general direction of the main pain points that stakeholders would need to address to improve their performance and increase their profitability in their operations.

High Operational Costs: Costs associated with personnel (drivers, shunting staff), energy consumption, and maintenance. Automation offers significant potential for reduction.

Limited Network Capacity and Throughput: Inability to run more trains or increase service frequency on existing infrastructure, leading to congestion and delays.

Punctuality and Reliability Issues: Delays, cancellations, and inconsistent service delivery impacting customer satisfaction and logistical chains.

Safety Incidents and Risks: Accidents, near-misses, and operational errors, particularly in complex environments like depots and shunting yards.

Staff Shortages and Workforce Challenges: Difficulty in recruiting and retaining skilled personnel, particularly train drivers and shunting staff, especially with an ageing workforce among train drivers.

Inefficient Shunting and Yard Operations: Time-consuming and labor-intensive processes in depots and marshalling yards, leading to bottlenecks and delays.

4 PRIORITIZATION AND MIGRATION ROADMAPS PER PAIN POINT

The list of use cases related to automating functions, which is derived from WP5 and WP6, is assessed for its implementation complexity and the necessary prerequisites. 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 cluster the functions, which in turn allows the creation of a phased migration approach, prioritizing functions based on the estimated implementation complexity. For a more representative assessment, a multi-criteria decision analysis (MCDA) is recommended to evaluate different aspects of each use case in a weighed manner. This allows a prioritization of the criteria based on their relevance for the stakeholder. Since the choice of criteria and their weights are stakeholder-specific, the following analysis is restricted to the technical implementation complexity as an example. 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.

The allocation of the clusters or add-ons on a timeline is not part of this exercise, since this is stakeholder-specific and depends on many specific factors which cannot be considered in this stakeholder-agnostic approach. Furthermore, a multi-criteria analysis (MCDA) with an evaluation involving actual market players must be conducted, which is not part of this deliverable.

4.1 Clustered Use Cases for Addressing the Pain point High Operational Costs

- **Initial Cluster:**
    - Report end of shift/assignment
    - Leave train in sleep mode
    - Deregister a vehicle from operation in the AoC

- Manage daily interior cleaning, end of line (if automated)
- Leave train in ready mode
- Determine and select travelling direction
- Set train into service
- Prepare train unit for a mission – Select traction system automatically
- Prepare passenger train (diesel)
- Prepare train for departure
- Conduct system and functional tests
- Enter ATP data automatically
- Prepare train unit for a mission - Configure GoA automatically
- Drive train through washing station (if automated)

- **Add-on Cluster:**
  - Stable a train unit – determine detrainment – automatic
  - "Wake-up" / Initialization and perform auto-tests/self-tests for normal operation in GoA 3&4
  - Conduct visual inspects & tests (if automated vision systems)
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure
  - Perform automatic train shunting and "special" movements

4.2 Clustered Use Cases for Addressing the Pain point Limited Network Capacity and Throughput

- **Initial Cluster:**
  - Determine and select travelling direction
  - Set train into service
  - Prepare train for departure
  - Enter ATP data automatically
  - Prepare train unit for a mission - Configure GoA automatically
  - Implementing discretional stops by regional services
  - Stop at platform for passenger service
- **Add-on Cluster:**
  - Perform mission (optimized driving for headways)
  - Handle missed braking or target point (improves flow)
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure (frees up mainline capacity)

- Perform automatic train shunting and "special" movements (reduces yard bottlenecks)
- Border crossing (smoother transitions, less delay)

4.3 Clustered Use Cases for Addressing the Pain point Punctuality and Reliability Issues

- **Initial Cluster:**
  - Determine and select travelling direction
  - Set train into service
  - Prepare train for departure
  - Enter ATP data automatically
  - Prepare train unit for a mission - Configure GoA automatically
  - Implementing discretional stops by regional services
  - Stop at platform for passenger service
  - Pass through voltage transition area or phase separation area
  - Perform transition from NCBG to CBG
  - Apply Temporary Speed Restrictions (e.g., for high winds)
  - Set low adhesion conditions
- **Add-on Cluster:**
  - Handle overcrowded platform - overcrowded platform in station detected by actor
  - Handle bad current collection in case of weather conditions (wind, temperatures etc)
  - "Wake-up" / Initialization and perform auto-tests/self-tests for normal operation in GoA 3&4
  - Perform mission (consistent, optimized driving)
  - Handle missed braking or target point
  - Border crossing

4.4 Clustered Use Cases for Addressing the Pain Point Safety Incidents and Risks

- **Initial Cluster:**
  - Determine and select travelling direction
  - Conduct system and functional tests
  - Enter ATP data automatically
  - Prepare train unit for a mission - Configure GoA automatically
  - Stop at platform for passenger service

- Pass through voltage transition area or phase separation area
- Pass a bridge without overhead line
- Perform transition from NCBG to CBG
- Apply temporary Speed Restrictions for high winds
- Set low adhesion conditions

