Rail to Digital automated up to autonomous train operation

D33.1 – Migration Strategy Research Report

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1 EXECUTIVE SUMMARY

The *Migration Strategy Research Report* (D33.1) examines strategies to support the migration and deployment of Digital and Automated Train Operation (DATO) within the European railway system. This report addresses key challenges identified across Europe's Rail activities. As DATO technologies advance, their successful implementation depends on effectively managing the inherent systemic complexity. This complexity arises from cross-border operations, multi-actor governance structures, and the need to integrate digital technologies with long-lived railway infrastructure. It therefore emphasises the need for a structured and complexity-aware approach to migration rather than a purely technology-driven perspective.

The objective of this Deliverable - D33.1 - is to support the objectives of WP33 by synthesising evidence from DATO demonstrators and related initiatives to identify transferable lessons, recurring risk patterns and structural gaps affecting migration trajectories. The report examines how organisational frameworks, technical coordination mechanisms and governance models influence migration outcomes. This process synthesises the principal insights derived from pilot efforts and delineates ongoing shortcomings that obstruct successful execution. This analysis yields recommendations to guide future DATO migration strategies in the European railway sector.

The study adopts a qualitative, framework-driven research approach grounded in complexity analysis and systems thinking. Empirical data from DATO demonstrators were analysed using the Delivery Environment Complexity Analytic (DECA) framework, adapted to the railway digitalisation context through the D-TRACK framework. This analytical structure enabled a systematic examination of complexity-related risks across governance and organisational capability, delivery scope, and systems integration, with a focus on decision-making contexts and interdependencies rather than detailed technical design.

The findings show that successful DATO migration is primarily shaped by the management of interdependencies among organisations, disciplines, and regulatory environments. The analysis revealed persistent factors contributing to complexity, highlighting the need for sustained stakeholder alignment, clear communication, and decision traceability. It also emphasised the importance of iterative integration and validation methods, alongside shared conceptual and modelling frameworks to support collaboration. Persistent gaps were identified, including limited guidance for cross-organisational and multilingual technical communication, inconsistent alignment of national regulatory frameworks, and insufficient availability of shared testing and validation environments.

Based on these insights, the report recommends strengthening cross-stakeholder alignment mechanisms, developing baseline approaches for modelling languages and interoperability, and promoting shared testing and validation environments to reduce integration risks. Overall, D33.1 concludes that DATO migration should be approached as a system-wide, long-term transformation process. By adopting structured, complexity-aware migration strategies and addressing the identified gaps, railway stakeholders can improve deployment robustness and support the coordinated advancement of automated rail operations across Europe.

ABBREVIATIONS AND ACRONYMS

ALARP	As Low As Reasonably Practicable
ATB	Automatic Train Control (Dutch)
ATC	Automatic Train Control
ATO	Automatic Train Operation
CAPEX	Capital Expenditure
CBTC	Communications-Based Train Control
CENELEC	European Committee for Electrotechnical Standardisation
CCS	Control Command and Signalling
DECA	Delivery Environment Complexity Analytic
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
EULYNX	European Initiative for Railway Signalling Interfaces Standardisation
GLA	Greater London Authority
GoA 1–4	Grade of Automation (Levels 1 to 4)
HTD	Hybrid Train Detection
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IM	Infrastructure Manager
IP	Intellectual Property
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LDDC	London Docklands Development Corporation
MBSE	Model-Based Systems Engineering
MOVINGRAIL	Moving Block and Virtual Coupling for Railways
NSA	National Safety Authority
OBIS	Onboard Information System
OEM	Original Equipment Manufacturer
TE	Technical Enabler
TRL	Technical Readiness Level
OCORA	Open CCS On-board Reference Architecture
OPEX	Operational Expenditure
PERFORMINGRAIL	Performance Improvement for Railways through Digitalisation and Automation
PSA	Passenger Service Agent
R2DATO	Rail to Digital automated up to autonomous train operation
RL	Relative Localisation
RU	Railway Undertaking
S2RAIL	Shift2Rail Project focused on railway innovation and digitalisation

SCR	Short-Range Communications
STIP	Sustainable Transport Investment Plan
SysML	Systems Modelling Language
TIMS	Train Integrity Monitoring System
TRL	Technology Readiness Level

DEFINITIONS

Digital and Automated Train Operation (DATO)
Technologies and operational concepts enabling higher Grades of Automation (GoA) in railway systems, including onboard automation, traffic management, communications, and associated organisational and regulatory arrangements.

Grade of Automation (GoA)
Standardised classification of train operation levels from manual operation (GoA1) to fully autonomous operation (GoA4).

Digital Map
A Digital Map in the railway domain is a secure, standardised digital representation of the railway infrastructure that includes the exact geometry of the track, the location of physical and virtual balises, and other key reference points required by ETCS on-board systems to validate and interpret train position data.

Digital Transformation (DT)
The process by which railway systems undergo significant technical, organisational, and operational change through the integration of digital technologies.

Complexity
A condition arising from multiple interdependent and evolving technical, organisational, human, and regulatory elements, generating uncertainty and risk, particularly in early project phases.

Delivery Environment Complexity Analytic (DECA)
A UK National Audit Office framework comprising twelve factors used to diagnose delivery-related complexity in public-sector projects during the front-end phase.

D-TRACK (Digital Transformation Railway Complexity Framework)
A railway-specific framework developed in this study, building on DECA, to support structured early identification of complexity-related risks in digital rail transformation projects.

Front-End Phase
The early stage of a project where strategic objectives, scope, governance, and delivery approaches are defined.

Lessons Learned
Structured knowledge derived from experience, used to improve future project performance and prevent recurrence of known problems.

Serious Game
A scenario-based, facilitated method used for learning, validation, or alignment purposes; applied here to validate the D-TRACK framework.

Thematic and Content Analysis
Qualitative analysis methods used to identify recurring patterns and examine their distribution across interview data.

Atlas.ti
Qualitative analysis software used to support coding, organisation, and analysis of interview transcripts.

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2 INTRODUCTION

The present document constitutes the Deliverable D33.1. “Migration Strategy Research Report” in the framework of the TE20/WP33 of FP2 R2DATO; providing input to TE1 Automating Functions, T9.1 “Analysis of migration and deployment strategies”, from FP2/WP9 “Prototype development of automating functions” and to TE7 Remote Driving, T12.1 “Analysis of migration and deployment strategies” of FP2/WP12 “Prototype development of remote control”.

WP33 provides guidelines for migration and deployment strategies for applying DATO technologies from a technical, operational and human-centred perspective. It does so by collecting lessons learned from R2DATO Demonstrators, State of the Art projects and other technical migration programmes for rail, like ATO and ETCS. This work constitutes T33.1. This Deliverable contains the results of that work, resulting in an overview of lessons learned, a gap-analysis and recommendations – the guidelines. The results also provide input to the second Deliverable of WP33, D33.2 Practical Migration Methods Report.

Technology migration in the railway sector on an inter-European scale is a long and risky road. For it to be smooth and successful, sustaining cross-border and cross-company collaboration for a longer period is required. Participants of WP33 recognised that apart from the many technical challenges that you will find along the way, success also depends on long term willingness and a certain level of risk appetite of involved stakeholders, based on the trust that the benefits lie not too far in the future. How to keep all kinds of stakeholders on board in a complex environment while the road ahead is full of uncertainty?

This report aims to lay the groundwork for guidelines for successful migration from a risk management perspective. During the preliminary phase of WP33, it was recognised that a fast and smooth technology migration - the overarching objective of the work package - can only be achieved when complexity-related risks are comprehensively identified and managed from the outset. From a methodological standpoint, this insight highlighted the need for a common framework to support the work of both Task 33.1 and Task 33.2, ensuring a shared foundation for risk identification and fostering a structured, system-wide exploration of risks that could hinder the successful migration and deployment of DATO systems.

To support this effort, the Delivery Environment Complexity Analytic (DECA) framework was selected as a baseline tool, to facilitate the structured conversion of knowledge from demonstrator projects into lessons learned. Developed by the UK National Audit Office (NAO), DECA identifies 12 complexity factors grouped into four overarching dimensions: Strategic & Political Context, Governance & Organisational Capability, Delivery Scope & Complexity, and Systems Integration.

Objectives

The specific objectives of this report (D33.1) are:

- Analyse relevant demonstrators

Review national and EU-level demonstrators and technical enablers to identify transferable insights related to ATO implementation.

- Analyse relevant ATO projects

Investigate cases such as the Betuweroute to understand practical migration steps and outcomes, and benchmark them against other European efforts.

- Analyse methodologies for technological migration within R2DATO

These include DevOps, Formal Methods, Architecturedesign4evolution and models for People-oriented change management

- Extract key lessons learned

What was effective, what failed and what could be improved in terms of technologies, processes, and coordination.

- Identify gaps and recommendations

Insights of what can be improved taken from the lessons learned lead to identified gaps. Actionable recommendations to inform future migration and deployment efforts are proposed to bridge these gaps.

Chapters

In Chapter 3 this approach of the work of WP33 is introduced and D-Track, our Methodology based on the DECA Framework, is explained.

In Chapter 4 two different questionnaires for the interviews that have been derived from this framework are presented, one for Task 33.1 and the other for T33.2.

Chapter 5 lists and describes all the cases that were studied. Firstly, the demonstrator WP's within R2DATO, secondly the state-of-the-art ATO projects and lastly methodology WP's within R2DATO. The scope and aim of the WP's are discussed briefly, the experience and role of the respondent is highlighted and the main lessons and reflection on the interview by the interviewer are presented in this chapter.

In Chapter 6 the outcomes of the interviews are summarised per risk category.

The detailed results from the interviews are presented in Chapter 7 which are structured as follows: Lessons learned – gap – recommendations

Chapter 8 is conclusion and discussion.

All sources for the research of WP33
Interviews within R2DATO – WP Leads • WP29 Railindustrial DevOps • WP29 Railindustrial Architecture4evolution • WP30 Automated authorisation by modelling techniques • WP31 Automated Train Supervision and Control • WP32 Strategic Business Support • WP37 ETCS HL3 Deployment Strategies (2 interviews) • WP38 Stabling/shunting (non-commercial runs) • WP39 Main Line • WP40/41/42 Autonomous Tram Demonstrator / Remote Driving and Telecommand Demonstrator / Tramway autonomous movements in depot demonstrator • WP44/45 Moving Block ETCS L3 Demonstrator – Specification & Realisation • WP48 Operational Solutions Interviews outside of R2DATO / State of the art – programme/project managers • Programme manager – decades of experience with technological migration within NS, lately involved with ERTMS implementation in the Netherlands • Project manager - decades of experience with technological migration within NS, lately involved with a programme focussed on testing ATO in the Netherlands • Project manager (ProRail) involved in Betuweroute, a cross-border freight line • Automated train Stuttgart Desk studies conducted outside of R2DATO / State of the art • Rio Tinto Rail Automation (Aus) • Docklands Light Railway (UK) Paper delivered by Change Mgt. Experts: • People Oriented Change Mgt aspects of the ATO Programme of NS

Table 1 List of sources for the research done by WP33

3 REPORT SCOPE

This study adopts a qualitative, framework-driven research design to extract and develop lessons learned from Digital and Automated Train Operation (DATO) demonstrators within Europe's Rail FP2–R2DATO, as part of Work Package 33 Task 1 (T33.1). This design was chosen to facilitate the structured conversion of knowledge from demonstrator projects into lessons learned. WP33 Task 2 focusses on the part that methodologies can play in mitigating the gaps that are identified and described in D33.1. These findings are part of D.33.2.

First, experiential knowledge generated within DATO demonstrators is often fragmented across projects and stakeholders despite its relevance for early migration decision-making. Second, existing reporting practices tend to rely on project-specific narratives, which limits comparability and reuse across programmes. Third, few studies provide a structured analytical approach that links demonstrator experience to complexity-aware guidance for front-end project phases. To address these limitations, this study focuses on the formalisation of lessons learned through a complexity-informed framework.

The scope of this report is limited to the identification and structuring of complexity-related risks in the early phases of DATO programmes. The analysis focuses on front-end decision-making contexts rather than detailed system design. The findings are derived from qualitative evidence within selected demonstrator and are not intended to provide quantitative risk prioritisation or performance metrics.

3.1 DESIGN SCIENCE RESEARCH METHODOLOGY

The D-TRACK framework was developed using a Design Science Research Methodology (DSRM). Railway digital transformational introduces multi-dimensional complexity. The complexity encompasses technical, organisational, human, and regulatory domains. DSRM was selected to enable iterative refinement and validation of a railway-specific framework for identifying front-end phase complexity risk.

A framework-driven research design was adopted to enable the systematic extraction, structuring, and evaluation of knowledge derived from complex socio-technical projects. Existing complexity and risk frameworks do not sufficiently address the specific characteristics of digital rail programmes. This is relevant during the front-end phase, when the impact of early intervention is most significant for strategic decisions under uncertainty. DSRM was employed to develop and validate D-TRACK, a railway-specific complexity framework designed to support structured, early identification of complexity-related risks in Digital and Automated Train Operation (DATO) programmes. The methodology follows an iterative process to ensure theoretical grounding, practitioner knowledge, and validation.

3.2 D-TRACK FRAMEWORK

In the first stage, the UK National Audit Office's Delivery Environment Complexity Analytic (DECA) framework was selected as the analytical baseline. DECA is widely used in public-sector programmes to diagnose delivery complexity during early project stages. DECA is designed to address evolving regulation, technological uncertainty, and socio-political scrutiny—conditions that closely mirror railway digital transformation contexts. Its twelve complexity factors and guiding-question format provided a robust and structured starting point for adaptation to the rail domain.

In the second stage, DECA was adapted to the context of railway digital transformation. DECA was contextualised for railway applications by integrating lessons learned from major rail infrastructure and digitalisation programmes, including railway-specific reports (Figure 1). Expert input was obtained from practitioners engaged in operations, infrastructure management and automation initiatives within Europe's Rail FP2–R2DATO. The process facilitated the translation of generic complexity factors into railway-specific drivers. This comprised drivers such as automation interfaces, system integration, safety certification, traffic management and organisational coordination.

In the third stage, the refined complexity drivers were organised into four overarching complexity dimensions and operationalised through tailored guiding questions. These questions were developed to support structured expert assessment and systematic risk identification in the initial project phases. The framework was designed as a diagnostic instrument, not a prescriptive solution, to ensure consistent assessment of project complexity risks.

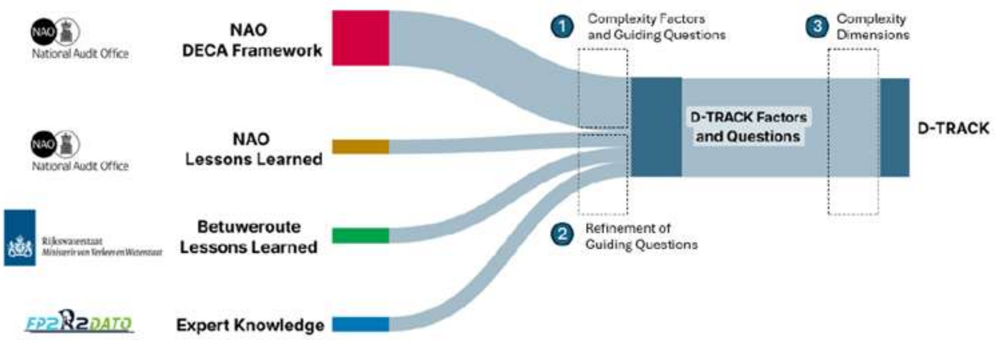

Figure 1 Sankey diagram illustrating the design process of the D-TRACK framework

The width of each flow is proportional to its contribution, highlighting how the framework is primarily based on the NAO DECA framework and subsequently refined through contextual insights from lessons learned and expert knowledge.

In the final stage, the framework was validated through a serious game–based workshop with participant from WP33. In the workshop, participants used D-TRACK to identify, evaluate and treat complexity-related risks associated with a digital rail migration scenario. This validation step assessed the framework's effectiveness in structuring early-stage risk identification and its usability in multi-stakeholder settings (Figure 2).

Figure 2 Participants engaged in the risk identification phase, using the workshop template to capture complexity-related risks associated

D-TRACK was developed as a railway-tailored extension of DECA, combining theoretical grounding, practitioner input, and empirical validation. As a result, D-TRACK functions as a structured methodological tool to support early, complexity-aware decision-making in railway digital transformation programmes.

Figure 3 D-Track - all four Risk Dimensions

4 METHODOLOGY

The results of interviews held by both Task 1 and Task 2 are part of the analysis presented in this report. Two separate questionnaires were developed for interviewing WP Leads: the questionnaire for Task 1 was comprised of guiding questions related to Risk Dimension Governance & organisational capability, whereas the questionnaire for Task 2 consists of guiding questions related to Risk Dimensions Delivery scope & Complexity and Systems integration. Both questionnaires investigate views and experiences of the respondents. For the purposes of WP33, the Strategic & Political Context dimension - while critical in many large-scale projects - was excluded, as it focuses on external forces beyond the direct control of project teams

The results of the interviews held for T33.2 also provide input to D33.2 Practical Migration Methods Report. In this Deliverable an analysis is presented in which the gaps and recommendations are linked to the work of the FP2-R2DATO methodology work packages.

4.1 INTERVIEW QUESTIONNAIRE T33.1

Introduction of the interview

WP33 aims to generate insights into migration and deployment strategies for DATO. Its core objective is to demonstrate the feasibility of implementing DATO technologies across European rail networks, addressing both technical and human-factor dimensions. To support this goal, Task 33.1 investigates lessons learned and analyses state-of-the-art demonstrators within the FP2-R2DATO framework.

Purpose of the Interview T33.1

This interview supports WP33.1 of the FP2-R2DATO project by capturing lessons learned, stakeholder experiences, and identifying risks or barriers encountered during the implementation of ATO demonstrators or innovation projects. Insights will inform a migration and deployment report for future DATO projects across Europe.

Interview Questionnaire Design T33.1

A semi-structured questionnaire was developed to align with the FP2-R2DATO WP33.1 Stakeholder Interview format. A DATO Migration questionnaire was developed using the Delivery Environment Complexity Analytic (DECA) to capture stakeholder insights across six defined sections, emphasising stakeholder experience and risk identification.

Section 1: Project & Role Context

- Please state your name, organisation, role, and primary work location (city and country).
- What was your role in the ATO innovation (demonstrator or case study) project?
- Please indicate the specific project stages (e.g., planning, integration, testing, evaluation) in which you were most actively involved.
- What were the demonstrator's main objectives, and how were these defined or adjusted over time?
- What does migration mean in your organisation/project? How do you know if it's successful?

