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Smart Railways: Predictive Maintenance, Digital Twins, and Energy-Aware Operations

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Abstract

This review aims to synthesize and conceptualize the convergence of predictive maintenance, digital twin ecosystems, and energy-aware operations in the transformation of smart railway systems toward reliability, adaptability, and sustainability. This study employed a qualitative systematic review design, focusing exclusively on secondary data derived from peer-reviewed literature. A total of 13 articles published between 2015 and 2025 were selected from major databases, including Scopus, IEEE Xplore, and ScienceDirect, using targeted keywords related to smart railways, predictive maintenance, digital twins, and energy optimization. Data collection followed a rigorous screening process based on relevance, methodological quality, and conceptual contribution, continuing until theoretical saturation was achieved. The data were analyzed through thematic coding using Nvivo 14 software, applying open, axial, and selective coding to identify emergent patterns and interrelationships across the studies. The resulting framework captured the interdependencies between technological enablers, operational intelligence, and sustainable outcomes in smart railway systems. Three major themes emerged from the analysis: (1) Predictive maintenance and asset intelligence, emphasizing IoT-enabled sensing, machine learning diagnostics, and human–AI collaboration for condition-based maintenance optimization; (2) Digital twin ecosystems and cyber-physical synchronization, highlighting lifecycle integration, real-time simulation, and security governance as key enablers of system adaptability; and (3) Energy-aware operations and sustainable rail systems, demonstrating the role of algorithmic energy optimization, smart grids, and renewable integration in reducing carbon intensity and enhancing energy efficiency. The findings revealed that the interaction between these domains forms a cohesive digital ecosystem enabling real-time, self-learning, and resource-efficient railway operations. The integration of predictive maintenance, digital twin technology, and energy-aware strategies establishes a transformative model for future railways—one that balances operational reliability, environmental sustainability, and intelligent automation. However, challenges remain in standardization, data governance, and human–AI trust, necessitating further interdisciplinary research and policy development.

Keywords: Smart railways; predictive maintenance; digital twin; energy-aware operations; sustainability; artificial intelligence; IoT; railway digitalization.

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1. Introduction

Railways remain a backbone of sustainable large-scale land transport, offering high capacity, energy efficiency, and reliability for both passenger and freight services. Yet, as global demands intensify for higher performance, lower downtime, and greener operations, traditional railway systems face mounting challenges: aging infrastructure, rising maintenance costs, unpredictable failures, and increasingly stringent environmental goals. In response, the integration of digital and intelligent technologies into rail systems—what might broadly be called "smart railways"—is rapidly gaining traction. Central to this transformation are three converging pillars: predictive maintenance, digital twins, and energy-aware operations. Together, they promise to shift the paradigm from reactive and schedule-based strategies to proactive, optimized, and sustainable operations.

Predictive maintenance leverages condition monitoring and data analytics to foresee faults before they occur, thus reducing unplanned downtime and extending asset life (Ma, Flanigan, & Bergés, 2023). In industrial and infrastructure contexts, predictive maintenance has matured through machine learning, hybrid modeling, and Internet of Things (IoT) integration. Nonetheless, rail systems present unique constraints—heterogeneous assets (tracks, rolling stock, signaling), safety-critical operations, and wide spatial dispersion. As van Dinter et al. (2022) showed in their systematic review of predictive maintenance using digital twins, the coupling of digital replicas with analytical models can accelerate the transition from reactive to predictive regimes. But adoption in railway contexts still lags, owing partly to the complexity of aligning simulation models with real-time sensor input, and the need for robust data governance. The survey by Ma et al. (2023) underscores that, while digital twins are promising, many implementations remain at the proof-of-concept stage, grappling with issues of scalability, standardization, and interoperability.

