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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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Introduction

The modern world we are living in has been expanding like never before yet it is becoming smaller, nearer and faster than any other point in history. Thanks to technological advancement, ease of communication and availability of transportation. At the center of these transportation means lays the railways, where it serves people in short and long distances as well as commercial goods, major advantages of railway to become the heart of transportation means is for its connectivity, mass transportation and affordability.

Yet, the railway is undergoing a major transformation accompanied with the revolution of internet, driven by digitalization, data-driven decision making, sustainability and maintenance 4.0. The concept of maintenance which started in a traditional way as a reactive maintenance, has advanced as well, and now it is a strategic enabler of operational excellence, asset longevity and safety. As rolling stock industry is becoming more complex integrated with mechatronics, advanced electronics and many softwares embedded into the trains, the traditional conventional approaches are becoming less adequate., specially strategically and financially.

Railway maintainers and operators are being challenged and put under pressure to reduce their unplanned downtime, increase fleet availability and optimize assets life cycles while maintaining high safety standard & complying with all rules and regulations.

While many are still relying on traditional systems, manual inspections, and time-based preventive maintenance regimes. This often results in inefficiencies, high maintenance costs, and missed opportunities for performance improvement.

In parallel, new technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and digital twins are redefining the new world of maintenance. These technologies enable the shift toward Condition-Based Maintenance (CBM), predictive diagnostics, and ultimately cognitive maintenance — systems that can anticipate failures, learn from patterns, and recommend or even automate optimal interventions. The destination is a state of zero-downtime operations, where maintenance becomes proactive, optimized when required, and seamlessly integrated into the digital ecosystem of rail transport.

Problem Statement:

The shift from traditional corrective or preventive maintenance to a fully digitalized cognitive system is complicated, expensive, and often misunderstood, despite the fact that automation and technological advancement have proven themselves in a variety of industries and sectors and offer numerous advantages to any location that implements them. A strategic, well-organized roadmap for a successful digital transformation is lacking in many firms. System integration, data governance, organizational preparedness, technological adoption, and interdepartmental alignment are all fraught with difficulties.

a lack of a strategy framework that enables rail firms to assess their current situation, manage risks, pinpoint organizational opposition, and then appropriately execute a phased transformation that strikes a balance between operational continuity and seamless adoption.

Significance of the Study:

This study is and significant for railway sector, however, in general maintenance consumes about 50-70% of total lifecycle costs of an asset, it also plays a critical role in availability, performance, efficiency and safety. As the railway industry undergoes digital disruption, this research contributes in several meaningful ways:

1. Strategic Industry Impact

Rail operators and maintainers can use the framework developed in this thesis to assess their current digital maturity, identify key transformation areas, and plan technological investments with confidence. The roadmap will help shift digitalization from a series of disconnected initiatives to a coordinated, value-driven transformation strategy.

2. Financial gains

Along the study a clear financial reviews and evidence will be provided to show the noticeable financial impact on operation and maintenance activities that would be

obtained by adopting digitalization. The ROI (Return On Investments) will act as a driving gear for higher management and officials be the key adopter for digitalization.

3. Academic and Theoretical Contribution

Despite the growing adoption of digital tools in rail, there is still limited academic literature integrating digital transformation theory, asset management strategy, and systems engineering within the specific context of rolling stock maintenance. This thesis bridges the gap, offering new insights for both business and engineering disciplines.

4. Policy and Infrastructure Planning

Governments and public transport authorities can benefit from the framework to guide national rail modernization programs, structure digital mandates in contracts, and design policies that accelerate the safe and sustainable digitalization of transport assets. By focusing on strategic alignment, organizational willingness, and real-world constraints, this thesis is designed not only to inform but also to enable and guide action.

Objectives of the Study:

The central aim of this thesis is to develop a strategic roadmap that will enable rail organization to go through a digital transformation path of railway maintenance, focusing on the transition from traditional Preventive (PM) systems to cognitive, zero-downtime operations. This transformation is only a technological transformational advancement it spans over organization, people, processes, and policies. Therefore, the roadmap has to be a multilevel strategy and should take into account several factors the organization maturity level, the dynamic of change in the organization, operational risk and regulatory constraints and boundaries.

The key objectives are:

- To analyze the current state of maintenance systems in the rail sector, taking CAF/SAR project as an example.
- To define the desired future state characterized of zero downtime capabilities

- To develop a structured transformation roadmap including maturity levels, enablers, and key success factors
- To identify challenges risks and propose mitigation strategies for implementation
- To propose Key Performance Indicators (KPIs) to monitor progress and value gained.