Section 2: Stakeholders

- Which external stakeholders (e.g., passengers, local communities, regulators, EU bodies) had the most significant influence on the demonstrator, either positively or negatively? Were there any tensions or opposing opinions among these stakeholders?
- Describe a real public perception or reputational challenge faced during the project (e.g., concerns about safety, job displacement, system failures).
- How was the situation addressed, and what would you recommend doing differently in future initiatives?

Section 3: Relations with Delivery Partners

- Which internal or external coordination challenges (e.g., among infrastructure managers, technology providers, operators) led to delays or rework? How were these issues resolved?
- What governance or communication gap had the most significant impact on project delivery, and how was it eventually managed or mitigated?
- How do you build trust with internal or external partners, and what breaks it?

Section 4: Organisational Capability & Performance

- What risks emerged due to limited experience with ATO or failure to integrate lessons learned from previous projects?
- How effectively were project complexity and uncertainty managed through leadership continuity, risk-based assurance, and change control mechanisms?
- Cite one case where these worked well, and one where they did not.
- How do you balance short-term operational pressures with long-term strategic vision?

Section 5: Disciplines & Skills

- Which specialist skills (e.g., automation, safety, cyber security, human factors, systems integration) were hardest to source or retain? What impact did this have on the project timeline or quality?
- Describe a misalignment caused by insufficient coordination between disciplines (e.g., signalling design conflicting with operational procedures or human-machine interface design).
- How was this managed, and what would you suggest as a future improvement?

Section 6: Overall Reflections

- What is the most critical lesson learned from testing this ATO demonstrator?

- Why should future projects take this into account?
- Which concrete action or priority should future ATO projects focus on above all others, and what justifies this recommendation?
- What's a question we should we be asking that we haven't thought of yet?

4.2 INTERVIEW QUESTIONNAIRE T33.2

Introduction of the interview

WP33 aims to generate insights into migration and deployment strategies for DATO. Its core objective is to demonstrate the feasibility of implementing DATO technologies across European rail networks, addressing both technical and human-factor dimensions. To support this goal, Task 33.2 investigates what risks are mitigated by using certain methodologies. Then a gap-analysis will be done: what risks are not being mitigated by the methodology?

Purpose of the Interview T33.2

This interview supports WP33.2 of the FP2-R2DATO project by identifying how methodology can support the mitigations of risks or barriers encountered during the implementation of DATO (related) or migration. Insights will inform a migration and deployment report for future DATO projects across Europe.

Interview Questionnaire Design T33.2

This questionnaire was developed using the Delivery Environment Complexity Analytic (DECA) to capture insights across six defined sections. Task 33.2 focusses on the Risk Dimensions 'Delivery Scope and Complexity' and 'Systems Integration', drawing from knowledge and experience from experts and leads of R2DATO Work Packages that focus on methodology. These two dimensions contain five risk categories: Requirements and benefits, Implementation complexity, Extent of change, Interdependencies and Interoperability.

During this interview we will identify core objectives of the Work Packages that develop methodologies to be applied to the rail sector and DATO migration in particular. Going over the Risk categories will help lead the conversation to establish possible barriers for a successful migration, and to see to what extent the methodology could mitigate these migration risks is five Risk Categories.

Section 1: Role Context

- Please state your name, organisation, role within your organisation and primary work location (city and country).
- What is your role within R2DATO and in your Work Package?
- Please indicate the specific project stages in which you are/were most actively involved.

Section 2: Work Package Context

- Please tell us about the methodology you are using within R2DATO?

- What are your Work Package's main objectives, and how were these defined or adjusted over time?
- What does migration mean in your view, your organisation (that you work for) and in your project/WP? What does migration entail in your view?
- When do you consider migration a success? How do you know if it's successful?

Section 3: Risk identification in relation to the Methodology

- To go a little more in depth we will now go over five risk categories with these questions in mind:
- To what extent does the methodology your WP is working on, mitigate these risks? Which risks are not mitigated by this methodology?
- What risks or issues would you think are the most critical in your view?
- Why should future projects take this into account?

Section 4: Risks regarding Requirements and benefits

- Risks that could arise if the requirements of the migration scenario are not defined from a full lifecycle perspective - including unclear scope, unresolved stakeholder expectations or late involvement of future users (e.g., operators)
- Risks that could arise if the business case for the migration scenario is based on unclear strategic goals, over-optimistic benefit assumptions or lacks clear ownership of benefit evaluation?

Section 5: Risks regarding Implementation complexity

- Risks that could arise from relying optimistically (and not realistically) on novel or rapidly evolving technologies in the considered migration scenario
- Risks that could arise from using new or untested delivery methods or management practices - especially when the work is modular and integration is deferred to later stages
- Risks that could arise if the migration scenario is planned on over-optimistic schedules or lacks robust risk analysis and data-driven monitoring to support delivery

Section 6: Risks regarding Extent of change

- What operational, organisational, or workforce behaviours will need to change for the migration scenario to succeed - and where might resistance or friction arise?
- Risks that could emerge if the scale or complexity of change is underestimated, uncoordinated, or unsupported by adequate change management resources?

Section 7: Risks regarding Interdependencies

- Dependencies with other projects, programmes or technological upgrades that the migration scenario depends on; risks that could arise if those dependencies are delayed, misaligned or fail?
- How could delays, underperformance or scope changes in this migration scenario affect other projects or organisations that rely on its success?

Section 8: Risks regarding Interoperability

- What risks could arise from technical, procedural, or regulatory incompatibilities between the systems, actors, or jurisdictions involved in the migration scenario?
- Where might a lack of harmonisation across technologies, standards, or operational procedures compromise safety, functionality or seamless integration during or after the migration?

Section 9: Overall Reflections

- Which concrete risk mitigations should future ATO projects focus on above all others, and what justifies this recommendation?
- What's a question we should be asking but haven't thought of yet?

4.3 Qualitative Analysis

Interview transcripts were analysed using thematic and content analysis, supported by the qualitative analysis software, ATLAS.ti. These analyses enable iterative abstraction and connect raw data to interpretations.

First, transcripts were reviewed to achieve familiarity with the data and to identify initial patterns. Second, systematic open coding was applied to capture concrete experiences, issues, and observations reported by participants. To preserve the context, the codes were kept detailed, and abstraction was avoided at this stage.

Subsequently, multiple cycles of code refinement and regrouping were conducted. First, related codes were merged. Second, higher-level thematic clusters were formed through iterative abstraction. Last, these clusters were aligned with the D-TRACK complexity dimensions. This facilitated the interpretation of individual observations as wider complexity mechanisms, rather than as isolated issues.

In parallel, quantitative content analysis was applied to examine the frequency and distribution of codes and themes across interviews (Figure 4). This enabled comparison between lessons learned, identification of dominant complexity drivers, and graphical representation of recurring patterns. Therefore, the analysis produced a structured set of lessons learned through iterative abstraction and alignment with the predefined complexity framework.

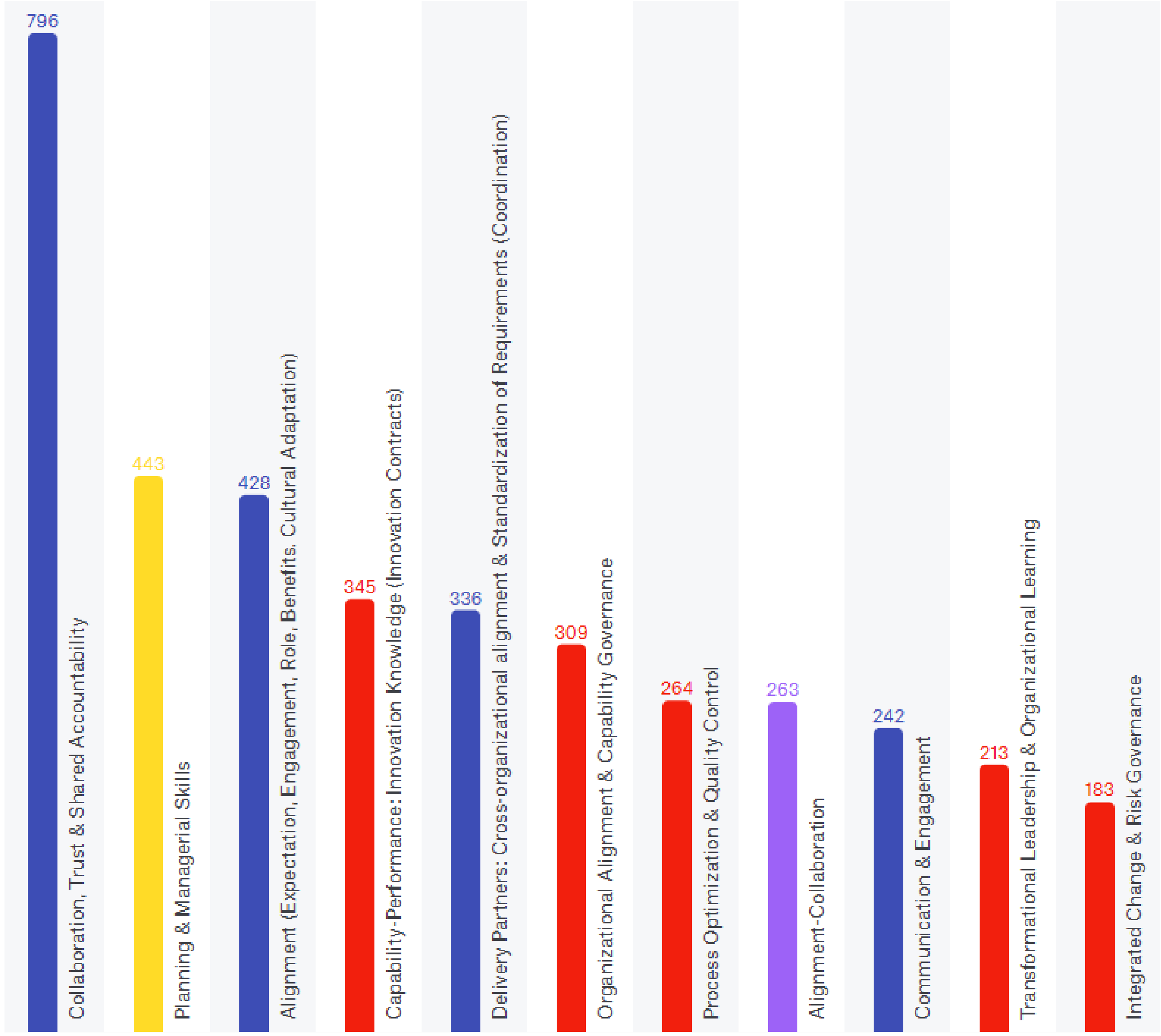

Figure 4 Distribution of coded observations across D-TRACK complexity factors

Distribution of coded observations across D-TRACK complexity factors, indicating the relative prominence of collaboration, capability alignment, and governance-related challenges in the analysed DATO demonstrators.

5 CASE STUDIES

In this chapter the FP2-R2DATO Demonstrators, the state-of-the-art ATO projects and the FP2-R2DATO are described. A brief introduction to the respondent and general reflection on the takeaway of each interview are included in each paragraph. In paragraph 5.2 some sub-paragraphs are structured differently, because the findings are based on case studies instead of interviews.

5.1 ERJU TECHNICAL DEMONSTRATORS AND DEPLOYMENT ENABLING WORK PACKAGES

5.1.1 WP37 ETCS HTD/HL3 Deployment Strategies

WP37 integrates ERTMS guidelines with technical lessons, criteria assessment and a road mapping methodology to create an ETCS HTD (Hybrid Train Detection) migration and deployment strategy. The framework involves stakeholders at all stages. The main objective is to find the optimal deployment strategies for deploying HTD. The subgoals are capacity assessment, standardisation, product and project development lifecycles for HTD deployment, and an overall impact assessment.

The respondent

The respondent serves as a project manager at ProRail and as a postdoctoral researcher at the Technical University of Delft, with more than 9 years of experience across international contexts and a track record spanning research, engineering and management. She leads WP37 and manages the planning, research, and content development related to deployment strategies for ETCS Hybrid Train Detection in R2DATO. The respondent has been involved in previous EU-funded projects within Shift2Rail like MOVINGRAIL and PERFORMINGRAIL. Her PhD Thesis focused on evaluating the impact of train-centric signalling, with particular attention to modelling, overall assessment, road mapping and railway signalling technologies, e.g., Moving Block and Virtual Coupling.

Reflection and insights

Among the various interesting topics mentioned by the interviewee, two are highlighted in this deliverable; stakeholder benefits and challenges, and key lessons learned about HTD.

Stakeholder benefits & challenges

Hybrid Train Detection (HTD) offers advantages for infrastructure managers by reducing the need for trackside detection equipment, leading to lower maintenance and operational costs. However, railway undertakings face substantial upgrade costs for onboard systems such as train integrity monitoring and positioning, which creates an imbalance in how costs and benefits are distributed across stakeholders. The asymmetric cost-benefit structure complicates the business case for operators. This highlights the importance of stakeholder alignment. She also highlighted the crucial role of shared understanding of internal definitions and concepts to actively address concerns and public perception.

HTD Key lessons learned

Effective deployment of HTD systems requires overcoming several interconnected challenges:

1. Clarifying Stakeholder Responsibilities
Ambiguity in stakeholder roles often leads to deployment inefficiencies. Clear role definitions, stronger engagement, and decisive leadership are essential to ensure coordinated action and accountability throughout the process.

2. Aligning Stakeholder Interests
Stakeholders often have differing priorities and objectives. Harmonising these interests is critical to avoid delays and foster collaboration. Strategic tools such as SWOT analysis and multi-criteria decision-making can help highlight the shared benefits of HTD and guide consensus-building.

3. Tackling Incompatibility and Harmonisation Issues
Cross-border standardisation, harmonisation and/or interoperability issues require coordinated efforts from the System Pillar, regulators and decision makers for smooth deployment.

5.1.2 WP38 Stabling/shunting (non-commercial runs)

The stabling/shunting demonstrators of this Work Package cover remote driving, ATO GoA2 remote driving, and GoA4 fully autonomous operations, including use cases like uncoupling train assets and staff training. There is also a demonstrator related to NG Brakes, which wasn't addressed during the interview.

The focus has expanded to include human factors and how drivers perceive remote driving solutions, alongside the continued technical feasibility tests.

The respondent

The respondent works for NS in Utrecht (NL) in the Train Digitalisation department as a business consultant. In that role he works on innovative solutions for train drivers and train command, control and signalling. Currently he is focussed on ATO and remote driving. He was part of the former Programme within NS as a test coordinator. Within R2DATO he is Work Package Lead for WP38 and Task Lead for the ATO Stabling and Shunting Demonstrator. Next to that he participates in WP's 6,10 and 48 in the area of stabling and shunting and ATO, remote driving and similar technologies from an operators' perspective.

Reflection and insights

The two most important lessons taken from the interview are:

Human-related aspects are as important as technical feasibility for successful migration and adoption

Prioritise human factors research, usability, and driver support tools alongside technical development. Understanding human aspects early prevents adoption barriers and ensures realised benefits. Failure could lead to risks of non-use, inefficiency, or to safety concerns.

Engage stakeholders early on

Engage all stakeholders, including regulators and operational staff, from the start of the project with transparent communication. Involving end-users in the innovation and communicating clearly about "why" will help acceptance and reduces resistance.

Incremental steps and early benefits

Migration should build incrementally, using subsystems and smaller steps to prepare for fully autonomous operations. Testing smaller components and evolving them offers a pragmatic migration path toward full GoA4 autonomy. In this process it is crucial to reap the early benefits to convince organisations and operators to continue investing and adapting. The advice is to demonstrate and - if possible - implement early wins and to scale gradually. Early, tangible benefits help to generate appetite for innovation.

5.1.3 WP39 Main Line

In this Work Package RFI's activity focuses on the objective of providing a next-generation ATC, based on a harmonised and scalable CCS system architecture, providing scalable automation in rail operations. Therefore, the aim is to create a railway system with unmanned train operations, including starting trains, driving, stopping trains and opening doors.

The goal is to improve the capacity of existing rail networks by achieving the objectives and impacts defined in the European Rail Master Plan and the Annual Work Programme, such as helping to increase punctuality, reliability, and productivity of personnel, rolling stock, and infrastructure.

During the project, adjustments were necessary, such as a reduction in scope (eliminating Level 3 with moving block) and the addition of a new task to evaluate the energy-saving benefits of ATO.

The respondent

The respondent works at RFI and is the Work Package Leader. He has over twenty-five years of experience working with both industry and infrastructure manager companies, mostly in the field of CCS placing in commercial operation and CCS systems innovation.

Reflection and insights

Most important lessons:

Stakeholder Management and Human Factors are Critical

- Managing Perceptions: A major concern is the perception of ATO technology by train drivers, particularly regarding potential job displacement. To address this, it is recommended to involve workers from the very beginning of the process and to communicate that the system is an aid for their daily work, not a replacement.
- Building Trust: Trust with both internal and external partners was built and maintained by involving them in all key decisions from the project's outset.

Regulatory and Normative Hurdles

A critical barrier identified is the need to update and revise current rules and regulations to permit commercial operations with ATO. National Safety Authorities (NSA) are particularly concerned about how to manage new regulations and how to migrate from the old ones to the new ones. This highlights the necessity for proactive engagement with regulatory bodies.

Technical Integration and Migration Strategy

- Most Critical Lesson: The most critical lesson, which is still being learned, relates to the integration of various technologies, including data communication and signalling. Future projects must take this into account to avoid facing the same difficulties.
- Top Priority for the Future: Future ATO projects should, above all else, focus on first establishing a clear vision of how ATO technology should be applied in commercial operations.

It was noted that the full benefits of ATO can only be realised in a homogenous environment where all trains are operated using the technology.

5.1.4 WP40/41/42 Autonomous Tram Demonstrator / Remote Driving and Telecommand Demonstrator / Tramway autonomous movements in depot demonstrator

The WP40–42 series is integrated into the WP demonstrator cluster for urban and light rail vehicles. These work packages progress from tram system preparation and regulatory approval (WP40) to remote driving and telecommand capabilities (WP41) and depot automation (WP42). WP's 40–42 reduce technical, human, and organisational risks, producing translatable knowledge for expanding autonomous tram deployment.

WP40 Autonomous Tram Demonstrator

WP40 established the technical and regulatory foundation for the autonomous tram demonstrations through three key tasks. The first task defined and validated five operational use cases. Each use case was mapped to operational rules and functional requirements, providing the baseline for test procedures and KPI development. The second task modified two Sporveien SL18 vehicles at CAF's Zaragoza facility, integrating mechanical, electrical, and software upgrades. Finally, the third task secured approvals, derogations, and permits from Oslo authorities. WP40 offers a framework that enables system and regulatory integration.