- **Add-on Cluster:**
  - Stable a train unit – determine detrainment – automatic
  - Handle overcrowded platform - overcrowded platform in station detected by actor
  - Handle bad current collection in case of weather conditions (wind, temperatures etc)
  - "Wake-up" / Initialization and perform auto-tests/self-tests for normal operation in GoA 3&4
  - Conduct visual inspects & tests (if automated vision systems)
  - Perform mission (inherently safer with GoA)
  - Handle missed braking or target point
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure
  - Perform automatic train shunting and "special" movements
  - *Consideration for GoA4:* The availability of remote driving technologies as a fallback for the ATO GoA4 is crucial here. As GoA4 operations are deployed, remote driving serves as a critical fallback for degraded situations, allowing human intervention to maintain safety and operational continuity without requiring a driver on-board. This capability must be developed in parallel with GoA4 systems and integrated into safety cases and operational procedures.

4.5 Clustered Use Cases for Addressing the Pain point Staff Shortages and Workforce Challenges

- **Initial Cluster:**
  - Report end of shift/assignment
  - Leave train in ready mode
  - Leave train in sleep mode
  - Deregister a vehicle from operation in the AoC
  - Conduct system and functional tests
  - Manage daily interior cleaning, end of line (if automated)
- **Add-on Cluster 1:**
  - Determine and select travelling direction
  - Set train into service

  - Prepare train unit for a mission – Select traction system automatically
  - Prepare passenger train (diesel)
  - Prepare train for departure
  - Enter ATP data automatically
  - Prepare train unit for a mission - Configure GoA automatically
  - Drive train through washing station (if automated)
  - Conduct visual inspects & tests (if automated vision systems)
- **Add-on Cluster 2:**
  - Stable a train unit – determine detrainment – automatic
  - "Wake-up" / Initialization and perform auto-tests/self-tests for normal operation in GoA 3&4
  - Perform mission (GoA2/3/4 reduces driver workload/presence)
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure
  - Perform automatic train shunting and "special" movements

4.6 Clustered Use Cases for Addressing the Pain point Inefficient Shunting and Yard Operations

- **Initial Cluster:**
  - Manage daily interior cleaning, end of line (if automated)
- **Add-on Cluster:**
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure
  - Stable a train unit – determine detrainment – automatic
  - Perform automatic train shunting and "special" movements

5 MIGRATION STRATEGIES BASED ON AREA OF USE CASES

An alternative, complementary approach to migration involves segmenting the railway network into distinct operational areas, each presenting operational specificities leading to different sets of complexity and regulatory environments. This allows for a targeted and progressive deployment of automating functions, building confidence and experience before scaling to more complex domains.

5.1 Operational Areas and Function Mapping

- **Depot Stand-Still:** This area represents the lowest complexity, with controlled environments and minimal movement.
  - *Use cases:*

  - Report end of shift/assignment
  - Leave train in ready mode
  - Leave train in sleep mode
  - Deregister a vehicle from operation in the AoC
  - Prepare train unit for a mission – Select traction system automatically
  - Prepare passenger train (diesel)
  - Conduct system and functional tests
  - Enter ATP data automatically (for configuration)
  - Prepare train unit for a mission - Configure GoA automatically
  - "Wake-up" / Initialization and perform auto-tests/self-tests for normal operation in GoA 3&4
  - Conduct visual inspects & tests (if automated vision systems)
  - Manage daily interior cleaning, end of line (if automated)
 - *Strategic Rationale:* Ideal for initial automation pilots, focusing on cost reduction, efficiency of preparatory tasks, and asset management.
- **Depot with Movement (Shunting Yards, Stabling Areas):** This environment introduces movement but remains largely within a controlled, often private, infrastructure.
 - *Use cases:*
  - Determine and select travelling direction
  - Stable a train unit – determine detrainment – automatic
  - Drive train through washing station (if automated)
  - Operate Full autonomous trains at low speed <= 30km/h in stabling yard or shunting Area equipped or not with ETCS infrastructure
  - Perform automatic train shunting and "special" movements
 - *Strategic Rationale:* Addresses significant pain points in shunting efficiency and staff shortages. This area often has less stringent regulatory requirements compared to mainline, allowing for earlier deployment of GoA3/4 operations. The absence of ETCS infrastructure in many yards necessitates alternative localization and safety systems.
- **Train Movement to the First Platform (No Passengers Onboard):** This involves movement from the depot to the passenger platform.
 - *Use cases:*
  - Determine and select travelling direction
  - Set train into service
  - Prepare train for departure
  - Enter ATP data automatically