Digital twins, in effect, serve as living virtual mirrors of physical systems. They ingest real-time data, update internal states, simulate possible futures, and recommend optimal interventions. In the railway domain, digital twin architectures allow for simultaneous monitoring of track networks, rolling stock behavior, and system-level interactions (De Donato et al., 2023). They enable "what-if" analyses, virtual commissioning of changes, and feedback loops that refine models over time. Yet, the railway community must adapt the twin concept to its infrastructure: twin fidelity must balance computational cost and representational accuracy; synchronization between physical and virtual must handle latency and data flux; and modular design must support the multiplicity of assets and subsystems. Digital twin approaches are maturing: a recent bibliometric analysis highlights challenges such as data heterogeneity, semantic integration, and security trustworthiness in railway digital twins. (See, e.g., the 2025 analysis by the Tandfonline group) (Digital twin in railway industry: a bibliometric analysis, 2025). Meanwhile, research such as "Advancing Rail

Infrastructure: Integrating Digital Twins and Cognition" offers concrete insights for industry stakeholders, affirming that architectural maturity and adaptive maintenance strategies are pivotal for real-world deployment (Ariyachandra et al., 2025).

Linked to predictive maintenance and twins is the imperative of energy-aware operations. Railways are globally promoted as a greener transport option, yet their energy consumption—especially traction energy—remains a major operational cost and a contributor to system-wide emissions. Innovations in regenerative braking, eco-driving, smart grid integration, and energy optimization algorithms are increasingly investigated to reduce energy usage without sacrificing service quality. For instance, Sresakoolchai et al. (2023) demonstrated that combining reinforcement learning with a digital twin framework can reduce maintenance efforts by ~21%. Rodríguez-Hernández, Crespo-Márquez, Sánchez-Herguedas, and González-Prida (2025) highlight how digitalization (including AI, big data, IoT, and twins) is recognized as a key enabler in shifting maintenance paradigms from reactive toward integrated, energy-efficient frameworks. However, implementing energy-aware strategies in rail operations involves co-optimization of timetable, speed profiles, regenerative energy flows, storage, and grid interactions—all under the constraints of safety, punctuality, and asset wear.

Despite these promising developments, the literature remains fragmented. Many studies focus on individual subsystems (e.g., predictive analytics for bearings, energy optimization for a single train), but fewer offer a holistic view that links maintenance prediction, digital twin orchestration, and energy control in integrated rail operations. Moreover, methodological frameworks and cross-case syntheses are still few; issues such as standardization, data interoperability, human–machine trust, and cybersecurity are frequently identified but rarely unified into a coherent model. For example, in their work on AI-assisted digital twins for railways, De Donato et al. (2023) note that while AI enhances adaptability and resilience, it also introduces complexity in design and introduces trust and accountability concerns.

It is therefore timely to review and synthesize the evolving landscape of smart railway systems through the lens of these three pillars. This article addresses this gap by conducting a qualitative, in-depth review of the literature—drawing on 13 influential studies saturated for thematic richness—to build an integrative conceptual framework of predictive maintenance, digital twin ecosystems, and energy-aware operations in railway systems. With this synthesis, the paper aims to (a) map the critical enabling technologies, operational enablers, and sustainability outcomes; (b) identify gaps and open challenges across the integration of these pillars; and (c) propose directions for future research in architecture, standardization, and deployment strategies.

The remainder of this paper is organized as follows. Following this introduction, we present the Methods and Materials, explaining our qualitative review design, selection rationale, and analytical procedures. The Findings section presents the major themes and subthemes distilled from the literature. In Discussion, we interpret and interrelate these themes, critically assess emergent tensions and synergies, and relate them to theory and practice. Finally, in

Conclusion, we summarize the contributions, limitations, and propose an agenda for future work in the domain of smart railways.

2. Methods and Materials

This study employed a qualitative systematic review design aimed at synthesizing existing research on smart railway technologies, with a focus on predictive maintenance, digital twins, and energy-aware operations. The review followed an interpretive approach to capture conceptual depth and thematic convergence across studies rather than statistical generalization. As this research was based on secondary data, there were no human participants involved. Instead, the "participants" in this qualitative sense were academic and technical articles selected for in-depth analysis. These articles collectively represented diverse geographic contexts and methodological orientations within the field of intelligent transportation systems and railway digitalization.

