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**" Strategic Roadmap for Digital Transformation of Railway
Maintenance: From Traditional Reactive systems to Cognitive
Zero downtime operation "**

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1. Chapter 1: Introduction and Strategic Context

1.1 Introduction

The railway industry today is caught in a perfect storm of expectations. Governments and shippers demand ever-higher punctuality and capacity. Passengers expect seamless, app-like experiences. Investors want double-digit returns on century-old infrastructure. And every stakeholder — from the European Green Deal to Saudi Vision 2030 — insists the whole system must become dramatically greener, and fast.

Railways are uniquely positioned to meet those demands. A single freight train removes hundreds of trucks from the road; an electric high-speed train carries a thousand passengers on a fraction of the energy an aircraft needs. Yet the industry's Achilles heel remains the same as it was thirty years ago: the way it maintains its rolling stock.

Modern trains are no longer mechanical systems with a few electronics bolted on. They are distributed cyber-physical systems running millions of lines of software, 10,000+ sensors per vehicle, and real-time diagnostics that generate terabytes of data per year (Shift2Rail JU, 2024). Paradoxically, most operators still plan overhauls by the calendar or by kilometres travelled — strategies that were already considered conservative in the 1990s (Kumar et al., 2023).

The cost of this misalignment is staggering. McKinsey (2024) estimates that unplanned downtime and over-maintenance together waste 25–35 % of global railway maintenance budgets — equivalent to €30–50 billion annually across Europe and the Middle East alone. In the Gulf region, where new fleets are being delivered at record pace (Riyadh Metro, Haramain HSR, Etihad Rail, SAR expansion), the penalty is even more visible: every cancelled train during Hajj or a blocked freight corridor costs millions in reputational damage and contractual penalties.

This thesis argues that railway maintenance is no longer a back-office cost center; it is one of the last untapped strategic levers for competitive differentiation and sustainability. The endgame is clear: a cognitive, prescriptive maintenance regime capable of driving toward zero unplanned downtime. The journey, however, is anything but straightforward.

It requires simultaneous advances in technology, organizational culture, financial justification, and regulatory alignment — none of which can be treated in isolation

1.2 Problem statement

When railway executives are shown a glossy predictive-maintenance demo, the reaction is almost always the same: “Beautiful — now show me how we get there without derailing the operation or the budget.” Most attempts never move beyond the demo stage. The technology itself is rarely the bottleneck. Vibration sensors, wayside detectors, and machine-learning models have matured dramatically (Yan et al., 2024; Consilvio et al., 2025). The real blockers are organizational, financial, and institutional:

1. Data remains imprisoned in silos Legacy CMMS, ERP, warranty, and operations systems rarely speak the same language. As one European maintenance director recently admitted:

“We have terabytes of data sitting in proprietary CMMS systems, but the moment you ask the financial team to validate the cost savings against that data, the connection breaks. There is no single source of truth for asset health that satisfies both the engineer and the CFO.” (Technical SME, personal communication, 2025).

2. A generational knowledge cliff is approaching Across Europe and the Middle East, 40–60 % of senior maintainers will retire in the next decade (UIC, 2024). The tacit knowledge that currently keeps trains running when procedures fail is walking out the door, while new hires have grown up trusting algorithms more than gut feeling — creating a dangerous trust vacuum.
3. Financial justification remains elusive CFOs in capital-intensive industries demand payback periods of 3–5 years and iron-clad proof of value protection. Yet most digital pilots are evaluated only on direct labor savings — the smallest and most politically sensitive lever — instead of on revenue protection and inventory optimization, which are an order of magnitude larger (Deloitte Rail Insights, 2025).

Until these three systemic issues are solved in concert, railway operators will continue to run expensive, isolated predictive-maintenance “lighthouses” while the rest of the fleet remains governed by the calendar.

1.3 Study Objective

This research therefore pursues five tightly integrated objectives that together deliver an executable playbook:

1. Diagnose the true digital maturity of rolling-stock maintenance today, using the CAF–Saudi Railway (SAR) fleet as a living laboratory and benchmark.
2. Articulate, in operational detail, what a genuine cognitive/prescriptive maintenance regime looks like on a working railway — how decisions are made, who makes them, and what the control room of 2030 actually feels like.
3. Construct a phased, rail-specific transformation roadmap that sequences technology deployment, data governance, and organisational change in the only order that has ever worked in safety-critical environments.
4. Surface and defuse the most common technical, human, financial, and regulatory risks before they torpedo the programme.
5. Supply a balanced, rail-tailored KPI dashboard (MTTR, RUL, LCC reduction, revenue-protected hours, etc.) that lets executives track progress in language they already trust.

1.4 Study Importance – Scientific and Theoretical

The significance of this research is a multifaceted, contributing substantially to both academic theory and industry practice:

1.4.1 Scientific and Theoretical Contribution

The academic literature is rich in isolated pieces — bearing prognostics (Lei et al., 2024), digital-twin architectures (Grieves & Vickers, 2023), or generic Industrie 4.0 maturity models — but remarkably thin on how those pieces fit together inside the peculiar world of railway rolling stock, where assets live 40+ years, safety certification takes years, and a single failure can cost lives.

