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TRANSFORMING RAILWAY TRANSPORTATION: THE ROLE OF EMERGING TECHNOLOGIES IN EFFICIENCY, SAFETY, AND SUSTAINABILITY

Qasim ZAHEER[1], Shi QIU[1,2,3,4], Zunaira ATTA[1], S Muhammad Ahmed HASSAN SHAH[1], Haleema EHSAN[1], Syed Faizan Hussian SHAH[1], Weidong WANG[1,3,4], Chengbo AI[5], Jin WANG[1,3,4]✉

[1] *School of Civil Engineering, Central South University, Changsha 410075, China*
[2] *Guangxi Transport Vocational and Technical College, Nanning, China*
[3] *MOE Key Laboratory of Engineering Structures of Heavy-haul Railway, Central South University, Changsha 410075, China*
[4] *Center for Railway Infrastructure Smart Monitoring and Management, Central South University, Changsha 410075, China*
[5] *Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA 01003, USA*

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Abstract. This review explores the transformative role of emerging technologies in railway transportation, emphasizing their contributions to efficiency, safety, and sustainability. With the integration of Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, and autonomous systems, the railway industry is transitioning towards intelligent and interconnected networks. These advancements address critical challenges such as predictive maintenance, energy optimization, and real-time decision-making, ensuring operational resilience and enhanced passenger experiences. The review methodically evaluates 199 studies, offering insights into regional and temporal trends, and highlighting innovations in automation, safety systems, and sustainability. Additionally, it examines the interplay between advanced technologies and environmental goals, underscoring the importance of green practices and resource efficiency. Despite significant progress, challenges in cybersecurity, regulatory compliance, and legacy infrastructure integration persist. By categorizing literature into thematic domains and identifying critical research gaps, this study provides a comprehensive roadmap for future advancements in intelligent railway systems. Ultimately, it positions emerging technologies as pivotal to addressing contemporary demands and fostering a sustainable and adaptive global railway network.

Keywords: railway transportation, transportation research, emerging technologies, temporal trends, future of railway transportation.

✉Corresponding author. E-mail: *jerryw@csu.edu.cn*

1. Introduction

Railway transportation, a vital mode of travel and freight movement, is at the forefront of a technological revolution fueled by emerging innovations (Fuchs et al., 2022). The integration of intelligent technologies such as artificial intelligence (AI) (Tang et al., 2022), digital twins and the Internet of Things (IoT) (Long et al., 2023) is transforming the operational and strategic landscape of railway systems (Ma et al., 2024). These advancements address critical demands for greater efficiency, enhanced safety, and improved reliability in railway networks (Yang et al., 2023). Technologies like digital twins, AI, and IoT are redefining the sector's capabilities through simulation, optimization, and real-time monitoring (He et al., 2023). This paradigm shift not only strengthens the industry's position in global transportation but also ensures it can meet the complex needs of a rapidly evolving world (Wu et al., 2022).

The impact of emerging technologies on railway transportation extends far beyond traditional enhancements (Szymula et al., 2024). Digital twin technology, creates a virtual replica of physical rail assets and networks, enabling real-time monitoring, predictive maintenance, and efficient planning (Wang et al., 2024c). Similarly, AI-driven traffic management systems analyze vast datasets to minimize delays, optimize scheduling, and ensure seamless operations (Xu & Dessouky, 2022). IoT devices embedded in trains and track infrastructure facilitate continuous data exchange, allowing operators to monitor system performance and preempt potential issues (Wittrup et al., 2020).

Collectively, these technologies enhance operational resilience and resource utilization, driving a more adaptive and efficient railway system (Yan et al., 2023). Their adoption reflects a broader commitment to innovation, enabling railways to remain competitive and responsive in the modern transportation landscape (Peng et al., 2024).

The adoption of intelligent technologies in railway transportation presents a transformative opportunity but also introduces multifaceted challenges (Wei et al., 2022). Integrating digital twins, AI, and IoT into legacy systems requires significant investment, technical expertise, and robust cybersecurity measures to safeguard sensitive data (Ghasempour & Heydecker, 2020). Additionally, standardizing these technologies across global rail networks poses difficulties, given the diverse regulatory frameworks and operational standards (Xu et al., 2023b). Despite these issues, the benefits like cost reduction and better passenger experience are greater (Chai et al., 2024). By addressing these challenges through strategic innovation and collaboration, the railway industry is poised to unlock a new era of transportation that is safer, more efficient, and aligned with the demands of the 21st century.

Therefore, the primary objective of this review is to critically evaluate the role of emerging technologies in transforming railway transportation research, focusing on their real-world applications and their contribution to system-level improvements. By investigating the impact of AI, IoT, Digital Twins, and autonomous systems on railway safety, efficiency, and sustainability, the review aims to provide a comprehensive understanding of how these technologies are shaping the future of the global rail industry.

Specifically, the objectives of this review are to:

- Identify and categorize the most significant emerging technologies currently influencing railway operations, particularly those focused on safety, efficiency, and sustainability.
- Examine the impact of these technologies on system performance, with a focus on how they improve operational efficiency, reduce environmental impact, and optimize resource use.
- Discuss the application of data-driven insights derived from real-time datasets and their role in enhancing decision-making processes, including predictive maintenance, energy optimization, and demand management.
- Analyze the role of autonomous trains and smart stations in advancing the railway industry, exploring their operational, regulatory, and social implications.
- Explore the challenges faced in integrating emerging technologies into existing rail infrastructures and propose strategies for overcoming these barriers to achieve sustainable, efficient, and safe railway networks.

This review will explore how emerging technologies directly enhance railway system performance in terms of **safety**, **efficiency**, **resource optimization**, and **sustainability**, answering the following key research questions:

Q1: How are emerging technologies such as AI, IoT, and Digital Twins being utilized to enhance safety and operational efficiency in railway systems?

Q2: What impact do emerging technologies have on the overall performance of railway transportation?

Q3: What are the implications of new technologies for optimizing resource consumption and decision-making in rail transport?

Q4: How do emerging technologies contribute to the sustainability and efficiency of rail networks, and what regulatory challenges need to be addressed?

Q5: What role do environmental sustainability goals play in the adoption of emerging technologies in railway transportation, particularly concerning energy optimization and carbon footprint reduction?

Q6: What data-driven strategies are being implemented to improve passenger and freight management, and how do these technologies influence the planning, operation, and control of railway networks?

By addressing these questions, the review will offer valuable insights into the transformative power of emerging technologies in railway systems, providing a roadmap for the continued development of intelligent, data-driven rail transportation systems that are safer, more efficient, and more sustainable.

2. Methodology

This review adopts a comprehensive methodology that begins with data collection and analysis, followed by an examination of temporal and regional trends. The study then progresses to an in-depth exploration of key topics within the domain, offering a thorough understanding of the subject. This structured method provides a broad view of how emerging technologies affect railway performance, sustainability, and regulation. The methodology enables a well-rounded discussion that integrates both theoretical insights and practical applications, contributing to the broader knowledge in this field.

2.1. Review protocol

The initial step in our review is to identify the need for a comprehensive analysis of intelligent railway transportation in the context of emerging technologies. A comprehensive literature search was conducted across multiple databases using strategically selected keywords that accurately represent the core concepts of the study. This approach yielded a substantial collection of scholarly articles, reviews, reports, and surveys – amounting to hundreds of relevant writings. To refine this vast pool of sources, we applied a set of rigorous inclusion and exclusion criteria, ensuring that only the most pertinent and high-quality publications were retained. This process resulted in a final selection of 199 articles that met the specific fo-

Table 1. Review protocol

Entity	Explanation
Keywords Search	Round 1: Railway transportation AND Transportation system AND Technology transportation systems AND Sustainability Round 2: Railway maintenance, Smart rail systems, Emerging technology
Databases Used	Google Scholar, PubMed, Web of Science (WoS), Scopus, and Individual journal homepages
Fields to Search	Title, Keywords, Abstract
Language	English
Criteria of Exclusion	Papers in language other than English, Papers covering the role of emerging technology outside railway transportation
Publication Type	Journal articles, Conference articles, Books, etc.
Time Frame	2015–Present (2025)

cus of our study. All the literature reviewed was sourced from English-language publications, ensuring consistency and accessibility across the selected studies. The search was conducted across several key fields, including the title, abstract, and keywords, allowing for a comprehensive retrieval of relevant works. We further narrowed the search to focus specifically on studies related to intelligent railway transportation systems and their integration with emerging technologies. This structured approach, shown in Table 1, not only ensured that the literature reviewed was relevant to our objectives but also allowed for a deeper understanding of the current state of research in this critical area, forming a solid foundation for the subsequent analysis and discussion of technological advancements in railway systems.

2.2. Literature classification

The research literature on railway transportation is systematically classified based on its applications and objectives. To provide a clear framework for understanding, we have grouped the existing literature into distinct categories that align with direction.

2.2.1. Classification framework based on applications

To highlight the alignment of emerging technologies with practical, real-world improvements and address critical railway transportation challenges, this study categorizes railway transportation research literature into four main groups, further subdivided into 10 specific classes based on their applications, as illustrated in Figure 1. This structured approach ensures a focused analysis of technological advancements and their contributions to the field.

2.2.2. Thematic categorization of objectives

To further refine the understanding of research directions within railway transportation, particularly in the realm of technological studies, this study categorizes objectives into nine distinct areas, as outlined in Table 2. These categories align research efforts with innovations and methodologies driving advancements in the field. By addressing these objectives comprehensively, the study emphasizes their practical implications, highlighting how emerging technologies enhance system-level benefits such as improved operational efficiency, optimized resource utilization, and greater environmental sustainability in railway transportation systems.

2.3. Data collection methods

A comprehensive literature review is conducted to explore the integration of emerging technologies into railway transportation, systems and their impact on performance. The review focused on high-impact journals and relevant publications within the railway transportation domain. To ensure a thorough and systematic approach, data was gathered from multiple sources, including prominent databases such as Google Scholar, PubMed, Web of Science (WoS), Scopus, and individual journal homepages. Additionally, Grey literature, including technical reports and conference proceedings, was also considered to capture emerging trends and practical insights not yet available in peer-reviewed publications. The initial search identified 326 articles, which were detailed screened using specific inclusion criteria focused on relevance to railways and emerging technologies. During the process, 127 articles were excluded due to duplication, unsuitability of the title or abstract, or their lack of focus on the core research area. Reference management tools and database filters were employed to streamline the data acquisition process and enhance the efficiency of literature screening. As a result, 199 articles were finalized for in-depth analysis, with approximately 85% of these sourced from the top ten journals in intelligent transportation systems, underscoring their significance and academic rigor.

This robust and structured approach, illustrated in Figure 2, ensured that the selected studies not only align with the research objectives but also provide meaningful insights into advancements in railway transportation. With diverse tools and platforms for data collection and curation, the review integrates both theoretical and practical knowledge, offering a comprehensive understanding of the transformative role of emerging technologies in modern railway transportation.

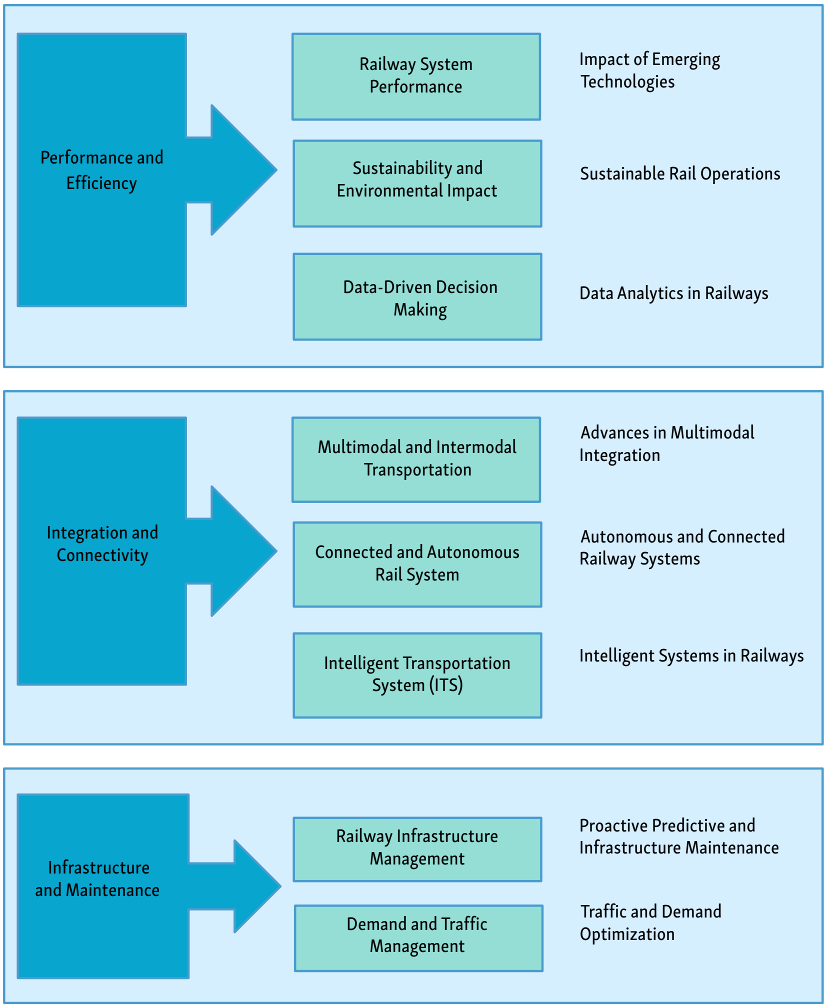

Figure 1. Literature classification

Table 2. Literature classification based on objectives

Objective	Description	Key Methods/Technologies	Key Contributions
Efficiency Improvement (Wittrup et al., 2020; Peng et al., 2024)	Enhancing operational efficiency, reducing costs, and optimizing resource allocation.	Predictive Maintenance, IoT, Big Data	Improved resource management, reduced operational downtime, and cost savings.
Safety Enhancement (Minh et al., 2022; Matzka, 2020; Speith, 2022; J. Zhang & J. Zhang, 2023)	Strengthening safety measures, reducing accidents, and improving surveillance in rail systems.	Autonomous Systems, Safety Monitoring, Cybersecurity	Enhanced incident detection, risk assessment, and overall safety in rail operations.
Sustainability and Environmental Impact (Ficzere, 2023; Wang et al., 2025a; Sikora et al., 2021)	Reducing environmental footprints and promoting sustainable practices in railway operations.	Energy Efficiency, Green Infrastructure	Lower emissions, improved energy use, and adoption of sustainable technologies.
Predictive Maintenance (Wei et al., 2022; Hadj-Mabrouk, 2019; Abduljabbar et al., 2019; Sharon Femi et al., 2023; Qiu et al., 2025b; De Donato et al., 2022; Yin et al., 2020)	Early fault detection and preventive maintenance to minimize disruptions and costs.	Machine Learning, IoT Sensors, Predictive Analytics	Reduced downtime and optimized infrastructure life cycle management.
Multimodal Integration (Fang et al., 2021; Moudgil et al., 2023; Attar et al., 2024; Saravanan et al., 2024; Bisio et al., 2024)	Seamlessly integrating rail with other transport modes for enhanced connectivity.	Traffic Management Systems, Intermodal Platforms	Increased efficiency in multimodal transport, reducing passenger travel times and logistical delays.

End of Table 2

Objective	Description	Key Methods/Technologies	Key Contributions
Real-Time Operations Management (Yan et al., 2023; Singh et al., 2022; Jo et al., 2018)	Optimizing traffic flow, scheduling, and decision-making through real-time data processing.	AI, Machine Learning Algorithms, Real-Time Data	Improved operational control and network performance through dynamic, data-driven strategies.
Cybersecurity in Railway Systems (Wang et al., 2025b; Zaheer et al., 2025b; Zhong et al., 2021)	Securing railway networks against cyber threats and safeguarding operational data.	Blockchain, Network Security, Cyber-Physical Systems	Reduced cyber vulnerabilities, ensuring uninterrupted and secure railway operations.
Passenger Experience Enhancement (Ficzere, 2023; Zaheer et al., 2025a; Li et al., 2017; Luo et al., 2019; Wang, 2024g)	Improving travel experience through accessibility, comfort, and reliability.	Smart Ticketing, IoT, User-Centric Platforms	Enhanced passenger satisfaction and streamlined travel processes.
Infrastructure and Asset Management (Li et al., 2017; Adom & Mahmoud, 2024; Qiu et al., 2025a, 2025c, 2025d; Fraga-Lamas et al., 2017)	Maintaining and improving railway assets through innovative management techniques.	Remote Sensing, Asset Management Platforms	Enhanced asset durability and efficient rehabilitation planning.