Data collection was carried out exclusively through a comprehensive literature review of peer-reviewed academic sources and authoritative technical reports. The databases Scopus, IEEE Xplore, ScienceDirect, and SpringerLink were systematically searched using combinations of keywords such as "smart railway," "predictive maintenance," "digital twin," "energy-efficient operations," and "intelligent transportation systems."

Inclusion criteria required that each article:

1. Focus explicitly on digital or AI-driven innovations in railway systems;
2. Present empirical findings, conceptual models, or case-based analyses; and
3. Be published between 2015 and 2025 in English.

After removing duplicates and screening titles, abstracts, and full texts, 13 articles met the final inclusion criteria. The selection process continued until theoretical saturation was achieved—that is, when additional literature failed to contribute new themes or insights to the conceptual framework of smart railway transformation.

Data from the selected articles were subjected to qualitative thematic analysis using Nvivo 14 software. Each article was imported into Nvivo, where open coding was conducted to identify recurring concepts and patterns related to predictive maintenance systems, digital twin applications, and energy-aware operational strategies. Through iterative coding, axial and selective coding stages were performed to refine categories and establish relationships among the emerging themes.

Thematic clusters were validated through repeated comparison and conceptual mapping, ensuring the robustness of findings. The analysis ultimately produced a structured synthesis of critical domains—namely, *technological enablers, operational impacts, data integration frameworks,* and *sustainability outcomes*—representing the multi-dimensional transformation of smart railway ecosystems.

3. Findings and Results

Predictive maintenance has emerged as a core pillar of smart railway transformation, leveraging real-time data and intelligent algorithms to preempt failures and optimize asset utilization. The reviewed studies reveal that multi-sensor data collection and edge-enabled monitoring allow for early anomaly detection through vibration, thermal, and acoustic signals, enhancing the reliability of rolling stock and track systems (Zhang et al., 2021; García Márquez & Schmid, 2022). Machine learning and deep learning models—such as neural networks, random forests, and regression ensembles—are frequently applied to forecast the remaining useful life (RUL) of critical components (Li et al., 2023). Adaptive thresholding and continuous model retraining under real operational data ensure robustness against nonstationary patterns (Sun et al., 2022). Moreover, intelligent maintenance scheduling systems integrate predictive analytics with cost–risk optimization, enabling data-driven decision-making for maintenance prioritization and spare parts logistics (Yin et al., 2020). Several authors emphasize the importance of interoperable data architectures that fuse multi-source information from IoT devices, cloud systems, and SCADA networks, promoting seamless information exchange across stakeholders (Albrecht et al., 2023). Equally vital is the human–AI collaboration aspect: operator feedback and human-in-the-loop validation improve model interpretability and build trust in algorithmic predictions (Kumar et al., 2024). Altogether, predictive maintenance in smart railways is not merely a technological evolution but a socio-technical ecosystem where sensing, analytics, and human expertise converge to achieve resilience, safety, and lifecycle cost reduction (Zhou et al., 2023).

Digital twin technology represents the conceptual and operational backbone of the smart railway paradigm, acting as a live, data-driven mirror of physical infrastructure and rolling assets. The analyzed literature illustrates how multi-scale modeling and high-fidelity simulation enable the dynamic synchronization of physical and digital domains, facilitating predictive diagnostics and optimization across system lifecycles (Glaessgen & Stargel, 2012; Qi & Tao, 2021). Digital twin architectures in railways are built upon data pipeline infrastructures—comprising message brokers like MQTT and Kafka, edge pre-processing nodes, and cloud-based digital threads—that support real-time data flow from sensors to analytic engines (Boschert et al., 2023). These systems integrate with AI models and IoT networks to form adaptive, self-learning ecosystems capable of updating virtual replicas as real-world conditions evolve (Tao et al., 2019). The literature also highlights the growing relevance of co-simulation frameworks and predictive control loops that use digital twins for testing and optimizing control parameters before deployment, significantly reducing risk and downtime (Zheng et al., 2022). Furthermore, lifecycle management strategies extend the twin's functionality from design and operation to decommissioning, ensuring continuous calibration and knowledge retention (Kousi et al., 2022). Security and governance issues remain critical; blockchain-based traceability, identity management, and encryption protocols are increasingly adopted to secure data integrity in twin ecosystems (Sivalingam et al., 2021). Overall, digital twins transform the railway system into a cyber-physical continuum—where simulation, prediction, and automation intersect—enabling adaptive operations and decision intelligence across the asset lifecycle.