Research Questions:

Since railway is a sector that is highly regulated and governed, railway organizations also usually are quite large organizations, this thesis will integrate various questions to act as the backbone of the research. The transformation is not only a technically digital change but it is an asset centric transformation. Following are the main questions that will be discussed;

1. What is the current state of digital maturity in railway rolling stock maintenance, and how does it vary across operators/maintainers and geographies?
2. What constitutes is a fully digital, cognitive maintenance system, and how does this model impact asset performance, availability, reliability and efficiency over time?
3. What technologies, processes, and organizational capabilities are essential for enabling a transition from Preventive maintenance (PM) systems to cognitive zero-downtime operations?
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?

This model would be challenged against the CAF/SAR projects as model and prototype of the study.

Hypotheses:

Three main hypotheses will serve as the foundation for this investigation. These theories highlight the crucial areas in rolling stock where digital transformation is anticipated to produce quantifiable output values. These are implementation effectiveness, financial outcome, and asset performance.

An academic literature review, current industry practices, and the difficulties faced by railway and rolling stock operators and maintainers worldwide will serve as the foundation for the development of each hypothesis. Where feasible, qualitative or quantitative analysis will be used to examine the difficulties.

Hypothesis 1 (Digital Maturity and Assets Performance):

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

Explanation

This hypothesis is based on the assumption that a better level of digital maturity will lead to more efficient and more effective maintenance strategies. Maturity is measured based on the Condition Based Monitoring, Advanced analytics and then AI driven decisions. As the digital maturity increases, availability, reliability & efficiency increases, unplanned stoppage time decrease.

Implications

- Demonstrates the operational value of investing in digital systems
- Highlights digital maturity as a measurable competitive advantage
- Supports the development of digital maturity models specific to rail

Hypothesis 2 :(Implementation of preventive cognitive maintenance approach results in a reduction of asset total lifecycle cost (LLC) and delivers a positive return on investment (ROI) within a defined time frame):

Explanation

Maintenance account for a substantial portion of assets total cost during its lifecycle. Predictive maintenance (PdM) is often promoted as a cost saving strategy, however, quantifying the financial impact is complex. In this hypothesis we will explore how these methods will deliver a tangible savings and cost reduction overtime, not only through a direct dollar reduction yet by having a higher uptime vs downtime (availability), prolonged maintenance periods thus less interventions which leads to labor cost savings (financial saving).

This includes analysis of:

- Reduced unplanned maintenance costs
- Optimization of inventory and spare parts
- Labor efficiency improvements
- Avoidance of revenue loss due to operational disruptions

Implications

- Supports the creation of ROI and LCC models tailored to digital rail maintenance in CAF/SAR project.
- Helps build the financial case for digital transformation to stakeholders.
- Identifies breakeven points and investment risks for technology adoption.

Hypothesis 3 (a structured phased roadmap increases the likelihood of successful implementation of cognitive predictive maintenance system in railway organization):

Explanation

Digital transformation in railway maintenance is not just about installing new software or sensors — it's about changing the way an entire organization thinks, operates, and makes decisions. Without a clear roadmap, many operators fall into the trap of launching isolated pilots or technologyt initiatives that struggle to scale or deliver lasting outcomes.

This hypothesis suggests that a structured, step-by-step approach, one that aligns technology rollout with organizational readiness and process evolution — significantly improves the chances of success. A transformation roadmap helps organizations move from basic digitization (like moving from paper to digital records) to more advanced stages like predictive maintenance and eventually cognitive, AI-driven operations. The roadmap doesn't just guide the adoption of tools. It also addresses critical enablers such as:

- People: building internal digital skills and supporting cultural change
- Processes: redesigning workflows and integrating systems
- Leadership: adopting setting direction, participating and ensuring alignment across departments
- Governance: measuring progress, documenting and set the ground rules.

In practice, this means breaking down transformation into manageable phases: starting with a clear vision, selecting the right use cases, conducting pilot projects, and gradually scaling across the fleet. It's about moving deliberately yet confidently, toward a smarter, more resilient maintenance ecosystem.

Implications

- Encourages operators to think beyond just technology when planning transformation
- Reinforces the value of strategic planning and cross-functional collaboration
- Offers a flexible blueprint that can be adapted to different contexts and maturity levels.