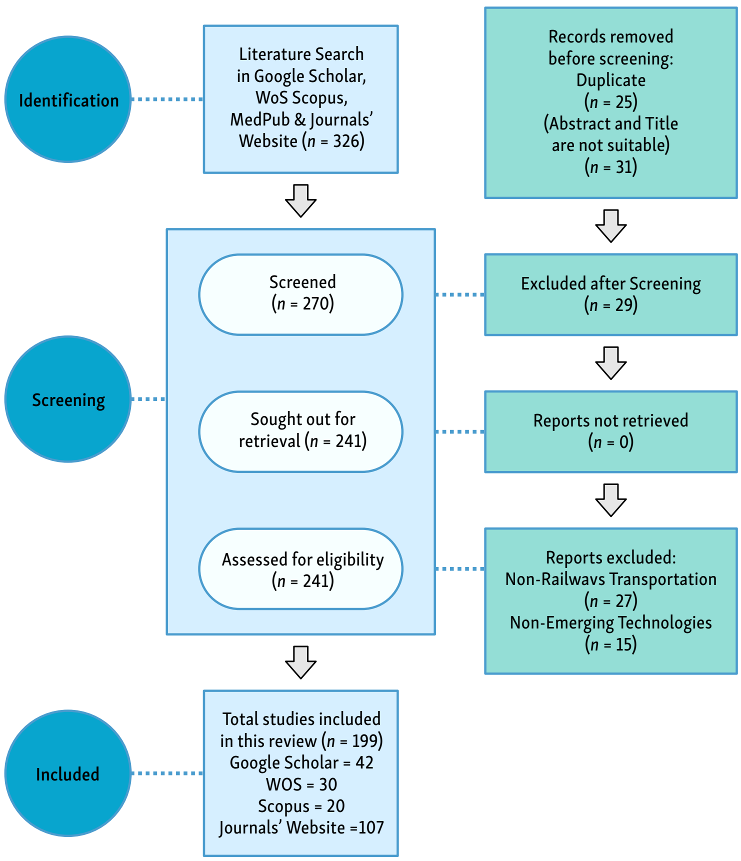

Figure 2. Articles selection

2.3.1. Keyword selection and search strategy

This review employed a targeted keyword strategy to focus on railway transportation performance rather than merely technological advancements. Emphasizing practical applications in railway systems, the strategy targeted areas like predictive maintenance, operational efficiency, safety, and sustainability. Keywords were selected to capture themes such as data-driven insights, energy efficiency, resource optimization, and the environmental and social impacts of railway technologies. The approach emphasized system-level outcomes such as multimodal integration and sustainability, linking technologies like IoT and AI to measurable improvements in planning, operations, and control. By aligning theoretical advancements with tangible benefits such as resource optimization, environmental impact reduction, and enhanced passenger experience, the search strategy ensured a practical and focused literature selection. Table 3 lists the full set of keywords used.

2.3.2. Data sources and filters (Year, Objectives, Classes)

The data for this study was collected from credible sources, including peer-reviewed journals and academic databases like Google Scholar, Web of Science, and Scopus, ensuring high-quality research reflecting the latest advancements in railway systems and emerging technologies. Studies published from 2015 onward were prioritized to capture recent developments in AI, IoT, digital twins, autonomous systems, and other innovations influencing railway transportation.

The selection process focused on research addressing real-world improvements, such as safety, efficiency, and sustainability, and aligned with themes like predictive maintenance, intelligent transportation systems, multimodal integration, and environmental sustainability. Articles were filtered using predefined criteria, emphasizing studies from top-tier journals and those offering significant insights or addressing critical gaps. A manual review by researchers ensured consistency, relevance, and the removal of redundancies. A classification framework was developed to organize studies by primary applications and research objectives, enabling the identification of trends, advancements, and gaps. This structured approach provides a comprehensive perspective on how emerging technologies transform railways while addressing broader challenges like sustainability, efficiency, and multimodal integration.

2.4. Bibliometric and analytical techniques

Data analysis employs two complementary methods: manual analysis for detailed, context-aware review, and bibliometric techniques supported by statistical tools to provide broad, data-driven insights. Citation and author network analyses revealed influential studies, leading contributors, and collaboration patterns, providing a detailed understanding of the research landscape. Visualization tools like VOS viewer highlighted key topics and evolving focus areas, enabling a clearer understanding of research trends. This comprehensive analysis forms the foundation for the critique in Sections 3 and 4 and provides insights to shape future research agendas and policy recommendations, aligning emerging technologies with the practical needs of modern railway systems.

2.4.1. Top journals articles

The analysis of publication trends (2015–2025) highlights the evolution of intelligent railway systems research and the contributions of leading journals. *Transportation Research Part C*: *Emerging Technologies* leads with 42 articles, followed by *IEEE Transactions on Intelligent Transportation Systems* with 41, both pivotal in advancing innovation in automation, safety, and predictive maintenance. *Automation in Construction* also made significant contributions, particularly from 2021 to 2023, focusing on automation and infrastructure-related studies. Moderate contributions come from *Transportation Research Part A* and *Part B*, emphasizing policy-oriented research and methodological advancements. The rise of multidisciplinary journals in the "Others" category signals the field's growth, attracting interest from domains like engineering, data science, and urban planning. Figure 3 illustrates that the dominance of specialized journals, along with growing diversification, signifies the field's maturity and interdisciplinary expansion, focusing on practical applications like efficiency, safety, and sustainability.

2.4.2. Objectives

The objectives of the selected literature, as outlined in Section 2.2.2, aim to comprehensively analyze research focus areas, identify emerging trends, and evaluate technological advancements in alignment with operational priorities within intelligent railway systems. Based on the data from the 199 selected articles, the primary research focus areas demonstrate a balanced distribution across several critical domains, as illustrated in Figure 4. It has been analyzed that Efficiency Improvement and Predictive Maintenance emerge as the top priorities, each comprising 18% of the total publications. This reflects a strong interest in optimizing railway systems to enhance operational performance and ensure long-term sustainability. Safety Enhancement follows closely at 15%, underscoring the essential role of advancing safety measures in railway infrastructure and technology. Sustainability and Environmental

Table 3. Keywords for literature selection

Category	Keywords
Transportation Systems	transportation systems, railway infrastructure, railway safety
System Performance	predictive maintenance, operational efficiency, system resilience
Emerging Technologies	IoT in railways, digital twins, AI-driven optimization, autonomous trains
Sustainability and Impact	sustainability in transportation, resource efficiency, green transportation technologies
Data-Driven Insights	real-time monitoring, big data in transportation, data-driven decision-making
Applications	demand management, transportation planning, railway control systems
Environment and Social	environmental impacts of railways, social impacts of rail transport
Innovations	digital transformation in transportation, smart rail systems, energy-efficient railways

Impact account for 14%, emphasizing the increasing integration of eco-friendly and energy-efficient technologies in modern railway systems. Real-Time Operations Management and Infrastructure and Asset Management each represent 10% of the research focus, highlighting the industry's drive toward improving system reliability through real-time tracking, monitoring, and effective asset management. Passenger Experience Enhancement constitutes 9%, reflecting efforts to improve user satisfaction, while Multimodal Integration, at 4%, showcases the growing focus on connecting various transportation modes to create seamless mobility solutions. Finally, Cybersecurity in Railway Systems, with a 2% share, highlights the emerging recognition of the need to protect critical infrastructure from cyber threats. This diverse distribution of research objectives, detailed in Figure 4, provides a clear picture of the evolving priorities in intelligent railway systems, balancing operational challenges with innovative technological solutions across multiple dimensions.

2.4.3. Bibliometric and statistical tools

The Web of Science (WoS) and PubMed databases were the primary sources for identifying high-quality research relevant to the defined keywords. Extracted data was converted into text files and imported into VOSviewer for trend analysis. A manual review was conducted to filter out irrelevant keywords and data, ensuring alignment with the study's objectives. Using this refined dataset, bibliometric networks were created, as shown in Figures 5 and 6, to map the distribution and influence of authors, citations, and collaborations within intelligent railway transportation research. These visualizations highlight key contributors, emerging trends, and significant works, offering insights into dominant themes and paving the way for identifying research gaps and future opportunities.

3. Regional and temporal trends in railway research

The regional and temporal trends in railway transportation research have displayed distinct patterns of development and emphasis across different periods. These trends not only reflect the evolving state of railway technologies but also provide valuable insights into how regions around the world are prioritizing various aspects of transportation system modernization and sustainability. As technological advancements have accelerated over the years, the volume of research has steadily increased, particularly between 2018 and 2023, which can be attributed to the rapid

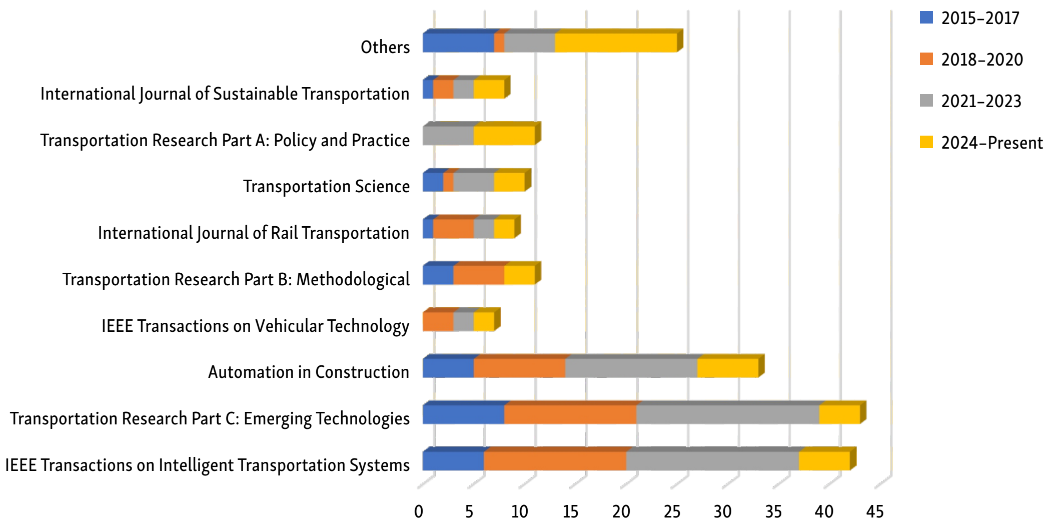

Figure 3. Selected journals

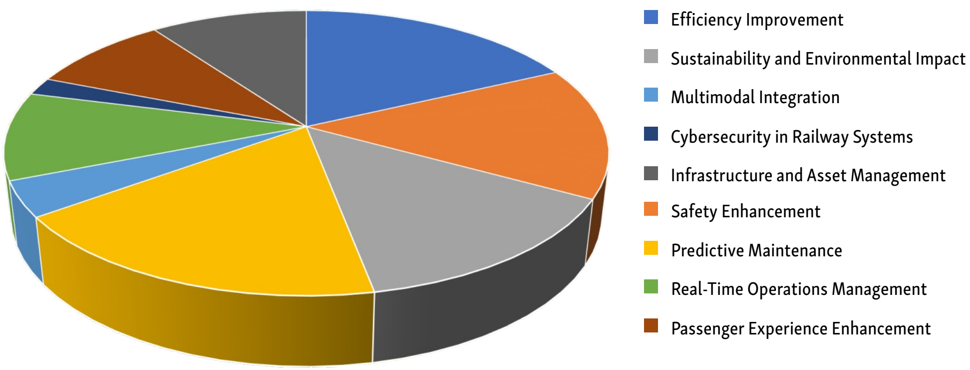

Figure 4. Articles distribution based on research objectives

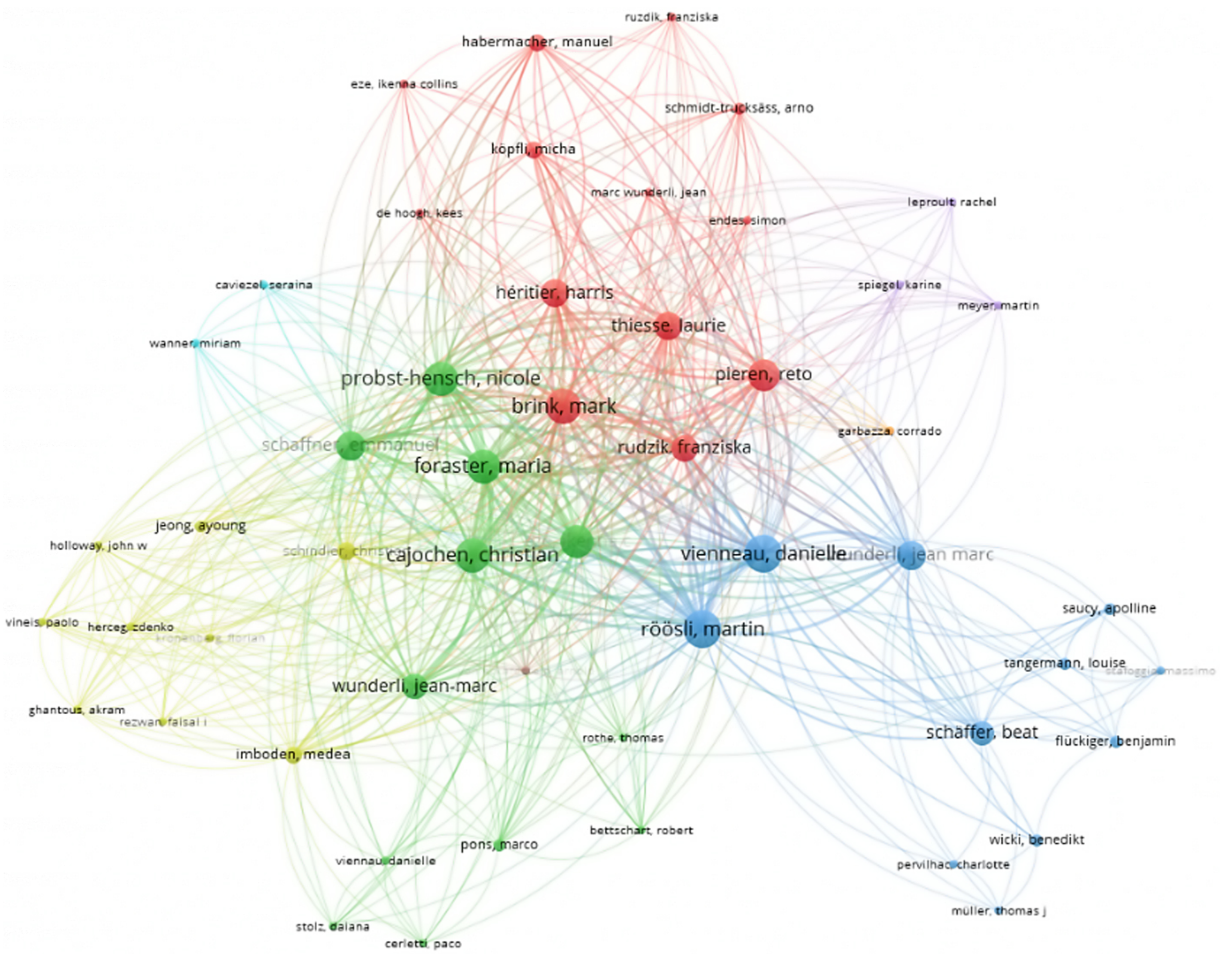

Figure 5. Authors in railway transportation research

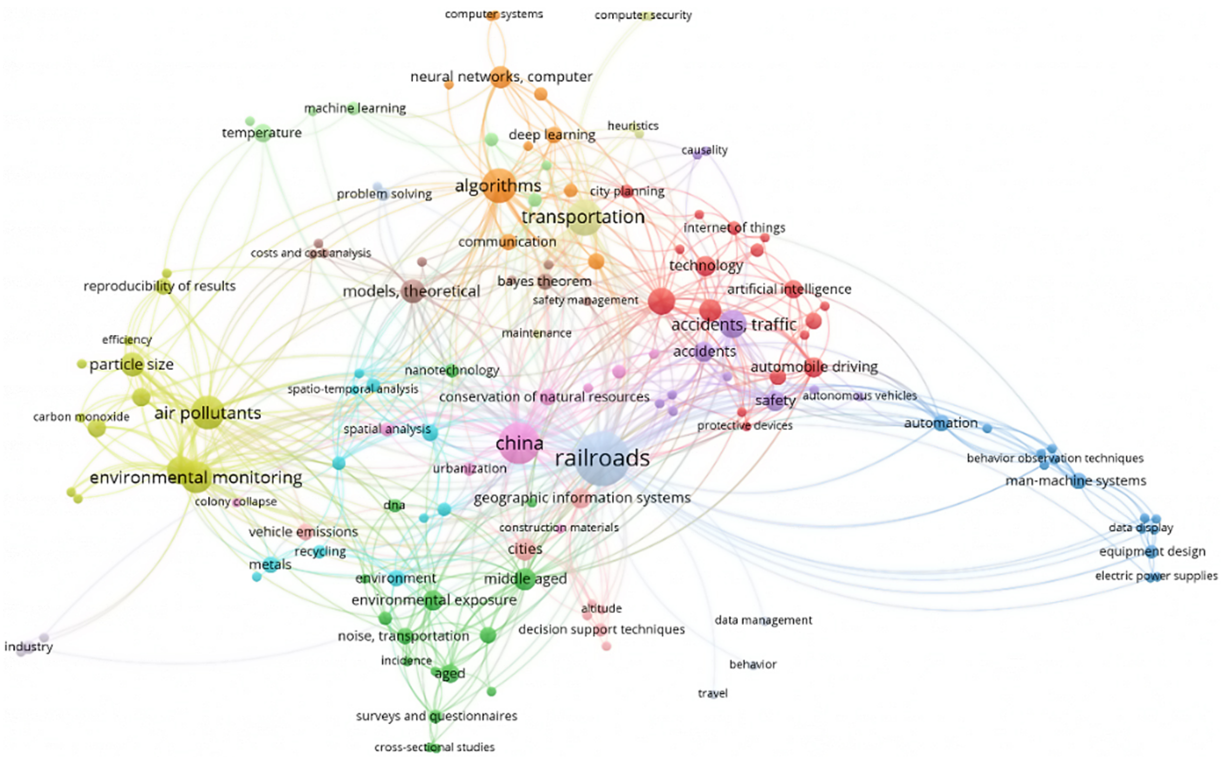

Figure 6. Citations in railway transportation research

adoption of AI, IoT, and machine learning in railway systems. The 2024 data, although from a single year, indicates continued momentum in the field, with a more specialized focus emerging, particularly on issues like cybersecurity and system optimization.