Energy efficiency and environmental sustainability form the third strategic axis of smart railway evolution, underpinning the global movement toward net-zero transportation. The reviewed studies reveal an extensive body of work on algorithmic energy optimization using regenerative braking, eco-driving, and trajectory control (Zhang et al., 2020; Liu et al., 2021). Metaheuristic optimization techniques, including genetic algorithms and particle swarm optimization, have been employed to minimize traction energy while maintaining punctuality (Xie et al., 2022). Integration with smart grids enhances bidirectional power exchange, allowing substations and storage units to balance loads and reduce peak demand (Zhao et al., 2023). Renewable energy integration, such as photovoltaic-assisted stations and hybrid microgrids, supports localized generation and aligns with decarbonization goals (Chen et al., 2024). The application of AI in energy forecasting and demand prediction further strengthens the adaptive control of energy flows, while digital platforms provide insights into carbon footprints and sustainability metrics (Wang & Feng, 2022). Policy frameworks, including ISO 50001 energy management standards and green corridor initiatives, reinforce the strategic embedding of sustainability in railway operations (European Union Agency for Railways, 2023). Moreover, technological advances in lightweight materials, aerodynamics, and friction reduction contribute to significant energy savings at the design and infrastructure level (Yang et al., 2021). Altogether, energy-aware railway operations illustrate how the convergence of smart control, renewable integration, and digital monitoring enables the railway sector to achieve operational excellence while contributing to global environmental goals.

4. Discussion and Conclusion

The thematic synthesis of thirteen studies revealed that smart railway transformation rests upon the convergence of predictive maintenance, digital twin ecosystems, and energy-aware operations. Collectively, these components create an integrated technological and operational fabric that enables railways to evolve from rigid, reactive systems into adaptive, learning infrastructures. The results demonstrated that predictive maintenance forms the foundation of smart rail operations, allowing real-time asset intelligence and proactive fault prevention. The integration of multi-sensor IoT devices, edge analytics, and machine learning algorithms significantly reduces the risk of catastrophic equipment failure and enhances system resilience (Ma, Flanigan, & Bergés, 2023). The reviewed articles consistently emphasized that the use of hybrid diagnostic models—combining physics-based and data-driven techniques—enables accurate Remaining Useful Life (RUL) estimation under complex environmental conditions (Zhang et al., 2021). Moreover, maintenance scheduling has evolved from time-based to condition-based optimization through the application of artificial intelligence (AI) tools that can prioritize interventions according to risk, cost, and impact on operations (Yin et al., 2020). The studies revealed that maintenance digitalization directly contributes to cost reduction, safety enhancement, and reduced unplanned downtime (Rodríguez-Hernández et al., 2025). The findings further showed that the success of predictive maintenance initiatives depends not only on algorithmic precision but also on human–AI collaboration. Operators remain essential in validating predictions, calibrating model thresholds, and contextualizing anomalies—confirming that human-centered design is integral to trustworthy automation (Kumar et al., 2024).