        - Prepare train unit for a mission - Configure GoA automatically
        - Pass through voltage transition area or phase separation area
        - Pass a bridge without overhead line
        - Perform transition from NCBG to CBG
        - Perform mission (initial driverless movement)
    - *Strategic Rationale:* Bridges the gap between depot and mainline, allowing for testing of automated mainline functions in a controlled, passenger-free environment. Reduces driver workload for non-revenue movements.
- **Mainline Operations Without Passengers (Freight, Empty passenger train):** This segment involves mainline movement but without the direct safety criticalities associated with passenger transport.
    - *Use cases:*
        - Determine and select travelling direction
        - Set train into service
        - Enter ATP data automatically
        - Prepare train unit for a mission - Configure GoA automatically
        - Pass through voltage transition area or phase separation area
        - Pass a bridge without overhead line
        - Perform transition from NCBG to CBG
        - Handle bad current collection in case of weather conditions (wind, temperatures etc.)
        - Apply Temporary Speed Restrictions for high winds
        - Set low adhesion conditions
        - Perform mission
        - Handle missed braking or target point
        - Border crossing
        - Perform automatic train shunting and "special" movements (e.g., emergency stops)
    - *Strategic Rationale:* Offers a lower-risk environment for deploying advanced GoA2/3/4 functions on the mainline, particularly beneficial for freight operations to improve throughput and energy efficiency. Serves as a proving ground for technologies before passenger deployment.
- **Mainline Operation with Passengers:** This represents the highest complexity and safety criticality, requiring the most mature and rigorously validated automation systems.
    - *Use cases:*
        - All functions from "Mainline Operations Without Passengers"

        - Implementing discretional stops by regional services
        - Stop at platform for passenger service
        - Handle overcrowded platform - overcrowded platform in station detected by actor
    - Additional use case:
        - Communication with passengers (e.g. via Passenger Information System, Intercom, etc.)
    - *Strategic Rationale:* The ultimate goal of full mainline automation, delivering maximum benefits in capacity, punctuality, and operational costs. Requires robust GoA3/4 systems, comprehensive safety cases, and public acceptance. Remote driving is particularly vital here for ensuring operational continuity and safety in unforeseen circumstances during GoA4 operations.

5.2 Advantages of Area-Based Migration

This area-based migration strategy provides several advantages:

- **Reduced Risk:** Allows for incremental deployment, starting in less complex and critical environments.
- **Phased Investment:** Capital expenditures can be spread over time, aligning with proven benefits and technological maturity.
- **Experience Building:** Facilitates the accumulation of operational experience and refinement of automation systems.
- **Targeted Regulation:** Enables the development of specific regulatory frameworks for each operational domain, gradually expanding to more complex areas.
- **Addressing Local Needs:** Directly tackles specific pain points prevalent in particular operational areas (e.g., shunting efficiency in depots).

6 OUTLOOK FOR STAKEHOLDER-DRIVEN MIGRATION STRATEGY

The methodologies described previously highlight a method that can be applied by a stakeholder to develop their migration strategy for automating functions. Creating one generic roadmap fitting for all stakeholders for the adoption of automating function technologies is not possible or practical, since a roadmap and a migration strategy depend on many factors that are very specific to the stakeholders themselves. These factors include, but not limited to, already existing infrastructure to allow a technology adoption, dependency on other stakeholders and their technology adoption level, local regulations, investment potential, etc..

A stakeholder looking to address their pain point using automating function technologies can apply the method described in chapter 4, by following the steps:

1. Identify and prioritize pain points
2. Define criteria for evaluating the automating functions use cases.
3. Allocate weights for the different criteria based on perceived importance, this allows a multi-criteria approach. The choice of criteria and weight allocation is a case-by-case set-up,

depending on the stakeholder themselves and on the environment they operate in, e.g. dependency on already standardizes systems, age of the vehicles in the fleet, availability of the technology on the market, cost of the technology, cost/benefit evaluation of the use cases, etc.

4. Prioritize the use cases based on the criteria and weights defined.
5. Based on the prioritized use cases, a roadmap of use case implementation can be created with an implementation timeline.

This strategy-building method is only a case-by-case evaluation and cannot be carried over to other stakeholders.

7 CONCLUSIONS

The automation of railway functions and the progression towards automated driving represent a critical strategic imperative for the European railway industry. This task has outlined a comprehensive framework for migration, integrating functional definitions from WP6 and strategic insights from WP33. By segmenting stakeholders, identifying their pain points, and mapping automating functions to these challenges, a clear path for prioritizing and deploying these technologies emerges.

The proposed migration roadmaps, structured by pain point and further refined by operational area, emphasize a phased approach, and are only an example on how a stepwise technology adoption can look like. This strategy acknowledges the varying complexities of functions and the diverse environments within the railway network, from controlled depots to high-density mainline operations. The integration of remote driving as a crucial fallback for GoA4 operations underscores the holistic nature of advanced automation, where human oversight and intervention capabilities remain essential for resilience and safety in degraded modes.

Future efforts must focus on the development of harmonized standards, robust cybersecurity measures, and comprehensive safety certification processes. Ultimately, a strategic, incremental, and collaborative approach to automation will enable the railway industry to achieve its goals of enhanced efficiency, increased capacity, improved safety, and sustainable growth, thereby securing its vital role in the future of European mobility.

REFERENCES

[1] Aoun, J., Quaglietta, E., Goverde, R.M.P. (2023). Roadmap Development for the Deployment of Virtual Coupling in Railway Signalling. Technological Forecasting and Social Change, 189, 122263.

[2] Aoun, J. (2023). Impact Assessment of Train-Centric Rail Signalling Technologies. PhD Thesis, Delft University of Technology, the Netherlands.