3.1. Research evolution (2015–2025)

The evolution of intelligent railway systems research from 2015 to 2024 reveals a dynamic shift driven by technological advancements, industry demands, and environmental goals. Research output steadily increased, reflecting a growing focus on efficiency, sustainability, and safety in railway systems.

Between 2015 and 2017, 33 articles laid the foundation by exploring emerging technologies like automation, real-time monitoring, and AI-driven decision-making, primarily targeting efficiency, predictive maintenance, and safety. From 2018 to 2020, research accelerated with 52 publications, emphasizing the integration of machine learning, IoT, and real-time analytics into railway operations, alongside sustainability and multimodal transport integration. The 2021–2023 period marked a peak with 68 articles, focusing on optimizing technologies to address broader challenges like infrastructure management, passenger experience, and cybersecurity. By 2024, although publications dipped to 46, research became more specialized, advancing AI, IoT, and sustainability while prioritizing cybersecurity in interconnected railway systems. Figure 7 illustrates this growth and evolution.

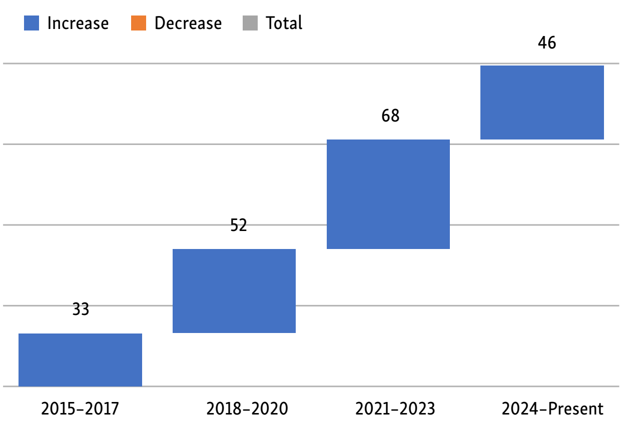

Figure 7. Publications per year

3.2. The shift from safety to efficiency, sustainability, and data-driven models

Over the past decade, research themes in railway transportation have shifted from safety-focused initiatives to efficiency, sustainability, and data-driven solutions. In 2015–2017, research primarily addressed safety, predictive maintenance, and reliability, tackling foundational challenges in operational risk reduction. As technologies like AI, IoT, and digital twins gained traction from 2018 to 2020, priorities shifted to system efficiency, energy optimization, and sustainability, reflecting a growing emphasis on eco-friendly operations.

From 2021 to 2023, research matured with 68 articles emphasizing predictive analytics, real-time monitoring, multimodal transport integration, infrastructure management, and passenger experience. Innovative applications of machine learning, IoT-based monitoring, and automated control systems addressed challenges associated with urbanization and environmental pressures. These technologies also contributed to enhanced network performance and reduced environmental impact. By 2024, research refined its focus, centering on predictive maintenance, efficiency, and sustainability, while advancing data-driven models for real-world applications. Cybersecurity emerged as a critical theme, addressing vulnerabilities in digital railway infrastructures. As Figure 8 illustrates, the shift from safety-focused research to efficiency and sustainability aligns with global technological and environmental goals. It highlights the growing role of intelligent railway systems in addressing climate change, energy efficiency, and urban connectivity. This shift underscores the sector's increasing sophistication and adaptability in creating sustainable and interconnected transportation systems.

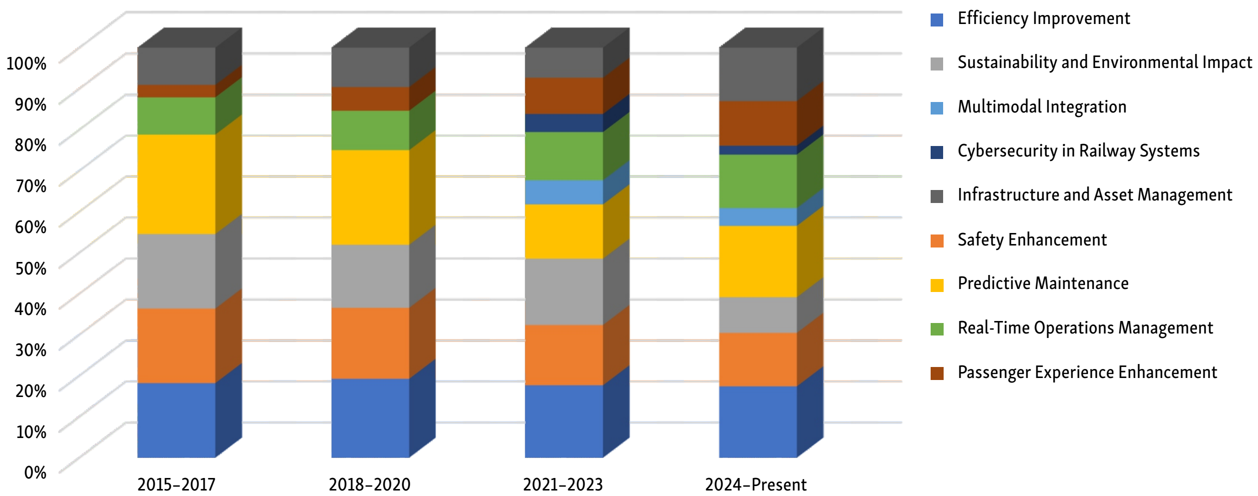

Figure 8. Year-wise trends in research objectives

3.3. Regional research dynamics

Railway transportation research differs considerably across continents, shaped by regional priorities, technological capabilities, and national policies. Collaboration among research institutions, governments, and industry stakeholders plays a critical role in advancing the field. Asia leads globally with 87 publications, driven by a focus on high-speed rail, automation, and AI-enabled traffic control. Collaboration in Asia is robust, with universities, research centers, and railway companies working together to accelerate technological developments in areas such as IoT integration, safety, and automation for smart rail systems. Europe follows with 43 publications, prioritizing sustainability and energy efficiency. Regional collaborations are facilitated by initiatives like the European Union's Green Deal, promoting partnerships across borders to tackle challenges such as carbon emission reduction, multimodal integration, and smart railway solutions. Research institutions, government bodies, and railway industries work collectively on advancing energy-efficient technologies, automation, and data-driven operational improvements across the continent.

Similarly, North America, with 27 publications, focuses on enhancing freight rail systems and modernizing aging infrastructure. Academic researchers, government agencies, and private technology developers collaborate to integrate AI, IoT, and machine learning into railway operations, driving progress in predictive maintenance, real-time monitoring, and energy management. These partnerships emphasize operational efficiency and sustainability within the region. Emerging contributors include Australia with 14 publications, where collaborations between academic institutions and government agencies focus on safety and infrastructure optimization. South America (8 publications) and Africa (6 publications) emphasize foundational research and development, with partnerships aimed at addressing safety, efficiency, and infrastructure challenges. These regions are gradually building capacity through collaborations that focus on adapting railway systems to local needs and constraints.

Across all continents, the increasing emphasis on collaboration reflects the global nature of challenges such as sustainability, multimodal integration, and operational resilience. Figure 9 illustrates the regional dynamics and their contributions to advancing intelligent railway systems.

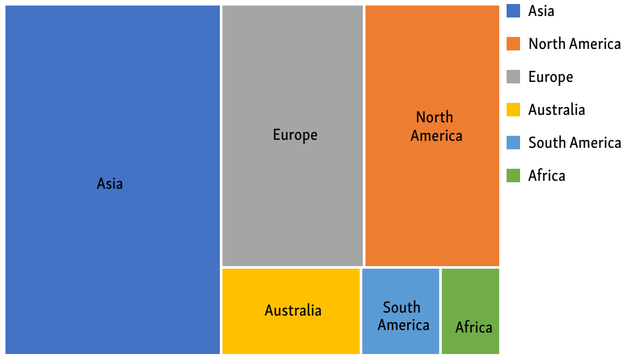

Figure 9. Regional contribution

3.4. Country-specific trends

Research trends in railway transportation vary by country, shaped by national policies and investments. China leads globally with 43 publications, driven by government initiatives and investments in high-speed rail, focusing on AI, automation, and IoT for predictive maintenance, traffic management, and train control. Germany, with 12 publications, emphasizes energy-efficient systems and predictive maintenance, aligned with sustainability goals. France, contributing 6 papers, focuses on high-speed rail innovations, including energy recovery and automated control, in line with its sustainability initiatives. The UK's 9 publications prioritize smart passenger management, AI-driven asset management, and data-driven optimization. Japan's research, led by its Shinkansen system, focuses on safety, seismic resilience, and AI-enhanced infrastructure.

In North America, the US produces 27 publications on modernizing freight rail, focusing on predictive maintenance, IoT, and freight logistics. Canada, with fewer publications, targets environmental sustainability, promoting electric trains and renewable energy integration. South Korea prioritizes IoT and automation, while Australia, with 14 publications, focuses on railway safety and infrastructure optimization. Overall, government policies play a key role in shaping the direction of railway research, reflecting priorities like sustainability, safety, and technological advancement. Detailed statistics are given in Figure 10.

4. Technological innovations in railways

The railway transportation sector is undergoing a significant transformation, driven by the rapid advancement of emerging technologies that promise to improve operational efficiency, safety, sustainability, and the overall passenger experience. Innovations such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, autonomous systems, and advanced predictive analytics are reshaping how railways are planned, operated, maintained, and optimized. These technologies not only address operational challenges but also align with global trends of environmental sustainability and smart infrastructure development. However, integrating these technologies into existing, often complex, railway systems presents both opportunities and challenges. As railways move toward becoming highly digitalized and automated networks, these advancements not only improve individual components but also influence system-wide performance, fostering a shift towards smarter, more connected, and more sustainable transportation systems. In this section, we explore the impact of AI, IoT, and other technologies on railway performance, system-level outcomes, and their broader implications for the transportation sector.

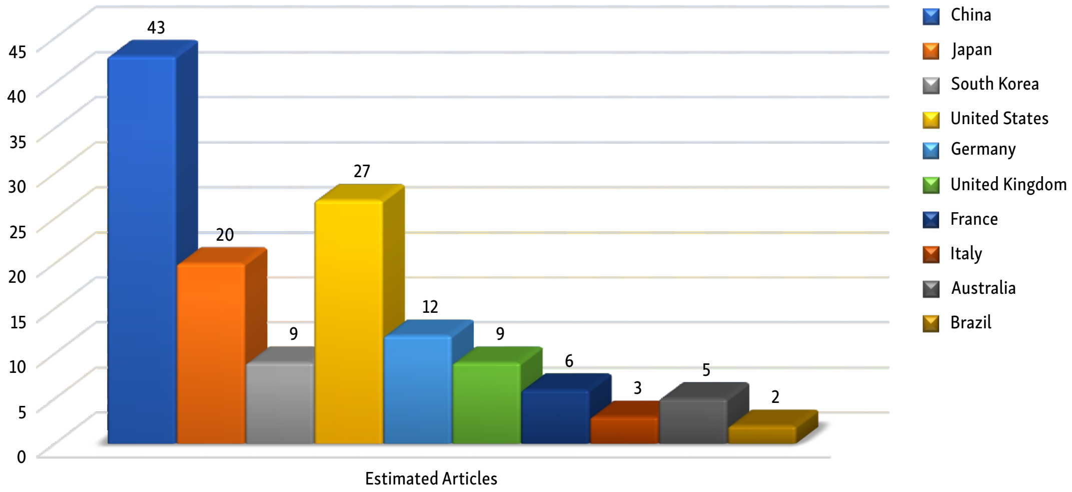

Figure 10. Country-wise contributions

4.1. Artificial Intelligence (AI) in railways

As the railway industry increasingly embraces digitalization, Artificial Intelligence (AI) plays a pivotal role in driving operational efficiency, optimizing decision-making, and improving system reliability. The emergence of Artificial Intelligence (AI) and Machine Learning (ML) is profoundly transforming the railway transportation sector. These technologies support innovations in traffic management, predictive maintenance, demand forecasting, and safety systems. As a result, they are redefining both operational efficiency and passenger satisfaction. Leveraging large-scale datasets from trains, tracks, and stations, AI not only enhances decision-making capabilities but also ensures the reliability and sustainability of railway networks (Tang et al., 2022). This section delves into the multifaceted applications of AI in railways, supported by key research findings and practical implementations.

Artificial Intelligence (AI) is revolutionizing railway operations by significantly outperforming traditional control systems in both scheduling and maintenance domains. In terms of scheduling, conventional rule-based or heuristic systems often result in average train delays of approximately 4.5 to 5 minutes per train. However, studies using deep reinforcement learning and genetic optimization for rescheduling – based on real-world railway scenarios – have reduced delays to about 1.8 to 2 minutes, representing a 60–65% decrease in delay times and enabling up to a 30% increase in overall network throughput (Argyroudis et al., 2022). When it comes to predictive maintenance, operators like Deutsche Bahn have implemented AI-powered systems (e.g., Konux) that monitor infrastructure components and analyze condition data. These systems have achieved ~25% reduction in maintenance costs and up to 50% fewer failure-causing incidents, thereby improving system reliability and availability (Pan & Zhang, 2021). Industry-wide statistics further suggest that AI-based predictive maintenance can reduce unplanned downtime by 20–30%, enhance asset utilization by up to 27%, and extend equipment lifespan by 15% (Minh et al., 2022). Collectively, these results substantiate AI's transformative impact on railway efficiency, cost effectiveness, and service resilience – offering clear superiority over legacy control and maintenance practices.

Real-world deployments of AI in operational railway systems underscore the practical relevance of these technological advancements (Matzka, 2020). For instance, SNCF, the French national railway company, utilizes AI for predictive maintenance, where machine learning models analyze sensor data from trains and infrastructure to anticipate failures before they occur. Similarly, Indian Railways has piloted AI-based surveillance systems at major stations for facial recognition and crowd control, enhancing both safety and operational oversight. In the United States, Amtrak leverages AI tools for customer demand forecasting, helping to optimize schedules and resource allocation. These cases reflect the growing integration of AI across diverse functions in real-world railway networks, illustrating the feasibility and impact of AI technologies beyond theoretical research (Speith, 2022).

One of the most prominent applications of AI in railways lies in traffic management systems, where real-time data analytics drive operational efficiency. AI-based tools optimize train schedules, reduce delays, and manage peak traffic conditions effectively. For example, advanced AI algorithms dynamically adjust train operations based on predicted demand, ensuring higher throughput and minimized congestion. J. Zhang and J. Zhang (2023) emphasized the integration of big data analytics and digital twins into traffic management systems, creating advanced platforms for real-time decision-making. These systems utilize autonomous adjustments, such as modifying traffic signals and rerouting trains, which collectively enhance the safety and fluidity of railway operations. Such advancements in AI have demonstrated their efficacy in streamlining complex systems, paving the way for smarter and more adaptive transportation networks.

Predictive maintenance is another domain where AI and ML have shown transformative potential. By analyzing sensor data from critical railway components, these technologies identify patterns and anomalies that indicate potential failures. This proactive approach minimizes unscheduled downtimes and extends the lifespan of railway infrastructure. Ficzere (2023) highlighted AI-driven maintenance systems as vital for optimizing resource allocation and reducing service disruptions. Deep learning models have further advanced this field, enabling precise detection of critical anomalies, such as defects in rail tracks and fasteners. These innovations address long-standing challenges in maintaining complex railway networks while ensuring the highest safety standards (Wang et al., 2025a).

AI's contribution to safety systems has also been noteworthy. Advanced surveillance technologies powered by AI are revolutionizing safety protocols, particularly at railway crossings. Systems like the Artificial Intelligence-based Surveillance System for Railway Crossing Traffic (AISS4RCT) employ deep learning models, such as YOLO, to detect vehicles, pedestrians, and potential hazards in real-time. Sikora et al. (2021) demonstrated that such systems achieve a high recall rate of 89%, significantly reducing the likelihood of accidents and ensuring compliance with safety regulations. These technologies exemplify how AI enhances not only operational safety but also public confidence in railway transportation systems.