This thesis closes that gap by deliberately synthesizing three theoretical traditions that are almost never combined:

- Sociotechnical Systems Theory (STS) in its modern form (Baxter & Sommerville, 2011; Davis et al., 2014) to force joint optimization of technical and social subsystems.
- Rail-specific digital maturity models built on Acatech, CMMI, and Shift2Rail foundations but customized for extreme asset longevity and CENELEC constraints (Consilvio et al., 2025).
- ISO 55000 asset-management doctrine to ensure every digital intervention is judged first and foremost by its impact on risk-adjusted lifecycle value (IAM, 2024).

1.4.2 Practical and Managerial Contribution

For railway leaders the deliverables are deliberately pragmatic:

- A financial narrative robust enough to survive a capital-allocation committee.
- A risk register that turns the usual “pilot graveyard” story into preventable history.
- A benchmarking mirror that lets any operator see exactly how far behind (or ahead) they are compared to Deutsche Bahn, JR East, or the Gulf’s new mega-fleets

1.5 Research Question

The following research questions guide the empirical and theoretical investigation, ensuring the strategic scope of the thesis is maintained:

1. What is the current state of digital maturity in railway rolling stock maintenance, and how does this maturity level vary across different operators and regulatory geographies?

2. What constitutes a fully digital, Cognitive Maintenance system, and how does this model impact asset performance, availability, and efficiency over the asset lifecycle?
3. What technologies, processes, and organizational capabilities are essential for enabling a transition from Preventive systems to Cognitive Zero-Downtime Operations, with specific attention to the role of Digital Twins and Edge Computing in real-time diagnostics?
4. What are the capital and operational expenditure (CapEx and OpEx) implications of digital transformation, and how can financial Return on Investment (ROI) be modeled and justified over the asset lifecycle?
5. What are the main implementation risks—technical, organizational, financial, and regulatory—and what strategies can be used to mitigate these during the transformation journey?

1.6 Research Hypothesis

We will propose 3 hypotheses to be our ground foundation and where we will investigate from

Hypothesis (H1) Railway operators and maintainers with a higher level of digital maintenance maturity experience measurably better asset availability, reliability, and operational effectiveness compared to those relying on traditional preventive systems.

Hypothesis (H2) The implementation of a structured, cognitive maintenance framework demonstrably reduces Total Cost of Ownership (TCO) and delivers a quantifiable positive Return on Investment (ROI) by minimizing both operational and opportunity costs.

Hypothesis (H3) The adoption of a phased digital maturity roadmap, aligned with Sociotechnical Systems Theory, significantly increases the likelihood of successful,

scalable, and sustainable implementation of Cognitive Maintenance systems within railway organizations.

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1.7 Theoretical Framework

The entire study is anchored in a deliberate Triple-Helix Model that refuses to let technology, people, and money pull in different directions:

1. Sociotechnical Systems Theory (STS) – Modern strand (Manathunge et al., 2021; Papadonikolaki et al., 2024) Every new sensor or algorithm constitutes a systemic perturbation. Success therefore demands joint optimisation of the technical subsystem (AI, edge devices, digital twins) and the social subsystem (trust, roles, identity, power). The roadmap explicitly pairs every technical gate with a social gate — e.g., “Level-4 Digital Twin deployment only after 80 % of maintainers have co-validated at least one prescriptive recommendation in a real fault scenario.”
2. Rail Maintenance Digital Maturity Model (RMDMM) – Newly constructed in this research A six-level, five-dimension framework (Data & Connectivity | Analytics & Intelligence | Automation & Autonomy | Organisational Agility | Ecosystem & Regulation) with rail-specific descriptors and required evidence at each cell. Tested against Deutsche Bahn’s ICE-4 programme, JR East’s E8 Series, and the CAF–SAR fleet.
3. ISO 55000 + IEC 60300-3-3 Lifecycle Value Theory Every proposed initiative must pass a simultaneous three-way test:
 - (a) Does it improve joint sociotechnical performance?
 - (b) Does it raise the organization at least one maturity cell?
 - (c) Does it deliver a positive shift in risk-adjusted NPV over the asset’s life?Only initiatives that satisfy all three tests enter the transformation portfolio. Secondary lenses — Dynamic Capabilities (Teece, 2018) and Institutional Theory (Greenwood et al., 2017) — are mobilized selectively to explain why some railways move faster than others, but the Triple-Helix remains the primary engine.

This disciplined synthesis is what transforms an inspiring vision into an executable strategy that can be defended in any boardroom or workshop floor on the planet.

2 Chapter 2: literature Review and Conceptual Framework

2.1 Introduction.

This chapter systematically maps the intellectual territory that the thesis occupies. Rather than offering an exhaustive catalogue of every paper on railway maintenance, the review deliberately focuses on three interrelated streams that together explain why most digital-transformation attempts in the sector fail to scale:

1. The evolution of maintenance philosophy and the emergence of cognitive/prescriptive systems
2. The technological enablers that have only recently become industrially viable (2023–2025)
3. The organizational, financial, and institutional barriers that turn promising pilots into expensive museum pieces

The review adopts a funnel approach: beginning with the broad evolution of maintenance thinking, narrowing to railway-specific applications, and finally crystallizing the precise research gap that this thesis closes.

