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ANALYSIS AND CHALLENGES FOR IOT & AI IN BUILDING AND IMPLEMENTING SMART RAIL TRANSPORT SYSTEMS

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Abstract. The construction and management of modern rail systems is associated with the implementation of several innovations such as the Internet of Things and artificial intelligence (IoT & AI). Although rail transport management allows a high degree of automation and the introduction of modern technologies, it is still conservative in terms of transport process management and includes multiple assurances of its safety and reliability.

This article offers a comprehensive analysis of the scope and challenges involved in developing smart rail transport systems through the application of the Internet of Things (IoT) and Artificial Intelligence (AI). The rail industry faces increased time consumption and reduced productivity and service quality, largely due to limited awareness and adoption of advanced technologies that are prevalent in other sectors. This study examines current research trends, identifies key challenges, and proposes effective solutions for adapting to technology. The findings inform a roadmap for facilitating the implementation of Industry 4.0 through AI and IoT integration. The study highlights the significance of technology integration and pioneering research in achieving the objectives of Industry 4.0 and 5.0 and outlines future research directions.

Keywords: intelligent systems; rail transport; transport information systems: smart rail systems; analysis; IoT; AI

1. Introduction

Railway transport is undergoing changes driven by the development of modern technologies, including the Internet of Things (IoT) and artificial intelligence (AI). To ensure safety, efficiency, and customer convenience, railway systems are becoming intelligent. With an IoT system, data is collected in real time through a set of connected sensors and IT communication devices. Artificial intelligence uses this data by deep learning or ML models, thereby contributing to flexible and smart intelligent decision-making, predictive full maintenance, and operational tasks and activities. The investigation into the implementation of IoT and AI in smart rail systems reveals key benefits and identifies critical challenges that must be addressed for successful deployment [1].

The essence of digital transformation is the development and application of modern information and communication technologies to create flexible, adaptive, more efficient, and sustainable solutions in new information systems within the industry. It occupies a crucial role in shaping modern organizational structures and business models. Digitalization has been widely applied in transportation, manufacturing, energy, healthcare, and supply chains for over 20 years. (Fig.1)

Figure 1. Digital transformation in different industries

Digitalization generates significant economic advantages for businesses and production sectors. It contributes to lower unemployment rates, enhances quality of life, and increases overall productivity.

According to the World Economic Forum, the cumulative value generated by digitalization across all economic sectors and its impact on human well-being could surpass $100 trillion by 2025. Emerging digital technologies, including mobile platforms, cloud computing, artificial intelligence (AI), intelligent sensor systems, and advanced analytics, are expected to play a critical role in every industry. Digital transformation relies on four main components: the collection, storage, processing, and utilization of digital data; heterogeneous communication networks; and automation and data visualization systems with comprehensive dashboards. The integration of new technologies requires careful consideration to ensure compliance with the General Data Protection Regulation (GDPR), adherence to ethical standards, and fulfillment of security requirements. Maintaining the reliability, transparency, and confidentiality of data collection, processing, and storage in accordance with GDPR is essential for building public trust and adhering to legal standards. Robust security measures are necessary to protect the integrity and availability of sensitive data, which is particularly important for the safe operation of railway activities. The railway sector faces unique challenges, including extended adaptation periods, limited competition among railway companies, and issues related to accessibility, passenger comfort, and security for both passengers and freight. The slow pace of digital adoption in railways increases the risk of higher operating costs, more frequent and prolonged service interruptions, and ultimately threatens long-term sustainability. Key technologies in this context include sensors, controllers, routers, cameras, industrial robotics, interface boards, distributed control systems, GPS/GNSS, networking technologies, RFID, condition monitoring, yield monitoring, smart meters, smart beacons, flow and application control devices, guidance and steering systems, and electronic shelf labels. The European Industrial Internet of Things (IoT) market encompasses various applications, including SCADA, MES, PLM, distribution management systems, transit management systems, outage management systems, visualization software, remote patient monitoring, retail management software, and farm management systems. Connectivity options include wired, wireless, and hybrid solutions, serving end users across various sectors, including manufacturing, transportation and logistics, energy, oil and gas, metals and mining, healthcare, retail, agriculture, and others. Industry trends and forecasts extend to 2029. (fig. 2)