Furthermore, demand forecasting has emerged as a critical application of AI in urban rail systems. AI models accurately predict passenger flow, enabling better capacity planning, resource allocation, and enhanced passenger experiences. Real-time forecasting supported by ML techniques minimizes overcrowding and underutilization, ensuring reliable services (Hadj-Mabrouk, 2019). Abduljabbar et al. (2019) suggested that integrating AI models into rail transport policies and revenue management could further optimize system efficiency, though these areas require additional exploration. Such forecasting models are indispensable for aligning operational strategies with dynamic passenger behaviors, ensuring adaptability and scalability in urban transit systems.

Despite these advancements, the adoption of AI in railways is not without challenges. Fragmented and outdated datasets often limit the efficiency of AI algorithms, while the computational demands of advanced models strain existing infrastructure (Sharon Femi et al., 2023). For example, deep learning models used in fault detection, object recognition, and predictive maintenance often require high computational resources, such as GPUs or edge accelerators, which are typically not available in trackside or onboard systems. This limitation affects the deployment of AI in real-time applications where latency and energy efficiency are critical. To address this, researchers are adopting lightweight architectures such as MobileNet, Tiny-YOLO, and model optimization techniques like pruning and quantization to enable faster inference on low-power devices without significantly compromising accuracy (Qiu et al., 2025b).

Additionally, the "black box" nature of many AI systems raises concerns about transparency and accountability, particularly in safety-critical applications. De Donato et al. (2022) highlighted the importance of developing explainable AI models that provide clarity in decision-making processes, thereby fostering trust among stakeholders. Tools such as saliency maps, attention mechanisms, and interpretable feature attributions can help visualize how models arrive at specific predictions, making them more trustworthy and verifiable – especially in applications like rail defect detection or automated signaling systems. Cybersecurity threats to AI-driven systems also pose significant risks, emphasizing the need for robust frameworks to safeguard against potential breaches. Addressing these challenges requires concerted efforts in research, infrastructure modernization, and policy-making to ensure the ethical and sustainable integration of AI in railway systems.

AI holds immense potential to transform railway transportation by addressing critical challenges and driving innovation across various domains. From enhancing traffic management and predictive maintenance to improving safety systems and demand forecasting, AI-enabled technologies offer unparalleled advantages in optimizing railway operations. However, realizing the full potential of AI requires addressing existing barriers, such as data fragmentation, transparency concerns, and cybersecurity risks. As Yin et al. (2020) noted, AI integration is a pivotal step toward building a more efficient, reliable, and sustainable railway transportation ecosystem, paving the way for a future where technology and infrastructure coexist seamlessly to meet evolving demands. Thus, AI not only streamlines operations but also aligns with the broader goal of creating more efficient, sustainable, and adaptive railway systems that can meet the challenges of the 21st century.

4.2. Internet of Things (IoT) and sensor technologies

While AI enhances decision-making, the Internet of Things (IoT) enables the foundational connectivity required for real-time monitoring, a crucial component in achieving operational efficiency and safety. The advent of the Internet of Things (IoT) has redefined the landscape of railway transportation, playing a pivotal role in addressing the growing demands for speed, safety, efficiency, and sustainability. As a hallmark of the Fourth Industrial Revolution, IoT merges cutting-edge technologies such as Artificial Intelligence (AI), cloud computing, and big data analytics to establish intelligent and interconnected railway networks (Fang et al., 2021). This integration fosters a seamless exchange of information across diverse systems, enhancing the operational reliability and responsiveness of railway infrastructures. The convergence of IoT and sensor technologies complements AI advancements by enabling real-time data acquisition, analysis, and decision-making (Moudgil et al., 2023). Together, these technologies contribute to the creation of "smart railways", characterized by enhanced performance, improved safety standards, and superior passenger experiences.

Real-world deployments of IoT technologies in railway systems demonstrate the tangible impact of these innovations (Attar et al., 2024). For example, Deutsche Bahn in Germany has implemented IoT-based condition monitoring systems that continuously track the health of tracks, switches, and rolling stock, allowing for timely maintenance and operational adjustments. In China, CRRC Corporation utilizes smart onboard IoT sensors in high-speed trains to monitor mechanical stress, temperature, and vibration, enabling efficient fault detection (Saravanan et al., 2024). The UK's Network Rail has adopted IoT sensors for monitoring bridges, tracks, and signaling infrastructure, integrating real-time data into their asset management platforms. These deployments highlight the maturity of IoT applications in enhancing operational safety, reducing maintenance costs, and increasing system reliability, reflecting the growing global trend toward intelligent, connected railway ecosystems (Bisio et al., 2024).

IoT technologies enable railway systems to transition from traditional, mechanical operations to highly responsive, data-driven networks. Through real-time monitoring and communication, IoT facilitates comprehensive insights into railway operations, infrastructure conditions, and passenger behaviors. Singh et al. (2022) provide a detailed analysis of IoT applications, highlighting their role in the real-time monitoring of key parameters such as track health, rolling stock conditions, and safety at railway level crossings. Emerging trends in IoT, such as low-power wide-area networks (LPWAN) and fifth-generation (5G) communication technologies, further improve connectivity while reducing energy consumption. These innovations align with the railway industry's commitment to sustainability, supporting environmentally responsible practices and promoting energy-efficient operations.

A critical advantage of IoT in railway systems lies in its capacity to enable predictive maintenance, which significantly reduces downtime compared to traditional periodic maintenance approaches. While conventional periodic maintenance follows fixed schedules regardless of asset conditions, often leading to unnecessary inspections or unexpected failures, resulting in 20–30% higher downtime, IoT-enabled predictive maintenance leverages continuous sensor data and real-time analytics to identify potential faults before failure occurs. This proactive maintenance strategy can reduce unplanned downtime by up to 50%, cut maintenance costs by 25–35%, and improve asset lifespan by 15–20% (Jo et al., 2018). For instance, the European Rail Traffic Management System reported a 40% decrease in track-related incidents after deploying IoT-based predictive maintenance technologies, underscoring their operational and safety benefits. These data-driven insights enable railway operators to schedule maintenance activities more efficiently, avoid costly disruptions, and enhance overall system reliability.

One of the most transformative applications of IoT lies in real-time condition monitoring and predictive maintenance. The integration of cost-effective sensors and IoT gateways allows railway systems to gather continuous data on infrastructure and rolling stock conditions. This data-driven approach minimizes unplanned downtimes, prevents equipment failures, and optimizes maintenance schedules. Jo et al. (2018) emphasize the significance of IoT-enabled Intelligent Rail Inspection Systems (IRIS), which leverage big data analytics to optimize inspection routines, thereby extending the lifespan of railway assets and enhancing operational efficiency. Furthermore, IoT networks enable the identification of safety-critical anomalies, such as rail defects or environmental hazards, facilitating timely interventions that ensure the safety and reliability of railway operations (Wang et al., 2025b).

In addition to predictive maintenance, IoT has revolutionized environmental and structural monitoring within railway systems (Zaheer et al., 2025b). Through advanced IoT architectures tailored for high-speed railways, such as the framework proposed by Zhong et al. (2021) railway operators can integrate distributed reinforcement learning and blockchain technologies. These systems enhance data security, energy efficiency, and multitarget tracking, allowing railway systems to adapt dynamically to changing operational demands. For example, such architecture can optimize traffic flow in real-time while maintaining safety and energy efficiency, addressing the unique challenges of modern railway systems, particularly in high-speed operations.

The shift towards IoT-enabled smart railways has redefined operational paradigms by introducing advanced technologies such as communication-based train control (CBTC) and the global system for mobile communication for railways (GSM-R) (Zaheer et al., 2025a). These technologies facilitate seamless communication between trains, infrastructure, and control centers, enabling real-time optimization of operations. Li et al. (2017) underscore the role of IoT in achieving the "five-higher" goals of modern railways: higher speed, capacity, safety, quality, and efficiency. Complemented by big data analytics, these systems provide actionable insights that improve decision-making processes, enhance passenger services, and ensure the efficient utilization of resources. For instance, dynamic scheduling systems empowered by IoT predict passenger flow patterns, enabling operators to reduce overcrowding and improve travel experiences. Luo et al. (2019) proposed an intelligent public transportation framework that integrates IoT-based scheduling for subways, buses, and shared mobility options, demonstrating its potential to optimize passenger flow and resource utilization while minimizing travel times (Wang et al., 2024g).

IoT applications also extend to the development of green and sustainable railways, a critical priority in the modern transportation landscape. Adom and Mahmoud (2024) highlight the role of green IoT solutions in achieving energy efficiency and eco-friendly operations. From employing renewable energy sources to designing systems that minimize carbon footprints, IoT-driven strategies have proven indispensable in advancing sustainability goals. By optimizing energy usage through data-driven monitoring and smart grid integration, IoT fosters a transition to environmentally conscious railway systems (Qiu et al., 2025c).

Despite its transformative potential, the widespread adoption of IoT in railways is not without challenges. Interoperability issues, stemming from the lack of standardized data formats and incompatible systems, remain a significant barrier to seamless integration (Wang et al., 2025a). High implementation costs and the need for substantial infrastructural upgrades further complicate IoT deployment. Additionally, real-world challenges like latency and bandwidth limitations significantly affect large-scale IoT deployments in railways. Latency – the delay between data generation and processing – can impact time-critical applications such as emergency responses and real-time traffic control, risking safety and efficiency (Qiu et al., 2025a). Bandwidth constraints limit the volume and frequency of sensor data transmitted, reducing the detail available for predictive maintenance and anomaly detection. Railway environments with tunnels and complex terrain also cause signal interference and network congestion, further affecting communication reliability. To mitigate these issues, edge computing processes data locally, reducing latency, while data prioritization and compression optimize bandwidth use. Emerging 5G networks offer ultra-low latency and high capacity but require substantial investment and infrastructure upgrades (Qiu et al., 2025d). Addressing these challenges is essential to fully realize IoT's benefits in smart railway systems. Additionally, concerns about data security and privacy pose risks to the reliability of IoT-driven operations. However, advancements in technologies such as blockchain, combined with the expansion of LTE and 5G networks, offer promising solutions to these challenges. Fraga-Lamas et al. (2017) and Ushakov et al. (2022) emphasize the need for collaboration between researchers, policymakers, and industry stakeholders to address these issues and unlock IoT's full potential.

Looking forward, the railway transportation sector must focus on developing innovative solutions to overcome existing challenges and expand the scope of IoT applications. Future research should prioritize the standardization of data formats, enhance interoperability across systems, and explore advanced communication protocols. Additionally, the integration of IoT with emerging technologies like edge computing and quantum cryptography could further enhance the scalability and security of IoT-driven railway networks. By addressing these critical areas, the railway industry can ensure the continued evolution of IoT technologies, driving the transformation of railway transportation into a safer, more efficient, and sustainable mode of travel.

The Internet of Things has emerged as a cornerstone of modern railway transportation, revolutionizing operations through real-time monitoring, predictive maintenance, and smart infrastructure management. By fostering seamless communication and data exchange, IoT enables railway systems to meet the growing demands for efficiency, safety, and sustainability. While challenges remain, ongoing advancements and collaborative efforts promise to unlock the full potential of IoT, positioning it as an indispensable component of the railway networks of the future. Ultimately, IoT's ability to provide real-time data from infrastructure and rolling stock empowers operators to make proactive decisions, directly contributing to the system's overall safety and efficiency.

4.3. Digital Twin technology in railways

Building on the insights provided by IoT, Digital Twin technology takes this data further by creating virtual models of the railway network, enabling advanced simulations that are crucial for both operational efficiency and predictive maintenance. As railway systems continue to evolve in complexity, Digital Twin (DT) technology emerges as a transformative innovation to address the challenges of modern infrastructure. Digital Twins, virtual replicas of physical assets and systems, provide a robust framework for integrating the physical and digital worlds (Huang et al., 2022). By leveraging real-time data, predictive analytics, and advanced simulation capabilities, DT technology empowers railway operators to enhance operational efficiency, safety, and sustainability. Building on advancements in Artificial Intelligence (AI) and the Internet of Things (IoT), DTs are redefining how railway systems are monitored, maintained, and managed.

Several real-world railway operators have begun deploying Digital Twin technologies, validating their transformative potential. For example, Siemens Mobility partnered with DB Cargo to implement a Digital Twin system that simulates locomotive conditions in real time, enabling condition-based maintenance and reducing downtime (Lim et al., 2020). In Hong Kong, the MTR Corporation has adopted Digital Twins to model rail assets and predict equipment failures, improving asset lifecycle management. Additionally, Singapore's Land Transport Authority (LTA) has invested in a nationwide Digital Twin initiative to support long-term infrastructure planning and maintenance across its rail network. These real-world implementations highlight the growing maturity of DT applications in railways and demonstrate their practical utility in enhancing system reliability, safety, and strategic planning (Lu et al., 2020).

A cornerstone of Digital Twin technology lies in its capacity to enhance asset health monitoring and lifecycle management. By integrating sensor data and computational models, DTs provide actionable insights into the performance and condition of railway components. Gao et al. (2021) demonstrated how DT frameworks enable accurate simulation of railway systems, allowing operators to assess infrastructure degradation and predict failures before they occur. This proactive approach not only improves system reliability but also extends asset lifespans. For example, Yan et al. (2023) showcased the application of DTs in electric railway power systems, where real-time simulations identified potential vulnerabilities, mitigating service disruptions. Similarly, Kushwaha et al. (2024) emphasized the role of DTs in automating maintenance workflows, particularly in detecting anomalies and predicting failures in critical components. Such capabilities are instrumental in reducing operational downtimes and optimizing maintenance schedules.

The integration of environmental monitoring systems into Digital Twin frameworks further amplifies their utility. Torzoni et al. (2024) proposed a DT-based approach to monitor railway turnout conditions, capturing real-time geometric and environmental data to inform maintenance decisions. This integration facilitates the seamless alignment of maintenance activities with environmental factors, ensuring system resilience in dynamic conditions. Additionally, DTs enable the continuous evaluation of railway performance metrics, allowing operators to adapt to changing operational demands swiftly and effectively. By combining real-time insights with advanced predictive models, DT technology enhances the overall safety and reliability of railway networks (Zou et al., 2025).

Digital Twin technology is redefining railway infrastructure planning, offering significant advantages over traditional static and CAD (Computer-Aided Design) based simulation models. For example, In Germany, a 50 km railway line was digitally mapped to centimeter-level accuracy using DTs, reducing on-site survey time from several weeks to just two days while eliminating track closures and manual measurement costs (Lv & Xie, 2021). According to McKinsey, digital twin implementations in public infrastructure can boost capital and operational efficiency by 20–30%, enabling faster scenario testing and better resource allocation (Zhou et al., 2022). In India, the deployment of digital twin environments in railway projects has led to projected cost savings of over $185 million and reductions in construction schedules by thousands (Lu et al., 2020). Moreover, operators using DTs for maintenance and operations report 25–30% reductions in unplanned downtime and up to 35% improvements in planning accuracy, outperforming conventional planning approaches (Lu et al., 2020). In China, Digital Twin (DT) deployments have delivered substantial efficiency and cost benefits compared to traditional planning and simulation approaches. In the Shaoxing Urban Rail Line 1 project (34 km), the use of Bentley's iTwin Digital Twin platform reduced site survey effort by 800 hours, saving approximately CNY 3 million (USD 460,000) and shortened the design cycle by 20%, with design savings of CNY 12 million (USD 1.53 million) (Gao et al., 2021). Another example comes from China Mobile and ZTE's 5G digital twin implementation on the Kunchu Dali high speed railway: this approach achieved 98.5% 5G coverage, reduced planning errors to within ±1 dB for antenna parameters, increased average data rate by 15%, and cut optimization time by nearly one month, resulting in cost savings of CNY 1.6 million (USD 221,800) compared to traditional planning (Al-Ali et al., 2020; Bado et al., 2022; Jiang et al., 2021a). These case studies show DTs reduce manual labor, accelerate workflows, improve accuracy, and lower costs capabilities that conventional CAD or static simulation models cannot match.

Digital Twin technology also plays a pivotal role in sustainable infrastructure management. Through its integration with Building Information Modeling (BIM), DTs enable comprehensive analysis and optimization of railway stations and other assets. Kaewunruen and Xu (2018) highlighted a case study on London's King's Cross station, where a 6D BIM model was developed to incorporate spatial, temporal, and environmental data. This enhanced framework allowed for precise lifecycle planning, including cost management and carbon emission evaluations. Such applications demonstrate DT technology's potential to align railway operations with sustainability goals, reducing resource consumption and minimizing environmental impacts. As global transportation systems pivot toward greener practices, DTs offer a valuable tool for achieving economic efficiency and environmental responsibility.