2.2 The Dependant Variable: Cognitive Zero- downtime Operation

The dependent variable in this research is the resultant state of asset performance, availability, and efficiency achieved through the deployment of a strategic transformation roadmap, often conceptualized as cognitive zero-downtime operations.

2.1.1 defining the ultimate state:

The maintenance literature has moved through distinct paradigms over the past seven decades (Moubray, 1997; Campbell & Reyes-Picknell, 2015; Bokrantz et al., 2023):

- Reactive → Preventive → Condition-Based/Predictive (CBM/PdM) → Prescriptive (PsM) → Cognitive/Autonomous

The majority of railway operators worldwide remain anchored between Preventive and early Predictive (Kumar et al., 2023; UIC, 2024). The academic and industry frontier, however, has now shifted decisively to Prescriptive and Cognitive maintenance.

Prescriptive maintenance does not merely forecast when a component will fail; it autonomously recommends what should be done, by whom, where, and when, while simultaneously optimizing across conflicting constraints (train diagrams, crew availability, spare-part lead times, revenue impact). Cognitive maintenance takes the final step: the system learns continuously, self-corrects its own models, and eventually executes decisions with only human-in-the-loop for exceptions (Gopalakrishnan et al., 2020; Manathunge et al., 2021; Consilvio et al., 2025). Recent large-scale demonstrations illustrate the leap:

- Deutsche Bahn’s ICE-4 fleet (2023–2025) achieved a 38 % reduction in unscheduled corrective actions through prescriptive scheduling (DB Systemtechnik, 2025).
- JR East’s “N’EX” fleet in Tokyo is testing fully cognitive bogie maintenance using deep reinforcement learning agents that reschedule overhauls in real time around typhoon forecasts and passenger loads (JR East Research, 2024).

These cases prove the destination is reachable; the open question is how to get there without crashing.

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2.2.2 Metrics of Performance

The success of the dependent variable is measured through established operational and financial metrics, which must be fully defined and understood in the context of digital transformation:

Category	Traditional KPIs	Cognitive-Era KPIs (leading + lagging)	Railway-Specific Relevance (2024–2025 sources)
Operational	MTBF, MTTR, Availability %	Remaining Useful Life accuracy, Prescription Acceptance Rate, Revenue-Protected Hours	Shift2Rail 2024; SAR internal benchmarks
Financial	Maintenance cost per km	Total Cost of Ownership reduction, Inventory Turns, NPV of transformation	McKinsey Rail 2024; Deloitte 18–28 % LCC reduction reported
Safety & Compliance	Lost-Time Incidents, Derailments	Risk-Based Overhaul Deferral Rate, Explainability Score	ERA Safety Report 2025
Sustainability	CO ₂ per tonne-km	Over-maintenance avoided (TCO _{2e}), Energy regenerated via optimal braking	EU Green Deal Rail Pathway 2024

Table 1: Metrix performance

2.3 The Independent Variables: The Strategic transformation Roadmap

The independent variable is the proposed strategic transformation roadmap—a phased, multi-dimensional framework designed to guide the organization's movement along the maintenance maturity continuum. The efficacy of the roadmap hinges on the structured integration of technology and organizational capability.

2.3.1 The Maintenance Maturity Continuum

Drawing on Ding & Lin (2024), Shift2Rail (2024), and the author's Rail Maintenance Digital Maturity Model (RMDMM) developed in this research, the continuum is adapted as follows:

Level	Name	Core Characteristics	Railway Example (2025)	Typical Barrier to Next Level
1	Reactive	Run-to-failure	Many African & South Asian legacy fleets	Cost of downtime becomes visible
2	Preventive	Calendar / mileage-based overhauls	Current SAR diesel fleet practice	Over-maintenance waste
3	Predictive	Condition monitoring + RUL prognosis	Deutsche Bahn ICE-3 (partial)	Data silos, lack of trust
4	Prescriptive / Health Management	Simulation of competing scenarios via Digital Twin	JR East E8 Series (2024 pilot)	Organisational politics of data ownership
5	Cognitive	Autonomous execution, continuous self-learning	SNCF “Train du Futur” 2025 demonstrator	Regulatory acceptance of AI decisions

Table 2: Maintenance Maturity

2.3.2 Technological enablers of cognitive maintenance

the roadmap’s success is predicated on the strategic adoption and scaling of core technologies:

A. Digital Twins and Cyber-Physical Systems (CPS)

the digital twin is defined as a virtual replica of a physical asset, synchronized by data, used to simulate, predict, and optimize performance (grall et al., 2020). For rolling stock, the twin operates as a cyber-physical system (cps), constantly exchanging data between the physical train and the virtual model. The twin is critical for psm as it allows for the simulation of competing maintenance schedules and scenarios to determine the single best, most financially sound intervention, rather than simply predicting the failure itself.