WP41 Remote Driving and Telecommand Demonstrator

WP41 validated remote driving and telecommand in Sporveien's SL18 trams up to TRL 7, focusing on operational readiness, operation centre design, and demonstrations. The first task defined operational test cases, acceptance criteria, and KPIs to assess braking, communication loss, latency, and obstacle detection. The second task tested a remote driving operation centre, covering human–machine interfaces and operator criteria for safe telecommand. Testing confirmed integration, operator acceptance, as well as gains in pre-operation, shunting and parking. The third task involved a demonstration phase in Oslo, which was composed of two stages: calibration at TRL 6 and validation at TRL 7. This validated the demonstrator's effectiveness, safety and operational benefits.

WP 42 Tramway autonomous movements in depot demonstrator

WP42 validates autonomous tram operations in depots, targeting TRL 6. The demonstrator focuses on non-commercial tasks—shunting, manoeuvring and maintenance—providing a safe environment before scaling to mixed-traffic contexts. The first task defines depot-specific operational tests, procedures, acceptance criteria, and KPI's for performance evaluation. The second task establishes a centralised autonomous movement operation centre, combining technical requirements with human factors to ensure safety. Depot trials commenced in 2025, consisting of two demonstration phases: calibration and validation. WP42 will deliver KPI evaluations, feedback, and recommendations to guide higher-TRL projects.

The respondent

The respondent serves as Project Manager at CAF and Work Package Leader for the autonomous tram demonstrations (WP40–42) in Europe's Rail FP2–R2DATO. Since 2021, he has led the urban and light rail demonstration phase. At CAF, he directs the autonomous mobility strategy within the Rolling Stock Business Unit, coordinating R&D and business units. He also acts as CAF's primary liaison in the project, engaging with operators and regulators. His leadership ensures that demonstrator initiatives translate applied research into operational deployment.

Reflection and insights

Project preparation began in early 2021, extending beyond the initial R2DATO call to cover multiple phases. This pre-planning produced the urban mobility roadmap (WP40–42) and established a structured framework of work packages, methodologies, and defined roles. The approach created consistency, clarified responsibilities, and secured stakeholder commitment, providing a solid foundation for demonstrations and higher levels of automation maturity. Early operator involvement ensured that use cases and requirements were grounded in operational realities.

Advancing autonomous tram demonstrations requires maintaining a balance of communication, stakeholder engagement, and structured planning. Clear communication fosters collaboration, trust and aligned expectations, while proactive risk management mitigates uncertainty. Flexibility in project definitions sustains stakeholder motivation as conditions evolve. Finally, a clear strategic vision anchors demonstrator activities, aligning them with organisational objectives and ensuring scalability across phases.

5.1.5 WP44/45 Moving Block ETCS L3 Demonstrator – Specification & Realisation

The "Moving Block Demonstrator" aims to test a new train-oriented safety logic intended to simplify operations, accelerate planning, and increase capacity.

Railway traffic is characterised by track guidance and long braking distances, which require special measures to ensure traffic safety. Current safety technologies divide the rail network into fixed sections (so-called blocks), and a train can only enter the next section once the previous one is completely cleared, monitored by technical installations in the tracks. Each section must be individually designed during planning, which is labour and time consuming and complicates later changes. Therefore, this work package aims to transition from the current block-oriented approach with fixed sections to a train-oriented perspective that secures the system based on train positions and braking distances without the need for fixed sections.

The result: higher train density becomes possible, allowing more trains on the network - all without building new infrastructure. Operational flexibility also increases as journeys from any point A to any point B become possible. Planning efforts can be reduced as fewer track elements may be needed in the future.

With the Moving Block Demonstrator project, the aim is to demonstrate a prototypically implementation of the core system of this train-oriented perspective and its functionality and benefits in the DB test field in the Ore Mountains for the first time in a real environment.

The respondent

The respondent works for DB Infra GO in Berlin as a project manager for Digital Rail Germany. Within R2DATO he is Work Package Leader for WP's 44 and 45.

Reflection and insights

Most important lessons are:

Use smaller, incremental releases

Instead of having a few big releases with a lot of new features, it's better to have more and smaller releases. This way you can integrate and test more often, which reduces the risk of failing. When you bring many new components at once and test them together, it becomes difficult to know where issues come from. Smaller releases help you identify problems earlier and keep a more constant flow of progress, rather than facing a "medium bang" of changes at once. This makes the whole development and testing process smoother.

Plan realistically with sufficient time for thorough field testing

Field testing always takes more time than you expect, and you should be ready for Murphy's Law - "what can go wrong, will go wrong." It's important to plan enough resources and time including a generous buffer for issues that will arise for testing in the real environment because it's not like the laboratory or simulation where you can run tests quickly. In the field, things like network problems or safety requirements can cause delays. Even though testing may feel expensive and time-consuming, it's necessary to spend enough time on it to get reliable results and avoid surprises later.

Build and Maintain Trust Among Partners

Trust comes from working together towards common goals and delivering on what you promised. It's about having a good overview of the work, being reliable, and aligning on tasks. When things don't go as planned that trust can suffer, and partners may hesitate to participate fully. To rebuild trust, you need open communication, look back on what worked and what didn't, and align again on how to move forward. This helps everyone feel involved and confident that the project can succeed together.

5.1.6 WP32 Strategic Business Support

WP32 assessed the potential of Digital and Automated Train Operations (DATO) and prepared guidelines for its deployment. The first task conducted a strategic and operational assessment, outlining business cases for new DATO concepts. The second task delivered an operational assessment, consolidating results from FA1 and FA2, and quantifying benefits such as capacity gains, reduced infrastructure wear, and energy savings. It also developed operational guidelines, workforce transition measures, and contingency plans.

The third task produced a business case outline for DATO projects, defining key parameters, integrating FP2–R2DATO results, and applying innovative modelling methods. WP32 established a framework for decision-making, moving beyond isolated appraisals toward integrated cost–benefit analyses that capture interdependencies across technology, operations and human factors.

The respondent

The respondent serves as Project Manager at ProRail and as Work Package Leader for DATO assessment and potential identification (WP32) in Europe's Rail FP2–R2DATO. She has worked at ProRail for 15 years and currently works within the Innovation department. Since 2024, she has led the integration of societal cost–benefit analysis (MKBA) and interface models into the programme's digital transformation phase, coordinating internal experts and European partners. Her leadership ensures that business case research is translated into practical frameworks for migration and deployment.

Reflection and insights

The interview highlights that the delivery of complex railway innovations depends on proactive engagement and structured collaboration. Creating subgroups of committed stakeholders was seen as essential to sustain initiatives, rather than waiting for change to emerge. Alignment between leadership and teams was emphasised as critical, as misalignment generates frustration and diverging visions. Collaboration with suppliers must be framed as long-term partnerships, with early involvement ensuring technical alignment and shared responsibility for outcomes. System integration, particularly across IT and infrastructure, requires interface models that can quantify capacity and human factors when reliable data is limited.

Advancing DATO migration requires balancing adaptive business planning, cultural learning, and risk management. Business cases were described as "living documents," developed iteratively through a minimum viable product approach and refined as projects mature. Embedding risk management into processes was seen as crucial, addressing both technical uncertainties and stakeholder motivations. A culture of learning from mistakes, with open discussion, prevents repeated errors and strengthens organisational capacity. Trust, built through direct interaction and personal relationships, underpins collaboration. A long-term roadmap ensures that short-term steps remain aligned with broader strategic objectives.

5.1.7 WP48 Operational Solutions

The project, led by an experienced team from DLR, integrated into the FP2-R2DATO WP 48 "Innovative Operational Scenarios" focused on virtually coupled train sets and self-driving freight wagons as a demonstrator. The primary objective was to test direct communication and positioning technologies between trains, both in controlled laboratory settings and real rail environments. The setup was achieved in close collaboration with NS, who contributed operational resources such as trains, shunting yard access, and drivers, while DLR provided the technical equipment and execution expertise. Though not an official demonstrator within the broader programme, the project served as a proof of concept showcasing the feasibility of direct data exchange and precise distance measurements between rail vehicles. The approach was inherently flexible, with lab-based testing as a fallback option and dynamic scheduling to capitalise on available testing windows.

The respondent

The interviewee is the Work Package Lead of WP48 and the project Lead for the demonstrator in task 48.4 "Technology development of short-range communications (SCR) and relative localisation (RL)". He is affiliated with the German Aerospace Centre, DLR. His research area technologies like communication and localisation for real applications for the future, as for example, the virtually coupled train sets, but also self-driving freight wagons that are part of WP48. He was actively involved in the planning and execution of the test campaign as well as the evaluation of the tests results.

Reflection and insights

The most critical lessons learned for the migration of ATO technology centre on the importance of flexibility, experienced teams, open and future-proof system architectures, as well as careful management of dependencies and time pressures. The demonstrator revealed that successful migration requires adaptable planning, strong collaboration with open-minded partners and the ability to adjust to evolving architectures and stakeholder requirements. Prioritising harmonised, open system design and allowing ample time for thorough testing emerged as essential for achieving high-quality outcomes and reducing migration risks.

Proactive adaptation was key to managing dependencies with other demonstrators and work packages, greatly reducing conflicts and delays. The extensive practical experience of the partners involved was a decisive factor in overcoming challenges and navigating operational complexities. Regarding scheduling, the interviewee highlighted that while some degree of time pressure stimulates performance, excessive scheduling pressure amplifies risk – particularly in complex, safety-critical migrations such as ATO.

The project faced evolving requirements due to external developments in system architecture (especially the introduction of new frameworks by the "system pillar"). Early – and recurring – alignment with such architecture efforts is vital to minimise costly rework. A forward-looking recommendation is for migration projects to always aim for harmonised, open architectures, designed to be flexible enough for future use cases and avoiding isolated, closed system solutions.

Accordingly, stakeholder interaction, even for internal proof-of-concept projects, is critical. Ongoing engagement with structural architects, standards bodies, and other stakeholders ensures early validation of requirements and realistic integration paths. To this aim, the project partners are involved into standardisation via participation in relevant organisations (such as ITU, IEEE, ETSI) and project context was delivered to STIP. This is essential in driving both technical acceptance and regulatory alignment.

5.2 ATO PROJECTS – STATE OF THE ART

5.2.1 Automated Train Stuttgart

The prototype project Automated Train aims to prove the technical feasibility of fully automated (GOA4) train operations, specifically automating the drive from a parking area to the first platform without a driver or passengers, in an environment that has been equipped with ETCS L2 without signals. The project duration is three years, with the first two years currently being completed. The project is structured into 12 subprojects, each with dedicated work packages, and involved a consortium of nine partners including DB InfraGO, DB Regio, Siemens Mobility, Bosch Engineering, duagon, RedHead, Codewerk, TU Dresden, and IAV. More information can be found on the project website (https://digitale-schiene-deutschland.de/en/news/2023/funding-fully-automated-train).

The respondent

The interviewee is the Project Manager of the project "Automated Train". She is part of the infrastructure manager DB InfraGo and was involved as project manager since the project setup and initiation, including project planning and currently project execution. As the project manager, she is both involved in the technological as well as the stakeholder management.

Reflection and insights

Key lessons learned include the necessity for early and comprehensive alignment on requirements, with development commencing only after requirements are finalised and documented as per CENELEC standards to enable later reuse. A minimum of three years, ideally four, is needed for requirements gathering, development and testing. Securing specialist skills in automation, safety, and cybersecurity before project initiation and preparing strategies for resource fluctuation, such as upskilling and using subcontractors, proved essential. Strong, ongoing coordination and transparent communication with stakeholders - particularly regulators, assessors and railway undertakings as customers - facilitated consensus-building and project progress, with a dedicated communication subproject adding value for public perception. Structuring the project around focused objectives within a set timeframe helped balance short-term operational needs with long-term strategic goals, contributing to sustained results. Contracts should be designed to ensure project outcomes can be reused and extended by partners and the wider railway sector. Data generated, particularly sensor raw data, holds significant value, so a strategy for making it available sector-wide is recommended. Finally, a clear plan for the reuse of project results, including requirements and data, should be established from the outset to ensure knowledge transfer across project phases and to subsequent initiatives.

5.2.2 Rio Tinto Rail Automation Programme (Australia)

Rio Tinto's AutoHaul programme represents the world's first fully autonomous, long-distance heavy-haul railway. Developed to enhance safety and productivity within the company's Pilbara iron-ore operations in Western Australia. The project connects multiple mines with coastal ports under continuous 24/7 operation. The $940 million programme began in 2012 and reached full commercial service in 2019 (Rio Tinto, 2019; RailJournal, 2019).

Operating at Grade of Automation 4 (GoA4), AutoHaul employs no onboard staff. Each 2.4 km train transports 28,000–30,000 tonnes of ore over an 800 km round trip completed in roughly 40 hours. More than 220 locomotives run on a 1,700–1,900 km network controlled remotely from Perth. By 2020, autonomous trains had logged over 11 million km, and by 2023 AutoHaul had become the backbone of Rio Tinto's logistics chain (Rio Tinto, 2020; Knorr-Bremse, 2023).

The system integrates advanced subsystems including automatic train operation (ATO), electronically controlled pneumatic braking, digital radio block signalling, real-time telemetry, and multilayered communications (Hitachi Rail, 2019). Safety features comprise obstacle detection at 42 level crossings, forward-facing cameras streaming to the control centre, and redundant communications layers. Deployment proceeded incrementally - from driver-assist trials to full autonomy - allowing certification under Australia's As Low As Reasonably Practicable (ALARP) safety framework. Reliability exceeded 98 % by 2023, with measurable operational gains: a 5 - 6% rise in average speed, elimination of 1.5 million km of annual crew road travel, shorter cycle times, and more flexible pit-to-port scheduling (Mining.com, 2024).

Reflection and insights

The programme demonstrates that large-scale automation requires both technical integration and organisational transformation. Implementation depended on staged deployment, system-wide upgrades, and collaboration with multiple technology partners (RailJournal, 2019). Delays and overruns revealed the importance of realistic scheduling, robust supplier governance, and integrated testing. Early and transparent engagement with the Office of the National Rail Safety Regulator (ONRSR) was pivotal in building regulatory confidence. Proactive communication with regional communities addressed public-safety concerns, particularly regarding level-crossing risks (Hitachi Rail, 2019).

Rio Tinto adopted a human-centred transition strategy by retraining drivers for supervisory, maintenance and control-room positions rather than implementing immediate redundancies (Rio Tinto, 2019). This approach mitigated labour-relations risks and preserved operational knowledge. The initiative underscored that autonomous-rail deployment depends on multidisciplinary collaboration - combining engineering, software, operations, regulation, and safety expertise.

Ultimately, AutoHaul illustrates that successful automation programmes hinge on integrated planning, stakeholder alignment, and continuous organisational learning. Technical achievement alone is insufficient; cultural readiness and adaptive capability determine long-term success.

5.2.3 Docklands Light Railway (DLR) London (UK)

The Docklands Light Railway (DLR) is a light metro system serving East London. It was opened in 1987 with an initial 15 km network linking Tower Gateway, Stratford, and Island Gardens, built on a low budget of £77 million (Kemp, 1987). The network was expanded during the 1990's and 2000's to support large-scale regeneration projects. The major expansion included Bank station (1991), Lewisham (1999), London City Airport (2005), Woolwich Arsenal (2009), and Stratford International (2011) [TfL, 2023]. Transport for London (TfL) owns the system, which is operated via private concession agreements, while the public authority manages supervision and performance. Annual ridership exceeded 116 million passengers by 2020, reflecting the system's role as a core element of London's urban transport.

The DLR is operated at Grade of Automation 3 (GoA3). Automated trains are operated via SelTrac CBTC moving-block signalling, which was implemented in 1994 to replace the initial fixed-block system [Lockyear, 1998]. Passenger Service Agents (PSAs) are present on every train to provide door control, customer service, and emergency operation when required. This model combines automation with visible staff oversight. The railway has undergone continuous upgrades to rolling stock, platforms, and signalling. During the 2012 Olympics, this also included the introduction of 3-car operations to address increasing demand. The system has established a strong reputation for punctuality and reliability, consistently delivering over 99% of scheduled services on time [TfL, 2023]. Current plans include fleet renewal with new CAF-built rolling stock from the mid-2020s.

Reflection and insights

The Docklands Light Railway (DLR) was conceived as a low-cost, automated light metro to support the regeneration of East London. The DLR emphasises the importance of combining automation with scalability, a robust safety culture, and integration with urban development. From its inception, the DLR demonstrated the benefits of turnkey procurement in delivering a low-cost automated system suited to constrained urban environments [Kemp, 1987]. However, early design shortcomings, such as the use of single-car trains and fixed-block signalling, soon necessitated costly retrofits as demand surged in Canary Wharf. This situation highlights the critical need to design for scalability right from the start [TfL, 2023]. The adoption of SelTrac CBTC in 1994 resolved capacity constraints and enabled high-frequency operations. However, commissioning delays revealed the complexity of aligning supplier readiness, delivery schedules, and operator capacity (Lockyear, 1998). Phased rollouts, real-time diagnostics, and predictive maintenance proved effective in managing complexity; however, they also exposed the risks of vendor lock-in due to proprietary architectures. Safety events in 1991 and 2009 highlighted the need for clear human–machine protocols and effective communication between staff and control centres (RAIB, 2009). During GoA3 operations, the presence of Passenger Service Agents (PSAs) provided both supervision and public assurance. More recent debates on GoA4 suggest marginal gains over GoA3, with surveys indicating public preference for staff presence in an open, barrier-free system, and cost estimates highlighting significant infrastructure needs, such as platform screen doors [IanVisits, 2021; TfL, 2023].

Stakeholder management and organisational learning were equally important to the railway's development. The London Docklands Development Corporation (LDDC) facilitated early delivery, which correlated transport investment directly with regeneration. Following governance by Transport for London (TfL), the DLR was integrated into London's multimodal network through fare integration and system-wide coordination (GLA, 2014). This transition demonstrates that automation gains legitimacy when it is aligned with broader urban strategies, rather than being treated as isolated engineering projects. Taken together, these insights position the DLR as a socio-technical system where the success of automation depends not only on technical delivery but also on organisational adaptability, stakeholder trust, and alignment with broader urban strategies.

5.2.4 Betuweroute (The Netherlands)

The Betuweroute is a 160 km dedicated freight line linking Rotterdam to the German border. In 2024, ProRail and DB launched a flagship ATO programme under the Joint Declaration of Intent (JDOI) for rail freight. Preparation began with drafting specifications, tendering, and selecting vendors, with operations planned for a one-year test programme starting in 2026. The demonstrator integrates ATO functions on freight trains operating with ERTMS Level 2, testing scenarios across weather conditions, incidents, and varied operational contexts. The goal is to assess capacity, energy savings, and safety improvements, while providing input for future European deployment.