In addition to maintenance and sustainability, Digital Twins contributes to operational optimization by improving logistics, scheduling, and resource allocation. Ghaboura et al. (2023) introduced a taxonomy of Digital Twin applications in railway logistics, outlining their utility in enhancing decision-making processes across complex networks. By simulating various operational scenarios, DTs provide railway operators with data-driven insights to optimize scheduling, reduce bottlenecks, and enhance passenger experience. Luo et al. (2019) further expanded on this by demonstrating how DT-enabled frameworks could dynamically manage traffic flow, particularly in high-speed railway systems. These advancements underscore the versatility of DT technology in addressing diverse challenges within the railway sector.

Despite their numerous benefits, the implementation of Digital Twin technology faces notable challenges. Ensuring high data fidelity and achieving real-time synchronization between virtual models and physical systems are critical hurdles. Inconsistent data integration can compromise the accuracy and reliability of DT applications, particularly in large-scale infrastructure networks. Moreover, the computational complexity of DT models demands substantial resources, both in terms of hardware and expertise. Ghaboura et al. (2023) emphasized the importance of standardizing data integration protocols to overcome these barriers, advocating for collaborative efforts among researchers, policymakers, and industry stakeholders. Similarly, Gao et al. (2021) and Jiang et al. (2021b) identified the need for robust interoperability frameworks to enable seamless integration of DT technology across diverse railway systems. However, one of the most pressing real-world challenges remains the lack of comprehensive standards for Digital Twin integration across heterogeneous railway infrastructures. Railway networks often comprise a mixture of legacy systems, varied equipment vendors, and differing data formats, which complicates the creation of unified Digital Twin models. This fragmentation hinders the scalability and interoperability of DT frameworks, limiting their effectiveness and adoption. Addressing this requires the development of universally accepted standards and protocols that facilitate data harmonization, seamless communication, and synchronized operation across disparate systems (Wang et al., 2024b; Yan et al., 2023).

Another significant challenge is the financial investment required to implement and maintain Digital Twin frameworks. The high costs associated with developing and operating DT models may deter smaller operators from adopting the technology. However, advancements in cloud computing and edge computing offer promising solutions to reduce these costs by distributing computational workloads and improving scalability. Additionally, incorporating blockchain technology for secure data management can address concerns related to data privacy and security, further facilitating the adoption of DTs (Wei et al., 2024).

Digital Twin technology represents a paradigm shift in railway management, offering unparalleled capabilities in predictive maintenance, decision support, and sustainability. By simulating real-world scenarios, DTs enable railway operators to address operational challenges proactively, enhancing system efficiency and safety (Qiu et al., 2024b). Furthermore, technology's potential to promote environmentally friendly practices aligns seamlessly with global sustainability objectives, ensuring the long-term viability of railway systems. However, the successful integration of DTs requires overcoming significant technical and financial barriers. Collaborative efforts among key stakeholders will be essential to develop standardized frameworks and innovative solutions that unlock the full potential of Digital Twin technology (Wei et al., 2025).

Looking ahead, the future of Digital Twin technology in railway systems is promising. Continued research and innovation will expand its applications, driving advancements in areas such as autonomous operations, energy efficiency, and passenger-centric services. As railway transportation embraces emerging technologies (Song et al., 2024), Digital Twins are poised to play an integral role in shaping a smarter, more sustainable future for the industry. By bridging the gap between the physical and digital worlds, DT technology will redefine the standards of efficiency, safety, and environmental responsibility in modern railway systems. By virtually replicating railway assets and systems, Digital Twins help enhance safety and streamline maintenance, thus playing an integral role in the continued drive for both operational efficiency and reliability in modern rail networks (Wang et al., 2023a, 2024c).

4.4. Autonomous systems and automation in railways

In addition to digital monitoring, the introduction of autonomous systems brings a new level of operational efficiency, reducing human error and improving overall system safety. The evolution of railway transportation has increasingly centered on automation, leveraging cutting-edge technologies to enhance efficiency, safety, and sustainability. Autonomous systems are no longer limited to incremental improvements; instead, they represent a transformative force reshaping maintenance practice, train operations, and control frameworks (Lagay & Adell, 2018; Sergeyev et al., 2019). With advancements in artificial intelligence (AI), sensor integration, and robust decision-making algorithms, automation is positioning railways as smarter, more adaptable, and resilient transportation networks capable of meeting the demands of modern society.

Among the pivotal advancements in railway automation is the integration of autonomous maintenance systems. These systems streamline inspection and repair tasks, mitigating the need for human intervention in hazardous or remote environments. A remarkable innovation in this domain is the development of autonomous railroad amphibious robotic vehicles. Liu et al. (2023) introduced a groundbreaking system capable of seamless transitions between tracks and roadways, employing advanced sensor fusion and mobile manipulation technologies. This capability enables the vehicles to execute a wide array of maintenance activities, from inspections to minor repairs, without necessitating track possession. The adoption of such systems reduces operational disruptions, enhances safety standards, and ensures continuous monitoring of railway assets. Furthermore, the rule-based expert system incorporated into these vehicles optimizes task execution, contributing to operational efficiency and significant cost savings.

The automation of train operations is advancing across urban, freight, and high-speed railway systems, redefining traditional operational paradigms. Urban railways, for instance, have increasingly adopted driverless technologies, streamlining commuter services with enhanced reliability and reduced energy consumption. In the realm of freight transportation, Aela et al. (2024) explored the deployment of fully automated commercial freight trains capable of navigating complex and open rail networks. These autonomous systems address challenges unique to freight operations, such as variable load conditions and intricate routing, through sophisticated communication protocols and dynamic control frameworks. The research also emphasized the importance of defining automation levels to facilitate regulatory alignment and encourage broader adoption (Lagay & Adell, 2018).

High-speed railway systems have similarly embraced automation to meet the stringent demands of rapid and safe transportation. Nazat et al. (2024) proposed the Autonomous Intelligent High-Speed Railway System (AIHSRS), a multi-layered architecture designed to integrate autonomous technologies across infrastructure management, safety monitoring, and train coordination. By leveraging real-time data fusion and adaptive algorithms, AIHSRS enables seamless operations while optimizing decision-making processes. This architecture enhances the flexibility, efficiency, and safety of high-speed railways, offering real-time responses to dynamic operational conditions and bolstering system reliability.

Innovations in train control systems have further accelerated the adoption of automation in railways. Traditional control systems, which rely heavily on centralized, ground-based operations, are being replaced by more decentralized and autonomous solutions. Song et al. (2023)

introduced the Autonomous Train Control System (ATCS), a predictive model-driven framework employing edge-based information fusion. Unlike conventional systems, ATCS enables trains to make real-time decisions regarding speed, positioning, and coordination, reducing dependency on centralized operations. This localized intelligence allows for dynamic adaptation to changing conditions, enhancing safety and optimizing network efficiency. The decentralized nature of ATCS marks a significant leap in ensuring operational reliability while minimizing delays and system vulnerabilities (Sergeyev et al., 2019).

Despite their transformative potential, integrating autonomous systems into existing railway infrastructure presents several challenges. Regulatory compliance, system compatibility, and safety assurance remain significant hurdles. Retrofitting legacy infrastructure with advanced automation technologies often involves technical complexities and substantial financial investment. Morey et al. (2024) employed the Soft Systems Methodology (SSM) to identify barriers such as stakeholder resistance, inconsistencies in data integration, and the lack of standardized frameworks for automation. Addressing these issues necessitates the development of robust communication protocols, standardized data integration frameworks, and comprehensive regulatory policies. Ensuring interoperability between autonomous systems and legacy infrastructure is critical to achieving widespread adoption without compromising safety or operational continuity (Li et al., 2024).

The integration of autonomous systems and automation into railways signifies a paradigm shift in transportation. From autonomous maintenance vehicles and fully automated freight operations to advanced control systems for high-speed networks, these innovations are redefining the industry's operational landscape (Kostrzewski et al., 2022). However, overcoming challenges related to regulatory frameworks, infrastructure compatibility, and stakeholder acceptance is crucial to realizing the full potential of these technologies.

Collaboration among researchers, policymakers, and industry stakeholders is essential for addressing these barriers. Continued investment in research and development, coupled with the creation of standardized, future-proof solutions, will facilitate the seamless adoption of automation across diverse railway systems. By doing so, the railway sector can harness the transformative capabilities of autonomous technologies to build smarter, safer, and more sustainable transportation networks for the future. As autonomous technologies evolve, they will become crucial for ensuring safe, reliable, and highly efficient operations, aligning with the railway industry's broader objectives of reducing accidents and improving system capacity.

4.5. Comparative analysis of emerging technologies in railway systems

To further clarify the understanding of emerging technologies in railway systems, we conduct a comparative analysis that explores key factors such as implementation cost, technological readiness, effectiveness, and scalability. This analysis provides a clearer perspective on how each technology – AI, IoT, Digital Twins, Autonomous Systems, Advanced Signaling, and Renewable Energy Solutions – contributes to improving operational efficiency, safety, and sustainability in railway networks. By examining these elements, we gain a better understanding of the strengths and challenges of each technology, as well as how they can work together to create more efficient and resilient railway systems. Table 4 gives a detailed insight into this comparative analysis.

4.6. Technological interconnections

Building on the individual strengths of technologies discussed earlier, their combined application reveals even greater transformative potential for railway systems. Integrating Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, and autonomous systems create a comprehensive ecosystem. This ecosystem enables railway operators to achieve unprecedented efficiency, safety, and sustainability. These technologies, when used in tandem, foster collaboration between digital and physical domains, revolutionize how railways operate and adapt to dynamic conditions.

The combination of AI and IoT enables the creation of highly intelligent railway systems. IoT devices, equipped with advanced sensors, continuously monitor various aspects of railway infrastructure, including track conditions, rolling stock, and environmental parameters. These sensors generate vast amounts of real-time data, which AI al-

Table 4. Comparative analysis

Technology	Implementation Cost	Technological Readiness	Effectiveness	Scalability
Artificial Intelligence (AI)	Moderate to High	High	Excels in predictive maintenance, scheduling, and decision-making.	High, depending on data availability and computational infrastructure.
Internet of Things (IoT)	Moderate to High	High	Real-time monitoring enhances safety and operational insights.	High, but dependent on network infrastructure.
Digital Twin (DT)	High	Moderate to High	Accurate simulations for maintenance, and lifecycle optimization.	Moderate, limited by computational resources and data integration.
Autonomous Systems	High	Moderate	Improves safety and reduces human errors in operations.	Moderate, reliant on regulatory and infrastructural readiness.

gorithms analyze to derive actionable insights. Predictive analytics powered by AI not only identifies potential maintenance needs but also optimizes train schedules, thereby improving overall efficiency. For example, IoT-based track monitoring detects anomalies like misalignments or wear. AI models then prioritize repairs based on severity and operational impact. This ensures proactive and effective responses (Qiu et al., 2025c; Zaheer et al., 2025a, 2025b).

Digital Twins rely extensively on real-time data inputs supplied by IoT devices. This integration produces highly detailed and accurate virtual models of railway assets and networks. These models allow operators to simulate various operational scenarios, assess potential risks, and predict equipment failures with remarkable precision (Ye et al., 2019). For example, IoT sensors embedded in trains and tracks feed continuous data into Digital Twin platforms, providing real-time visualization and analytics. This capability significantly enhances operational planning by enabling dynamic adjustments to maintenance schedules, reducing downtime, and extending the lifecycle of critical infrastructure components.

Autonomous systems in railways, including driverless trains and automated maintenance vehicles, are significantly enhanced by the combined capabilities of AI and IoT. IoT provides foundational data streams, capturing intricate details about operational conditions and environmental factors, while AI processes this data to facilitate real-time decision-making. This synergy ensures that autonomous systems can dynamically adjust to changing conditions, such as weather variations or unexpected obstacles, enhancing operational reliability and safety. By reducing the reliance on human intervention, these integrated technologies also minimize errors, streamline workflows, and improve efficiency across the railway ecosystem (Singh et al., 2021).

A compelling example of these synergies is the integration of AI-driven traffic management systems with IoT-enabled monitoring and Digital Twin simulations (Qiu et al., 2024a; Wang et al., 2024b; Zaheer et al., 2023). These interconnected systems are now operational in advanced railway networks, where they have demonstrated significant improvements in efficiency, passenger experience, and cost reduction. AI algorithms optimize train routing and scheduling, while IoT devices provide real-time performance metrics, and Digital Twins simulate potential scenarios to preemptively address issues. Together, these technologies not only tackle immediate operational challenges but also lay the foundation for a resilient and environmentally sustainable future in railway transportation.

5. Insights from thematic analysis

The literature on railway transportation highlights key themes that are shaping the future of the industry. Central to these discussions are objectives focused on enhancing efficiency, safety, and mitigation, while also addressing sustainability, environmental concerns, and economic and social impacts. This section critically examines these themes in the context of current research, exploring how emerging technologies and innovations are contributing to the transformation of railway systems and meeting the evolving demands of modern transportation.

5.1. Enhancing efficiency in railways

The pursuit of efficiency is a central goal in modernizing railway systems, and emerging technologies play a pivotal role in achieving this objective by streamlining operations and reducing costs. Railway transportation is being transformed through emerging technologies. These innovations address sustainability, cost-effectiveness, and operational reliability (Qiu et al., 2025a, 2025d). Railways, which serve as a critical backbone of global transportation infrastructure, are increasingly embracing innovations that optimize operations, reduce energy consumption, and streamline maintenance (Grandio et al., 2023; Wei et al., 2022; Yang et al., 2023). These advancements span several areas, from intelligent scheduling systems to predictive maintenance strategies, energy-efficient technologies, and real-time communication networks. The goal is to build a sustainable and reliable railway network. This network should address modern transport challenges while lowering environmental and operational costs (Jeong & Law, 2018).

Real-world implementations of these technologies further demonstrate their practical value. For example, Deutsche Bahn in Germany utilizes IoT-enabled sensors and AI algorithms for real-time monitoring and predictive maintenance, while Hong Kong's MTR has deployed Digital Twin systems to optimize infrastructure planning and fault detection. Similarly, India's railway network integrates AI for intelligent surveillance and crowd management at busy stations (Jeong & Law, 2018). These deployments validate the role of emerging technologies in improving operational efficiency and provide valuable insights into the challenges and opportunities of real-world adoption (Bisio et al., 2022).

The primary focus of technological advancements in the railway sector is improving the efficiency of train scheduling. Artificial intelligence (AI) and machine learning algorithms are now being employed to dynamically adjust train schedules in real-time, enabling more efficient use of resources and minimizing delays (Aela et al., 2024). For example, Zhang et al. (2019a) explored the application of AI-driven methods for optimizing train movements during unexpected disruptions. Their approach reduces energy consumption by minimizing idle times and ensuring trains operate at optimal speeds. Although the implementation of such AI models holds great promise, challenges related to real-time data processing and computational power remain. These technologies require significant infrastructure upgrades, such as the installation of advanced sensors and computing systems, which can present barriers to their widespread adoption in legacy railway systems.

Predictive maintenance is another groundbreaking development that is transforming how railway operators manage their assets. Traditional maintenance methods often involve scheduled inspections or reactive repairs after a failure occurs (Qiu et al., 2024a). However, predictive maintenance, powered by machine learning algorithms and real-time data analytics, allows operators to monitor the health of railway assets continuously. This proactive approach enables early detection of potential failures, such as track wear, brake malfunctions, or engine problems, and ensures timely repairs before these issues escalate. Research by Xu et al. (2020b) and Wang et al. (2023c) demonstrated the effectiveness of machine learning techniques, such as neural networks and support vector machines, in predicting maintenance needs based on data from sensors embedded in railway infrastructure. These technologies not only extend the lifespan of critical assets but also reduce costly downtime and enhance system reliability. However, implementing predictive maintenance requires substantial investment in sensor networks and advanced data analytics capabilities, which can be a barrier for some rail operators.

In addition to predictive maintenance, energy efficiency is a major focus for modern railway systems, particularly as environmental concerns and sustainability goals continue to gain prominence. One key technology that has proven effective in improving energy efficiency is regenerative braking. This system allows trains to capture and reuse the kinetic energy generated during braking, reducing the need for external energy sources and lowering overall energy consumption. Popescu and Bitoleanu (2019) examined the application of regenerative braking in alternating current (AC) networks, highlighting its potential for energy savings in urban and suburban rail systems where frequent stops occur. Their research underscores the importance of developing hybrid systems that combine regenerative braking with other energy-saving technologies to optimize energy management. The integration of such technologies not only reduces operational costs but also contributes to the broader goal of reducing carbon emissions and improving the environmental sustainability of railway systems (Grandio et al., 2023).

As railway systems become more digitized, the introduction of advanced communication technologies has played a crucial role in enhancing operational efficiency. The deployment of 5G and Wi-Fi 6 technologies has significantly improved the speed and reliability of data transmission between trains, control centers, and signaling systems. Wu et al. (2019) explored the use of multi-agent reinforcement learning to optimize communication in railway networks, ensuring seamless data flow even under high-demand conditions. These communication advancements, in tandem with the integration of Internet of Things (IoT) devices, provide operators with real-time insights into various operational factors, such as train performance, track conditions, and environmental variables. This enables more efficient scheduling, maintenance, and coordination across the network. Furthermore, the use of IoT in conjunction with AI-powered systems enables the continuous monitoring of railway infrastructure, offering new levels of precision in fault detection and preventative maintenance.