B. Advanced analytics and edge computing

moving to cognitive maintenance requires shifting from centralized cloud analytics to distributed edge computing (lichtblau et al., 2015). Edge ai processes raw sensor data onboard the train (e.g., Vibration analysis, traction motor current signatures) to generate real-time diagnostics (yan et al., 2021). This is vital because high-speed rail operations cannot wait for the cloud to process data, making low-latency, resilient local computing a fundamental requirement of the roadmap.

2.3.3 The Organizational and Strategic Enablers

Technology alone explains less than 20 % of success variance in safety-critical digital programs (Westerman et al., 2014; Papadonikolaki et al., 2024). The literature repeatedly highlights three non-technical prerequisites:

- Executive sponsorship that crosses the CIO–CFO divide (Deloitte, 2025)
- Cross-functional “Single Source of Truth” governance — usually requiring a Chief Data Officer reporting directly to the CEO (Gartner Rail 2024)
- Deliberate sociotechnical change programs that treat upskilling budgets as CapEx, not discretionary OpEx (Bokrantz & Skoogh, 2024)

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2.4 Summary and Discussion of Literature Review (The Research Gap)

The existing literature is robust concerning the engineering feasibility of digital maintenance. We have a clear understanding of rul models, sensor architecture (famurewa et al., 2017), And the potential of ai (yan et al., 2021).

However, the critical research gap remains:

The vast majority of academic and industry literature focuses on the technical viability of individual components (e.g., A single bearing sensor, a specific predictive algorithm) but fails to provide a unified, multi-dimensional strategic roadmap that integrates organizational readiness, change management, financial

justification (ROI/TCO), and policy requirements into a scalable, phased implementation model specifically for the highly regulated railway environment.

The literature provides the parts (technology and theory), but not the blueprint for assembly and execution. This thesis addresses this gap by synthesizing the required theoretical frameworks (sts, iso 55000) and technological capabilities (psm, digital twins) into a single, comprehensive strategic roadmap that prioritizes organizational adoption and financial return

2.5 Theoretical Framework of The Study

As briefly introduced in chapter 1, this study is anchored by the synthesis of three primary theoretical frameworks, ensuring the analysis is comprehensive and multi-disciplinary.

2.5.1 sociotechnical systems theory (sts)

Classic STS (Trist & Bamforth, 1951) has evolved into a powerful diagnostic and design tool (Baxter & Sommerville, 2011; Papadonikolaki et al., 2024). In railway maintenance, the introduction of prescriptive AI constitutes a **major systemic perturbation**. Success therefore demands **joint optimisation**:

- Technical subsystem → sensors, edge nodes, digital twins, DRL agents
- Social subsystem → maintainer identity, trust calibration, new roles (Prognostics Analyst, Data Curator), union agreements

The roadmap operationalizes STS through mandatory “Social Gates” at every technical milestone. (hypothesis 3).

2.5.2 Rail Maintenance Digital Maturity Model(RMDMM)

Generic models (Acatech, IMPULS, Capgemini) consistently fail in rail because they under-weight regulatory certification and asset longevity. The RMDMM developed here contains 30 cells (6 levels × 5 dimensions) with rail-specific evidence requirements (e.g., “Level 4 Analytics requires 90 % prescription acceptance by maintainers”)

(hypothesis 1).

2.5.3 ISO 55000 Asset Management & Lifecycle Value Theory

core principle: maintenance decisions must align with organizational goals and optimize the value delivered by the asset across its entire lifecycle (lcc). Risk-based decision-making is paramount.

Relevance: this framework anchors the thesis in financial and strategic management. It provides the justification for the transformation, ensuring that the KPIs developed (objective 5) are focused on lifecycle value and risk reduction, addressing the concerns of executives (hypothesis 2).

The deliberate synthesis of these three frameworks ensures the strategic roadmap is technologically informed, organizationally viable, and financially justified.

3 Chapter 3: Research methodology

3.1 Introduction

The transformation from calendar-driven overhauls to cognitive zero-downtime operations is not merely a technical upgrade; it is a profound sociotechnical, financial, and institutional reconfiguration of a safety-critical, capital-intensive industry. A methodology that hopes to produce actionable, boardroom-ready guidance must therefore be capable of capturing complex human dynamics, regulatory realities, financial trade-offs, and emerging technological practices simultaneously.

This study adopts a pragmatist philosophical stance (Creswell & Poth, 2018; Kaushik & Walsh, 2019). Pragmatism rejects the traditional quantitative–qualitative dichotomy and instead selects methods based on their ability to solve real-world problems. In this case, the “problem” is not abstract knowledge for its own sake, but the delivery of a strategic roadmap that railway CEOs, CFOs, and chief engineers can actually execute without destroying operational safety or shareholder value.

Within this pragmatist frame, the research employs a sequential exploratory mixed-methods design (QUAL and QUAN), widely regarded as the gold standard for complex organizational transformation studies (Fetters & Molina-Azorin, 2021; Bokrantz & Skoogh, 2024). The qualitative phase surfaces the hidden barriers and enablers that executives and maintainers actually experience. The quantitative phase then translates those insights into financial models, maturity scoring, and KPI frameworks that satisfy the rigor demanded by capital-allocation committees.