The respondent

The respondent serves as Project Manager at ProRail, leading the infrastructure part of the ATO pilot on the Betuweroute since 2024. He has coordinated the preparation of specifications, vendor selection, and stakeholder engagement. At ProRail, his work focuses on integrating Automatic Train Operation, managing operational scenarios, simulations, and a year-long testing programme set to begin in 2026. Previously working at DB Cargo, he gained direct experience with freight operations and procurement, which he now applies in cross-border collaboration.

Reflection and insights

The project began under a rigid contract with narrow specifications, leaving little scope for innovation. The project manager notes that ATO pilots require flexible arrangements designed for experimentation and adaptation, not traditional procurement frameworks. Early involvement of drivers and unions was critical. Clear communication that ATO would support, not replace, drivers was essential. ProRail translated operational knowledge and driver experience into technical requirements through workshops, cab ride-alongs and GoPro video logs.

Collaboration worked when stakeholders met physically. Remote cooperation via Teams proved inefficient and integration suffered when dialogue stopped after vendor selection. The project manager emphasises that co-design and open dialogue should extend throughout delivery, instead of ending at tendering. “If I had to boil everything down: an open dialogue and a more collaborative working mode would have helped a lot. Get people in the same room, invest in relationships. It pays off.”

The involvement of multiple suppliers and subcontractors created fragmented risk management. This caused a delay of nearly nine months, underscoring the need for a single integrated framework and consistent terminology. Staff turnover challenged knowledge retention, making documentation and on-site learning critical. Since European expertise was limited, ProRail brought in a specialist in Rio Tinto's AutoHaul. The project team benefited from lessons learned from Rio Tinto.

5.2.5 ETCS Programme management Expert NS (The Netherlands)

ICE Amsterdam–Frankfurt Services

The Amsterdam–Frankfurt ICE services marked NS's first cross-border high-speed collaboration. In the late 1990's, the interviewee served as project manager. He oversaw the integration of NS rolling stock with DB for ICE operations. The project shifted NS from system integrator to co-creator with Siemens. Operational, technical, and regulatory alignment was required across two national networks. It introduced digitalised control systems and interoperability challenges. This provided NS with its first lessons in managing international, software-driven integration.

HSL-South and ERTMS Deployment

The HSL-South (HSL-Zuid) is a 125 km high-speed line linking Amsterdam to the Belgian border. It was the Netherlands' first large-scale ERTMS Level 2 project and a €6.8 billion investment (Cantarelli, 2011). Delivered through a public–private partnership with Infraspeed, the project introduced new infrastructure alongside retrofitted Thalys sets, Bombardier TRAXX locomotives, and AnsaldoBreda V250 trains. Assets were delivered to specification but failed to integrate, exposing weaknesses in governance, testing, and cross-system coordination. Retrofitting costs reached €2.6 million per Thalys set. Early reliance on immature technology led to delays and overruns; however, the line is now integrated into Dutch and international services.

Fyra Project

The Fyra project aimed to deliver Amsterdam–Brussels services using AnsaldoBreda V250 trains. Operations began in late 2012 but collapsed within weeks because of technical failures, safety defects, and certification issues. Belgian authorities revoked approval when train components detached in service. By 2013, the fleet was withdrawn, the Fyra brand retired, and operations ceased. A parliamentary inquiry concluded that weak procurement, poor integration, and opportunistic decision-making created systemic failure (Tweede Kamer, 2015). The project became a defining lesson in the need for transparency, quality assurance and cooperative governance.

National ERTMS Programme

Since 2020, the respondent has led the System Design & Integration workstream of NS's national ERTMS programme. The programme is one of Europe's largest digital rail transitions, involving nationwide fleet retrofits, infrastructure upgrades and traffic management integration. The work balances rolling stock adaptation with ProRail's infrastructure rollout, IT integration and workforce training.

The respondent

The respondent serves as Programme Manager for ERTMS System Design and Integration at NS. He has over 40 years of experience in the railway industry. His career includes rolling stock engineering, program management and international standardisation. Since 2020, he has led the System Design & Integration workstream in NS's national ERTMS programme. His focus is on ensuring integration in a complex brownfield transition. He uses systems engineering and the V-model to align technology, operations and human factors.

The respondent began his career in the 1980's with the digitalisation of train control systems. He worked on the early standardisation of programmable electronics and communication protocols. He later managed the ICE Amsterdam–Frankfurt services, shifting NS from system integrator to co-creator with Siemens. At NedTrain (now part of NS as train maintenance division), he served as Head of R&D and Head of Project Management, leading rolling stock engineering and accreditation. He then managed rolling stock compatibility and ERTMS rollout on HSL South, including TRAXX and Thalys retrofits, and experienced the challenges of the Fyra project. In later roles, he built NS's quality management, safe integration, and certification capacity. Today, he continues to promote co-creation, organisational learning, and resilience in the Dutch ERTMS programme.

Reflection and insights

The interview illustrates the evolution of integration thinking within Dutch rail throughout his career. His early experience with ICE Amsterdam–Frankfurt showed that interoperability is not purely technical. It also depends on aligning operational rules, digital protocols, and cross-border governance. The project showed that long-term supplier partnerships and co-creation models are more effective than contract-driven silos. Trust and collaboration across borders are as critical as technical compliance.

The HSL-Zuid project highlighted the risks associated with fragmented governance and inadequate integration planning. Infrastructure and rolling stock were delivered to specification but failed to operate as a system. System integration must be managed as a system-of-systems challenge. Delivering infrastructure and rolling stock to specification is insufficient if they cannot operate together. The absence of a design authority left no mechanism to ensure coherence, resulting in costly retrofits and delays. He stresses ERTMS is a revolution, not an evolution: it requires integrated adaptation of assets, IT systems, processes and people - supported by continuous testing.

Fyra left, as he described, a "mark on the soul." Political pressure and opportunistic decision-making prioritised budget and speed over quality and integration. Fyra highlighted the risk of separating procurement from maintenance and operations. It also revealed the difference between lessons identified and lessons learned. In his words, "it's only a lesson learned if you take measures in your organisation to do it differently, not merely intend to do so." Fyra demonstrated that organisations must embed quality assurance, transparency and stakeholder alignment to transform failures into learning opportunities.

These experiences inform his current role in the national ERTMS programme. The respondent stresses that projects must follow intention, not rigid goals: "you must not be afraid of changing your project goal if it is not contributing to the intention." He explains that railway digitalisation cannot be managed as a fixed blueprint but as a dynamic programme. Progress must be iterative - set goals, test, adapt, and align with supplier roadmaps, since national requirements cannot dictate global supply chains.

He underscores the value of supplier co-creation. He emphasises that system integration is not only technical. It is rooted in people, culture and patterns of working. He notes that cultural differences exist not only between different countries but also within the Dutch railway system itself: between ProRail and NS, and between rolling stock engineers and operations staff. These differences can be invisible because “everyone thinks they speak the same language,” yet assumptions can mask deeper divergences. He argues that awareness is critical: “as soon as you are aware of that difference, you can take measures for it. But if you are not aware, you think you understand each other while you are far from that.” For him, the human part of the system is often more important than the technology.

5.2.6 ATO Programme management Expert NS (The Netherlands)

Introduction of ICT in Rolling Stock

The ICT-on-Trains programme deployed an onboard ICT platform (OBIS) to enhance the passenger experience (Wi-Fi, real-time info) on NS trains. The first task developed the OBIS platform under the IOTA architecture, creating a digital link between trains. The second task integrated telecom systems and onboard hardware into operational rolling stock. The third task coordinated acceptance and maintenance readiness. The project reached TRL 7, but fragmented ownership exposed the need for a dedicated digitalisation department.

Automatic Train Operation (ATO) Project

The ATO programme tested automation proof-of-concept across shunting yards and mainline services. The first task developed proof-of-concept trials under GoA2–GoA3 conditions, including remote driving with 5G. The second task managed pilot operations, fallback procedures, and union engagement. The third task prepared migration planning toward full deployment. The project started at TRL 5, progressing toward TRL 9 by 2025, and framed automation as driver support rather than replacement.

Shunting Yard Amersfoort

The Amersfoort yard project expanded and modernised the train yard to increase capacity for new rolling stock. Introduced new systems for digital maintenance and remote control of train operations to serve as a platform for automation. Reaching TRL 8, the project showed the importance of planning, stakeholder alignment, and clear governance. It also revealed that digitalisation within yards requires synchronised development between physical infrastructure, IT systems, and operational procedures.

R2DATO Programme (2021–2031)

Implement digitalisation and automation to achieve scalable, next-generation train operations up to autonomous (GoA4) across Europe. R2DATO structured ATO development into three phases. The first phase advanced pre-existing demonstrators to TRL 5–6. The second phase (2026–2028) focuses on external validation and readiness testing. The third phase (2029–2031) will translate specifications into European standards and procurement guidance. The programme integrates technical testing, regulatory coordination and supplier alignment for automation deployment across Europe.

The respondent

The respondent served as Programme Manager for Automatic Train Operation (ATO) at NS. He has over 35 years of experience in the railway sector. His career spans operations, ICT integration, programme management, and digital transformation. From 2021 onward, he led NS's ATO programme, managing pilots in shunting, remote driving and 5G, and directing NS's role in Europe's Rail FP2–R2DATO. His work positioned ATO as both a technical upgrade and a cultural shift, requiring workforce engagement and safety integration.

Between 2018 and 2021, he managed major capacity projects, including the Amersfoort stabling yard and Arnhem Goods yard, delivering new infrastructure to support fleet expansion. From 2010 to 2018, he directed NS IT and asset management programmes, embedding digital tools and risk-based maintenance into operations.

From 2006 to 2010, he introduced Wi-Fi, internet, and passenger information systems under the OBIS programme, creating NS's first digital architecture for rolling stock.

Reflection and insights

The interview highlights the evolution of digitalisation and automation thinking at NS. His early leadership in the ICT-on-Trains programme showed that technology integration was never just about hardware. Success depended on trust, transparency, and on convincing managers and maintenance staff to accept change. The respondent stressed that a culture of honesty was essential: "failure is not an option" created denial, not solutions. When failure was allowed, the team could adapt, rebuild, and deliver a working system. A culture that embraces failure as a learning opportunity can lead to better outcomes. The project exposed the dangers of fragmented ownership and led to the later creation of NS's Train Digitalisation Department.

The Automatic Train Operation (ATO) programme demonstrated the challenges of automation in a live railway. Proof-of-concept trials in shunting yards and on mainline services under GoA2–GoA3 conditions confirmed technical feasibility, but he emphasised that automation must be framed as support for drivers, not replacement. Acceptance relied on union involvement, fallback procedures, and extensive testing.

The Amersfoort Shunting Yard project reinforced the centrality of people. Expanding stabling capacity required coordination across operators, engineers and contractors. The respondent observed that "technology is never the main problem — it is about getting the right people with the right motivation." Clear communication of vision, honest stakeholder engagement and team alignment ensured successful delivery. The project showed that effective collaboration and realistic planning are as critical as technical execution.

Leading an innovation project involves accepting that risks will emerge and that full control is impossible. Effective management of complexity requires knowing your limitations and involving the right people who can cover those gaps. He warned against seeing ATO as a blueprint project: "you have to go one step forward, look around, see what happens, and then decide the next." Managing ATO required agile, programmatic thinking, not rigid planning.

5.2.7 People oriented Change management within ATO Programme at NS (The Netherlands)

The deployment of Automatic Train Operation (ATO) across European rail networks poses both strategic and operational complexities. Between 2018 and 2024, a multidisciplinary team in the Netherlands explored how ATO could be successfully integrated within NS, while addressing not only technical readiness but also human-centric transformation. By combining the DECA Framework with field-tested change insights, this case study outlines lessons learned for future digital innovations in rail transport.

ATO implementation revealed that successful digital innovation in a European rail context depends on more than technology. Using the R2DATO Migration Framework as a risk compass - and combining it with deep, people-focused engagement - enabled a safer and more credible path forward. This requires that management, regardless of personnel changes, continuously emphasise and keep in view its importance, regardless of the duration of the research and implementation, so that future migrations can continue to integrate technical and human dynamics to navigate the complex tracks of change

A technology-driven approach alone is insufficient

The driving of trains with a form of ATO directly affects the profession of the train driver. Internal research at NS by the department of HMI (Human Machine Interaction) shows that the daily work in the driver's cabin changes drastically. From operator to controller of the train. This alters the function so much that the drivers involved indicate in the research that they did not choose this profession to work in this manner. ATO must be positioned as a strategic initiative, embedded in broader organisational objectives such as safety, capacity, and workforce development.

Because ATO has an impact in all these areas, the people who experience the impact must be involved in guiding this and identifying and mitigating the risks. This lesson learned has also been experienced in previous NS technical innovation projects and is supported by the theory (D33.2). However, unclear mandates and shifting priorities within senior leadership posed risks. Mitigation required elevating ATO to the strategic agenda of the Operations MT, ensuring long-term governance, and financial alignment. This requires that (regardless of staff changes), the strategic direction must remain firmly in place and be adhered to, unless research results show that there are good reasons for a change in direction.

The governance structure of the programme was initially fragmented, creating ambiguity in sponsorship. Change practitioners learned that ownership of change cannot reside solely in projects; it must be shared with line organisations. Early engagement with unions, safety boards, and operational leaders was vital. A multidisciplinary core team — combining change, communication, IT, and operations — improved alignment and helped overcome trust deficits. Reality checks with stakeholders (e.g., ProRail, regional authorities) ensured external legitimacy and inter-organisational readiness.

To improve the organisational capability, we periodically shared the results during the research with our partners. The results were shared through several sessions with both external stakeholders, such as ProRail (Dutch IM) and the Province of Groningen, as well as internal stakeholders, such as works councils and operational staff. The vision and input of these stakeholders were added to the results. Digitalisation in rail transport is not possible without close cooperation with the infrastructure manager. National (Ministry of Infrastructure and Water Management) and regional politics (i.e., Province of Groningen) also influence developments: they want reliable, efficient, and affordable public transport and often have high expectations of digital developments, specifically ATO. Collaboration with these stakeholders helps to keep developments on the political agenda, ensuring that these parties allocate time and money.

The technological promise of ATO required rigorous, iterative testing to validate assumptions. Pilots demonstrated both successes and critical gaps - including near “stop signal passed” (STS) events - underscoring the need for joint evaluation with drivers and engineers. Success hinged on realistic planning and transparent timelines. Co-created human-centred narratives explained “why change is needed.” Involving train drivers in test rides led to higher ownership and trust.

The complexity of integrating ATO with legacy systems, signalling infrastructure, and cross-border interoperability was underestimated. Technical dependencies were compounded by varying levels of digital maturity across regions. Interoperability risks were addressed through modular design and progressive rollout scenarios. However, the greatest gains came from mapping these interdependencies early and communicating them through visual tools and stakeholder sessions.

Human-Centric Change as a Risk Mitigation Strategy

ATO introduced a “digital colleague” into the train cabin. While some feared job losses, others saw opportunity. Resistance often stemmed not from the technology itself, but from lack of transparency. A major insight: effective migration requires not just technical handbooks but emotional readiness. Workers must feel heard and involved - from union reps to train conductors. Honest communication, even about what is uncertain, created space for dialogue rather than resistance.

To improve the readiness for the end users, the participation of the operator user group, as well as the staff representation, is involved at various times during the research period. It became clear that the staff participation of NS has concerns about the change in the profession of train drivers: they see the transition from operator to controller as a 'hollowing out' of the profession. Previously, the profession of train driver changed at a relatively low pace, but with the advent of digitalisation, those changes are happening yet faster. The relatively high average age of both the train driver corps and the representatives in employee participation reinforces these concerns. This is a risk because the current members of employee participation hardly represent the future users. On the other hand, newly recruited staff may appreciate this digitalisation, if attention is given to the required change skills from the recruitment and training stage and if there is open communication about inevitable, but often still uncertain (digital) developments in the profession.

5.3 METHODOLOGIES

5.3.1 WP29 Railindustrial DevOps and Architecting4evolution (DevOps)

The main objective of work package (WP) 29 is developing a software architecture for the onboard computer of trains to ensure evolvability and continuous improvement of the software onboard.

Some architectural goals the work package is focussing on are the single responsibility principle, the open-closed principle, focus on interface design and coupling & encapsulation, finding architectural patterns. This is very important because the focus is on software boxes for on board units, that facilitate development, deployment and testing.

DevOps was the scope of this interview, and the main objectives are:

- Develop a DevOps-based methodology for software architecture in onboard train computers.
- Ensure evolvability and continuous improvement of railway software systems.

The respondent

The respondent serves as a researcher at CEIT and is an expert in DevOps. He is participating in WP29 since January 2025.

Reflection and insights

Implementing a DevOps-based methodology in a railway environment faces several challenges, like:

- Strict regulations and homologation procedures limit flexibility.
- Inter-organisational collaboration is difficult due to credentialing, IP concerns and siloed processes.
- Legacy systems pose barriers to integration and adaptation.
- Lack of risk assessment and unclear goals regarding legacy infrastructure adaptation.

DevOps as a methodology is flexible, automation-driven, and experimentation-friendly. Railways, however, are characterised by e.g. heavy regulation & long asset lifecycles. These conditions restrict the input DevOps normally relies on (e.g., rapid changes, modern interfaces, modularity, cross-team autonomy). Mentioned limitations are therefore contextual, not methodological.

Lessons learned

- DevOps is promising but is not a plug-and-play implementation within the railway environment, it demands cultural and architectural changes.
- Iterative validation through digital twins accelerates software testing and reduces dependency on physical assets.
- Clear regulatory boundaries for modifiable software components prevent homologation conflicts.

- Adapting DevOps to legacy systems requires intermediate integration stages.

5.3.2 WP29 Railindustrial DevOps and Architecture4evolution (A4e)

As previously mentioned, the main objective of work package (WP) 29 is developing a software architecture for the onboard computer of trains to ensure evolvability and continuous improvement of the software onboard.

Architecture4evolution is focused on the long-term including operations with the need for adaptations and change over the decades, that could be adding new functions or remove it, migration to newer versions or newer technologies, supporting new scenarios.

To differentiate from DevOps whose approach is in the short term, is oriented to long term.

To improve the evolvability of software architecture is the main goal and main objective to make it a software architecture that avoids disruptive changes in the rail sector's long living systems.

The respondent

The respondent works in Siemens and is an expert in SW architecture. He is WP leader from the beginning of the project. His technical involvement is mainly in Arch4evolution and less in DevOps.

Reflection and insights

A software architecture should mitigate risks of "losing money" facing problems towards migration to updates or new versions that need an intensive effort/cost.

Also, a big risk is losing balance between excessive modularity and performance, that makes it not achieve requirements. Over-granularity is a linked risk to performance.