Another transformative technology reshaping railway efficiency is the use of digital twins. A digital twin is a virtual replica of physical assets, such as trains, tracks, and signaling systems, that enables real-time monitoring and simulation of various operational scenarios. Shan et al. (2021) applied digital twin technology to optimize maintenance scheduling and lifecycle management in the railway sector. By creating a digital representation of the physical infrastructure, operators can simulate potential failures, assess the impact of different maintenance strategies, and predict the future condition of assets, thus improving decision-making and resource allocation. Digital twins also enable real-time performance tracking, which helps operators respond more quickly to changes in system conditions, ultimately improving efficiency and reducing downtime (Wang et al., 2023b; Wei et al., 2024).

Furthermore, automatic train operation (ATO) systems are another promising development in the quest to enhance railway efficiency. ATO systems use advanced algorithms and real-time data to control the speed, acceleration, and braking of trains, reducing the reliance on human operators and minimizing the risk of human error. Yin et al. (2017) and De Rivera and Dick (2021) explored the potential of ATO systems to optimize energy consumption by dynamically adjusting train parameters to the most energy-efficient operating conditions. These systems are particularly beneficial in reducing energy use during high-traffic periods or in challenging operational environments. While the widespread implementation of ATO systems faces hurdles, such as the need for significant infrastructure investment and regulatory approval, the potential for energy savings and increased operational efficiency makes them a valuable technology for the future of rail transportation (Feng et al., 2022).

Despite the many advancements, challenges remain in fully realizing the potential of these technologies. One of the most significant barriers is the integration of emerging technologies into existing railway infrastructure. Upgrading legacy systems to support advanced AI algorithms, predictive maintenance models, and real-time communication networks requires substantial investment, both in terms of finances and time (Ma et al., 2022). Additionally, the scalability of some technologies, such as AI-based scheduling and predictive maintenance, remains an ongoing challenge, particularly for smaller rail operators or those in developing regions (Xu et al., 2023a).

The efficiency of railway systems is being reshaped by a wide range of emerging technologies that optimize energy management, improve operational performance, and enhance maintenance capabilities. From predictive maintenance powered by machine learning to energy-efficient solutions like regenerative braking and digital twins, these innovations are setting the stage for a more sustainable, reliable, and cost-effective railway system. While challenges related to infrastructure upgrades, scalability, and regulatory considerations persist, the continued exploration and implementation of these technologies offer significant promises for revolutionizing the way railways operate and serve passengers in the future.

5.2. Safety and risk mitigation in railways

Building on the efficiency gains discussed earlier, safety is another critical area where emerging technologies, particularly AI and IoT, are driving substantial improvements in risk mitigation and accident prevention. Ensuring safety and mitigating risks are fundamental to maintaining sustainable and efficient global rail operations. The growing complexity of modern railway networks, driven by increased passenger demands and higher train speeds, necessitates the adoption of emerging technologies (Ai et al., 2024; Qiu et al., 2024a; Wang et al., 2024b). Innovations such as artificial intelligence (AI), the Internet of Things (IoT), advanced signaling systems, and robust cybersecurity frameworks are at the forefront of enhancing infrastructure resilience, minimizing operational risks, and improving overall safety. This section delves into how these technologies are transforming railway safety while addressing the technical, financial, and regulatory challenges that accompany their adoption.

AI-powered predictive models are revolutionizing railway safety by leveraging real-time data and machine learning algorithms to anticipate and prevent potential accidents. For example, Chai et al. (2024) developed a comprehensive model for train capacity allocation and timetable coordination in multimodal railway networks. This approach uses data-driven decision-making to dynamically adjust schedules, reducing risks such as delays, traffic congestion, and unforeseen disruptions. While scalability issues remain a challenge for larger networks, these AI frameworks demonstrate immense potential in enhancing operational safety. Similarly, Corman and Quaglietta (2015) proposed a closed-loop control system for real-time railway traffic management, integrating real-time data to optimize train movements and minimize accidents caused by delayed responses or communication failures. These advancements highlight AI's pivotal role in ensuring the safety and efficiency of high-risk railway operations.

IoT-based monitoring systems further bolster railway safety by enabling real-time incident detection and proactive maintenance interventions. Durazo-Cardenas et al. (2018) introduced a predictive maintenance model that integrates real-time condition monitoring with advanced analytics. This approach allows railway operators to detect and address issues such as track misalignments and signal failures before they escalate into major problems. By reducing infrastructure-related risks and unplanned downtimes, IoT systems significantly enhance operational efficiency. Widespread adoption requires significant investment in data infrastructure and analytical tools. In many regions, these foundational capabilities remain underdeveloped. Despite these challenges, IoT-based solutions are rapidly becoming a cornerstone of modern railway safety strategies, providing unparalleled insights into system health and performance.

Risk assessment models also play a critical role in identifying and mitigating specific hazards in railway operations. Deng et al. (2018) developed a probabilistic risk analysis framework to address the risks associated with flying ballast in high-speed rail systems. Flying ballast poses severe threats to both trains and infrastructure, particularly at extreme speeds. By pinpointing high-risk track sections, this model enables operators to prioritize maintenance efforts, thereby enhancing safety and resource allocation. While the success of such models depends heavily on the availability and quality of input data, probabilistic approaches have proven invaluable in accident prevention and resource management.

Emerging derailment prevention strategies are benefiting from technological innovations, particularly when integrated with IoT sensors and predictive analytics. Zahurul et al. (2016) conducted a cost-benefit analysis of various derailment mitigation techniques, including track strengthening, derailment detection systems, and advanced braking mechanisms. These technologies allow early detection of anomalies, such as track or train defects, enabling timely interventions to prevent accidents. Implementing these solutions demands considerable financial investment and ongoing monitoring. However, they provide notable improvements in derailment prevention, contributing to enhanced safety and reduced economic losses. Advanced signaling systems, such as the European Train Control System (ETCS) and Positive Train Control (PTC), are instrumental in preventing collisions, signal failures, and unsafe train separations. Aoun et al. (2021) conducted a multi-criteria evaluation of signaling systems, emphasizing the balance between safety, capacity, and cost. These systems utilize real-time data to monitor and control train movements, automatically intervening to prevent accidents caused by human error or miscommunication. Despite challenges such as high infrastructure costs, retrofitting complexities, and regulatory hurdles, advanced signaling systems remain integral to modern railway safety, offering substantial improvements in operational efficiency and accident prevention (Wang et al., 2024e, 2024h).

As rail networks become increasingly digitized and interconnected, the importance of cybersecurity in safeguarding railway systems cannot be overstated. Kljaić et al. (2023) underscored the critical need to protect communication and control networks from cyber threats. Cyber-attacks on railway systems pose severe risks, ranging from operational disruptions to compromised passenger safety. To mitigate these risks, railway operators must adopt robust cybersecurity measures, including encrypted communication protocols, routine personnel training, and comprehensive incident response plans. With the increasing sophistication of cyber threats, ensuring the cybersecurity of railway systems is a crucial aspect of risk mitigation that complements physical safety measures (Wang et al., 2024f).

The integration of emerging technologies – AI-driven predictive models, IoT-enabled monitoring systems, advanced signaling mechanisms, and robust cybersecurity frameworks – has revolutionized safety and risk mitigation in railways. These innovations not only address critical safety challenges but also improve operational efficiency and resilience. However, the adoption of these solutions is not without obstacles. Technical complexities, high implementation costs, and stringent regulatory requirements pose significant barriers. Nevertheless, the transformative potential of these technologies makes them indispensable for modern railway networks (Balta et al., 2021; Zhang et al., 2024b). By leveraging these advancements, rail systems can meet the growing demands of global transportation, ensuring safer, more reliable, and sustainable operations. As these technologies evolve, they will continue to shape the future of railway transportation, enhancing infrastructure management, decision-making strategies, and the overall performance of rail networks. Ultimately, the convergence of these technologies enhances railway safety by proactively identifying risks, reducing human error, and ensuring continuous monitoring, which is essential for maintaining a secure operational environment.

5.3. Sustainability and environmental responsibility

As railways strive for greater efficiency and safety, environmental responsibility has become an equally important consideration, with new technologies helping the sector reduce its carbon footprint and improve sustainability. Sustainability in railway transportation has emerged as a fundamental objective in global efforts to minimize environmental impacts while ensuring the accessibility and efficiency of mobility systems. As one of the most energy-efficient modes of transport, railways inherently hold an advantage in sustainability (Bressi et al., 2018; Karlson et al., 2016). However, with increasing demands on urban and intercity transit, there is a pressing need to integrate innovative technologies and strategies to further reduce their environmental footprint. The adoption of green technologies, systemic advancements, and digital tools has become essential in addressing challenges such as carbon emissions, resource efficiency, and lifecycle environmental impacts. These innovations position railways as a pivotal player in the transition toward more sustainable and environmentally responsible transportation networks.

The role of green technologies is particularly noteworthy in the pursuit of sustainability. Renewable energy integration and railway electrification have been transformative in reducing the reliance on fossil fuels. Electrification of rail networks, particularly in densely populated regions, offers significant potential for cutting greenhouse gas emissions. Shouket et al. (2019) highlight the environmental implications of railway operations in Pakistan, emphasizing the dual role of technological interventions. While technologies can exacerbate certain challenges, they also offer unparalleled opportunities to mitigate environmental impacts. Expanding on this foundation, the adoption of solar-powered rail systems and the deployment of hydrogen fuel cell trains demonstrate the feasibility of achieving near-zero emission rail transport. These technologies, when integrated with advanced energy storage systems, can further enhance energy efficiency and reduce operational costs. However, their implementation is often hindered by high initial investments and the need for policy support, underscoring the importance of government incentives and private-sector collaboration (Bressi et al., 2018).

Operational sustainability forms another critical dimension of environmental responsibility in railway systems. Efficient operations not only enhance the cost-effectiveness of rail transport but also minimize waste and energy consumption. Miller et al. (2016) underscore the broader role of public transportation in promoting urban sustainability, particularly through its capacity to mitigate the environmental impacts of urban mobility. Within the rail sector, operational advancements such as regenerative braking systems and optimized scheduling algorithms have emerged as key contributors to energy savings. Regenerative braking, for instance, allows trains to capture and store energy during deceleration, which can then be reused, significantly reducing electricity consumption. Additionally, incorporating smart scheduling systems that optimize train frequency and capacity utilization can lead to reduced energy use while ensuring passenger convenience.

The lifecycle assessment of rail infrastructure provides a holistic perspective on the environmental impacts of railway systems, encompassing construction, operation, maintenance, and decommissioning. Kaewunruen and Xu (2018) draw attention to the carbon-intensive nature of railway construction, particularly in large-scale projects like the Beijing-Shanghai High-Speed Railway. Cement and steel, critical components in railway construction, contribute heavily to greenhouse gas emissions. To address these challenges, adopting alternative construction materials such as geopolymer concrete, which has a lower carbon footprint, can significantly reduce emissions. Additionally, modular construction techniques, which enable more efficient material use and reduced waste, offer promising avenues for sustainable railway development. Furthermore, carbon capture technologies, still in their developmental stages, could potentially revolutionize the way emissions are managed in infrastructure projects, offering a proactive approach to mitigating environmental damage during construction (Song et al., 2020b).

Innovative utilization of existing railway infrastructure also holds potential for environmental benefits. Behiri et al. (2020) explore the integration of urban freight transport within passenger rail networks, which can reduce road congestion and lower emissions associated with traditional freight logistics. This dual-use approach not only optimizes existing infrastructure but also reduces the need for constructing additional freight corridors, thereby curtailing resource consumption. However, the sustainability of this concept can be further enhanced by incorporating green technologies such as electric freight trains and renewable energy systems into freight operations. Such advancements ensure that the environmental gains from optimizing infrastructure are not offset by emissions from conventional freight systems.

Digital technologies are increasingly recognized as transformative tools for enhancing railway sustainability. Issa et al. (2023) introduce the "Avatar" system, a digital twin technology for railway infrastructure management. Digital twins integrate real-time data from diverse sources to optimize operations, maintenance, and resource use. By enabling predictive maintenance, these systems can significantly reduce resource waste and extend the lifespan of railway assets. Moreover, integrating environmental monitoring sensors within digital twin platforms can provide insights into energy consumption patterns and environmental impacts, facilitating more targeted sustainability interventions. Digital tools also support decision-making processes by offering data-driven insights, allowing operators to implement measures that align closely with sustainability goals.

The implementation of these technologies and strategies, however, faces numerous challenges. High capital costs, technical complexities, and regulatory barriers often hinder the widespread adoption of green and digital technologies. For instance, while electrification and hydrogen fuel cell technologies show immense promise, their adoption requires significant investment in infrastructure upgrades and supportive regulatory frameworks. Similarly, digital twin systems necessitate advanced data management capabilities, which are underdeveloped in many regions (Huang & Wang, 2020). These challenges highlight the need for collaborative approaches involving governments, private stakeholders, and research institutions to develop scalable, cost-effective solutions. Public-private partnerships can play a pivotal role in bridging funding gaps, while international cooperation can facilitate the transfer of technical expertise and best practices (Bouraima et al., 2020).

Looking forward, there is a critical need for further research and innovation in sustainable railway practices. Exploring alternative materials with lower environmental footprints, such as bio-based composites, could transform construction practices (Adshead et al., 2019). Similarly, integrating artificial intelligence (AI) into digital twin systems for more sophisticated predictive analytics can enhance resource efficiency and environmental monitoring. The fusion of these technological advancements with systemic innovations, such as circular economy principles in railway asset management, offers a comprehensive approach to sustainability. Circular principles emphasize recycling and repurposing materials at the end of their lifecycle, reducing waste, and conserving resources.

Sustainability and environmental responsibility are central to the future of railway transportation. Through the integration of green technologies, operational innovations, lifecycle assessments, and digital tools, railways can significantly reduce their environmental impact while meeting growing mobility demands. Although challenges such as financial constraints and regulatory hurdles persist, the potential benefits of sustainable railway systems far outweigh these obstacles. By fostering innovation and collaboration, the railway sector can play a leading role in global efforts to combat climate change, enhance resource efficiency, and promote environmentally responsible infrastructure development. This evolving focus not only aligns with global sustainability goals but also positions railways as a cornerstone of future transport systems. Through the adoption of renewable energy solutions, energy-efficient technologies, and advanced data analytics, the railway sector is poised to contribute meaningfully to sustainability, reducing emissions and aligning with global environmental goals (Ilyas et al., 2024; Jin et al., 2023; Wang et al., 2024a).

5.4. Multimodal transport integration

In addition to enhancing efficiency and sustainability, the integration of multimodal transport solutions plays a crucial role in improving the connectivity of railways with other transportation systems, offering a seamless travel experience for passengers and optimizing freight logistics. The integration of multimodal transportation systems has emerged as a cornerstone in advancing efficient and sustainable urban mobility (Fazio et al., 2023; Jo et al., 2018). High-speed rail (HSR) plays a pivotal role in this context by seamlessly connecting urban centers and complementing conventional transportation modes (Pham & Yeo, 2018). This integration not only enhances accessibility but also transforms how passengers interact with interconnected transport systems. Zhang et al. (2021a, 2021b) analyze the impact of HSR accessibility at Tanggu Railway Station in China, illustrating significant improvements through the alignment of HSR, conventional railways, and road network enhancements. However, their findings also reveal unintended consequences, such as increased travel times to certain regions due to reductions in conventional rail routes. This highlights the critical need for balanced infrastructural development, particularly in ensuring that complementary road networks support the broader goals of regional accessibility and mobility equity. Future studies must explore long-term sustainability, particularly in the context of urban growth and environmental considerations (Cvetkovski et al., 2022).

In the domain of road-rail intermodal transport, Wang et al. (2021) propose a bi-objective optimization model that employs genetic algorithms and local search strategies to address uncertainties in demand, cost, and travel time. Their research, applied within the Turkish context, underscores the importance of adaptability in managing large-scale transport networks under dynamic conditions. However, its application to other regions remains unexplored. Expanding the model to include HSR systems could provide insights into managing diverse transport demands while ensuring seamless passenger transitions between modes. This aligns with broader efforts to optimize passenger experiences by minimizing uncertainties and creating reliable connections between transport systems (Specht & Koc, 2016).

Understanding the operational dynamics of multimodal systems is crucial for optimizing real-world applications. Zhang et al. (2024c) explore the interaction of multimodal dispersive waves in railway systems through numerical modeling and experimental analysis, offering insights into phase and group velocities. However, their work is confined to laboratory settings, leaving a gap in the application of these findings to real-world rail systems and multimodal hubs. Addressing this gap would allow for the refinement of operations in environments where railways interact with other modes of transport, such as buses, trams, and shared micro-mobility solutions. This is particularly relevant in enhancing the passenger experience through improved operational efficiency and better integration of modes (Barrientos et al., 2016; Mulerikkal et al., 2022).