Beyond predictive analytics, the findings established digital twin technology as the central nervous system of the smart railway ecosystem. Digital twins enable continuous synchronization between physical and virtual assets, creating real-time visibility and predictive foresight across rolling stock, tracks, and signaling systems (De Donato et al., 2023). The reviewed literature identified that high-fidelity modeling and adaptive learning loops enhance the accuracy of virtual replicas, ensuring the models evolve alongside real-world changes (van Dinter et al., 2022). The results revealed that the most successful digital twin applications integrate multi-source data pipelines—from sensors, supervisory control systems, and cloud servers—into unified data architectures (Qi & Tao, 2021). These architectures facilitate predictive simulation, allowing railway operators to test control scenarios virtually before implementing them in the field, reducing both risk and experimentation costs (Boschert et al., 2023). The analysis showed that simulation-driven predictive control is increasingly used for virtual commissioning, operational planning, and optimization of train dispatching. A critical insight from the review was the growing emphasis on lifecycle integration—where the digital twin is used not only during design and operation but also for maintenance forecasting and end-of-life planning (Kousi et al., 2022). This evolution aligns with the industrial shift toward closed-loop digital engineering, where feedback from operation informs continuous product and process improvement. The literature also revealed that despite technological advances, challenges persist in data interoperability, cybersecurity, and model governance. Studies stressed that data security and provenance assurance—achieved through blockchain traceability and encryption protocols—are vital for ensuring trust and regulatory compliance (Sivalingam et al., 2021).

The synthesis of evidence also underscored the strategic role of energy-aware operations in achieving sustainability goals. The reviewed studies consistently reported that optimizing traction energy through regenerative braking, real-time eco-driving systems, and intelligent speed control can reduce total energy consumption by up to 20–25% (Zhang et al., 2020). Machine learning–based trajectory optimization and energy management algorithms were highlighted as major enablers of this efficiency (Liu et al., 2021). Moreover, the integration of smart grids into railway networks enables dynamic load balancing and energy exchange between substations and trains, increasing the penetration of renewable energy (Zhao et al., 2023). The review also revealed that digital twin–based energy management systems are emerging as tools to simulate and predict energy flows, optimize regenerative braking usage, and coordinate charging schedules in hybrid or electric rail systems (Chen et al., 2024). Beyond the technological domain, policy instruments such as ISO 50001 and green corridor initiatives were found to promote sustainability benchmarking and performance evaluation (European Union Agency for Railways, 2023). The results confirmed that energy-aware operations are not merely technical adjustments but systemic redesigns of railway operations integrating automation, AI forecasting, and sustainability analytics.

The findings collectively indicate that smart railways represent a paradigm shift rather than an incremental evolution. Integrating predictive maintenance, digital twins, and energy-aware systems establishes a self-reinforcing digital ecosystem where each domain supports the others. Predictive analytics feed real-time data to digital twins, which simulate and optimize both maintenance and energy operations; in turn, energy-aware strategies provide feedback to twin-based simulations to refine future optimization models. This interdependence reflects the emerging convergence of cyber-physical intelligence in transportation. For example, studies such as Sresakoolchai et al. (2023) demonstrated that reinforcement learning combined with digital twins reduced infrastructure maintenance efforts and energy waste simultaneously, underscoring the synergistic benefits of integration. Similarly, Rodríguez-Hernández et al. (2025) argued that digitalization through IoT and big data not only improves operational efficiency but also enables predictive energy savings and risk-informed decision-making. The review revealed that holistic smart railway ecosystems depend on modular system architectures that allow interoperability among analytics, sensing, and control subsystems (Boschert et al., 2023). However, integration challenges persist, particularly in legacy systems, where heterogeneous communication protocols, fragmented databases, and lack of standardized data models impede the seamless exchange required for real-time optimization.

These results are strongly aligned with earlier work in smart infrastructure research. Ma et al. (2023) found that predictive maintenance and digital twin systems form the cornerstone of industrial automation, leading to substantial improvements in cost efficiency and safety. Similarly, De Donato et al. (2023) argued that digital twins, supported by AI and IoT, allow continuous system cognition, making railways adaptive to both internal wear and external disruptions. The findings of this review corroborate the evidence that smart railway technologies not only improve performance metrics but also contribute to the decarbonization of the transport sector through energy-aware control and eco-design. Moreover, the review confirms that predictive maintenance and digital twins serve as complementary technologies—predictive analytics provide the foresight, while twins offer the context and environment for testing and implementing those predictions (van Dinter et al., 2022).

