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SMART RAILWAY AS A SMART CITY SERVICE

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Abstract: *The railway system is a large-scale, complex, and multidisciplinary technical, transportation, and business subsystem. As an energy-efficient and environmentally friendly mode of transport, railways record the lowest levels of greenhouse gas emissions compared to other transport modalities. The development of modern information and communication technologies (ICT), the Internet of Things (IoT), and artificial intelligence (AI) has triggered substantial changes in the railway sector, steering it toward digital transformation and system modernization. This paper analyzes the concept of the "smart railway" as a key infrastructural component of smart cities by examining its structure, core functions, and selected urban implementation cases. Special emphasis is placed on comparative analysis of global practices and the identification of development priorities. The aim of the research is to assess the strategic relevance and comparative advantages of smart railways within the broader smart city ecosystem. The paper concludes that a well-planned and integrated smart railway system can significantly contribute to sustainable urban development and enhance citizens' quality of life.*

Keywords: *smart railway, smart city, information and communication technologies (ICT), Internet of Things (IoT), sustainable transport, urban mobility*

1. INTRODUCTION

Contemporary trends in the development of information technologies and digitalization have fundamentally transformed social systems and numerous industrial sectors, including railway transport (Bogdanović et al., 2021; Stojanović & Domazet, 2020). The emergence of the Industry 4.0 paradigm has enabled the integration of knowledge and resources from various sectors—public administration, business, education, civil society, and individual actors—with the aim of joint participation in innovation processes and the improvement of complex systems (Stojanović et al., 2021).

Within this context, the railway sector gains particular significance as a complex, multidisciplinary technical, technological, transport, and business system. In modern conditions, thanks to the development of the Internet of Things (IoT), mobile technologies, blockchain, and other digital solutions, the prerequisites have been created for the railway system to respond more efficiently to challenges that exceed the capabilities of traditional, often costly and time-consuming, technical approaches (Kupriyanovsky et al., 2020; Stanisavljević, Stojanović, & Bogdanović, 2023; Thurner & Gershman, 2014).

Through the concept of open innovation and the application of crowdsourcing, it has become possible to include various stakeholders—from citizens and passengers, to the academic community and industry experts—in processes of identifying problems, proposing solutions, and co-creating innovations in the railway sector (Radenković et al., 2020; Stanisavljević et al., 2022). This contributes to greater flexibility, efficiency, and rationality in the management and technical operation of railways.

The modernization and optimization of the railway system represent key factors in achieving a sustainable, safe, and competitive transport environment. According to data from the International Union of Railways (UIC), railway transport is highly energy-efficient and environmentally friendly, emitting significantly lower levels of harmful gases compared to other modes of transport.

In this light, the implementation of advanced technologies and the development of intelligent railway management systems become essential for building an integrated and smart railway ecosystem that ensures greater safety, reliability, and sustainability, while simultaneously enhancing the overall user experience (Sharma & Kumar, 2017).

2. SMART RAILWAY

The exponential growth in demand for Internet of Things (IoT) technologies in recent years has driven significant advances in sensors, radio access, network protocols, and hardware/software platforms designed for large-scale applications (Jo et al., 2018). IoT has found wide application across various industries, and particularly in the railway sector, where it is used to enhance operations management, maintenance, video surveillance, and safety at level crossings (Singh et al., 2022).

Modern high-resolution sensors, such as high-speed cameras and LiDAR systems, enable real-time monitoring of railway infrastructure and rolling stock. These technologies support early detection of technical faults and potential risks, allowing for predictive maintenance and reduced operational costs. At the same time, data analytics powered by artificial intelligence and machine learning allows for the optimization of train scheduling and operational efficiency (Wang et al., 2022). Automated control systems, including advanced train control mechanisms, further improve safety by preventing collisions and derailments.