The resilience of multimodal transport systems is another area requiring attention, particularly in the face of disruptions. Wang et al. (2018) examine the vulnerability of the China-Europe Railway Express (CR Express) multimodal transport network (MTN) under cascading failures. Their layered road-rail model reveals that moderate inter-layer coupling enhances network resilience, ensuring continuity even during disruptions. However, their findings lack practical case studies to validate these theoretical models. Real-world implementations could provide actionable strategies to bolster system robustness, particularly in regions with dense and complex multimodal setups (Bruckmann et al., 2016; Chen & Kim, 2018).

Low-carbon efficiency is increasingly a priority in multimodal transport integration, particularly given the growing emphasis on sustainability in urban planning. Zhang et al. (2024a) analyze rail-water multimodal transport through a cross-efficiency network DEA approach, uncovering regional disparities in low-carbon performance across China. While their study underscores the role of urban industries and transport infrastructure in influencing efficiency, it stops short of addressing the policy implications of their findings. Future work should explore how such analyses can inform strategic planning, particularly in designing policies that promote environmental and operational benefits. Integrating renewable energy sources and electrification in multimodal systems could significantly reduce emissions and align transport networks with sustainability goals (Ai et al., 2015).

First- and last-mile connectivity remains a critical challenge in the successful integration of multimodal systems. Torabi et al. (2022) provide valuable insights into passenger preferences for first- and last-mile transport modes at Delft Campus railway station, highlighting the potential of emerging options such as shared bicycles, e-scooters, and autonomous vehicles (AVs). While the study demonstrates the viability of AVs, it notes that cost and time considerations heavily influence user choices. The scalability of these modes within larger urban networks and their integration with rail systems remain areas for further research. Advancements in AV technologies, coupled with their deployment in multimodal networks, could streamline transitions and enhance passenger experiences by offering cost-effective and time-efficient solutions (Huseien & Shah, 2022).

The optimization of timetables in urban railway systems plays a crucial role in improving coordination between modes of transport. Huang et al. (2021) propose a three-step model that synchronizes last-train schedules with other transport modes, significantly enhancing the efficiency of Beijing's Urban Rail Transit (URT) network. While the model demonstrates success in the local context, its generalizability to other urban areas remains uncertain. Extending such frameworks to diverse urban environments could reveal universal strategies for optimizing multimodal networks, ensuring seamless passenger transitions across interconnected systems (Jansson et al., 2023).

Finally, the role of emerging technologies in multimodal transport systems cannot be overlooked. Abe (2021) examines the elasticity of demand for AVs within urban rail networks, emphasizing their potential to substitute slower transit modes and reduce private car usage. While price sensitivity emerges as a critical factor, the broader implications of AV adoption on urban mobility patterns remain unexplored (Borecka & Bešinović, 2021). Long-term studies on the integration of AVs into multimodal systems could provide valuable insights into shaping future urban mobility landscapes, particularly in enhancing sustainability and operational efficiency.

Collectively, these studies underscore the transformative potential of integrating railways with other transport modes to create efficient, resilient, and passenger-focused networks. However, there remains a pressing need for real-world validations, scalability analyses, and policy-driven approaches to bridge existing gaps (Wang et al., 2024d; Hu et al., 2024). By leveraging innovative solutions such as advanced optimization models, renewable energy systems, and digital technologies, future research can pave the way for holistic multimodal transport systems. These efforts will not only redefine urban mobility but also contribute to the broader goals of sustainability and accessibility in transportation. This integration not only enhances operational efficiency but also contributes to a more sustainable, interconnected transportation network, with railways serving as a backbone for multimodal solutions.

5.5. Economic and social impacts of railway innovations

Beyond the operational aspects, the economic and social impacts of these technological innovations are significant, as they shape not only the future of rail transport but also contribute to regional development, job creation, and social equity. The advent of high-speed rail (HSR) and modern light rail systems has transformed transportation, offering significant economic and social impacts across regions. These innovations are often touted for their potential to drive regional economic growth, improve accessibility, reduce environmental burdens, and support sustainable urban development (Gao & Zheng, 2020; Vickerman, 2018).

However, their effects are far from uniform, varying widely based on geographical, infrastructural, and socio-economic factors. Recent studies delve into the nuanced implications of railway innovations, providing insights into their transformative capabilities and the challenges they present (Kim et al., 2018).

Liang et al. (2020) explored the economic impacts of the Guangdong-Guangxi-Guizhou High-Speed Railway (GGGHSR), a strategic project designed to connect China's developed eastern regions with its less-developed western counterparts. By analyzing remote sensing data from 2012 to 2017, they identified increased light intensity along the railway route – a proxy for heightened economic activity – particularly in less-developed areas (Meng et al., 2018; Zhang et al., 2019b). However, the study found no substantial "corridor effect", a phenomenon where infrastructure projects catalyze widespread regional economic growth. Instead, the benefits appeared localized, disproportionately favoring areas further from major cities. This underscores the need for targeted investment strategies to maximize HSR's potential in driving balanced regional development (Cheng et al., 2015). The study highlights a gap in understanding the spatial variations in HSR's economic impacts, calling for a more nuanced approach to planning and investment that considers the diverse needs of urban and rural regions (Albalate et al., 2017).

In addition to economic growth, railway innovations contribute significantly to environmental efficiency. Song et al. (2020a) examined the environmental performance of China's railway network, which has seen rapid expansion in recent decades. Their research revealed that between 2006 and 2011, the environmental efficiency of railway transportation improved markedly, particularly in eastern regions where HSR adoption was highest (Zaheer et al., 2023). This improvement stems from HSR's lower energy consumption and reduced emissions compared to road transport. However, western regions lagged, reflecting regional disparities in infrastructure development. These findings suggest that while HSR can significantly enhance environmental outcomes, achieving equitable efficiency gains requires increased investment in less-developed areas. Policymakers must prioritize initiatives that bridge this gap, ensuring that all regions benefit from advancements in railway technology (Zhang et al., 2020).

The environmental and economic impacts of railway systems are further elucidated by Banar and Özdemir (2023) who assessed Turkey's HSR and conventional rail systems using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies. Their analysis revealed that for HSR, infrastructure accounted for 58% of the environmental impact, while operations contributed the remaining 42%. Conversely, conventional rail systems exhibited a higher operational environmental load, at 61%. Economically, HSR's infrastructure costs were substantial, yet operational costs were more balanced for conventional systems (Qiu et al., 2024a; Song et al., 2024; Zaheer et al., 2022). These findings emphasize the importance of evaluating both environmental and economic dimensions when planning railway innovations. Notably, the study identified a critical gap: the absence of longitudinal data to assess the long-term sustainability of these systems. Addressing this limitation could provide deeper insights into how railway technologies evolve and perform over decades of operation (Acheampong et al., 2022).

Modern light rail systems, while distinct from HSR, also play a pivotal role in shaping urban economies. Knowles and Ferbrache (2016) examined the economic contributions of light rail in unlocking new development opportunities and stimulating regional growth. Their findings highlight the transformative potential of light rail investments in revitalizing central business districts, enhancing property values, and expanding labor market accessibility. These benefits are particularly pronounced in urban areas where transportation constraints have historically impeded economic development (Li et al., 2019). However, the extent of these benefits is highly dependent on local conditions, including land use policies and existing infrastructure. Their study advocates for a more integrated approach to urban planning, ensuring that light rail systems align with broader economic and developmental goals. Further research is necessary to explore how these systems interact with diverse urban contexts and how their economic impacts can be maximized (Alfonso et al., 2015).

Despite the promising outcomes associated with HSR and light rail systems, challenges persist. The benefits of railway innovations are often context-dependent, with significant variations across regions. For instance, rural and less-developed areas frequently experience more pronounced economic gains from HSR, while urban centers may face limitations in realizing widespread benefits (Lu & Cai, 2021). Additionally, the long-term sustainability of these systems remains a pressing concern. Environmental impacts, particularly those stemming from infrastructure development, require ongoing scrutiny to ensure that railway innovations contribute positively to sustainability goals. Similarly, the economic viability of these systems depends on their ability to balance infrastructure and operational costs over time (Jin et al., 2020).

The integration of railway innovations into regional development strategies is critical to their success. Infrastructure alone cannot drive transformation; instead, its effectiveness depends on how well it integrates with local economic, social, and environmental contexts. Policymakers must adopt a holistic approach, considering not only the immediate benefits of railway systems but also their broader implications for urban and rural landscapes. This includes tailoring policies to address regional disparities, promoting equitable access to transportation advancements, and fostering sustainable practices in railway development (Jia et al., 2017; Wang et al., 2019).

Collectively, these studies underscore the transformative potential of railway innovations in driving economic growth, enhancing environmental efficiency, and supporting urban development. However, their impacts are complex and multifaceted, requiring careful planning and strategic investment. Future research should focus on understanding the differential effects of railway technologies across diverse geographical contexts, exploring the long-term sustainability of these systems, and identifying policies that maximize their economic and social benefits (Wang et al., 2023b). By addressing these challenges, railway innovations can continue to play a central role in shaping the future of transportation and urbanization. By improving accessibility and stimulating economic growth, these technologies ensure that railways remain a vital component of a sustainable, efficient, and inclusive transportation system for the future (Hu et al., 2024).

6. Emerging challenges and opportunities

6.1. Current gaps in research and applications

The rapid adoption of emerging technologies in railway transportation has significantly transformed the industry. However, critical gaps in research and implementation remain, hindering the full realization of their potential (Jiao et al., 2020). One major gap lies in the standardization and scalability of predictive maintenance systems across diverse railway networks (Chai et al., 2024). AI-driven predictive maintenance has successfully reduced unplanned downtimes and optimized resource allocation. However, the variability in infrastructure, train models, and operational contexts across regions limits these systems' adaptability and scalability. Research into universal frameworks that are modular and customizable is essential to address this disparity and enable widespread application (Shan et al., 2021). Another pressing issue is the regulatory and infrastructure challenges associated with deploying autonomous trains. Autonomous systems promise unprecedented improvements in efficiency and safety, but transitioning from human-driven to automated systems requires comprehensive changes in operational standards and public policies (Torabi et al., 2022). Regulatory bodies and railway operators must establish consistent safety, interoperability, and public acceptance standards. Current research often overlooks the legal and societal implications, such as workforce displacement and public trust in automated systems. Investigating how autonomous systems can be integrated while addressing public concerns and labor impacts remains a critical area for further exploration (Bhatt & Kato, 2021; Zhang et al., 2019b).

Sustainability is another domain with significant gaps. Emerging technologies like AI, IoT, and renewable energy integrations have the potential to dramatically reduce the carbon footprint of rail transport. However, most studies prioritize short-term energy optimization over comprehensive life-cycle assessments of these technologies, from manufacturing to disposal (Abduljabbar et al., 2019; Fazio et al., 2023). Furthermore, their systemic impact on broader transportation ecosystems remains underexplored. Future research should adopt a holistic perspective to evaluate how rail innovations can align with global sustainability goals. The adoption of big data and smart station technologies also reveals gaps in scalability and integration (Peris & Goikoetxea, 2016; Singh et al., 2022). While big data analytics has been used to optimize operations and manage congestion, limited research exists on how data-sharing frameworks between rail systems and other transportation modes can enhance multimodal mobility. Additionally, data privacy and security concerns remain inadequately addressed (Fazio et al., 2023; Primmer, 2023). Robust governance frameworks are needed to protect sensitive information while enabling seamless data integration across mobility networks (Abduljabbar et al., 2019).

Finally, the human and social dimensions of emerging railway technologies are often overlooked. Innovations are primarily assessed for their technical efficiency, with little attention to their societal impact. Accessibility, inclusivity, and equity must be integral considerations (Zhang et al., 2020). For example, smart ticketing systems and autonomous platforms should be designed to accommodate marginalized groups, including the elderly and disabled (Ke et al., 2017). Understanding how these technologies can address societal disparities is crucial for creating equitable transport solutions (Yin et al., 2020). Cybersecurity represents another significant concern as rail systems become increasingly reliant on interconnected technologies (Tang et al., 2022). Despite advances in basic security protocols, more sophisticated solutions are needed to address the unique challenges of railway systems, including protection against cyber-attacks targeting critical infrastructure. Developing advanced, industry-specific cybersecurity frameworks and contingency plans will be vital to ensuring the resilience of intelligent rail systems (Alfonso et al., 2015; Dawson et al., 2016; Li et al., 2019).

6.2. Barriers to technology adoption in railways

The convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and blockchain technologies holds transformative potential for modernizing railway systems. Each technology contributes uniquely to enhancing operational efficiency, safety, and sustainability, and their integration can revolutionize how rail networks are managed (Tang et al., 2022). AI emerges as a cornerstone of intelligent railway systems, particularly through predictive analytics and machine learning models. These capabilities allow for real-time monitoring and predictive maintenance of rolling stock and infrastructure, significantly reducing costs associated with unplanned repairs and downtime (Mohamed et al., 2020). For instance, AI algorithms can analyze sensor data to detect anomalies in track conditions or mechanical components, enabling proactive interventions. Moreover, AI can optimize scheduling by dynamically adjusting routes and operations based on demand fluctuations, weather conditions, and network congestion. Autonomous trains powered by AI represent another leap forward, promising increased safety and operational efficiency by reducing human error. However, integrating AI into legacy railway systems and aligning it with stringent regulatory frameworks remain formidable challenges requiring further research and development (Wang et al., 2024b; Yan et al., 2023).

The Internet of Things (IoT) complements AI by providing a robust network of connected devices that collect and exchange real-time data. IoT-enabled sensors embedded in tracks, trains, and stations can monitor infrastructure conditions, environmental factors, and passenger flows. This data can be utilized for condition-based maintenance, enhancing safety, and extending asset lifespans (Shi et al., 2024). IoT also improves the passenger experience by enabling smart ticketing, real-time travel updates, and personalized service recommendations. However, the widespread adoption of IoT faces challenges related to interoperability between different systems, data security vulnerabilities, and the scalability of networks in complex, large-scale operations. Overcoming these hurdles is essential to fully harness IoT's potential in railway transportation.

Blockchain, though relatively underexplored in the railway sector, offers significant opportunities for enhancing transparency, security, and operational efficiency. Its decentralized, immutable nature can revolutionize ticketing systems by eliminating fraud and ensuring seamless transactions. Blockchain can also improve supply chain management in freight operations, enabling real-time traceability of goods and reducing delays (Awodele et al., 2024). Additionally, blockchain can facilitate secure data exchanges between IoT devices and AI systems, creating a unified and trustworthy ecosystem for railway operations. However, its adoption faces barriers, including high implementation costs, scalability issues, and the need for collaborative frameworks among stakeholders to build interoperable blockchain systems.

When integrated, AI, IoT, and blockchain offer synergistic benefits. IoT devices can provide the data required for AI-driven decision-making, while blockchain ensures secure and transparent sharing of insights across the network. This combination can enable a fully autonomous, data-driven railway system characterized by enhanced safety, operational efficiency, and passenger satisfaction. Addressing challenges related to interoperability, regulatory adaptation, and data security is critical to achieving this vision.

6.3. Opportunities in the digital transformation of railways

The future of railway transportation lies in the seamless integration of advanced technologies with a focus on sustainability, resilience, and equity (Smith, 2001). The interconnected roles of AI, IoT, and blockchain form the foundation of intelligent railway systems, but their broader impact depends on addressing systemic challenges. Emerging research should focus on creating adaptive frameworks that enable these technologies to work in concert within diverse operational contexts. For instance, developing modular systems that integrate AI for predictive analytics, IoT for real-time monitoring, and blockchain for secure data management can create a cohesive network capable of responding dynamically to both routine operations and unexpected disruptions (Shambira & Mandiudza, 2021).

Furthermore, the societal implications of these technologies must not be overlooked. Ensuring accessibility and inclusivity in smart rail systems is as important as technical advancements. Equitable solutions, such as voice-activated ticketing for visually impaired passengers or autonomous services tailored to underserved communities, can redefine public transportation as a truly universal resource (Cheng & Huang, 2013). Finally, a robust approach to cybersecurity is essential as interconnected railway systems become increasingly vulnerable to cyber threats. Advanced encryption techniques, real-time threat detection, and contingency protocols tailored specifically to rail systems must be developed to ensure uninterrupted operations and passenger safety (Xu et al., 2020a). The integration of AI, IoT, and blockchain technologies, combined with a focus on sustainability and social equity, has the potential to redefine the railway industry. By addressing existing gaps and fostering innovation, these technologies can pave the way for a transportation system that is intelligent, resilient, and inclusive, meeting the complex demands of the future.

6.4. Cybersecurity challenges in connected railway systems

As railway systems become increasingly digitized and interconnected through Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin (DT) technologies, cybersecurity has emerged as a critical concern (Flammini, 2021). While these technologies greatly enhance operational efficiency, maintenance strategies, and passenger experience, they also expose railway networks to a new range of cyber threats. This section outlines the major cybersecurity challenges associated with these technologies and highlights specific attack vectors that could compromise the safety, reliability, and functionality of modern rail systems (Wei et al., 2024).