Significance of the Study

Railways across the globe are undergoing tremendous pressure to do more with less, to remain reliable, to be on maximum availability and run safer with aging fleets, this goes with constraints of tight budget and fixed schedules. Thus, in such environment maintenance is not only a function however, it is becoming a center of competition, a pillar of the organization reputation, and source of customer's satisfaction. Yet, many operators are still attached to the casual preventive, paper-based maintenance record, fixed schedules maintenance regimes which is no longer meet the evolving demands on today's world.

This study comes at a pivotal moment for the railway sector. Digital technologies have matured to the point where predictive analytics, Internet of Things (IoT), AI, and cognitive systems are no longer theoretical, they are being piloted, deployed, and scaled. But while the technology is ready, many organizations are not. This thesis addresses that gap by providing a strategic roadmap to help rail operators and maintainers move confidently from traditional maintenance practices to data-driven, intelligent operations that aim for zero unplanned downtime.

Strategic Value for Operators and Asset Owners

This research is designed to support decision-makers, maintenance directors, operation directors, CIOs, CFOs, and rolling stock asset managers, who are facing and challenged with complex transformation choices. Should we digitize now, or wait? Where do we start? How do we justify the investment? What are the risks? How long the transformation should and will take?

These are not just technical questions; they are strategic and financial dilemmas that directly affect service delivery and asset longevity.

By offering a holistic framework that blends technology, finance, and change management, this thesis can help leaders make better-informed, lower-risk decisions as they plan for the future of maintenance.

Financial and Lifecycle Relevance

Terms like “predictive maintenance,” “digital twin,” and “AI in rail” are mentioned everywhere but their actual recognized value is still often unclear or overpromised. This study digs deeper. It focuses not just on the promise of digital transformation, but on its measurable impact: reduced lifecycle costs, improved reliability, better safety, increased return on investment (ROI) and On-time schedules . These are the outcomes that matter most to railway operators and the public they serve.

By exploring how cognitive systems can reduce downtime, extend the life of critical components, and optimize resource use, the study provides the financial logic and operational case for transformation, helping organizations move to from a concept to commitment.

Academic and Theoretical Contribution

Many digital initiatives fail not because the technology is flawed, but because the roadmap is missing. This thesis doesn't simply highlight what to implement, it focuses on the how. It recognizes that successful transformation requires much more than deploying sensors or buying software. It takes cross-functional collaboration, strong governance, cultural change, new KPIs, and often, a fundamental rethink of how maintenance is planned and delivered.

This study contributes a practical, phased roadmap for transformation from early digital readiness assessment to full cognitive maintenance that organizations can adapt to their own context, maturity level, and strategic priorities.

4. Policy, Regulatory, and Public Sector Impact

Finally, this study contributes to a larger goal, making rail more resilient, sustainable, and future-ready. As governments invest in rail as a low-emission transport mode and look to expand capacity without expanding carbon footprints, smarter maintenance will be key. It will enable operators to sweat existing assets longer, avoid service disruptions, and align performance with public expectations without compromising safety or compliance.

In this way, the research offers insights not only for commercial operators and maintainers but also for public policymakers, infrastructure authorities, and investors looking to build a rail system that is digitally enabled, economically efficient, and environmentally responsible.

Scope and Limitation:

This study sets out to explore how railway operators can move beyond classical, reactive maintenance practices and instead embrace a smarter, more connected, and predictive way of managing their rolling stock fleets. The focus is not just on the technologies available, but on how these tools can be applied strategically to transform operations, creating real business value through improved uptime, cost savings, and better decision-making.

The core of this thesis is centered around the maintenance of rolling stock assets trains, locomotives, EMUs (Electric Multiple Units), DMUs (Diesel Multiple Units), and freight wagons, rather than fixed infrastructure such as track or signaling. While the same digital principles can apply across the entire rail system, this research zooms in on the vehicles themselves, where digital transformation can have immediate and measurable impact.

The scope includes four key areas:

1. **Technology** we will explore the enablers of digital transformation: condition monitoring, IoT sensors, cloud platforms, analytics, and AI. However, the focus is not on how to build these technologies, but on how to strategically choose, adopt, and scale them.
2. **Organization and Culture** This research takes a close look at how people, teams, and leadership play a role in transformation. Success doesn't come from software alone — it comes from aligning people, workflows, training, and leadership around new ways of working.
3. **Financial Impact** Maintenance is a major cost driver in rail operations. This thesis explores how smarter maintenance strategies can reduce lifecycle costs, improve asset utilization, and generate a meaningful return on investment.