In the context of digital transformation, a railway system that integrates advanced information and communication technologies, sensor networks, IoT devices, wireless communication, real-time data processing, and AI algorithms is referred to as a Smart Railway (Ai et al., 2020; Z. Yu et al., 2023). The main objective of such a system is to enhance the management of trains, infrastructure, and logistics while simultaneously improving energy efficiency, safety, and operational reliability.

A smart railway is composed of the following interconnected elements: smart trains and intelligent control systems, IoT sensors embedded in tracks and stations, integrated control centers, digitized railway stations, automated signaling and traffic lights, video surveillance and safety systems, visual interfaces for citizen interaction, sustainable energy infrastructure, interoperability, and system connectivity.

Given the continued evolution of digital technologies, railway transport is expected to become even more intelligent, flexible, and integrated within smart cities and multimodal transport networks. Therefore, research and development in the field of smart railways is a strategic priority for achieving sustainable mobility, safety, and efficient transportation in the near future (Da Fonseca-Soares et al., 2023).

3. SMART CITY

Thanks to information and communication technologies, a smart city improves operational efficiency, shares information with the public, and ensures better quality of urban services and citizens' well-being. The goal of a smart city is to enhance the quality of life through the use of smart technologies and data analytics, while simultaneously optimizing its functions and ensuring economic growth.

Smart cities regulate and manage, among other things, the entire transportation infrastructure, including the railway system, to provide the highest quality services using minimal resources, thus meeting set goals (Sabory et al., 2021). Initiatives for using smart technologies are launched jointly by local governments and citizens.

The concept of smart cities dates back to the 1960s and 1970s when the U.S. Bureau of Community Analysis began using databases, aerial photography, and cluster analysis to collect data, direct resources, and issue reports to guide services, mitigate disasters, and prevent poverty. Today, we are witnessing the third generation of smart cities, characterized by community engagement and inclusion. For example, in Vienna, Austria, citizens can invest in local solar plants and take part in initiatives related to gender equality and housing accessibility. In Vancouver, Canada, over 30,000 residents participated in the creation of the "Greenest City Action Plan." Among today's global leaders in smart city development are Singapore, Kansas City, Barcelona, and Dubai.

One of the most important foundations of a smart city is smart transport. Smart cities and their industrial facilities are most efficiently supplied through road and railway transport (Miksa Hell & János Varga, 2018). Railways are the backbone of urban mobility, and in future smart cities, railway stations must offer easy access, multiple ticket booking and payment channels, and seamless integration with other modes of transport (Fantechi et al., 2021). The development of IoT has enabled the broader society to contribute to solutions across various domains, including railways. The application of open innovation facilitates the development of smart rail transport within smart cities (Stanisavljević, Stojanović, Miletić, et al., 2023).

4. SMART RAILWAYS AS A SERVICE

According to studies on smart city standards, transportation is one of the core services that defines a smart city. Smart railways, as the future of rail transport, relying on smart technologies and continuous innovation, will be the foundation of sustainable and safe mobility (Cruz et al., 2018; Fadel & Abu-Eisheh, 2024).

Cities are seeking to implement smart city strategies aimed at significantly improving the quality of life, particularly in terms of mobility and reducing CO_2 emissions. In this context, railways play a critical role. The location of stations and their accessibility to other transport modes are crucial for the use of rail. Therefore, the concept of a smart city must integrate rail transport (Bubelíny et al., 2021).