Building on this growing digital infrastructure, AI-based applications, such as intelligent scheduling, fault prediction, and autonomous control systems, are susceptible to adversarial attacks. These involve maliciously crafted data inputs that mislead machine learning models (Srivastava et al., 2022). For instance, an attacker could exploit vulnerabilities in AI-based scheduling algorithms by introducing slightly modified data that causes incorrect train dispatching or prioritization, leading to delays or even collisions. This type of adversarial machine learning (AML) attack can be particularly damaging because AI models are often seen as "black boxes" and lack transparency, making detection difficult. Furthermore, without robust model validation, the system may continue to operate on manipulated inputs without alerting human operators (Gkioulos & Chowdhury, 2021; Pawlicki et al., 2024).

Complementing these AI systems, IoT devices embedded across railway infrastructure – such as trackside sensors, cameras, and signaling systems – present another layer of vulnerability. These devices often operate in unsecured environments and may lack built-in security protocols, making them vulnerable to a range of attacks including sensor tampering, spoofing, denial-of-service (DoS), and data injection (Gollmann, 2013; Krishnaveni et al., 2024). For example, if a malicious actor tampers with vibration sensors on a railway bridge to report normal conditions during structural degradation, it could result in undetected risks and severe safety issues. Moreover, since IoT devices serve as data collection endpoints for AI models, any compromise in their integrity directly undermines the reliability of AI-driven decisions, compounding the overall risk.

Expanding further into the ecosystem, Digital Twin technology, which creates real-time virtual representations of physical railway assets, introduces yet another significant cybersecurity challenge. As DT frameworks rely heavily on continuous data exchange between physical and digital environments, they are particularly susceptible to ransomware, unauthorized access, and man-in-the-middle attacks (García de Soto et al., 2022b; Karabacak et al., 2016a). If attackers gain access to the digital twin, they could alter simulations, falsify maintenance forecasts, or disrupt system-wide monitoring. This could lead to misguided operational decisions, potentially causing system-wide failures or unsafe conditions. Furthermore, the use of cloud-based infrastructure to manage DT platforms extends the attack surface, especially in the absence of strong encryption and multi-factor authentication protocols (Charmet et al., 2022; García de Soto et al., 2022a).

To mitigate these interconnected risks, it becomes essential for railway operators to adopt a cybersecurity-by-design approach, embedding security mechanisms across all layers of technological deployment. This includes implementing real-time anomaly detection, end-to-end encrypted communication protocols, and conducting frequent penetration testing (García de Soto et al., 2020; Karabacak et al., 2016b). AI systems should incorporate adversarial training techniques, while IoT and DT setups must conform to industry-wide cybersecurity standards. Beyond technical defenses, fostering human preparedness through staff training, regulatory compliance, and interagency collaboration is vital for creating a resilient digital railway ecosystem.

Therefore, while AI, IoT, and Digital Twins offer transformative benefits to the railway sector, their convergence also introduces complex and evolving cyber threats. By addressing these risks through proactive, multi-layered strategies, railway networks can ensure safe, secure, and future-ready operation.

7. Future directions and research agenda

7.1. Advancing predictive maintenance models

The integration of advanced predictive maintenance models is pivotal to optimizing the operational efficiency of railway systems (Qiu et al., 2024a). As rail networks become more complex and interconnected, predictive maintenance powered by Artificial Intelligence (AI) is proving to be a game changer. However, to fully realize its potential, it is crucial to enhance the accuracy and applicability of these models by combining AI with physics-based models. While AI excels in identifying patterns from historical data, physics-based models offer deep insights into the underlying mechanics of railway systems, such as stress on tracks, wear on train components, and other physical dynamics that influence maintenance needs (Ghadekar et al., 2024). By merging these two approaches, researchers can create more accurate, context-aware predictive maintenance systems that not only forecast potential failures but also understand the root causes of these issues. This hybrid model would provide a more robust predictive capability, reducing false positives and ensuring timely interventions (Allah Bukhsh et al., 2019).

Additionally, one of the major challenges in predictive maintenance models is addressing the issue of data imbalance in failure prediction. Railway systems often suffer from an underrepresentation of failure data, as the majority of components may operate smoothly without incident for extended periods. This results in a skewed dataset where failures are rare and often not well-documented (van Dinter et al., 2022). To overcome this challenge, research should focus on developing techniques to handle imbalanced datasets effectively. This could include using synthetic data generation methods, transfer learning, or anomaly detection algorithms that can identify early signs of failure, even in the absence of significant prior failure data. By addressing data imbalance, predictive maintenance models can be more effective at detecting incipient issues, reducing downtime, and improving resource allocation across the network (Luo et al., 2020). The AI-Driven Predictive Maintenance Pipeline (Figure 11) enhances railway infrastructure reliability through a closed-loop framework. It starts with sensor data collection from components like tracks and wheelsets, followed by preprocessing for consistency. Key features are extracted and used to train AI models for real-time anomaly detection and failure prediction. Based on these insights, the system recommends and executes optimal maintenance actions. A continuous feedback loop updates the model with new data, enabling adaptive, data-driven, and cost-effective maintenance.

7.2. Building sustainable and resilient rail systems

The ongoing evolution of global transportation systems necessitates a strong focus on building sustainable and resilient railway networks. Railways, while already recognized as one of the most energy-efficient modes of transport, still contribute to global greenhouse gas emissions and face operational challenges related to climate change and environmental degradation. To address these issues, future railway systems must adopt innovative green infrastructure designs and materials, alongside strategies for improving climate resilience. Innovations in green infrastructure de-

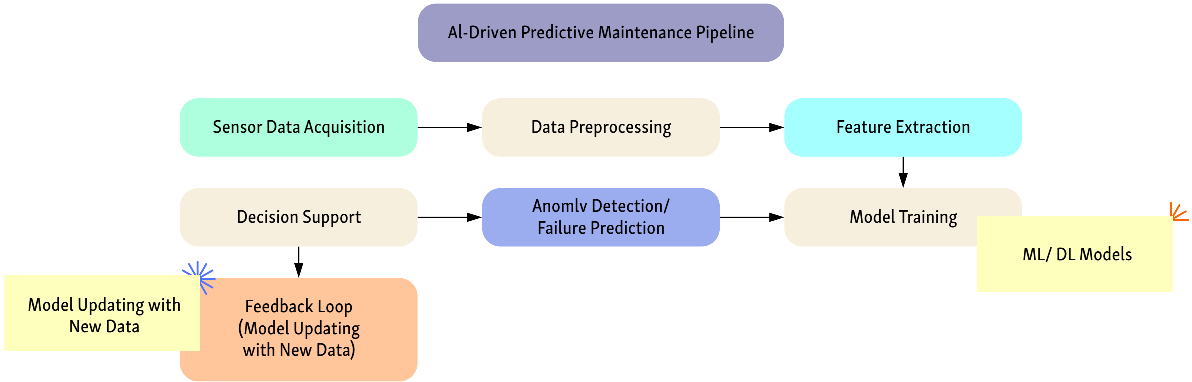

Figure 11. AI-driven predictive maintenance pipeline for railway infrastructure

sign are crucial for minimizing the environmental impact of rail systems. The development and adoption of energy-efficient train stations, eco-friendly materials for track construction, and the integration of renewable energy sources – such as solar panels or wind turbines – into the rail network are key steps toward sustainability (Negri et al., 2021). For example, train stations can be designed to harvest solar energy, reducing their reliance on grid power. Moreover, low-emission materials used in the construction of tracks and stations, such as recycled steel or carbon-neutral concrete, can further lower the carbon footprint of rail networks (Bešinović, 2020).

Equally critical is enhancing the climate resilience of rail systems. With increasing incidences of extreme weather events – such as flooding, heatwaves, and heavy storms – rail networks must be designed to withstand these challenges without compromising their operational capabilities. Research efforts should focus on developing infrastructure that can adapt to changing environmental conditions (Kaewunruen & Lian, 2019). This includes the use of advanced materials that resist wear and degradation from extreme weather, as well as the deployment of real-time monitoring systems that allow operators to respond quickly to adverse weather conditions. For instance, IoT sensors that monitor track conditions and weather data can feed into predictive models, enabling proactive adjustments to train schedules or rerouting to avoid areas prone to flooding or landslides. Additionally, the integration of climate resilience strategies, such as elevated tracks in flood-prone areas or reinforced bridges, will ensure that rail networks continue to function smoothly despite extreme weather events. The goal should be to create a railway system that can not only mitigate the effects of climate change but also play a role in addressing it by reducing its carbon footprint.

Real-world deployments in countries such as China, Germany, and Singapore illustrate the potential of technologies like AI, IoT, and Digital Twins in achieving sustainable and resilient rail systems (Mu & Antwi-Afari, 2024). These implementations demonstrate benefits such as optimized energy usage, automated fault detection, and improved emergency responsiveness. However, they also expose challenges related to interoperability, high infrastructure costs, and lack of unified data standards. These insights emphasize the importance of developing globally adaptable frameworks and modular architectures that enable broader adoption and long-term resilience across diverse railway environments (Bibri et al., 2023).

7.3. Digital twin integration across rail systems

Digital twins – virtual replicas of physical systems – are revolutionizing the way rail networks are managed and optimized. These digital models provide an opportunity to monitor and simulate the behavior of railway infrastructure, rolling stock, and network operations in real-time, offering a comprehensive, dynamic view of system performance (Bešinović, 2020). To realize the full potential of digital twins in railway systems, their integration with IoT technologies is critical. IoT devices embedded throughout the railway system generate vast amounts of real-time data, ranging from the condition of tracks and trains to environmental factors like temperature and humidity. By linking digital twins with IoT, railway operators can create comprehensive simulations that allow for more accurate predictions, better decision-making, and more effective maintenance strategies. For example, IoT sensors on train components could track wear and tear, while the digital twin model could predict the remaining lifespan of these components under various operational conditions (Afrin & Yodo, 2020).

However, the true value of digital twins can only be realized if they are integrated into a broader framework of interoperable data exchange platforms. Railways are complex, with multiple stakeholders involved – ranging from infrastructure providers to train operators and regulatory bodies. For digital twins to be effective, they need to be able to communicate seamlessly with other systems, exchanging data and insights in real-time. Research should focus on developing standardized protocols for data exchange that enable different systems to work together seamlessly (Negri et al., 2021). This includes ensuring that digital twins can integrate data from a variety of sources, such as IoT sensors, GPS data, weather forecasts, and passenger information systems. Interoperability between these platforms will allow operators to simulate different operational scenarios, optimize maintenance schedules, and respond dynamically to changing conditions (Kaewunruen & Lian, 2019). For example, predictive analytics from digital twins could inform better train scheduling decisions, reducing delays and improving efficiency across the network (Ben Hassen & El Bilali, 2022). Real-time data from IoT-enabled physical assets – such as tracks, sensors, and rolling stock – is continuously transmitted to a centralized Digital Twin platform. This platform dynamically models and analyzes the railway environment using AI-driven simulations. The resulting insights support decision-making processes in control centers, which issue feedback and control commands back to the physical infrastructure. This closed-loop system enables adaptive operations, predictive maintenance, and improved safety across the railway network. This integration process is illustrated in the schematic representation of the Digital Twin architecture (Figure 12).

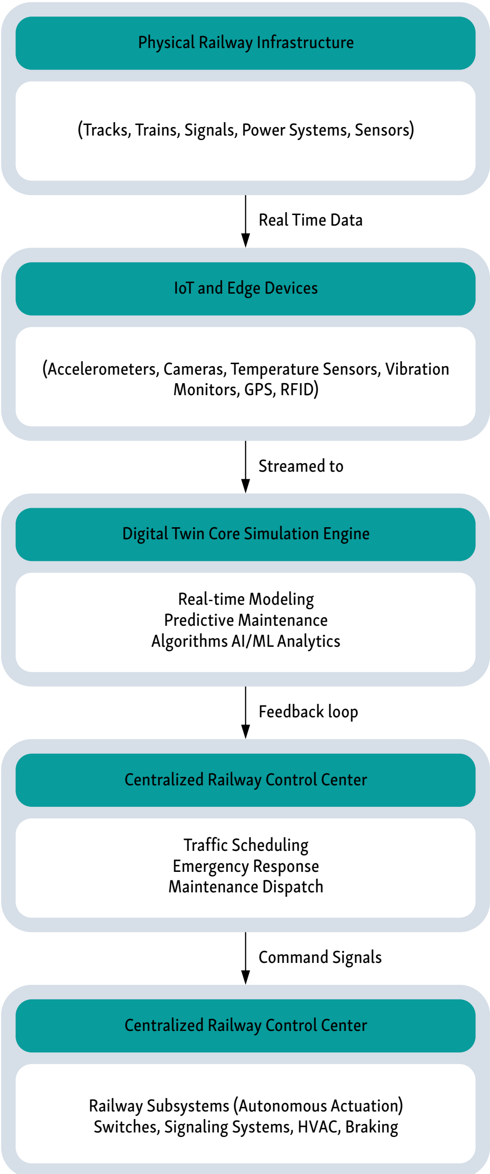

Figure 12. Schematic representation of digital twin integration with railway control systems

7.4. Policy and standardization needs for emerging technologies

As emerging technologies – such as AI, IoT, blockchain, and digital twins – become increasingly integral to the railway industry, it is essential to develop robust policies and global standards to guide their integration into the sector (Fagnant & Kockelman, 2015; Pojani & Stead, 2015). The rapid pace of technological advancement, coupled with the complexity of railway networks, creates a pressing need for standardization to ensure that different systems and technologies can operate cohesively. The development of global standards for IoT devices and digital twins is crucial for fostering interoperability across the railway sector. These standards should address technical aspects such as data formats, communication protocols, and security measures to ensure that devices from different manufacturers and service providers can work together seamlessly (Harris et al., 2015; Kaewunruen et al., 2016). By establishing these global standards, the railway industry can prevent fragmentation and create an environment where innovation can flourish while maintaining compatibility between diverse technologies.

In addition to technical standards, there is an urgent need to establish regulatory frameworks that govern the deployment of autonomous systems within rail networks. Autonomous trains, for example, have the potential to improve safety and efficiency, but their integration into existing systems requires a clear set of safety standards and operational guidelines. Research into regulatory compliance for autonomous systems should address issues such as safety protocols, cybersecurity measures, and the interaction between human-operated and autonomous trains. This will involve developing comprehensive safety testing frameworks, ensuring that autonomous trains can operate safely alongside human drivers and under varying conditions (González et al., 2020; Gürdür et al., 2022; Xia et al., 2022). Moreover, the legal and ethical implications of automation in rail systems must be carefully considered. Research should explore the liability issues surrounding autonomous operations, as well as the potential societal impact of job displacement due to automation. Ensuring that autonomous systems comply with existing regulations while also addressing new challenges posed by automation is essential for enabling their successful deployment.

Furthermore, as technologies like IoT and blockchain are increasingly deployed in railway operations, policymakers must ensure that regulations evolve to keep pace with technological advancements. This means creating flexible regulatory frameworks that can accommodate new developments while safeguarding safety, data privacy, and cybersecurity. Collaboration between industry leaders, regulatory bodies, and technology providers will be vital in developing regulations that foster innovation while ensuring that new technologies are implemented responsibly and safely.

8. Conclusions

The integration of emerging technologies in railway transportation marks a paradigm shift in operational efficiency, safety, and sustainability. Innovations such as AI, IoT, Digital Twins, and autonomous systems are reshaping the landscape, enabling smarter decision-making, predictive maintenance, and real-time optimization of resources. This review underscores their profound impact on addressing critical challenges such as infrastructure degradation, energy inefficiency, and passenger safety. AI's application in traffic management, demand forecasting, and predictive maintenance highlights its role in enhancing operational precision and resilience. IoT, complemented by sensor technologies, facilitates real-time monitoring and proactive interventions, significantly reducing unplanned downtimes and ensuring safer operations. Digital Twin technology emerges as a transformative tool for lifecycle asset management, enabling detailed simulations and predictive analytics to optimize system performance. Additionally, autonomous systems offer groundbreaking solutions in maintenance automation and train operations, addressing both safety and efficiency. However, the adoption of these technologies is not without challenges. The review identifies key barriers, including interoperability issues, high implementation costs, and regulatory complexities. Cybersecurity remains a pressing concern, necessitating robust frameworks to protect interconnected systems. Furthermore, integrating advanced technologies into legacy infrastructure requires strategic planning and significant investment. This review highlights the critical need for collaboration among researchers, policymakers, and industry stakeholders to address these barriers and unlock the full potential of intelligent railway systems. Future research should prioritize the standardization of data integration, advancements in cybersecurity, and the scalability of innovative solutions. By overcoming these challenges, the railway sector can achieve its goals of enhanced efficiency, safety, and sustainability, positioning itself as a cornerstone of modern, environmentally responsible transportation systems.

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Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

The author declared that there is no conflict of interest.

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