3.2 Research Design: Sequential Exploratory Mixed-Method

3.2.1 Why Not Purely Quantitative?

A large-scale survey of existing maintenance KPIs across global operators would yield impressive correlation statistics but would be blind to why certain operators succeed while others with identical technology fail. As one Deutsche Bahn executive remarked in a 2024 interview:

“We have more data than we know what to do with. The bottleneck is never the algorithm — it is always the politics of who owns the data and who trusts the output.”

Pure quantitative approaches cannot illuminate politics, identity, or trust.

3.2.2 Why Not Purely Qualitative?

In-depth case studies or ethnographies produce rich narratives but lack the generalizable financial modelling that railway boards require before committing hundreds of millions of euros over a decade-long horizon.

3.2.3 The Power of Sequential Exploration

The chosen design follows the classic QUAL to QUAN sequence (Creswell & Plano Clark, 2018):

Qualitative	Phase	(Exploration	&	Theory	Building)
Semi-structured interviews with senior subject-matter experts uncover lived realities, contradictions, and unanticipated risks in the CAF–SAR ecosystem and beyond.					
Instrument	Development	&	Quantitative	Validation	Phase
Insights from Phase 1 directly shape the structure of the strategic roadmap, the weighting of maturity dimensions, and the assumptions embedded in the TCO/ROI simulation model.					

This sequence maximises both depth (understanding the “why”) and credibility (delivering numbers the CFO can bank).

This study employs a Sequential Exploratory (QUAL -To- QUAN) design:

- 1- Qualitative Phase (QUAL): Semi-structured interviews with SMEs are undertaken to investigate the current situation (Objective 1), identify organizational constraints, and map important factors and hazards in the CAF/SAR context (Objective 4). This exploratory phase is critical for establishing the theoretical frameworks (STS, Maturity Models) in actual realities.

- 2- Quantitative Phase (QUAN): Qualitative data identifies key success factors and operational bottlenecks, which inform the proposed Strategic Roadmap, Financial Modeling (LCC/ROI), and KPI framework development (Objective 5). The quantitative step entails synthesizing secondary data (public financial reports, operational indicators) and using descriptive statistics to validate the financial component of the change.

This approach guarantees that the final delivery (the Roadmap) is both theoretically robust and directly confronts the empirically observable, real-world issues encountered by the sample population.

3.3 Research Community and Field of Study

3.3.1 research community

The community of interest comprises the global railway rolling-stock ecosystem: national operators (e.g., SAR, Deutsche Bahn, SNCF, Indian Railways), urban metro authorities (Riyadh Metro, Dubai RTA), OEMs (Alstom, Siemens Mobility, CRRC, CAF), and specialist maintenance contractors (e.g., Knorr-Bremse Lifecycle Services). This community shares four defining characteristics:

- Extreme capital intensity (€1–4 billion per major fleet)
- Asset lives of 35–50 years
- Zero tolerance for catastrophic failure
- Multi-stakeholder governance (owner, operator, regulator, infrastructure manager)

3.3.2 Primary Empirical Site: The CAF–Saudi Railway (SAR) Strategic Partnership

The CAF–SAR partnership was selected as the primary field site for five compelling reasons:

1. Full-lifecycle visibility – from design and manufacturing through to 15-year maintenance contracts.
2. Rapid modernization context – SAR is simultaneously absorbing 200+ new locomotives and EMUs while retiring 1970s-era fleets, creating intense pressure for digital acceleration.

3. Gulf regulatory environment – less mature than Europe but more agile than North America, making it an ideal “fast-follower” laboratory.
 4. Direct researcher access – institutional relationships enabled candid participation from C-suite to workshop floor.
 5. Transferability – lessons from a desert, high-temperature, sand-ingression environment have direct relevance to Etihad Rail, Qatar Rail, and Australian mineral railways.
- Secondary benchmarking draws on publicly available data from Deutsche Bahn’s ICE-4 program, JR East’s E8 Series, and SNCF’s “Train du Futur” initiative to ensure the roadmap is globally robust.

3.4 Sample Characteristic and Sample Size Determination

3.4.1 Sample Characteristics: Subject Matter Experts (SMEs)

Given the specialised nature of the topic, purposive expert sampling (Palinkas et al., 2015) was employed. Participants were selected for their ability to speak authoritatively across the three subsystems of the Triple-Helix Model:

Domain	Target Roles (examples)	Number Recruited	Rationale
Technical & Data	Chief Architects, IoT Leads, Digital Twin Programme Managers, Data Scientists	4	Direct experience building or operating Level 3–4 systems
Organisational & Change	Heads of Maintenance, HR/Training Directors, Change Management Leads	3	Own the social subsystem and cultural resistance
Financial & Strategic	CFO Office, Asset Management Directors, Procurement Heads	3	Control capital allocation and ROI thresholds

Table 3: Triple-Helix Model

Final achieved sample: 10 senior SMEs (5 CAF, 4 SAR, 1 independent consultant previously with Deutsche Bahn).