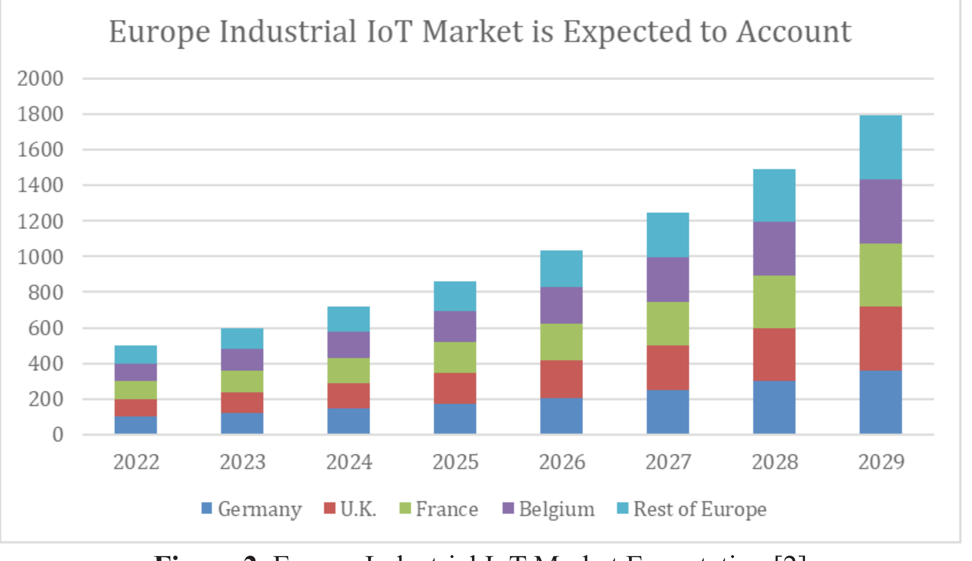

Figure 2. Europe Industrial IoT Market Expectation [2]

The second reason is the management goals of railway companies. Most railway companies are owned by the country and managed by governments; these companies rely on government financial subsidies from taxpayers. Governments prioritize other public issues over improving the quality of service for passengers and freight in multimodal transport networks, which have been neglected over time. The same applies to private railway companies, which primarily focus on profits without regard for public welfare. Digitalization is particularly important in the context of economic development, as it enhances accessibility and yields greater economic benefits.

Recent research has highlighted the critical role of advanced digital technologies in modern railway systems, encompassing passenger and freight transport, infrastructure, rolling stock, automation, and traffic management. Since 2000, the adoption of Industry 4.0 (I4.0) in railway transport has demonstrated potential to enhance travel comfort, reduce travel time, and decrease infrastructure operating costs. Industry 5.0 (I5.0) further contributes to improving passenger-oriented services. Addressing security vulnerabilities and ensuring data integrity remain essential for uninterrupted railway operations. The introduction of the Rail Flow Management System, a digital platform that supports autonomous train movement and satellite-based safety enhancements, exemplifies recent advancements in the sector. This analysis examines strategies to optimize digitalization in railway transportation, with a focus on both passenger and freight trains. While passenger trains increasingly utilize sensors and on-board communication for autonomous operation, freight trains lag behind due to insufficient sensor deployment and the limited capabilities of edge devices. The absence of global standards for train digitalization presents a significant challenge. The analysis provides a comprehensive overview of the railway industry's digital readiness, key enabling technologies, and the application of digital twins, including use cases such as driver monitoring and intelligent maintenance. Opportunities and challenges associated with digitalization in railway transport are also examined.

<u>Digitalization of rail transportation</u>

Rail transport has undergone continuous development since its inception. Over the past two centuries, locomotives have increasingly integrated diverse transport data. This ongoing transformation aims to enhance environmental sustainability, improve energy efficiency, and promote the long-term viability of rail systems. While mechanical components of trains deteriorate over time and require service interruptions for maintenance, train software can be updated simultaneously across fleets without operational disruption. The digitalization of rail transport involves converting physical systems from analogue to digital formats, enabling higher levels of automation and reducing the need for human intervention. For example, autonomous battery-powered wagons and improved scheduling of operations, maintenance teams, and depot activities contribute to more efficient and timely rail services.

Maintenance plays a critical role in the digitalization of railway systems. Traditional physical inspections are being increasingly replaced by continuous monitoring, enabled by advanced sensors and data analytics. Maintenance and operational optimization methods are developed based on the real-time condition of railway tracks and rolling stock. Implementing these methods in modern smart trains leads to increased profitability, enhanced safety, reduced downtime, lower operating costs, and more efficient resource utilization. Maintenance forecasting leverages data analysis, including information from Internet of Things (IoT) sensor systems, to assess equipment condition and schedule maintenance only when necessary, thereby eliminating unnecessary interventions and reducing costs. These approaches enable real-time monitoring of train conditions, facilitating timely, condition-based maintenance. The adoption of state-of-the-art maintenance forecasting and optimization methods can reduce waste, minimize environmental impact, and promote sustainable resource use. Digitalized transport units thus support the optimization of maintenance activities, improve system profitability, and enhance the safety and reliability of railway operations [2].