4. Strategic Roadmap Finally, the study proposes a phased transformation roadmap that organizations can tailor to their specific starting point. Whether an operator is just beginning to digitize maintenance records or already piloting predictive systems, the framework helps guide the next steps in a structured, manageable way.

Although the thesis takes a global perspective, it is designed to be adaptable across regions and rail systems. The examples, insights, and roadmap can apply to operators in mature markets with high digital capability, as well as those in emerging economies beginning their modernization journey.

Limitations of the Study

Although this thesis has a wide scope, it is important to recognize its practical limitations, these limitations are:

Technical Depth

The study does not address the technical design of digital tools, but rather their strategic application. It doesn't go into great detail about cloud computing and cybersecurity, software platform architecture, machine learning methods, or the physics underlying different field equipment. The emphasis is still on how these technologies can be successfully incorporated into maintenance procedures.

Confidentiality and Access to Data

Internal operator data, a large portion of which is secret or sensitive to commercial interests, provides many of the most significant insights regarding cost reductions, failure rates, or return on investment from predictive maintenance. As a result, this thesis uses secondary research, expert interviews, and public case studies, but it is unable to verify its conclusions using operational data from private companies.

One Framework, Many Realities

Railroad operations vary from one another. The fleet ages, worker arrangements, legal demands, and even environmental challenges may make what works for one corporation or country impractical for another. This roadmap is intended to be flexible and adaptable rather than rigid.

A Moment in Time

The field of digital transformation is developing quickly. Artificial intelligence, digital twins, and automated diagnostics are examples of quickly developing technologies. The environment and the road map may change over time, even if this thesis represents the level of practice and thought at the moment.

Previous Studies:

Over the past decade, there has been an increasing amount of interest from academia and industry in the digitization of the railway sector, especially in maintenance. Data-driven maintenance techniques, predictive analytics, and asset management frameworks are becoming more and more popular in research as operators look to cut costs, increase asset availability, and meet growing service demands. However, there are still a number of gaps in the research, especially when it comes to integrated roadmaps, organizational preparation, and financial implications. The breadth and depth of the current literature also differ greatly.

Evolution from Preventive to Predictive Maintenance.

The majority of earlier research on railway maintenance was devoted to preventive maintenance, which involves calendar-based interventions intended to lower the probability of failures. For example, *Ghazal et al. (2014)* and *Tsang (2002)* discussed reliability-centered maintenance (RCM) as a way to balance cost, risk, and safety. However, these models often resulted in over-maintenance or missed degradation signals.

With the advancement of or technological apparatus such as sensors, actuators and monitoring system as well as onboard diagnostics, research began shifting toward predictive maintenance (PdM). Studies by *Famurewa et al. (2017)* and *Zhou et al. (2019)* highlight the use of condition monitoring systems in wheelsets, traction motors, and braking systems, enabling early detection of wear and faults. These studies show significant reductions in unplanned downtime and cost when predictive models are used effectively.

Data Analytics and Artificial Intelligence

The ways in which that AI and data analytics are altering maintenance paradigms have been the subject of several recent studies. The use of machine learning models in predicting equipment failure based on sensor data and past performance was examined by *Bárbara et al. (2020)*. Similarly, *Yan et al. (2021)* suggested AI-based prognostic systems that evaluate components' Remaining Useful Life (RUL) to prioritize interventions. This thesis seeks to fill the gap left by these promising research, which frequently concentrate on technical viability with little regard for organizational implementation, change management, or strategy alignment.

Digital Twins and Cognitive Maintenance

Digital twins, or virtual versions of actual systems, are a concept that is gaining popularity. The potential of digital twins to model and optimize rolling stock performance in real time is examined in *Grall et al. (2020)* and *Accenture's rail digital twin white paper (2021)*. When the system not only anticipates failure but also suggests or carries out action on its own, these models promote cognitive maintenance. Nevertheless, the majority of current research is driven by suppliers or OEMs and is frequently connected to particular platforms or commercial offerings. Research on scalable deployment, governance issues, and integration with current IT/OT systems is lacking in open-source or operator-led studies.

Organizational and Strategic Aspects

While the technology behind digital transformation is evolving fast, research that looks into the human, cultural, and strategic aspects of this shift, especially in the railway sector remains quite limited. Studies like those by *Lichtblau et al. (2015)* and *Westerman et al. (2014)* have done solid work exploring digital maturity and leadership in broader industrial and manufacturing settings. However, when it comes specifically to railway operations and maintenance, the available guidance becomes much thinner. Some transport-focused studies such as the UIC Digital Platform Reports and the EU's Shift2Rail initiatives, they do touch on strategies and key enablers across departments. But more often, they stop short of offering clear, actionable roadmaps that railway operators can follow.