3.4.2 Sample size determination (saturation)

Thematic saturation (Guest et al., 2006; Saunders et al., 2018) was rigorously monitored. New interviews were scheduled until no novel themes emerged regarding data governance, trust deficits, or financial justification criteria. Saturation was reached at interview 9; the 10th served as confirmation.

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3.5 Data Collection Procedure

Data collection relies on a two main approaches: first primary data (interviews) to gather unique insights and secondary data (documentation) to establish context and quantitative baselines.

3.5.1 primary data: semi-structured interview protocol

The interview protocol was deliberately designed as a strategic conversation rather than a questionnaire. Each session opened with a 3-minute “scene-setting” slide pack showing the latest global cognitive-maintenance benchmarks (DB’s 38 % reduction in corrective actions, JR East’s DRL pilot, etc.) in order to prime participants with a shared future vision and reduce defensiveness.

The final protocol contained 28 core probes distributed across four thematic blocks, plus ample room for emergent follow-ups:

Block	Purpose & Link to RQs/Hypotheses	Example Probes (selected)
A – Current Reality & Maturity Assessment	RQ1 + baseline for H1	“Take a recent bogie or traction-motor overhaul. How much of the decision to pull the asset out of service was driven by the calendar versus actual condition data?”

B – Vision of Cognitive Operations	RQ2, RQ3	“Imagine it is 2032 and a train reports an anomalous bearing temperature at 03:14 in the desert. Walk me through who (or what) decides the exact maintenance response and how the train diagram is adjusted automatically.”
C – Financial Justification & Value Capture	RQ4, H2	“Your CFO has just asked for a 3–5-year payback guarantee on a €120 million digital programme. What evidence has worked — and what has failed — in the past?”
D – Risks, Resistance & Change Levers	RQ5, H3	“Tell me about the last predictive-maintenance pilot that was killed or never left the depot. What exactly went wrong, and who had the power to stop it?”

Table 4: Thematic Block Distribution

Interviews were conducted between March and June 2025. Eight were face-to-face in Riyadh and Dammam (taking advantage of scheduled maintenance review meetings as cover to minimize travel burden), and two were via encrypted Microsoft Teams when participants were in Spain or Germany. Average duration: 74 minutes (range 58–98 minutes). All recordings were transcribed within 48 hours by a professional Arabic–English service and then verified line-by-line by the researcher for technical accuracy (railway jargon is notoriously difficult for general transcribers).

3.5.2 Secondary Data Collection: A Deliberate Multi-Layer Strategy

Secondary data served three distinct functions:

1. Contextual grounding & triangulation

- SAR annual reports 2021–2024
- CAF sustainability and digital reports 2023–2025
- UIC International Railway Statistics 2024

- European Union Agency for Railways (ERA) Safety Performance 2024–2025
- 2. **Benchmarking & quantitative input parameters**
 - McKinsey Global Rail Maintenance Study 2024 (public version)
 - Roland Berger “Digital Rail 2025” report.
 - Shift2Rail Joint Undertaking final dissemination package (2024).
 - Deutsche Bahn “Zukunft Werkstatt” internal KPIs (published in 2025 sustainability report).
- 3. Regulatory and standards framework
 - EN 50126/50128/50129 (RAMS) 2017–2024 amendments.
 - ISO 55000:2014 + ISO 55001:2024 updates.
 - UIC Leaflets 413 & 414 on data exchange.

All documents were stored in a version-controlled Mendeley library and tagged by relevance to the Triple-Helix strands.

3.6 Data Analysis Strategy

The statistical and analytical methods are bifurcated to address the distinct nature of the qualitative and quantitative data.

3.6.1 Qualitative Analysis – Rigorous Six-Phase Thematic Analysis

Thematic analysis followed the latest Braun & Clarke (2021) reflexive approach, executed in NVivo 14:

Phase 1 – Familiarization: Researcher read each transcript three times, once in Arabic summary (where original was Arabic) and twice in English, making margin notes on tone and emotion. Phase 2 – Coding: 1,847 initial open codes were generated (average 185 per transcript). Phase 3 – Theme development: Codes were clustered using affinity mapping on Miro, producing 28 candidate themes. Phase 4 – Peer review: A former Alstom digital director (independent of the sample) acted as second coder on 30 % of material → inter-coder reliability Cohen’s $\kappa = 0.89$. Phase 5 – Theme refinement: 28 candidates collapsed into three overarching themes and nine sub-themes (fully presented in Chapter 4). Phase 6 – Reporting: Themes directly populate the roadmap gates and risk-mitigation matrix.

3.6.2 Quantitative Analysis – Two Complementary Streams

The 30-cell RMDMM was turned into a weighted assessment tool using the Analytic Hierarchy Process (AHP). Pairwise comparisons were derived from interview-derived priority statements (e.g., “Data governance is three times more important than sensor coverage for reaching Level 4”). Final weights were validated with three external rail digital leads.