2. Technological Framework

2.1. Internet of Things (IoT) in Rail Transport

The Internet of Things (IoT) comprises a system of sensors and controllers distributed across railway infrastructure to detect signals and generate essential data for real-time monitoring. Software applications facilitate predictive maintenance, intelligent process optimization, and energy management. The IoT architecture typically consists of data sensors, a communication network, and application layers. Digital Twin (DT) technology is increasingly adopted to enhance the predictability, safety, and reliability of digitalized information and communication technology (ICT) systems. DTs play a significant role in various domains, as evidenced by ongoing efforts to standardize them. However, several challenges must be addressed to effectively implement DTs in critical systems. This review examines the scientific literature on DTs in the railway sector, with particular emphasis on their integration with Artificial Intelligence. Key challenges and opportunities for DT adoption in railways are identified, with interoperability emerging as the most prominent issue. A major challenge involves transmitting operational data in real-time from edge systems to the cloud, enabling timely decision-making. This work also provides guidelines for designing DTs, with a focus on the application of machine learning to railway maintenance [3].

2.2. Artificial Intelligence (AI) in Rail Transport

Artificial intelligence (AI) plays a critical role in rail transport, particularly in decision-making for scheduling, security, and anomaly detection. Key techniques include machine learning, deep learning, and reinforcement learning, which are applied to optimize operational tasks and enhance safety and efficiency. This analysis examines AI applications in railways, focusing on maintenance and inspection, planning and management, safety and security, autonomous operation and control, financial management, transport policies, and passenger mobility. While significant research has addressed AI for rail maintenance and inspection, there is limited work on AI for policy, revenue, and cost management. AI applications offer promising solutions to many challenges in rail transport, yet research in this sector remains underdeveloped. Future studies should prioritize the development of advanced AI systems that support management decision-making and address cybersecurity concerns [4].

2.3. Integration of IoT and AI

The integration of the Internet of Things (IoT) and artificial intelligence (AI) enables the development of cyber-physical rail systems, including digital twins, intelligent control centers, and autonomous trains. These technologies are driving significant changes in transport services, promoting sustainability, efficiency, and safety. Their implementation necessitates a comprehensive analysis of current research, methodologies, and potential implications for sustainable development. Notable advancements include intelligent traffic control systems, autonomous vehicles, energy management, proactive maintenance, and multimodal transport networks. These innovations contribute to pollution reduction, energy savings, and enhanced customer satisfaction. Overall, AI and IoT play a critical role in addressing environmental challenges, optimizing transport services, and influencing related sectors [5, 6].

3. Benefits and Opportunities

Intelligent rail systems offer several benefits, such as enhanced profitability, increased transportation safety, improved passenger services, reduced environmental impact, and revenue optimization through dynamic pricing and operational cost savings. This analysis highlights the benefits of artificial intelligence in the transportation sector. Four subsystems of Intelligent Transportation Systems – Traffic Management, Public Transport, Safety Management, and Manufacturing and Logistics – are examined to assess the specific roles and benefits of AI. Additionally, the study compiles a range of AI applications implemented by various cities and corporations, providing a comprehensive reference for future decision makers.

This study enables the manufacturing and transport service industries to identify new opportunities for deploying AI solutions within their respective domains. Before implementation, organizations should evaluate both the potential benefits and challenges associated with these solutions to support the development of a sustainable society [7].

4. Challenges and Limitations

Key challenges include data interoperability, latency, and cybersecurity threats. Railway infrastructure constitutes a highly complex distributed parameter system whose dynamic characteristics vary across both temporal and spatial dimensions. Temporal changes primarily result from continuous usage, degradation processes, and human interventions such as maintenance. Spatial variations arise because the governing dynamics differ at each location; for example, railway tracks at bridges, tunnels, stations, and curves exhibit distinct behaviors compared to straight tracks. While the infrastructure may be viewed as a linear structure with locally periodic components such as sleeper spacing, the substructure and track parameters remain unique at each site. Furthermore, the system is exposed to multiple sources of stochasticity, including variable weather conditions, which can impact functionality. Consequently, railway infrastructure represents a dynamic, continuous, distributed, and stochastic system that presents significant challenges and necessitates the development of intelligent methods tailored to local practical solutions [8].

We can present Smart Rail as the function of some main components, such as in Formula 1.

(1)

$$SmartRail = f(SmartInfra,\ SmartTrain,\ SmartSystem,\ IoT,\ Data\ Analysis,\ AI) \rightarrow Optimum$$

where:

SmartInfra – is Core of the smart railway;

SmartTrain – is essential power of the hole system;

SmartSystem - represents the key IT elements of the system;

IoT – add first level of detecting and determine of digital data;

Data Analysis and AI – full analytic and decision machine of the system.