The need to agree on specific technology, or at least on protocols is a challenge because each party involved has its own wishes.

The use of different protocol versions, even when standardised and open source, can create incompatibilities. Since there are interfaces and adapters between different communication protocols, that is one of the main problems.

The most significant risk identified in WP29 is the challenge of achieving certification for safety-critical systems. Certification is done in the latest phase of the life cycle.
A practical mitigation strategy: instead of certifying entire architectures (whole projects) that can be done at the end, it is proposed, in the beginning when a specific technology is selected, to stack and test it and certified through small, representative examples. This approach helps assess feasibility and reduce effort.

Lessons Learned
Certification is the most critical risk in deploying new architectural approaches for onboard systems. To mitigate this, future projects should avoid certifying entire systems at once. Instead, focus on small, well-defined examples using a consistent technology stack at the beginning.

Interoperability depends on standardised interfaces, not on internal system design. Adopting open communication protocols at system boundaries is essential to ensure compatibility across suppliers and operators.

Migration success must be measured through objective metrics and KPI's. Without quantifiable indicators, it's difficult to evaluate whether architectural changes have truly improved evolvability or operational efficiency.

5.3.3 WP30 Automated authorisation by modelling techniques (Formal Methods)

WP 30 "Automated authorisation by modelling techniques" focuses on implementing model-based and formal methods within the European railway domain ("Automated Authorisation"). WP30 consists of two tasks: Task 30.1: Proving interoperability and transformation from model-based specifications (SysML, EULYNX) to formal languages, thereby validating the transformation and preconditions for automation and Task 30.2: Developing a demonstrator and guidebook to provide stakeholders with practical deployment guidance. The work also bridges different modelling environments (e.g., Capella, SysML) and aims to harmonise guidelines across domains to increase interoperability within the railway sector. An important part of the work is to support future automated authorisation processes, benefiting not only system suppliers but also infrastructure managers and certification bodies.

The respondent

The interviewee is the work package 30 lead, representing the infrastructure manager DB InfraGO in WP30. He is a senior, technical consultant, specialised in formal methods and model-based systems engineering. He was involved in European research in this field for the last seven years, first in shift2rail projects (in X2Rail2 as a contributor to a technical work package based on formal methods, then in X2Rail5, as the lead contributor). Furthermore, he is or was involved into EULYNX and OCORA projects.

Reflection and insights

The most critical lessons learned are that successful migration and deployment of ATO technology depend on adopting formal methods early to reduce ambiguity, manage risks, and ensure system safety. Organisational openness to model-based approaches and proactive change management are vital for overcoming resistance and achieving consistent implementation. Technically, standardising tools and specifications, along with bridging diverse modelling environments, is essential for interoperability. Clear and comprehensive requirements alongside rigorous risk analysis and early demonstrators support smoother transitions and foster stakeholder acceptance.

For future migration projects, it is recommended to adopt model-based and formal specification methods from the outset, foster early and close stakeholder collaboration, invest in training and organisational change management, and prioritise interoperability through standards, executable models, and common guidelines. Demonstrators and case studies should be used to build practical confidence in formal methods, while harmonised processes should support scalable, future-proof solutions across borders and domains.

Ambiguity in traditional, non-formal requirements poses considerable risks for migration and deployment, whereas model-based systems engineering (MBSE) significantly reduces such ambiguity by defining data types, transitions, and preconditions explicitly. Engaging all stakeholders – including operators, users, and suppliers – early in the process ensures that requirements reflect the complete system lifecycle and minimises late-stage misunderstandings. Standardised and harmonised requirement specifications are essential for successful migration, particularly in cross-border and multi-vendor contexts.

The early application of formal methods – ideally from the tender phase – enables errors to be uncovered and addressed before they escalate, reducing rework and project delays. These methods provide strong assurance in the integrity of safety-critical systems and enable rigorous, automated verification and validation. Acceptance of formal methods increases through practical, use case-based demonstrators, which are vital for stakeholder buy-in and for reducing perceived complexity.

Migration projects also require substantial cultural and organisational change, especially regarding widespread adoption of formal methods among a broader engineering audience, not just specialists. Targeted change management resources and strategies are crucial to govern the scale and increasing interconnectedness of digitalised systems. The use of modular systems and harmonised processes is recommended to address the complexity of automation and digitalisation.

A major interoperability risk is posed by the lack of standardised modelling tools among suppliers and operators; bridging these gaps – as shown in WP30 – through conversion between tool-specific models is necessary. Supplying executable models instead of static documents accelerates integration, reduces iterations, and shortens the time-to-market for new systems. Ongoing gap analyses and harmonisation efforts are required to keep up with rapid technological and regulatory changes.

5.3.4 WP31 Automated Train Supervision and Control (Formal Methods)

WP31 focuses on applying formal methods to automated train supervision and control, aiming to produce technical specifications that are rigorous, measurable, and unambiguous. These formal methods leverage software tools for requirements engineering, data- and architectural modelling, and verification to ensure that requirements fully meet operational needs and can be validated by systematic testing.

WP31 covers two main tasks: one concentrating on on-board ATO aspects (rolling stock), the other on trackside data and traffic management. The goal is to enable modular architectures with testable interfaces to reduce system complexity, accelerate validation, and support scalable migration—such as moving from GoA2 automation levels toward GoA4, including retrofit solutions which are critical for freight locomotives.

The work within WP31 aims to improve interoperability and reduce lifecycle costs through better design, transparency, and early error detection.

The respondent

The respondent works at DB Cargo in the European Rail programme management department, based in Mainz, Germany. He is DB Cargo's representative in the R2DATO project and leads WP31 "Automated Train Supervision and Control." He also leads Task 31.1. His expertise is in applying formal methods - rigorous, often mathematically based processes for railway technology development, especially related to automated train operation (ATO) systems. His role is to ensure that technical specifications are clearly defined, testable and harmonised to support interoperability and risk mitigation.

DB Cargo will need retrofit solutions to be able to implement ATO for freight, which makes the ability to install ATO systems on older rolling stock essential. Cross-border operations demand harmonised specifications and standards to support interoperable migration.

Reflection and insights

Applying tools based on Formal Methods can help to establish:

- Clear and testable specifications (which are essential to avoid misunderstandings and ambiguities that can derail technical harmonisation efforts)
- Early detection of errors (which will reduce the risk of costly late-stage fixes)
- Modular and scalable solutions with well-defined and testable interfaces (which will help managing complexity and costs of migrating ATO systems)

Out of scope of this WP, but essential for successful application of Formal Methods based tools:

- Complementary organisational roles from the start: involving roles such as safety managers early in projects is important to ensure that formal method processes align with safety requirements and regulatory demands.
- Transparency and trust among suppliers: to be able to develop interoperable subsystems, there is a need for trust and openness between suppliers, which is a political and commercial challenge.
- Open and formalised - but non-binding - specifications: having an open, formalised framework on the table gives suppliers and operators a reference point to plan development and mitigate risks, acting as a fallback option.

5.3.5 WP37 ETCS HTD/HL3 Deployment Strategies

ETCS HTD (Hybrid Train Detection), previously known as ETCS HL3 (Hybrid Level 3), is a railway signalling concept aimed at increasing railway capacity and efficiency while maintaining safety. HTD combines the ETCS L2 functionalities to enable gradual migration and compatibility with different train types.

HTD uses virtual sub-sections to divide track segments into smaller blocks, allowing for more precise train tracking and supporting trains with various equipment types, e.g., TIMS (Train Integrity Monitoring System), ERTMS without TIMS and non-ERTMS trains. Train location is determined through a combination of onboard systems and trackside detection. Train integrity is verified either onboard (via TIMS) or by trackside systems. The main challenge of this approach is ensuring safe and reliable detection for all types of trains.

The main goal of WP37 is to develop strategies that accelerate the deployment of HTD, helping to avoid costly infrastructure upgrade investments. Using ETCS and existing trackside detection systems, the objective is to define optimal implementation strategies, with a focus on the 2025–2030 period. These strategies will serve as tools to help infrastructure managers increase line capacity while reducing development time and operational costs.

It should be noted that the adoption of Hybrid Train Detection (HTD) can be decoupled from the deployment of Automatic Train Operation (ATO), as defined within the FP2 framework (see GA). ATO requires ETCS Baseline 4 to ensure regulatory compliance and full interoperability across Europe. At present, many European railway undertakings are facing significant challenges with the rollout of ETCS Baseline 3, even in its most advanced form (B3 SRS 3.6.0). The costs associated with ERTMS on-board deployment have risen sharply, with retrofit expenses increasing from €450,000 to €900,000 per vehicle and upgrade costs rising from €200,000 to €400,000 between 2018 and 2022 (ERTMS on-board deployment - Publications Office of the EU).

In this context, the adoption of HTD implies that Railway Undertakings (RUs) would need to install or retrofit both an ERTMS on-board system and TIMS for EMUs/DMUs. While the financial return for RUs remains unclear, this is not the case for Infrastructure Managers (IMs). In any case, it is evident that the railway system as a whole stands to benefit from the implementation of HTD, particularly through increased capacity.

WP37 is divided in four subtasks, the first covers overall management of the WP, Task 37.2 focuses on standardisation and deployment of HTD, in close alignment with the System Pilar. Task 37.3 involves the optimal line signalling engineering modelling through simulations in collaboration with FP1 WP8/9. The last Task 37.4 focuses on evaluating the HTD application from both the product and project development lifecycle perspectives. This includes the generic and specific applications, and the cost analysis (CAPEX and OPEX).

The Respondent

The respondent serves as a project manager at ProRail and as a postdoctoral researcher at the Technical University of Delft, with more than 9 years of experience across international contexts and a track record spanning research, engineering and management. She leads WP37 and manages the planning, research, and content development related to deployment strategies for ETCS Hybrid Train Detection in R2DATO. The respondent has been involved in previous EU-funded projects within Shift2Rail like MOVINGRAIL and PERFORMINGRAIL. Her PhD Thesis focused on evaluating the impact of train-centric signalling, with particular attention to modelling, overall assessment, roadmapping and railway signalling technologies, e.g., Moving Block and Virtual Coupling.

Reflection and insights

"The key idea is that any proposed change should clearly improve the existing solution and actively involve all relevant stakeholders, only then will it be convincing enough for broad acceptance and successful adoption." (quote from the respondent) Most important lessons taken from the interview:

Flexibility is essential in migration strategy

The implementation of HTD implies migrating from current signalling systems and various baselines/benchmark systems. Therefore, the migration and deployment strategy must adapt to different baselines (e.g., ATB, Class B, ETCS L1, greenfield) and market segments (high-speed, mainline, urban, regional, freight, etc.).

Stakeholder engagement is crucial

Early and continuous engagement of diverse stakeholders, including infrastructure managers, railway undertakings, suppliers, manufacturers, the ERA and the System Pilar ensures relevance, credibility and unbiased results.

Balance different stakeholders' priorities.

The cost-benefit distribution of the HTD technology is uneven between Infrastructure Managers (IMs) and Railway Undertakings (RUs). When benefits mainly favour the IMs, RUs often bear most of the costs. A multi-criteria analysis can support a more balanced stakeholder alignment.

Planning in advance to avoid cascading delays

Given that the capacity simulations required for WP37 are being developed within FP1 WP8/9, delays in the delivery of WP8/9 are considered a critical path risk that will directly impact subsequent work packages and the overall project timeline. Therefore, effective anticipatory planning and proactive schedule management are essential for mitigating (future) projects interdependency risks.

The Methodology developed in WP37 can be used in other technologies

The core methodology developed in WP37 is highly versatile and applicable to any other technology or system. HTD may be an intermediate step, given the rapid evolution of technologies that may shift priorities away from HTD, e.g., migration to moving block. In such cases, alternative solutions must be clearly defined and contextualised based on their specific objectives and operational purposes.

Incompatibilities between countries and/or jurisdictions

Interoperability challenges arising from diverse national regulations and jurisdictional incompatibilities pose a significant risk to cross-border implementation. To address this problem, centralised coordination (e.g., the European Commission) and standardised documents are needed to avoid regulatory cross-border barriers and ensuring systemic harmonisation across different countries.

6 ANALYSIS OF INTERVIEWS

In this chapter the outcomes of the interviews for T33.1 (paragraph 6.1) and for T33.2 (paragraph 6.2) are summarised per risk category of Risk Dimensions Governance Organisational Capability (T33.1), Delivery Scope & Complexity (T33.2) and Systems Integration (T33.2).

6.1 RISK DIMENSION GOVERNANCE & ORGANISATIONAL CAPABILITY

Task 33.1 showed that DATO migration feasibility was driven not solely by technical progress but by interactions across four dimensions: Capability–Performance, Delivery Partners, External Stakeholders, and Discipline and Skills (Figure 5). Strategic alignment shaped performance, supplier interdependencies affected integration pace, regulatory interpretation governed authorisation, and skills continuity influenced operational readiness. D-TRACK governance focus enables early identification of systemic constraints and provides a structured complement to technical integration. This supports a more reliable shift from pilot deployment to pilot demonstration to operational deployment.

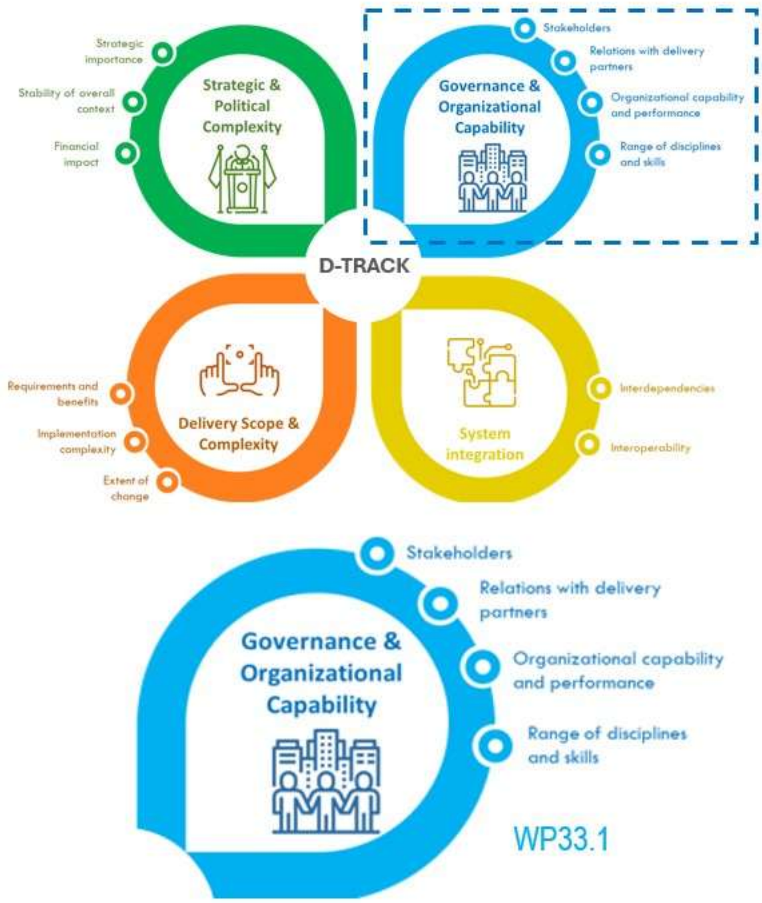

Figure 5 Scope of WP33.1: D-Track Risk Dimension Governance and Organisational Capability

The four categories applied in task 33.1—Stakeholders, Relations with Delivery Partners, Organisational Capability, and Range of Disciplines and Skills—were selected because they consistently shaped demonstrator progression. Stakeholder interpretation directly influenced authorisation timelines, coordination with delivery partners determined interface readiness, organisational capability governed retention of system knowledge beyond pilot phases, and specialist skills availability determined integration pacing as ATO functions advanced. As such, they provided an analytically coherent lens for organising, comparing, and synthesising lessons learned within task 33.1 (Figure 6).

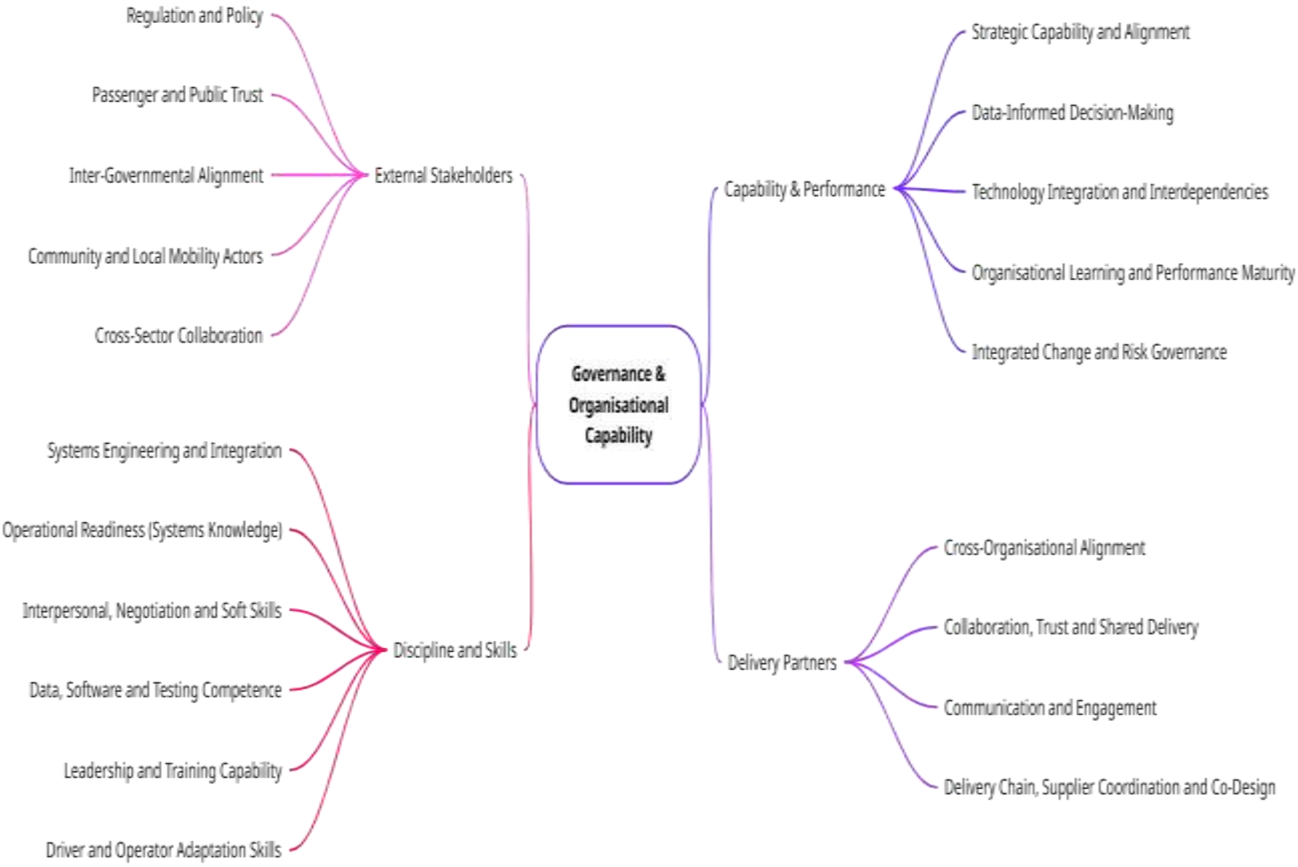

Figure 6 Results of lessons learned over 4 categories

Results of the lessons learned mapped across the four analytical dimensions of Governance and Organisational Capability: External Stakeholders, Discipline and Skills, Capability and Performance, and Delivery Partners.