This points a major gap in both the research and industry practice: the technology is advancing, but many organizations are still catching up when it comes to internal readiness, cross-functional alignment, and building real capabilities to implement this transformation. That's where this study aims to make a meaningful contribution.

Case Studies and Industry Applications

Several case studies both academic and industry-sourced provide useful illustrations of partial transformations:

- Deutsche Bahn's Predictive Maintenance Program has been widely cited for using big data to forecast component wear and improve service reliability.
- NS (Netherlands Railways) has implemented sensor-driven maintenance for bogies and doors, with strong results in reducing asset downtime.
- Japan's Shinkansen and JR East have integrated condition-based maintenance through extensive use of trackside and onboard diagnostics.

Contribution of the Current Study

The digital transformation of railway maintenance is no longer a distant ambition - it's becoming a necessity. Operators across the globe are experimenting with advanced smart device, analytics, and automation, looking forward to modernize aging systems and meet challenging rising expectations around availability reliability, cost-efficiency, and safety. Yet despite this momentum, there's still a gap between what's technically possible and what's practically being achieved and it is actually in use.

This study aims to bridge the gap; offering more than just a review of technology trends or predictive algorithms. It brings together strategic thinking, industry insight, and organizational realities to help rail operators navigate the complex path from traditional maintenance toward intelligent, zero-downtime systems. Here's where this research makes a meaningful contribution:

A Practical, Strategic Roadmap Not Just Theory

Rather than diving deeply into algorithms or sensor hardware, this thesis focuses on how to lead transformation. It offers a clear, phased roadmap that helps operators move from fragmented digitization toward fully integrated, cognitive maintenance. This is especially valuable for organizations that don't have a blank slate but instead have decades-old systems, paper-based processes, and risk-averse cultures.

The goal isn't to reinvent the wheel, but to show how digital tools can be integrated thoughtfully, supporting long-term goals like reliability, cost reduction, and performance.

Connecting Maintenance to Financial and Strategic Value

Maintenance is often seen as a cost center. This study reframes it as a strategic asset one that can unlock major financial benefits when optimized through technology. Unlike many research papers that stop at technical feasibility, this work explores how digital maintenance impacts:

- Lifecycle costs and asset longevity
- Downtime and service quality
- Return on investment for capital upgrades
- Risk management and business continuity

By making this connection, the study becomes directly relevant to senior executives, investors, and policy makers, not just technical teams.

Putting People and Culture at the Center

Digital transformation isn't just about technology it's about changing how people work. This study brings much-needed focus to the human side of the journey: upskilling the workforce, engaging teams, reshaping roles, and building a culture that's ready for change. It acknowledges that tools alone don't create impact — people do.

This people-centric lens makes the research more grounded in reality, especially for operators navigating unionized environments, legacy contracts, and cross-functional silos.

Drawing Lessons from Real-World Best Practices

While many studies highlight isolated pilot projects or vendor-driven innovations, this thesis takes a broader view. It draws lessons from real-world examples such as Deutsche Bahn, JR East, and Dutch Railways and uses them to build a scalable, flexible transformation model that can work across different countries and organizational types. The roadmap is not prescriptive, but adaptable, recognizing that every operator starts from a different point.

Bridging Academia and Industry Practice

Finally, this study brings together two worlds that are often disconnected: academic insight and industry application. By combining frameworks, case studies, and consulting experience, it delivers something that's both intellectually solid and practically usable — a guide that can support leaders in designing strategies, securing investment, or leading organizational change.

In short, this thesis is not just about what's new — it's about what's next. It contributes by offering a clear, strategic, and human-centered approach to one of the most critical challenges facing the railway industry today: transforming maintenance into a driver of value, resilience, and innovation

Theoretical Framework:

Digital transformation in railway maintenance is a fundamental shift that affects people, procedures, tools, and governance; it goes beyond simple technological advancement. to comprehend and direct this change;

1. Sociotechnical Systems Theory
2. Digital Maturity Models
3. Asset Management and Lifecycle Theory (ISO 55000)

When combined, these frameworks offer a comprehensive perspective on change that encompasses leadership, asset value, culture, and operational strategy in addition to sensors and AI.

Sociotechnical Systems Theory

- Digital transformation in railway maintenance is a systemic change that affects people, procedures, and governance; it is not just a technical improvement. This study is grounded in three theoretical frameworks to comprehend and direct this transition.

