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-

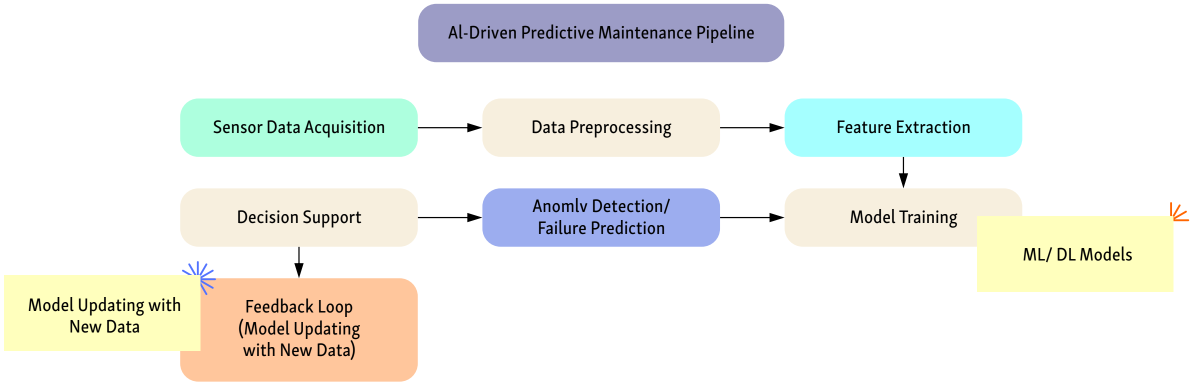

Figure 11. AI-driven predictive maintenance pipeline for railway infrastructure

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).

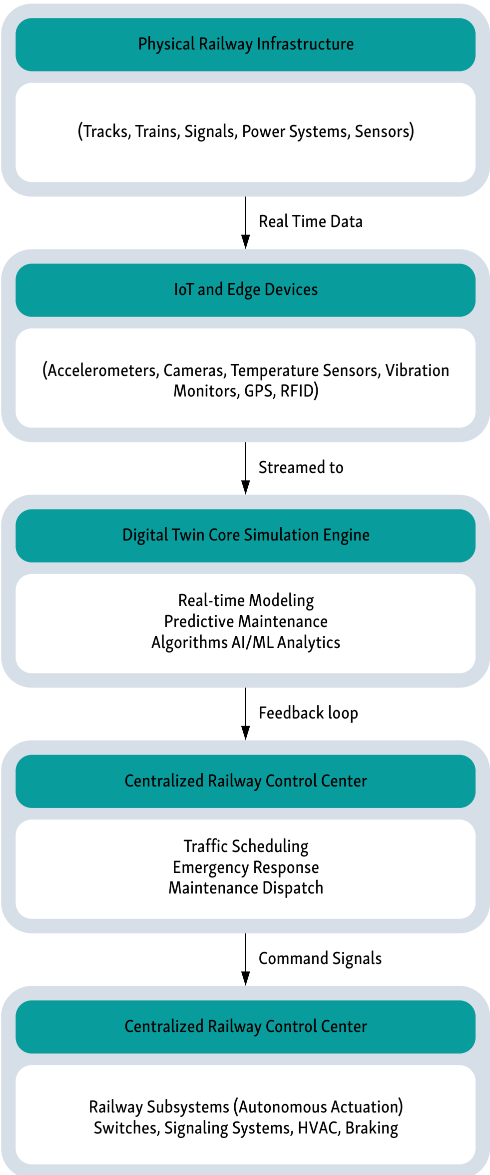

Figure 12. Schematic representation of digital twin integration with railway control systems

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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