6.1.1 Stakeholders

Regulatory authorities, passengers, regional governments, and local mobility actors collectively shaped the feasibility envelope within which automation could progress. Authorisation logic, safety interpretation, and societal acceptance proved to be cumulative rather than transferable across automation generations, requiring each programme to reconstitute trust, legitimacy, and policy fit. Cross-border alignment and government funding functioned as structural enablers, while community engagement moderated disruption perception in demonstration areas. Unlike suppliers, external stakeholders are enduring system stewards; their interpretive continuity anchors public legitimacy and regulatory stability over time.

6.1.2 Relations with delivery partners

The multi-actor nature of rail automation exposed coordination weaknesses that mirrored classic patterns of complex system delivery: trust deficits, shifting accountability, and ambiguity around supplier interdependencies. Shared delivery improved as soon as work boundaries were explicit, interface assumptions were documented, and communication stabilised. Co-design with suppliers reduced redesign loops and limited integration deadlocks, confirming that delivery performance cannot be relegated to contract execution but requires continuous interpretive negotiation. The program's advancement is directly associated with the constancy of partner engagement, indicating that delivery chains perform optimally when institutional alignment is present.

6.1.3 Organisational capability and performance

The evidence demonstrates that ATO deployment viability is governed by the organisation’s ability to sustain alignment, data credibility, and integration sequencing. Strategic intent must remain stable while continuously re-interpreted through operational evidence. Simulation outputs, iterative testing, and data validation cycles provided the analytical backbone for decision authority, yet their influence diminished when interpretive ownership fragmented across partners. Integration dependencies, particularly between signalling, onboard software, communication networks, and supervisory control, required early mapping to prevent cascading delays. Performance maturity, therefore, emerged not as a technical end state but as a function of organisational learning capacity and structured risk governance.

6.1.4 Range of disciplines and skills

Continuous reinforcement is essential to prevent degradation in integration capacity, software testing proficiency, and operational supervisory skills throughout deployment cycles. The workforce required for automated operations must be retrained, especially when the transition shifts human roles from direct control to exception management and oversight. Interpersonal negotiation and conflict-resolution skills proved as vital as technical expertise in managing subsystem interdependencies and in certification dialogue. Leadership continuity and structured adaptation pathways for operators supported emotional readiness and mitigated resistance associated with role displacement. The human skills landscape, therefore, constitutes a core infrastructure of automation, comparable in necessity to technology.

6.2 RISK DIMENSIONS DELIVERY SCOPE & COMPLEXITY AND SYSTEMS INTEGRATION

The risk dimensions in this section address issues related to the scope and complexity of delivering digital railway solutions and their integration into existing technical, operational, and organisational environments.

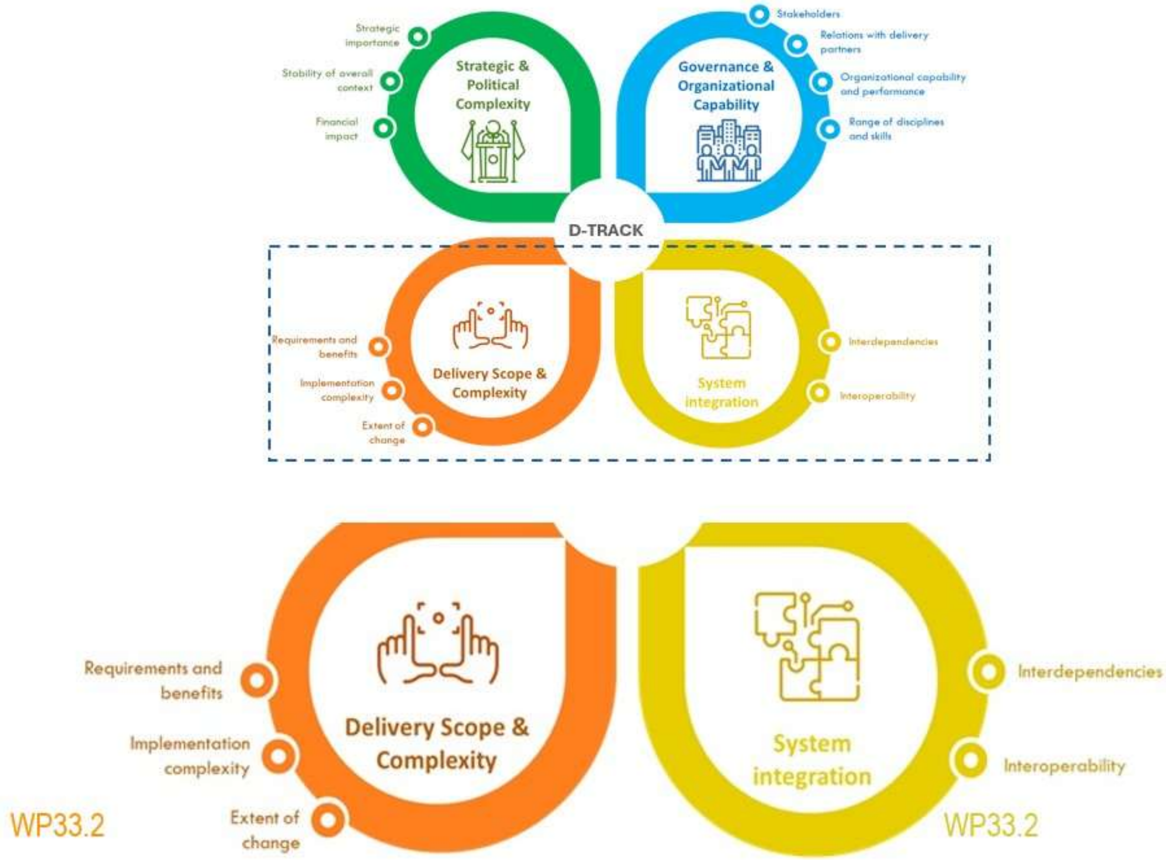

Figure 7 Scope of WP33.2: D-Track Risk Dimensions Delivery Scope & Complexity and Systems Integration

The interviews indicate that deployment and migration risks are not solely determined by technological maturity, but are strongly influenced by how solutions are specified, implemented, integrated, and embedded within existing systems and organisations. These risks are particularly relevant in the context of R2DATO, where deployment scenarios involve multiple technologies, stakeholders, and national contexts.

By analysing the expert interviews, we can extend the analyses presented in Chapter 6.1, which focus on Governance and Organisational Capability. This second part of the analysis shifts attention to the other two dimensions of the D-TRACK framework: Delivery Scope & Implementation and System Integration. Using the questionnaires, the goal is to identify the risk dimensions associated with these two elements of the framework. Subsequently, the identified risks and potential mitigations can be examined in greater detail and transformed into lessons learned.

6.2.1 Requirements and benefits

The interviews reveal recurring risks associated with the definition and management of requirements. Several interviewees reported that requirements are often inadequately specified, ambiguous, or subject to change throughout the project lifecycle. This uncertainty complicates implementation, verification, and integration processes, increasing the risk of misalignment among stakeholders.

Moreover, the interviews suggest that requirements are not always clearly connected to anticipated operational, business, or safety benefits. In such cases, the added value of new technologies or methodologies remains unclear to stakeholders, potentially limiting their engagement and acceptance. A lack of a clear benefits narrative emerged as a significant risk factor, especially in complex deployment environments involving multiple decision-makers.

Differences in domain knowledge, terminology, and language further complicate requirement management. Several interviewees emphasised that these disparities can cause misunderstandings, particularly in multidisciplinary and multinational contexts. Consequently, requirements-related risks are frequently cited as a major contributor to downstream complexities during deployment and migration.

6.2.2 Implementation complexity

Implementation complexity emerged consistently as a major risk in the interviews. Interviewees observed that the effort required to deploy digital railway solutions is frequently underestimated, especially in safety-critical and heavily regulated environments. This complexity stems from technical design and especially from certification demands, legacy system limitations, and organisational procedures.

Several interviewees highlighted rigid system architectures that constrain flexibility in software modifications or system evolution. In these settings, even minor changes can necessitate extensive validation or homologation processes, increase implementation effort and thus reduce predictability in planning and execution.

The integration of new solutions with existing systems was also identified as a significant source of complexity. Legacy components, proprietary interfaces, and insufficient documentation amplify integration efforts and increase dependency on specific suppliers. Together, these factors heighten implementation risk and can delay deployment timelines.

6.2.3 Extent of change

The interviews indicate that risks related to the extent of change introduced by deployment and migration activities are often underestimated. Changes associated with DATO solutions typically affect not only technology, but also operational processes, organisational roles, and required competencies. Several interviewees reported that resistance to change is common, particularly when the benefits of new solutions are not clearly demonstrated or when alternative technologies are evolving in parallel. This resistance may not always be explicit, but can manifest through limited engagement, delayed decision-making, or partial adoption.

The extent of change was also found to vary significantly depending on national context, organisational maturity, and existing system baselines. The interviews suggest that insufficient consideration of these contextual factors increases the risk of misalignment between solution design and operational implementation.

6.2.4 Interdependencies

Interdependencies between systems, work packages, organisations, and external inputs were identified as a main source of risk across the interviews. Interviewees described situations where delays or changes in one area affected multiple downstream activities, leading to schedule pressure and reduced robustness of outcomes. These interdependencies are particularly relevant in large collaborative programmes, where results from one activity are required as input for others. The interviews indicate that risks increase when interdependencies are not explicitly identified, owned, and monitored. In several cases, late involvement of key stakeholders or decision makers further amplified dependency-related risks. Limited visibility across organisational boundaries was also mentioned as a contributing factor. As a result, interdependencies were identified as a critical challenge in managing delivery scope and complexity, and system integration.

6.2.5 Interoperability

Interoperability related risks were prominent in all interviews. These risks stem from technical, procedural and regulatory differences between systems, organisations, and countries. Interviewees reported that lack of harmonisation in standards, interfaces, operational rules, and documentation complicates integration and deployment. National requirements and language barriers were frequently mentioned as additional challenges in cross-border contexts. Differences in interpretation of standards and the use of proprietary solutions further limit interoperability and reuse.

The interviews also indicate that interoperability issues are not limited to technical aspects. Organisational processes, contractual arrangements, and communication practices play a significant role. Insufficient documentation, unclear interface definitions, and fragmented governance structures increase the risk of misalignment during deployment and migration.

7 LESSONS LEARNED & GAPS

7.1 Lessons learned Governance & organisational Capability

7.1.1 Capability – Performance

7.1.1.1 Strategic Capability & Alignment

Lesson Learned

Long-term capability planning determines whether DATO migration remains coherent as systems evolve. Interview evidence indicated that automation, ETCS development and operational practices progress through continuous adaptation. In such environments, strategic roadmaps must be periodically re-examined to ensure alignment with system maturity, operational constraints and regulatory expectations. When plans remain static, divergence emerges between targeted automation capabilities and the readiness of enabling systems, increasing corrective work and slowing migration progress.

Gap

Strategic plans were not consistently updated as conditions shifted. While implementation progressed, partners continued to rely on assumptions set earlier, leading to divergence between planned automation levels and actual readiness. The observation that "you almost need an adaptive or 'living' business case—one that you revise regularly" reflects the structural need for continual recalibration rather than adherence to fixed milestones. When revisions did not occur, coordination slowed and corrective work increased, revealing that static roadmaps are incompatible with the continuous evolution characterising DATO environments.

Recommendations

- Institute a structured annual roadmap review that integrates regulatory interpretation updates, operational feedback from test corridors, and assessed system maturity, ensuring the plan remains aligned with evolving conditions.
- Define capability targets in incremental stages rather than fixed end-states to accommodate changes in signalling dependencies, operational readiness, and technology development.
- Use scenario-based migration assessments to evaluate alternative progression paths, enabling timely adjustment when underlying assumptions shift.

7.1.1.2 Data-Informed Decision

Lesson Learned

Reliable DATO migration decisions depended on high-quality, consistently validated and jointly shared datasets. Interview evidence indicated that test outcomes varied not because system performance shifted but because data references were not uniform across operational, simulation and test conditions. Dense network usage limited the possibility of identical repeat runs, requiring strict control of baseline datasets to ensure that comparisons remained meaningful. As testing shifted toward higher automation levels, particularly GoA4, data integrity and a continuously updated digital map became central to maintaining predictable ATO behaviour and avoiding performance degradation. Consequently, decision-making must rest on verifiable and synchronised evidence rather than context-dependent data snapshots.

Gap

Validation practices differed across partners and datasets lacked consistent traceability and version control. Test comparisons were occasionally drawn between fundamentally different operational conditions—for example, scheduled services versus inserted test trains—leading to misleading performance interpretations. The digital map was not always current and missing or outdated data elements directly influenced DATO responses, complicating fault attribution. These inconsistencies increased troubleshooting cycles and produced divergent evidence bases in decision forums.

Recommendations

- Maintain a single validated reference dataset for all integration and performance assessments.
- Update the digital map and associated register on a continuous cycle, ensuring alignment between trackside configuration, TMS logic and ATO data inputs.
- Restrict comparative testing to equivalent operational contexts to prevent inaccurately inferred performance differences.

7.1.1.3 Technology Integration-Interdependencies

Lesson Learned

Interface stability and dependency mapping determine whether Digital & Automated Train Operations evolve coherently or accumulate technical debt. Experience across multiple demonstrators shows that integration in DATO is never purely technical: it is an exercise in coordinating signalling behaviour, legacy constraints, rolling-stock logic, traffic management, operational rules and safety authority expectations.

The complexity of linking ATO to existing ETCS configurations and real operational workflows was underestimated. Systems matured only when dependencies were identified early and when technical decisions aligned with a long-term migration pathway rather than short-term operational fixes. When integration efforts focused on isolated subsystems, interface maturity lagged, and rework multiplied—mirroring patterns seen in multi-decade system evolution programmes.

Gap

Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated. Several technical decisions were driven by immediate constraints rather than long-term migration logic, leading to incompatible interfaces, duplicated effort and delays in achieving stable ATO–ETCS interaction. This slowed readiness assessments and difficulted harmonisation across partners.

Recommendations

- Develop a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic management and safety-case requirements across their full lifecycle.

- Anchor all major technology decisions to a modular migration roadmap to avoid short-term optimisations that undermine long-term compatibility.
- Introduce early dependency-mapping and interface-control processes, ensuring that all partners identify and review system dependencies, interface boundaries, and ownership responsibilities.

7.1.1.4 Organisational Learning & Performance Maturity

Lesson learned

Testing phases and deviations generated essential operational and technical insights, yet interview evidence underscored that learning produced value only when it was actively institutionalised rather than acknowledged informally. Stakeholders differentiated between recognising an insight and embedding it into practice, noting that lessons remain just “identified” until organisational measures ensure they are enacted consistently. Learning must be treated as a deliberate design output: analysed, shared, and embedded into standards, procedures and migration logic. In the absence of formal capture and transfer processes, knowledge is retained individually, which compromises institutional memory, particularly during employee transitions and manifests as repeated troubleshooting issues. This is a problem that often arises in long-term, multi-party initiatives.**Gap**

Learning capture was inconsistent across partners. Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams. The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.

Recommendations

- Establish mandatory learning reviews after every major test, deviation, or integration issue, with clearly assigned ownership and follow-up actions.
- Integrate short, facilitated storytelling exchanges after major tests to capture tacit insights before they dissipate.
- Create an interactive shared cross-partner lessons-learned repository with traceability, accessibility and consistent documentation requirements.
- Require that lessons directly inform updates to procedures, standards, operational logic and migration planning.
- Introduce structured knowledge-transfer mechanisms—such as cross-team briefings and retrospectives—to reduce dependence on individual memory.
- Implement a learning-maturity metric to monitor whether lessons are being captured, interpreted and institutionalised across the DATO ecosystem.

7.1.1.5 Integrated Change & Risk Governance

Lesson Learned

Change and risk functioned as a single governance system within DATO migration. Interviews showed that iterative requirement baselines, controlled change increments and work-package-specific risk identification enabled adaptation without destabilising ongoing testing or certification activities. Active risk dialogue—where concerns could be raised without penalty—supported timely escalation and clarification of impact, ensuring that only risks with operational consequences triggered corrective action. When change control was coupled with incremental requirement releases, partners could continue development while recognising that system maturity would evolve through successive baselines rather than fixed one-time specifications.

Gap

Risk escalation and ownership did not consistently align with change decisions. Some risks remained embedded in project layers, delaying visibility for operational stakeholders. While structured mechanisms existed, engagement was uneven, and several late adjustments required substantial rework due to absent early synchronisation between change proposals, safety implications, and operational constraints. Work-package risk framing functioned effectively where applied yet was not universal across teams.

Recommendations

- Create a unified Change–Risk Board that evaluates every modification with explicit assessment of risk impact and mitigation ownership.
- Facilitate collaborative ownership of change actions between project and operational teams to mitigate siloed decision-making.
- Define clear escalation paths and decision authorities to ensure accountability when risks evolve across subsystems.
- Conduct regular cross-partner governance reviews to verify that change and risk remain integrated as the system matures.

7.1.2 Delivery Partners

7.1.2.1 Cross-Organisational Alignment

Lesson Learned

The establishment of continuous alignment cycles across operators, infrastructure managers, OEMs, and safety authorities provided the depth of system understanding required to maintain integration stability throughout DATO development. As these alignment routines matured into a standing operational mechanism, not an ad-hoc exchange. They enabled partners to synchronise technical assumptions, timelines, and interface dependencies early enough to prevent divergence.

The interviews show that early detection of misalignments allows minor course corrections, while undetected discrepancies can rapidly become structural risks. Therefore, recurring alignment cycles enabled partners to compare assumptions, review interface readiness, and address emerging differences early, allowing adjustments without disrupting ongoing subsystem work unless critical inconsistencies surfaced. In doing so, alignment functioned as an ongoing operational discipline rather than a one-time synchronisation activity. This created a controlled environment in which interdependency risks could surface, be interpreted collectively, and be addressed incrementally rather than through late-stage structural rework.