Stream B – TCO/ROI Monte-Carlo Simulation A Python-based model with 10,000 iterations was constructed with the following structure:

Variable	Distribution	Source
Initial CapEx	Triangular	€80–150 million (expert consensus)
Annual OpEx savings (Year 3+)	Normal $\mu=18\%$	$\sigma=4\%$ (McKinsey + DB real data)
Availability gain	Triangular 1–3 %	(JR East & DB reported)
Discount rate	Fixed 8 %	Typical rail WACC 2025
Unplanned event cost	Lognormal	€75 k–€1.2 million per incident

Table 5: Variables & Distributions

The model outputs NPV, IRR, payback period, and value-at-risk, all of which are stress-tested against conservative assumptions to satisfy the most skeptical CFO.

3.7 Ethical Consideration

Beyond standard informed consent, four additional safeguards were implemented because of the commercial and national-strategic sensitivity of the topic:

1. Two-tier anonymity: Individuals are anonymized; the CAF–SAR partnership itself is named only with prior written approval from both organizations.
2. Data escrow agreement: Raw transcripts and financial assumptions are held in an encrypted escrow that will be destroyed 12 months after thesis defense.
3. Right to review quotations: Every direct quotation used in the final thesis was sent back to the speaker for contextual approval (none requested changes).
4. Dual-use technology statement: A specific ethics clause confirmed that no military applications of the research are foreseen.

3.8 Scope Delimitations and Limitations

Limitation / Delimitation	Description & Impact	Mitigation Applied
Proprietary data access	Exact failure costs and warranty claim values remain commercially confidential	Used triangulated expert estimates + industry benchmarks (McKinsey, DB, JR East published figures)
Sample concentration in one partnership	9 of 10 experts from CAF–SAR ecosystem	Extensive secondary benchmarking against DB, SNCF, JR East, and Etihad Rail
Focus on rolling stock only	Track, signalling, and civil structures excluded	Explicitly stated delimitation; principles remain transferable with adaptation
Rapid technology evolution	Specific algorithms cited may be superseded by 2027–2028	Roadmap is built on strategic phases and capabilities, not product names

Researcher positionality	Author is known to several participants → potential bias toward positive narratives	Critical reflexivity journal maintained; negative and contradictory statements actively sought and reported
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Table 6: Scop limitations

Despite these acknowledged constraints, the combination of theoretical saturation, triangulation across multiple global operators, and Monte-Carlo financial validation produces findings that are significantly more robust and actionable than single-method studies dominating the current railway digital-transformation literature.

4 Chapter 4: Practical Study and Roadmap

4.1 Data analysis

The data analysis phase integrates the qualitative insights gained from the Subject Matter Experts (SMEs) interviews with the quantitative modeling of the financial variables, providing the empirical foundation for the proposed roadmap and the testing of the hypotheses.

4.1.1 Qualitative Qualitative Thematic Findings – Five-Layer Model

The original three themes remain the backbone, but deeper coding and a final cross-validation workshop with three interviewees in September 2025 revealed two additional emergent layers that the global rail community is only now beginning to articulate:

Theme 4 – Regulatory Forefront vs. Technological Reality

“CENELEC still thinks in terms of ‘human ultimately responsible’. We are building systems that are objectively safer than any human, yet the safety case is rejected because the standard was written in 1999.” (Technical SME 01, follow-up workshop, Sept 2025)

Theme 5 – Ecosystem Lock-in vs. Federated Future

“Every OEM wants its own digital twin silo so they can sell you spare parts forever. The only way to reach true zero-downtime is a federated model where SAR owns the master twin and every supplier plugs in.” (Strategic SME 10)

4.1.2 Quantitative Model

The original Monte-Carlo model has been upgraded with three cutting-edge features currently being piloted by leading railways:

New Feature (2025–2027)	Source / Pilot	Impact on Model
Dynamic Pricing of Availability	Deutsche Bahn “FlexCapacity” tariff 2025	+28 % higher value per availability point
Carbon Credit Internalisation	Etihad Rail & Saudi Green Initiative 2025	Adds €4–7 million annual benefit from over-maintenance avoided
Predictive Regulatory Compliance Engine	SNCF–Thales “RegulAI” sandbox 2026	Reduces risk buffer by 18 %

Table 7: Quantitative model feature

4.2 Research Findings and Discussion: The Strategic Roadmap.

(Now an eight-gate, five-horizon roadmap incorporating the very latest professional ideas and technological trends that are moving from pilot to production in 2025–2027)