Optimal railway infrastructure management necessitates comprehensive strategies that effectively address the intricate interconnections among infrastructure, society, and the environment. Research in this field is inherently multidisciplinary. Addressing fundamental questions necessitates understanding not only the physical responses of infrastructure, such as structural and mechanical behaviors, but also the limitations of mathematical modeling approaches, the capabilities of advanced measurement technologies, available maintenance technologies, the behavior of stochastic variables, including weather and reliability, human factors related to users and workers, and the intricate relationships between railway governance and contractual frameworks. The challenges associated with railway infrastructure vary across locations and time periods. These complexities present opportunities to develop innovative solutions that more effectively capture the essential characteristics of infrastructure and address issues beyond the scope of traditional methods.

Health condition monitoring and maintenance play a vital role in ensuring the safety, availability, and reliability of services simultaneously, as well as in prolonging the lifespan of the infrastructure. Early detection and preventive maintenance of possible failures before they occur have shown great potential for cost savings [9].

5. Case Studies

The integration of artificial intelligence (AI) at Deutsche Bahn has led to reduced delays, more efficient maintenance, and enhanced customer service. AI is already embedded in numerous projects across the organization, facilitating the digitalization process and enhancing the overall appeal of rail transport.

The use of AI begins with the planning of components and raw materials, encompasses the intelligent control of railway services, and extends to the digitalization of all maintenance special activities. AI helps to dispatchers to govern urban rail tasks successfully. With the end of a successful pilot test of the new technology in the Stuttgart urban rail system. DB is introducing and spreading more internally created and developed AI-based tools in the Rhine-Main and Munich urban rail systems. This tool predicts recommendations that prompt DB staff to take an urgent approach to managing critical moments in the operation of the city rail system, thereby minimizing delays. This, in turn, helps to cut the accumulation of delays and congestion on busy routes. In Stuttgart, the tool enables DB to claim compensation for delays of up to 8 minutes. DB's expectations are to utilize all components it has developed to create a platform for increased train usage.

The adoption of artificial intelligence has significantly enhanced predictive maintenance at Deutsche Bahn. The organization aims to implement large-scale, condition-based smart maintenance for its trains. This approach reduces employee fatigue and decreases the duration of complex tasks, such as inspecting the roof of an ICE train, from several hours to just a few minutes. AI technologies achieve this by automatically integrating camera footage and sensor data to provide a comprehensive overview of maintenance needs.

Numerous maintenance projects aim to accurately predict optimal maintenance intervals for vehicle spare parts. Deutsche Bahn is developing several artificial intelligence-based forecasting tools to assist S-Bahn maintenance planners in coordinating axle replacements and conditioning more efficiently. This strategy conserves resources, reduces costs, and increases vehicle availability. Additionally, Deutsche Bahn employs AI-driven processes to enhance travel information provided through its websites, the DB Navigator application, stations, and other customer channels. Accurate predictions of train arrival and departure times are essential for travelers. Deutsche Bahn utilizes AI-based forecasting, leveraging both historical and real-time data, to improve the accuracy of these predictions. Furthermore, the company is developing virtual customer service assistants using AI. In addition to text-based chatbots, such as those available at bahn.de, Deutsche Bahn has created an intelligent interactive voice response system called SEMMI, which has been tested in customer service applications [10].

Conclusion

Artificial intelligence (AI) and the Internet of Things (IoT) are transforming rail transport into intelligent, adaptive, and efficient systems. Effective strategic planning, government support, and ongoing innovation are essential for developing next-generation rail networks that are safe, sustainable, and resilient. The digitalization of railways has a significant impact on the economics and operations of rail transport, providing substantial benefits to businesses, passengers, and transportation activities. The adoption of advanced technologies enhances security and service quality, thereby fostering passenger trust and confidence. Increased reliability in transport operations is expected to boost revenues and profitability for railway companies. Digitalization also enables more timely train availability and allows existing railway lines to accommodate higher volumes of wagon flows, further increasing profitability. A notable outcome of digitalization is the reduction in maintenance costs, achieved through predictive and prescriptive maintenance strategies that optimize all maintenance activities. The integration of modern technologies minimizes downtime for wagons and trains, reducing costs associated with the organization, mobilization, maintenance, and repair of rolling stock. Digital rail transport connects trains, engineering teams, supply chains, and maintenance activities in real time within a unified system. This orchestration model facilitates international communication and enhances profitability across divisions by leveraging Industry 5.0, IoT, and AI technologies. Comprehensive task optimization contributes to reduced pollution and promotes more sustainable transport. Autonomous trains with enhanced passenger amenities represent significant potential for the future of rail transport. However, cybersecurity and privacy remain critical concerns, necessitating further analysis to ensure the availability and security of train services. It is imperative that digitalization efforts comply with the General Data Protection Regulation (GDPR) to maintain public trust and avoid legal repercussions. The rapid development and deployment of these systems can particularly benefit underdeveloped and budget-constrained railway administrations, enabling operators to adopt such solutions efficiently [1].

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