Gap

Alignment was initially treated as a milestone activity rather than a persistent operational function. As a result, internal planning assumptions diverged between cycles, interface dependencies were identified too late, and corrective actions had to be executed at scale rather than at micro-adjustment level. Interdependency maps across work packages were incomplete or late, increasing the risk of cascading delays. Finally, reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.

Recommendations

- Maintain continuous alignment cycles with scheduled cross-partner dependency checks.
- Require transparent exchange of plans, constraints, and system architecture design decisions to prevent divergence from remaining undisclosed.
- Introduce alignment indicators to detect early drift in timelines, interfaces, and operational interpretations.
- Establish a multidisciplinary alignment team spanning engineering, operations, safety, and IT to ensure unified interpretation of system dependencies.
- Incorporate human-centred transition discussions early to support role clarity and emotional readiness during system evolution.
- Implement a cross-organisational governance protocol with defined roles, escalation pathways, and synchronisation routines.

7.1.2.2 Collaboration, Trust & Shared Delivery

Lesson Learned

In DATO, trust functioned as a key component, streamlining decision-making, minimizing obstacles, and ensuring the stability of collaborative project outcomes. Teams that shared information openly resolved issues faster, coordinated more effectively, and avoided avoidable rework. Mistrust, by contrast, created defensive behaviour, slowed integration more than technical constraints, and led to siloed decision-making.

Effective collaboration relied on interpersonal engagement—consistent, face-to-face interactions, familiarity with each partner’s work, and deliberate relationship-building. These practices restored shared understanding after misalignments and improved resilience during high-pressure testing. Partners who invested in trust navigated uncertainty more confidently and adapted faster to shifting technical or operational conditions.

Gap

Trust degradation emerged when information was withheld, delayed, or mediated through too few individuals. Collaboration fluctuated with interpersonal dynamics instead of being supported by structured trust-maintenance practices. Partners lacked structured mechanisms to rebuild trust after setbacks or failed tests. Over-reliance on a single expert increased fragility when availability changed. Retrospectives were inconsistent, limiting opportunities to repair collaboration patterns.

Recommendations

- Adopt structured trust-maintenance protocols, such as joint retrospectives after milestones.
- Require early cross-functional engagement, including periodic in-person alignment sessions.
- Develop dependency and responsibility maps to clarify interrelations and reduce resistance.
- Monitor collaboration-health indicators to detect early signals of mistrust.
- Create a shared issue-resolution charter that defines how partners escalate and resolve problems constructively.
- Reduce reliance on single experts through redundancy plans and shared knowledge bases.
- Institutionalise collaborative learning in onboarding and governance frameworks.

7.1.2.3 Communication & Engagement

Lesson learned

The process of maintaining continuous, bidirectional communication loops across operators, infrastructure managers and suppliers, to generate a unified picture. Regular interface updates and shared data enabled alignment, which was essential for early integrated coordination in DATO. If communication was slow or inconsistent, partners had different assumptions, leading to avoidable rework during late integration and testing. Constrained communication created blind spots.

Effective communication was not merely information. Efficient communication stabilizes mechanisms, strengthens trust, enhances handover reliability and allows teams to escalate issues without fear. Projects that normalised open conversation navigated uncertainty more effectively and maintained alignment even during high-pressure testing phases.

Gap

For DATO demonstrators, involving multiple parties and requiring technical decisions, continuous, inclusive communication is essential. However, engagement structures must be practical and consistently applied. The uneven distribution of information hindered the timely recognition of new risks. Stakeholders hesitated to raise concerns early, leading to actions that shifted from prevention to correction. Communication relied on a few intermediaries, slowing shared interpretation. Status updates emphasised outputs rather than constraints or risks. Engagement with some partners remained limited, constraining alignment.

Recommendations

- Establish mandatory open-communication cycles (e.g., weekly cross-team situational briefings) where risks, constraints and dependencies are openly discussed.
- Adopt a shared situational awareness dashboard including risks, assumptions, blocking issues and interdependencies—not just progress indicators.
- Institute a “speak-up early” protocol encouraging engineers and operators to raise concerns without fear of repercussion.

- Reduce reliance on communication bottlenecks by formalising communication pathways and ensuring multiple people share interface knowledge.
- Require all status reports to include explicit risk narratives (what has changed, what is emerging, what requires attention).
- Apply structured communication routines with delivery partners to maintain alignment and prevent unexpected constraints.
- Conduct communication retrospectives after major milestones to assess what information flowed well, what was withheld, and how to improve transparency moving forward.

7.1.2.4 Delivery Chain, Supplier Coordination & Co-Design

Lesson Learned

The process of engaging system suppliers from the initial design stages, using shared requirements interpretation and iterative interface reviews, provided alignment early on. Once established, this co-design approach enabled suppliers to address complex constraints and configuration scenarios without disrupting upstream development cycles.

Effective collaboration depends on relationship-building and openness. Teams that treated suppliers as co-developers resolved issues faster and maintained coherence across the technical chain. Trust accelerated integration and reduced the friction caused by misinterpretation.

Gap

Sometimes, suppliers were consulted with insufficient time to impact decisions, after requirements or architectures were already established, limiting their ability to validate assumptions. The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.

Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.

Recommendations

- Adopt mandatory early co-design cycles involving suppliers from the initial requirement definition through architectural modelling and interface design.
- Require joint workshops to interpret requirements and ensure that operators, IM's, and suppliers share a common understanding of functions, assumptions and constraints.
- Implement iterative integration checkpoints (minor, frequent releases) to identify divergence early, reduce rework and stabilise interfaces.
- Integrate suppliers into long-term migration planning so technology choices align with future architectural needs rather than short-term work package constraints.
- Create a formal supplier engagement playbook documenting co-design expectations, communication protocols, and integration responsibilities for future projects.

7.1.3 External Stakeholders

7.1.3.1 Regulation & Policy

Lesson Learned

Early and continuous regulatory engagement reduced uncertainty in DATO migration by shifting certification from a final checkpoint to an iterative clarification process. When regulatory bodies participated throughout requirements maturation, safety interpretations became consistent, the evidentiary baseline was shared, and risks were identified early enough to avoid large design reversals. As automation, perception systems and AI-driven components operate on shorter update cycles than traditional signalling and rolling-stock assets, regulatory dialogue must also adjust to iterative system evolution rather than assume static configurations. This continuity enables certification frameworks to accommodate controlled, modular updates in line with future TSI and CENELEC interpretations, rather than treating each digital enhancement as a whole-fleet re-authorisation event.

Gap

Regulatory engagement did not always precede design stabilisation, leading to interpretation gaps once system behaviour, safety logic, and interface assumptions had already been fixed. Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates. This created uncertainty around how emerging functions—such as recurring perception-logic improvements or sensor recalibration—could be authorised without invoking full homologation resets, slowing approval cycles and complicating business-case viability.

Recommendations

- Establish regulators as permanent contributors in early workshops on requirements definition and safety logic interpretation.
- Co-develop certification pathways that clarify evidence expectations, acceptable interpretations, and evaluation milestones.
- Conduct structured alignment sessions between EU, national and regional authorities to harmonise certification expectations and reduce conflicting interpretations.

7.1.3.2 Inter-governmental Alignment

(Policy Consistency, EU–National–Regional Coordination, Homologation Acceleration)

Lesson Learned

Policy consistency across the EU, national and regional levels act as a stabilising force in large-scale migration programmes. When these agendas diverge, the migration pathway becomes fragmented: homologation slows, funding cycles fall out of sync and cross-border interoperability deteriorates. When governance is synchronised—through aligned timelines, regulatory expectations and shared strategic direction—approvals become more predictable and delivery partners face less uncertainty, enabling faster and more coherent implementation.

Gap

EU, national and regional policies were not consistently aligned in timing, scope or regulatory emphasis, creating uncertainty for long-term planning. Homologation processes differed across borders, with varying interpretations of requirements. Cross-border interoperability discussions began too late to harmonise technical and operational assumptions meaningfully. Funding windows and strategic priorities were sometimes misaligned, contributing to delays and fragmented rollout trajectories.

Recommendations

- Establish a structured EU–national–regional coordination forum to align strategy, timelines, and migration expectations.
- Co-develop synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations.
- Align funding cycles with technical migration phases to enable predictable investment and staged deployment.
- Begin interoperability alignment early by holding joint workshops to clarify cross-border assumptions, safety logic and interface expectations.

7.1.3.3 Passenger & Public Trust

Lesson Learned

Automated rail systems depend on public and passenger trust as much as on technical reliability. Even highly robust systems risk rejection if people do not understand how safety logic works or how automation improves their journeys. Clear, accessible communication reduces uncertainty, builds legitimacy and shifts automation from a perceived threat to a recognised societal benefit. Data from the Docklands Light Railway suggests that confidence is enhanced by clear communication about safety and automation roles, as well as by passengers' observation of the system's practical operation. During the GoA3 operation, Passenger Service Agents provided operational assistance and served as a visible reassurance, enhancing oversight and accountability. Trust is cultivated when the public can observe, experience and comprehend the system rather than relying exclusively on technical assurances.

Gap

Communication about the benefits of automation and safety principles was not embedded early in the programme. Technical information was rarely translated into non-expert language, limiting public comprehension. Mechanisms to monitor or respond to public sentiment were limited, and opportunities for demonstrations. These gaps constrained trust-building during the ATO/GOA4 process in the Docklands case study.

Recommendations

- Develop a dedicated communication plan for passengers and the public, explaining safety logic, benefits, and operational changes in accessible terms.
- Use demonstrations, visual explainers, and open events to familiarise the public with ATO/GOA4 behaviour.
- Track trust indicators (public sentiment, feedback, concerns) and integrate them into migration decisions.
- Ensure transparency through periodic public updates, shared performance data, and visible evidence of safety assurance.

7.1.3.4 Community & Local Mobility Actors

Lesson learned

Local mobility actors—municipal authorities, depot operators, infrastructure maintainers and surrounding communities—directly shape the operational feasibility of DATO deployment. Their rules and site conditions determine what can be tested, when access is possible and which safety and disturbance thresholds must be observed. Interview evidence emphasised that involving municipalities and the National Safety Authority not only in formal approval but as on-site observers during demonstrations increased acceptance and clarified safety expectations. Face-to-face engagement and site visits proved helpful in translating abstract plans into shared operational understanding, reinforcing the need to embed local actors early rather than introduce them once technical decisions are fixed. *"It was beneficial to have one train driver as part of the project members, who was from the local area. He knew everyone, had a lot of experience. And he could also address some of the concerns raised. He was our operational person on the train."*

Gap

Engagement with local authorities and mobility actors often began after technical planning, limiting flexibility to adjust test scenarios. Operational constraints (crossings, depot rules, noise limits) were not consistently mapped early, leading to rework and rescheduling.

Municipal expectations regarding safety, disturbance and public perception were not consistently integrated into migration planning. Communication cycles with local actors were irregular, reducing shared situational awareness and slowing approval processes.

Recommendations

- Initiate structured engagement with local authorities at project inception, including workshops to identify depot, crossing and test-field constraints.
- Develop a Local Operational Constraints Map that must be validated and updated with municipal partners before major design or test decisions.
- Establish a continuous communication loop with local actors (biweekly or monthly touchpoints) to maintain shared awareness and rapid issue escalation.
- Co-design test feasibility plans with municipalities to align safety expectations, public communication needs and operational restrictions.

7.1.3.5 Cross-Sector Collaboration

Lesson Learned

Innovation in complex digital-rail programmes progressed most effectively at sector boundaries where operators, regulators, suppliers, technology partners and universities worked in combination rather than isolation. Interview data showed that simulation improvements and testing refinements occurred when academic analysis, industrial tooling and operational constraints were aligned rather than sequential. Collaboration served as a structural mechanism: it prevented duplication, challenged early assumptions with external expertise and enabled international developments to be directly incorporated into operational planning. When this model was present, advances were not limited to a single organisation's capacity but reflected shared knowledge and complementary capability.

Gap

Engagement across sectors was not consistently organised through a dedicated knowledge-integration programme. Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment. A structured collaboration mechanism is therefore required to convert dispersed expertise into coordinated advancement, avoiding reliance on informal exchanges or individual initiative.

Recommendations

- Create a Cross-Sector Innovation Council (CSIC): a standing body linking operators, IMs, OEMs, academia, and technology networks to coordinate innovation agendas and share frontier developments.
- Formalise boundary-innovation workshops: conduct structured workshops to translate advances from adjacent sectors (autonomous vehicles, aviation safety, telecom networks) into rail-specific use cases.
- Adopt joint pilots with external actors: run small-scale co-development demonstrators with research institutes or tech companies to test frontier solutions before full integration.

7.1.4 Discipline and Skills

7.1.4.1 Systems Engineering & Integration

Lesson Learned

DATO integration required sustained, specialised competence across signalling, onboard logic, network configuration, simulation environments and evolving digital subsystems. Interview insights showed that when this expertise was concentrated in only one or two individuals, subsystem teams advanced independently, creating interface gaps that later appeared as integration failures. The parallel introduction of ATO, ETCS upgrades, perception systems and accelerated software cycles further increased the integration load. Under these conditions, systems integration is not a temporary implementation activity but an enduring professional discipline that must remain within the operational organisation to support continuous adaptation over the 30–40-year lifecycle of automated rail systems.

Gap

Systems-integration skills were not systematically retained in-house. Engineering, testing, and integration activities were frequently outsourced during peak phases and associated knowledge departed at contract completion. This loss occurred despite the long operational horizon of ETCS and ATO and the need for recurrent digital updates. Dependence on a small cadre of experts created bottlenecks and repeated upskilling cycles became necessary as external teams left. With AI-supported logic and software updates occurring far faster than rail asset renewal, internal specialist capacity proved insufficient to support continuous system recalibration and integration oversight.

Recommendations

- Establish a formal Systems Integration Team (SIT): a dedicated cross-domain group responsible for architecture coherence, interface definition, configuration control, and release governance.
- Adopt a DevOps-style continuous integration model: introduce incremental sub-releases, enabling frequent, small-scale integration rather than medium-size "integration events."
- Use a unified system configuration baseline: maintain a single, source-controlled architecture map (hardware, network, software) accessible to all partners.
- Institutionalise system-level visibility: require weekly cross-domain integration reviews to monitor impacts across signalling, onboard, network and testing environments.

7.1.4.2 Operational Readiness (Systems Knowledge)

Lesson Learned

Initial DATO progress benefited from the fact that technological components were delivered before full operational preparation, thereby avoiding immediate delivery risks. However, once testing shifted into active railway settings, predictable validation conditions proved difficult to secure. Technical delivery progressed without significant difficulty; however, once testing moved into live traffic conditions, consistent validation became challenging. Dense, mixed-traffic networks prevented repeatable test scenarios, as delays and traffic interactions altered validation conditions on a day-to-day basis. In parallel, ATO performance was highly dependent on the accuracy of the digital register. When mapping data was outdated or incomplete, ATO behaviour degraded, confirming that reliable testing requires continuously updated trackside and TMS data.

Gap

Operational preparation and data quality sometimes did not keep pace with technical deployment. Limited ability to reproduce identical test runs and irregular digital-map updates reduced reliability of test outcomes and complicated performance assessment. Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.

Recommendations

- Co-design test plans with dispatchers and field coordinators to match live network constraints.
- Create a unified integration team covering signalling, onboard systems, traffic management, and testing coordination.
- Use simulation with full operational parameters, including dispatching rules and real traffic behaviour.
- Require interface documentation to state operational dependencies and procedural limits.
- Hold regular operational–engineering alignment reviews to ensure assumptions remain consistent with day-to-day practice.

7.1.4.3 Interpersonal, Negotiation & Soft Skills

Lesson Learned

The interviews demonstrated that communication, facilitation and negotiation capabilities are as influential to progress as technical performance. Instances arose in which partners interpreted the exact requirements differently, not because of system ambiguity but because expectations were not adequately mediated. Complex digital-rail programmes rely on communication practices that accommodate uncertainty and organisational diversity. Insufficient facilitation skills may result in operational errors. Where facilitation was active and negotiation structured, partners articulated assumptions early and disagreement was managed constructively. In these settings, coordination accelerated and technical milestones advanced without obstruction.

Gap

Soft-skill capabilities varied across partners, creating vulnerabilities in tasks that require cross-organisational agreement. Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration. Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.

Recommendations

- Develop a structured negotiation protocol for resolving cross-partner conflicts.
- Require facilitation methods (e.g., joint issue framing, agreement mapping) for all significant disagreements.
- Mandate interpersonal-skills training for task leaders and WP leads.
- Focus on diplomacy, expectation management, active listening and multi-stakeholder facilitation.
- Introduce a formal “alignment session” mechanism before critical milestones. These sessions ensure partners articulate assumptions, constraints and concerns openly.
- Document negotiation outcomes with traceable decision logs. This reduces repeated disagreements and ensures continuity even when personnel change.
- Require issue owners to verify whether the dispute is technical or relational before triggering formal escalation.

7.1.4.4 Data, Software & Testing Competence

Lesson Learned

Stable ATO/GoA4 integration depended on disciplined testing logic, controlled release scope, and uninterrupted access to simulation and validation environments. Incremental deployments allowed clear defect attribution, faster resolution and lower escalation risk. In contrast, multi-component releases increased the likelihood of cascading failures and complicated interface analysis. Reliability was achieved when updates remained narrowly scoped, testing cycles were continuous, and diagnostic learning was supported by consistent access to simulation. Overall, system dependability emerged from frequent, controlled, methodical diagnostic routines.

Gap

Specialised skills in data configuration, software behaviour analysis and validation are sometimes limited and concentrated in a small number of individuals. The programme demonstrated a structural need for dedicated specialists in GoA 4 configuration integrity across simulation and field environments. Lacking this proficiency, processes slowed and it was harder to identify the source of problems. A defined specialist track, supported by continuous training and clear role allocation, is required to ensure sufficient capacity for future automated testing and data-centric verification task.

Recommendations

- Adopt a strict small-increment release strategy. Require that new features or components be introduced in isolated increments to make failures identifiable and manageable.
- Implement mandatory pre-validation of every component before system integration.
- Establish a dedicated system-integration and testing team. Like a DevOps model, this group maintains configuration oversight, supervises test environments and ensures continuity across releases.
- Ensure redundancy for critical simulation and testing infrastructure.
-

7.1.4.5 Leadership & Training Capability

Lesson Learned

Leadership directly influenced cross-team communication and the pace of ATO/GoA4 integration. Teams adapted more effectively when leaders maintained transparent decision-making pathways, enabled open discussion of failures and ensured continuity amid shifting test conditions. Psychological safety allowed operational concerns to surface early rather than in late deployment. As testing cycles accelerated and digital interfaces evolved, training demands emerged rapidly, demonstrating that future operational competence requires data interpretation, oversight of automation and system-interaction skills beyond traditional driving expertise. Leadership that combined clear communication with proactive skill development supported smoother integration and higher trust across testing phases.