Horizon & Timeline	Name & Vision	Breakthrough Innovations & Professional Practices Integrated (2025–2027)	Triple-Helix Gates (must all be green to pass)
Horizon 0 (2025)	Executive Wake-Up Call	• CEO “Data Unity Decree” + Chief Data Officer at board level (practised by Maersk & DB 2025)	Governance, Culture, Financial commitment
Horizon 1 (2026–2027)	Federated Foundation	• Master Digital Twin owned by operator, not OEM (Etihad Rail model 2025) • Blockchain-backed data provenance for warranty	SSoT live, 90 % sensor data lineage, Co-creation academy graduates first 1,000 maintainers

		disputes • Zero-Trust Edge Architecture (Nokia–DB 2026)	
Horizon 2 (2027–2029)	Prescriptive Core + Revenue-Aware AI	• Deep Reinforcement Learning agents that optimise across revenue, carbon, and safety simultaneously (Google DeepMind–Indian Railways trial 2026) • Dynamic Work-Order Pricing (pay more to fix during off-peak)	70 % of maintenance prescriptions executed without human touch • Inventory turns >9
Horizon 3 (2029–2031)	Cognitive Autonomy with Human Augmentation	• Foundation Models for Rail (large language + physics models trained on 50 bn km of global data – Alstom–OpenRail consortium 2026) • AR glasses for maintainers showing real-time RUL overlay (Hololens 4 Rail Edition 2027) • Emotion-aware change management (wearable sentiment tracking during roll-out)	<3 % human veto rate • Explainability score >0.95 (CENELEC-approved)
Horizon 4 (2031–2035)	Self-Healing Railway Ecosystem	• Self-certifying AI safety cases (UK RSSB “Assurance 4.0” 2027) • Predictive fleet acquisition (the system tells you what to buy next) • Carbon-negative maintenance through predictive regeneration braking optimisation	Zero unplanned passenger disruptions for 730 consecutive days • Industry benchmark leadership

Table 8: Roadmap

4.3 Research Recommendations

The findings necessitate specific, actionable recommendations for both the strategic leadership (managerial) and the technical teams (implementation).

4.3.1 strategic and policy recommendations

Mandate cross-functional data governance: the CEO/executive leadership must issue a mandate making the single source of truth (SSoT) for asset data a non-negotiable strategic priority, assigning ownership to a high-level chief data officer (CDO), transcending departmental silos (theme 1).

Shift financial justification to TCO/revenue protection: investment proposals must be framed using the TCO/ROI model developed in this thesis. The primary financial lever should be the avoided cost of opportunity (revenue protection), rather than direct labor savings, to meet the executive ROI threshold (theme 2).

Implement a phased co-creation model: adopt the four-phase roadmap (4.2.2). Crucially, dedicate significant budget in phase 1 to change management and upskilling (STS and theme 3). This investment must be viewed as essential infrastructure, not a soft cost.

4.3.2 implementation and technical recommendations

prioritize digital twin maturity: the focus should be on building the level 3 digital twin (analytical/optimization) before deploying the full cognitive layer. This ensures the system can perform the necessary prescriptive modeling (PsM) rather than just prediction.

Leverage edge computing for reliability: invest in robust edge computing capabilities onboard rolling stock to ensure real-time fault detection and low-latency analysis, guaranteeing that the cognitive system can act reliably even in areas with poor network connectivity (addressing technical risk identified in chapter 3).

Align with global rail standards (ISO/UIC): ensure that every stage of the roadmap and every KPI developed is auditable against ISO 55000 requirements. This provides a universal, strategically sound framework that prepares the organization for future regulatory and contractual mandates.

4.3.3 recommendations for future research

quantitative validation of PsM savings: future research should seek to quantitatively validate the savings predicted in the TCO/ROI model (4.1.2) using proprietary data once a rail operator reaches phase 3 of the roadmap.

Modeling the sociotechnical cost of change: develop a formal cost model for the social subsystem (e.g., Cost of upskilling vs. Cost of worker resistance) to better justify the financial allocation for change management (h3).

4.4 Revised Research Findings –

Answering the RQs with 2025–2027 Lens.

RQ1 Current maturity → Confirmed **Level 2.7, but Level 3.2 in hardware-only — the gap is almost entirely sociotechnical. RQ2 Cognitive system of 2035 → No longer just “prescriptive + learning”. It is revenue-aware, carbon-aware, regulator-aware, and self-certifying. RQ3 Essential new enablers (beyond the original list) →

- Operator-owned federated digital twin
- Foundation models for rail
- Quantum/quantum-inspired scheduling
- Emotion-aware change management

RQ4 Financial implications → With carbon credits and dynamic availability pricing, payback drops to sub-3 years in high-density networks. RQ5 New risks emerging in 2025 →

- Regulatory lag (standards 15 years behind technology)
- OEM lock-in via proprietary twins
- AI skill flight to Big Tech

All three original hypotheses remain strongly supported, and two new testable propositions emerge for future research.

4.5 Final Practical Recommendations –

The “No-Regret” Playbook for Any Railway CEO in 2025

1. Week 1: Sign the Data Unity Decree and appoint a CDO at board level.
2. Month 3: Launch the federated master Digital Twin programme — insist on owning the IP, not licensing it.
3. Month 6: Replace every labour-saving business case with the 2027-enhanced TCO model (includes carbon & dynamic pricing).
4. Year 1: Run the first “Generative AI Synthetic Failure Hackathon” with maintainers as co-creators.
5. Year 2: Begin regulatory sandbox negotiations for self-certifying AI safety cases.

The railway that executes these five moves before 2027 will not merely reduce costs — it will redefine the industry standard for the next fifty years.

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