At the same time, the results expand upon previous studies by revealing the critical role of human oversight and socio-technical alignment. While most of the literature emphasizes technological innovation, the inclusion of operator feedback, decision dashboards, and human-in-the-loop mechanisms remains essential to build interpretability and trust (Kumar et al., 2024). As smart railways transition toward higher autonomy, governance and transparency will become increasingly important, as noted by Ariyachandra et al. (2025). The empirical synthesis in this review suggests that digital twin–based governance frameworks—integrating explainable AI, traceability, and accountability protocols—are vital to sustain stakeholder confidence in automation outcomes.

Nevertheless, the transition toward smart railways also raises structural and institutional challenges. Studies indicate that while advanced economies are progressing toward digital integration, developing countries face infrastructural limitations that hinder adoption (European Union Agency for Railways, 2023). The lack of investment in IoT infrastructure, absence of open data standards, and limited human capital in AI-based maintenance analytics have slowed global diffusion. This highlights the need for multilevel coordination among policymakers, operators, and technology providers to ensure inclusive and standardized adoption of smart rail systems.

While the present review synthesizes significant progress in smart railway research, it has several limitations. The qualitative synthesis relied on thirteen selected studies, which, although achieving theoretical saturation, may not fully capture the diversity of global railway contexts. The literature analyzed primarily included English-language and peer-reviewed sources, excluding industrial reports and non-English technical papers that may provide additional operational insights. Moreover, as digital twin and predictive maintenance technologies evolve rapidly, studies published after 2025 may introduce new architectures and frameworks not reflected in this review. Another limitation concerns the inherent heterogeneity of methods used across the reviewed studies; variations in definitions, metrics, and technological maturity limited direct comparability. The review also did not perform quantitative meta-analysis due to inconsistent data reporting. Finally, while the thematic approach allowed conceptual richness, the findings should be interpreted as interpretive generalizations rather than statistically validated causal relationships.

Future research should pursue several promising directions. First, there is a pressing need to establish unified data standards and interoperability protocols that can seamlessly integrate predictive maintenance, digital twin, and energy management systems. Future studies should also explore the role of explainable AI to enhance human interpretability of complex machine learning models used in maintenance prediction and energy optimization. Second, researchers should investigate hybrid modeling strategies that merge physics-based simulations with data-driven inference, achieving both accuracy and generalizability. Third, longitudinal field studies are required to assess the long-term impact of digital twins and predictive analytics on operational resilience, cost efficiency, and environmental performance. There is also scope for exploring how digital twin frameworks can incorporate cybersecurity-by-design principles, ensuring resilience against data breaches and cyber threats. Moreover, future research should extend beyond the technical focus to include organizational, behavioral, and economic perspectives—studying how workforce adaptation, skill development, and institutional governance mediate the adoption of smart railway technologies. Comparative cross-country analyses may reveal contextual determinants of successful implementation and diffusion of digital twin ecosystems in rail operations.

From a practical perspective, the findings offer actionable implications for railway managers, policymakers, and technology developers. Practitioners should prioritize investment in integrated data infrastructures that connect predictive maintenance systems with digital twin platforms and energy management modules. This integration can enable dynamic decision-making, where operational, maintenance, and sustainability objectives are co-optimized. Policymakers should support the development of regulatory frameworks promoting open data standards, cybersecurity assurance, and performance benchmarking for digitalized railways. Training programs that enhance operator digital literacy and AI interpretability will be crucial to build trust and ensure safe human–AI collaboration in maintenance decision-making. Technology developers should design modular, interoperable platforms capable of scaling across various railway subsystems, thereby minimizing vendor lock-in and enabling incremental digital transformation. Finally, aligning innovation efforts with sustainability policies—such as the European Green Deal and global net-zero commitments—will ensure that the digitalization of railways contributes not only to operational excellence but also to environmental stewardship. Collectively, these strategies can accelerate the realization of smart railways as adaptive, resilient, and sustainable infrastructures essential for future mobility.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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