Gap

Leadership practices and training provisions were not consistent across teams. Communication during plan adjustments was intermittent, and retrospectives were held irregularly. Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks. Training remained largely reactive with no shared competency framework. These shortcomings reduced organisational confidence, slowed operational alignment and increased hesitation during migration.

Recommendations

- Institutionalise psychological safety practices.
- Require leaders to open meetings with uncertainty statements, encourage dissent and normalise the reporting of issues without penalty.
- Embed structured reflective routines.

- Conduct mandatory retrospectives after every major test, demonstration, or release, documenting lessons and actions.
- Adopt transparent decision-making protocols.
- Develop a forward-looking digital skills framework. Define future competencies for ATO/GoA4 operations, including system integration, data interpretation, testing logic, and automation supervision.
- Begin operator and engineer training during early requirements definition, rather than after system development, to reduce resistance and support faster adoption.
- Create a joint cross-organisational training academy. IM–RU–OEM partners should co-develop simulation-based training to build common situational awareness and technical fluency.

7.1.4.6 Driver & Operator Adaptation Skills

Lesson Learned
Workforce adaptation constituted a critical determinant in the transition to ATO/GoA4. When operators were introduced only after technological decisions had been finalised, uncertainty and resistance increased. Early involvement, coupled with clear role articulation, established confidence and reduced interpretive ambiguity during testing. Integration outcomes were stronger when human factors were embedded directly into design practice, rather than appended at later stages.

Key observations:

- Training initiated after deployment extended adaptation timelines and intensified resistance.
- Explicit clarification of role adjustments provided a stable reference for professional identity within new operational modes.
- Communicating unresolved technical questions openly reduced informal speculation and mistrust.
- Adaptation progressed most effectively when framed as a human-centred transition, not a downstream effect of automation maturity.
- When operators participated in early design and testing, migration proceeded with fewer objections and higher operational confidence.

Gap

Operators were at times engaged only after major requirements and procedures had been set, limiting their influence on operational concepts and reducing readiness. Training occasionally began after technical configurations were fixed, narrowing preparation for supervision and fallback functions. Role definition was not always explicit, creating uncertainty about authority and task boundaries. Communication on unresolved system questions was sporadic, encouraging informal interpretation. Feedback channels existed informally but were not consistently integrated into design cycles. When the human implications of automation were not addressed, resistance surfaced later in testing, slowing acceptance and diminishing confidence in migration processes.

Recommendations

- Engage drivers and operators from the outset. Include them in use-case definition, requirement reviews, and early testing to ensure operational realism.
- Implement clear role-framing protocols. Communicate explicitly how the operator's role will evolve (e.g., supervision tasks, fallback responsibilities).
- Create a human-centric adaptation roadmap. Align technical milestones with workforce adaptation milestones to prevent bottlenecks.
- Establish an operator feedback loop. Use structured interviews, test ride-along sessions and periodic workshops to surface concerns early.
- Communicate uncertainties transparently. Acknowledge what is not yet known to reduce speculation and strengthen trust.

7.2 Lessons learned Delivery Scope & Complexity

7.2.1 Stakeholder involvement

Lesson Learned

Engaging all relevant stakeholders such as operators, suppliers, safety assessors, maintainers, infrastructure managers, and regulators early and consistently throughout the migration and deployment process is essential for aligning expectations and requirements. Early involvement ensures that operational, safety, and maintenance constraints are incorporated upfront, limiting the risk of costly rework and late-stage objections. Successful migration depends on shared ownership, reinforced through structured co-design practices or formal engagement frameworks. Using decision-support tools such as multi-criteria analysis (MCA) helps balance diverse inputs, mitigate bias, and ensure that all perspectives meaningfully influence requirements and design decisions.

Gap

In practice, stakeholder involvement in R2DATO and comparable projects is still fragmented and inconsistent. Access restrictions related to credentials, intellectual property, and siloed organisational processes hinder open coordination. Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements. Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges. This uneven or late engagement causes redesign, resistance in later phases, and inefficient migration planning.

Recommendations

- Engage stakeholders and decision-makers early in the process.
- Implement a structured and transparent stakeholder engagement process from the start of the project, including mandatory early review checkpoints synchronised with key lifecycle milestones.
- Create inclusive forums for continuous collaboration where roadmaps, deliverables, and risks are jointly defined.
- Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.
- Develop governance models that promote open communication while managing confidentiality constraints.
- Ensure documentation of stakeholder inputs and decisions is accessible to strengthen trust and shared accountability.
- Early and sustained alignment significantly improves migration success by limiting redesign and organisational resistance.

7.2.2 Adoption of formal methods

Lesson Learned

Introducing formal methods (FM) and model-based or systems engineering approaches early in the project lifecycle, beginning at tendering, reduces ambiguity, increases precision, and enables automated verification and validation. These methods produce clear, standardised, and harmonised requirements upfront, which are essential for successful migration, especially in multi-vendor and cross border environments.

By creating unambiguous, machine interpretable specifications, FM minimises costly rework caused by misinterpretation among infrastructure managers, suppliers, and integrators. Early clarity strengthens stakeholder alignment and supports modular; scalable architectures needed for efficient migration. Demonstrators and practical use cases are important for proving the benefits of FM and addressing cultural resistance based on misconceptions about complexity.

Gap

Despite clear advantages, formal methods such as model-based systems engineering adoption continues to face cultural and organisational resistance, partly due to the perception that formal methods are overly complex or suitable only for specialists. The railway sector lacks harmonised standards and interoperable tooling across suppliers and operators, complicating model exchange and integration. Although other industries widely apply formal methods, the railway domain has not yet institutionalised comparable practices. Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient. These challenges slow adoption and prevent organisations from realising the full potential of FM in migration projects.

Recommendations

- Position formal methods adoption as a strategic priority starting at tendering and early design phases.
- Develop harmonised, interoperable toolchains supported by clear guidelines.
- Invest in change management programs that include role based training and internal FM champions to shift organisational culture.
- Use demonstrators and pilot projects to provide tangible evidence of benefits and build stakeholder confidence.
- Collaborate with regulatory and safety bodies to establish formal acceptance criteria and integrate FM into certification processes.
- Emphasise modular design and interface specifications aligned with FM principles to support scalable, flexible migration underpinned by trusted validation throughout the lifecycle.

7.2.3 Incremental Certification in Modular Development

Lesson Learned

ATO development increasingly follows iterative and modular approaches that allow components and subsystems to evolve independently and enable incremental deployment strategies. Certification processes, however, often remain monolithic and focused on system level approvals, which is inconsistent with iterative development cycles. As a result, even minor modifications in one component can trigger re-certification of unrelated subsystems, create bottlenecks and slow progress. Certification that mirrors the modular architecture and supports incremental approval pathways simplifies validation and reduces unnecessary delays.

Gap

There is no widely accepted incremental or component level certification framework tailored to ATO systems developed iteratively. Without a consistent modular certification pathway, integration risks build up toward the end of the project. The variety of tools and technologies complicates efficient certification even further. Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges. Certifying every software of system element independently could increase vulnerability by introducing unnecessary fragmentation.

Recommendations

- Establish a structured modular certification route that enables component level approvals and staged integration validation.
- Select and implement a technology stack standardised across projects early in the initiative and pilot certification on smaller representative subsystems to uncover issues early.
- This approach eases the certification of software and tools later in the process since they use the same technology stack.
- Strengthen documentation to clarify certification scopes and eliminate ambiguity.
- Collaborate closely with certification authorities to evolve regulatory processes that acknowledge iterative and modular development practices, reducing time to market and cost while ensuring safety and compliance.
- Clear documentation and shared understanding of certification boundaries also help stakeholders plan and execute migration steps more effectively while minimising rework and delays.

7.2.4 Change management

Lesson Learned

Successful migration to innovative railway technologies and methodologies such as ATO, formal methods, DevOps and modular architectures require significant cultural and organisational change. Resistance often arises from entrenched mindsets, misconceptions (for example, that formal methods are only for experts) and concerns about complexity or cost. Moving from legacy processes and waterfall development to agile (if circumstances allow and require it), modular and formalised approaches demand a readiness mindset and recognition that adjustment takes time and effort. A transitional integration step is often necessary to bridge new methods with legacy practices.

Gap

In practice, change management efforts are often insufficient or fragmented. Leadership engagement is limited, role-specific training is lacking and communication is unclear. Demonstrators to showcase the benefits of new methods are scarce. Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity. Without addressing these human and organisational factors, technical innovations risk poor adoption or underutilisation.

Recommendation

- Invest in dedicated change management strategies that secure leadership buy-in and provide tailored training across roles.
- Leverage pilot projects and demonstrators to demonstrate value and build confidence.
- Enhance the change readiness in companies by encouraging a culture of openness and collaboration.
- Establish clear communication channels and cross-organisational forums to break down silos.
- Implement gradual integration phases that bridge legacy and new systems to mitigate resistance.
- Addressing both culture and technology is essential for sustainable migration and deployment success.

7.3 Lessons Learned Systems Integration

7.3.1 Deliverable Dependencies

Lesson learned

Effective migration and deployment in the complex FP2-R2DATO project depend on the early identification and management of inter-work package deliverable dependencies. Many deliverables across different work packages are tightly interdependent. For instance, WP37's capacity simulations rely on inputs from other WPs, while outputs from the formal methods work packages influence certification efforts affecting multiple WPs. Uncoordinated efforts can cause delays or scope changes in one work package to cascade, impacting others and the overall migration timeline. Parallel workstreams are feasible where possible, but their success requires transparent, structured communication and explicit synchronisation of schedules and deliverables across WPs.

Gap

R2DATO needs to keep working towards a harmonised methodology to model, track and sequence dependencies between deliverables across work packages. Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed. These gaps create risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.

Recommendations

- Continue collaboration and communication across work packages.
- Keep developing and implementing a standardised, project-wide methodology for mapping and sequencing inter-work package deliverables, right from the start.
- Establish centralised tools and communication channels for real-time tracking of dependency status and changes.
- Assign clear responsibility owners for key dependencies to manage and coordinate delivery proactively.
- Support iterative, parallel execution of independent or loosely coupled deliverables.
- Implement systematic monitoring to enable early risk detection and collaboratively define mitigation plans to prevent cascading schedule impacts.
- By fostering disciplined coordination practices, R2DATO can reduce integration risks and ensure smooth migration execution.

7.3.2 Interfaces

Lesson Learned

A key predictor of successful migration and deployment in railway projects such as FP2-R2DATO is the presence of well-defined, stable and contractually owned interfaces between subsystems. Interviews across multiple work packages revealed that incomplete, evolving or ambiguously interpreted interface definitions frequently cause integration failures, schedule delays and disputes. Clear interface boundaries reduce supplier interdependencies, lower integration risks and facilitate component reuse across demonstrators and technologies. Modular system architectures, supported by formal methods, enable well-specified, testable interfaces that underpin interoperability, transparent validation and scalable migration.

Gap

FP2-R2DATO and the broader European railway domain currently lack a harmonised, open interface framework with clear ownership, version control, and change governance. Disparate interface implementations and multiple protocol versions from different suppliers create compatibility issues. The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated integration and delays delivery.

Recommendation

- Develop and institutionalise a European reference that defines standardised, testable interface contracts with explicit ownership, versioning and change management.
- Embed these interfaces as contractual requirements and certify compliance to build stakeholder trust.
- Promote open communication protocols and provide tools and guidelines for interface validation.
- Close collaboration among system integrators, suppliers, infrastructure managers and regulators is essential to align interface standards and enable seamless multi-vendor migration and deployment.

7.3.3 Standards and procedures

Lesson Learned

National requirements, regulatory differences and language barriers present significant challenges in cross-border railway migration projects. Interviews indicated that multilingual teams often experience misinterpretations in technical discussions and subtle nuances in requirements are frequently lost, particularly when interpreters lack domain expertise. These misunderstandings delay development, complicate verification activities and negatively affect design accuracy and quality. Successful migration of complex railway systems requires proactive, structured management of linguistic and regulatory differences to prevent costly misunderstandings and rework.

Gap

Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.

Recommendations

- Engage early with cross-border stakeholders and participate in EU-level regulatory harmonisation efforts to promote consistent requirements interpretation and regulatory alignment.
- Deploy domain-expert translators as needed and establish bilingual documentation standards to ensure clarity.
- Prioritise model-based, executable specifications to minimise ambiguity.

7.3.4 Testing Environments

Lesson Learned

Digital twins, shared simulators, and interface emulators accelerate testing and reduce dependence on limited on-track validation for complex railway systems. By replicating hardware and operational conditions virtually, shared test environments enable early, iterative validation and verification across diverse suppliers and stakeholders. Early testing identifies integration issues sooner, lowering the risk of costly delays and duplicated work. Well-aligned testbeds also promote collaborative development, providing clearer communication of system boundaries and homologation limits.

Gap

The railway domain currently lacks harmonised, cross-organisational digital test environments. This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs. Legacy constraints and intellectual property concerns further complicate the establishment of shared platforms.

Recommendation

- Develop interoperable, accessible shared (ATO) test environments that incorporate realistic digital twins and simulation interfaces.
- Promote cross-stakeholder collaboration on tool standardisation and testing procedures.
- Establish governance and data-sharing agreements to ensure effective use of test environments.
- Leverage demonstrators and pilot projects to validate approaches and build trust.
- Institutionalise shared testbeds as integral components of safe, efficient migration and deployment.
- Establish testable specification (e.g. official reference test systems).

7.3.5 Interoperability

Lesson Learned

Interviewees from multiple work packages highlighted that the wide variety of modelling languages and tools combined with the lack of harmonised data models, causes compatibility issues, misinterpretations, and duplicated efforts among stakeholders. Fragmented tooling and inconsistent technologies hinder seamless model exchange, increase integration risks, and complicate supplier collaboration in ATO development and deployment. Inconsistent data standards, including structures, semantics, and protocols result in unpredictable behaviour when components are shared across organisations or borders.

Gap

No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.

Recommendations

- Develop a baseline for modelling languages and interoperability standards for tools used by all ATO stakeholders.
- Establish an authoritative semantic data model with standardised APIs and rigorous version control.
- Promote early and continuous cross-stakeholder collaboration to evolve and maintain these standards, enabling robust integration across organisations and ensuring future-proof migration paths.

7.4 THREATS TO VALIDITY

Several limitations should be considered when interpreting the findings of this study. First, the analysis relies on qualitative data derived from semi-structured interviews, which reflect participant perceptions and experiences and may be influenced by recall bias, personal positioning or organisational context. Second, the selection of interviewees and demonstrator projects was largely constrained to the Europe's Rail FP2–R2DATO programme, which limits the transferability of the findings to other railway contexts or digital transformation initiatives outside this scope. However, FP2–R2DATO brings together a broad range of key European DATO stakeholders, which supports the relevance of the findings for the European railway context. Third, the analytical process was guided by the D-TRACK framework, which may have shaped the interpretation of data by foregrounding predefined complexity dimensions. To mitigate these limitations, iterative coding, framework alignment, and cross-case pattern identification were applied; nevertheless, the findings should be interpreted as context-dependent insights rather than exhaustive or universally generalisable conclusions.

8 CONCLUSIONS

The aim of Task/Deliverable 33.1 was to gather and consolidate relevant lessons learned from past and ongoing demonstrators and ATO projects and from methodologies for technological migration within FP2-R2DATO in order to inform future migration and deployment efforts.

Objectives were fulfilled as follows:

- Data was collected and analysed from R2DATO demonstrators and ATO projects
- Key lessons learned were extracted from this data
- Identified gaps were translated into recommendations

At the start of the Work Package, the team selected an approach in which data would be collected from the in the Grant Agreement mentioned demonstrators and projects, completed by earlier experience in related projects – projects involving testing and/or implementing (D)ATO technologies, as well as other similar technological migrations in the rail sector. A theoretical framework, D-TRACK, was selected to support a structured approach to data collection and analysis. This framework enabled a systematic examination of complexity-related risks across governance and organisational capability, delivery scope, and systems integration, with a focus on decision-making contexts and interdependencies rather than detailed technical design.

Lessons learned from Demonstrators within R2DATO as well as Betuweroute, DATO related projects in the UK, Australia, The Netherlands and Germany were collected and analysed. Eleven Work Package Leads (Cluster 4 and 6) were interviewed about their experiences leading demonstrators within FP2-R2DATO. Additionally, three programme/project managers with experience in similar programmes outside of ERJU were interviewed, and one chapter summarising lessons learned from previous ATO testing was delivered.

Limitations should be considered when interpreting the findings of this study. The analysis relies on qualitative data, and the selection of cases was defined by the Grant Agreement, meaning that the DATO demonstrator projects within FP2–R2DATO formed the primary focus. Furthermore, the use of the D-TRACK framework for analysing the data may have influenced the interpretation by providing predefined analytical categories. Although iterative coding, framework alignment, and cross-case pattern identification were applied, the findings should be interpreted as context-dependent insights rather than exhaustive or universally generalisable conclusions. At the same time, because FP2-R2DATO brings together a broad range of key European DATO stakeholders, the relevance of the findings for the European railway context is clear.

The findings show that successful DATO migration is primarily shaped by the management of interdependencies among organisations, disciplines, and regulatory environments. The analysis revealed persistent factors contributing to complexity, highlighting the need for sustained stakeholder alignment, clear communication, and decision traceability. It also emphasised the importance of iterative integration and validation methods, alongside shared conceptual and modelling frameworks to support collaboration. Persistent gaps were identified, including limited guidance for cross-organisational and multilingual technical communication, inconsistent alignment of national regulatory frameworks, and insufficient availability of shared testing and validation environments.

Based on these insights, this report recommends strengthening cross-stakeholder alignment mechanisms, developing baseline approaches for modelling languages and interoperability, and promoting shared testing and validation environments to reduce integration risks. Overall, D33.1

concludes that DATO migration should be approached as a system-wide, long-term transformation process. By adopting structured, complexity-aware migration strategies and addressing the identified gaps, railway stakeholders can improve deployment robustness and support the coordinated advancement of automated rail operations across Europe.

As Migration Strategies will also be a part of FP2 in the Second Wave of ERJU, this report together with D33.2 Practical Migration Methods Report, can be used as a foundation for further development. If the D-TRACK framework is selected again in Wave 2 to provide an analytical structure, an additional risk dimension, Strategic and Political Complexity, could be incorporated into the scope.

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