Digital Maturity Models

The process of digital transformation is a continuum rather than a dichotomy.

Operators progress through phases, from simple paper digitalization to integrated maintenance planning driven by AI. This evolution is evaluated and supported by the thesis using a number of digital models:

- Capgemini's Digital Maturity Framework, which defines progress across four domains: technology, people, governance, and innovation.
- Industry 4.0 maturity models, which help assess the sophistication of automation, connectivity, and data integration.
- UIC and Shift2Rail guidelines, which provide rail-specific benchmarks for digital capability development.

These models offer a structured way to map where an operator is today, and what capabilities must be developed to reach a future state of cognitive, zero-downtime operations.

This study builds on these models to propose a customized digital maturity framework for rail maintenance, blending academic theory with real-world applicability.

1. Asset Management and Lifecycle Theory (ISO 55000)

Modern train maintenance must also be viewed through the lens of strategic asset management. From acquisition and operation to renewal or disposal, the global asset management standard ISO 55000 offers a framework for optimizing the value of tangible assets.

This standard highlights:

- Alignment with organizational goals
- Risk-based decision-making
- Lifecycle costing
- Cross-functional collaboration

In this thesis, ISO 55000 serves as a financial and operational backbone for evaluating the value of digital transformation. By linking digital interventions (e.g., predictive maintenance, digital twins) to lifecycle impact, the roadmap ensures that proposed strategies are not only innovative but also economically and operationally sustainable.

Synthesis of Frameworks

These three frameworks; sociotechnical systems, digital maturity, and asset lifecycle management, converge to shape a transformation strategy that is:

- Technologically ambitious, but grounded in human and actual realities.
- Strategically aligned, with measurable financial and operational KPIs
- Incrementally actionable, through defined maturity stages and road mapping.

It allows this study to go beyond hype and offer a realistic, structured, and adaptable pathway for railway operators seeking to modernize their maintenance ecosystems.

Methodology and Research Methods

This study adopts mixed methods to explore the transformation from traditional preventive maintenance (PM) to zero-downtime operations, and strategic research approach. We will provide a practical roadmap for this transformation from real-world insights. The mix of quantitative analysis, operational performance KPIs and experts interviews will be the center in which the research will be conducted around. The current focus model will be CAF as OEM & maintainer and SAR as the operator and owner.

Research Tools

Research Design

The study follows three phase research design approach blending research, case study and expert interviews

1) Literature and Framework Analysis

- A structured review of academic publications, technical reports, and standards (e.g., ISO 55000, UIC guidelines, OEM strategy documents).
- Identification of digital maturity models, sociotechnical frameworks, and asset lifecycle strategies relevant to railway maintenance.
- Synthesis of theory to create a conceptual model for assessing digital transformation readiness and performance.

2) Multiple Case Study Approach

- Selection of global railway operators that have similar digital transformation initiatives.
- Review of public documentation, project outcomes, digital strategies, and organizational practices.

- Comparative analysis across cases to uncover patterns, challenges, enablers, and innovation pathways.

3) Structured Expert Interviews

- Interviews with 5–15 professionals across the railway ecosystem, selecting from OEMs, operators, suppliers, consultants, and regulators.
- Topics include investment rationale, barriers to adoption, organizational culture, technology integration, and asset lifecycle impact.
- Interviews are transcribed, coded, and thematically analyzed to enrich case findings and validate the strategic roadmap.

Document and Literature Review

Sources include:

- Peer-reviewed journals (e.g., IEEE, Elsevier, Taylor & Francis)
- Reports from global institutions (UIC (International Union of Railways), Shift2Rail, UNIFE (The European Rail Supply Industry Association), Railway Gazette)
- Technical documentation from OEMs and digital solution providers
- Government strategy papers (e.g., Canadian Department for Transport, Digital ambition 202-2023, Saudi digital government strategy).

This review provides both theoretical grounding and a landscape of current digital maintenance practices.

Case Study Selection

Cases are selected based on:

- Progress in digital transformation of maintenance
- Data availability and transparency
- Geographic diversity and operational complexity

Expected case studies:

- Deutsche Bahn (Germany)
- JR East (Japan)
- Metrolinx (Canada)
- SAR (Saudi Arabian Railway) pilot project

Summary

Adopting and riding the current wave of AI era is becoming a necessity, eventually all industries should be utilizing such advancements and railway is no difference. The adoption would come with benefits which would be reflected and with proper guidance adoption shall be smooth. This study will act as guide for organization for such transformation

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