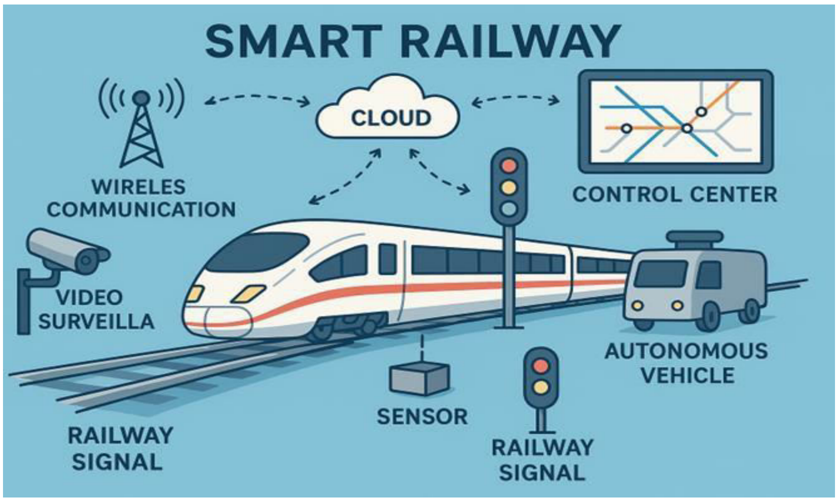

Figure 1: Smart Railway System Concept

Figure 1 presents the key components of a smart railway system that enable safe, efficient, and automated rail traffic management. The system is based on the integration of various technologies: video surveillance ensures continuous monitoring of infrastructure and surroundings; wireless communication enables real-time data exchange between vehicles, infrastructure, and the control center; sensors placed along the tracks detect field conditions and send data to the cloud, while railway signals and autonomous vehicles support automated control and timely responses to traffic situations. The control center, connected to all components, manages the entire system based on the analysis of collected data, relying on technologies such as IoT, AI, and cloud computing. This integration enhances the safety, efficiency, and sustainability of the railway system within the context of a smart city.

Efficient, long-term development of railway infrastructure is one of the key components in improving the performance of transport systems and quality of life, as demonstrated by the example of Prague. This case shows that not only advanced traffic control and signaling systems, but also efficient service concepts, can significantly enhance the railway system's efficiency and network capacity (Drábek & Michl, 2017).

Although public transport is central to urban mobility, current trends in Slovakia show a preference for individual transport. By addressing citizens' mobility needs through smart city concepts, local governments can promote greater use of public transport while improving air quality and overall quality of life (Bubelíny & Kubina, 2021).

Studies conducted in China have shown that smart city pilot projects positively impact regional economic growth through infrastructure and market effects. The rapid development of Chinese high-speed rail in the 21st century has reshaped the regional innovation landscape (X. Yu & Wan, 2022; Zhou et al., 2023).

In Sydney, the railway system was assessed as a component of the smart city based on indicators related to transportation and urban mobility across 12 municipalities within a 35 km radius of the city center. New rail infrastructure has provided significant technological benefits to suburbs, improving urban mobility (Gharehbaghi et al., 2023).

Mobility—both physical and economic—is a key factor in smart city development. The introduction of smart concepts into transport infrastructure will influence population growth and business demands. Railway stations that can provide strong economic development, environmental performance, and punctuality are recognized as core components of urban development (Shaltout, 2021).

Digital rail is the most important global trend in the development of rail transport. The "smart station" is a part of the digital railway concept. In Russia, this includes building new or reconstructing existing station complexes according to the smart station model (Nikonova et al., 2022).

Finnish Railways has defined train stations as strategic locations for implementing smart city concepts. These stations are becoming part of broader urban development efforts that align with economic and innovation policies, linking stations with smart city goals and open innovation frameworks (Hynynen & Kolehmainen, 2019).

Rail transit hubs play a critical role in modern urban development discourse as focal points of social, economic, and environmental interest. A railway station can effectively form a "city within a city," often referred to as a Railpolis. In India—a country facing complex urban challenges—such Railpolis models are expected to align with sustainable development goals and help cities become globally competitive (Banerjee, 2024).

Smart transportation is a key factor in smart city development, and its competitiveness depends on aligning management approaches with global best practices. Researchers have analyzed European and Russian approaches to smart transport governance to develop systematic standards (Bolgova et al., 2022).

However, studies of smart city concepts during the reconstruction of three railway stations in the Netherlands show that practical results are still insufficient. Although stakeholders were aware of the opportunities smart cities offer, knowledge sharing and innovation were hindered by limited acceptance and understanding, as well as institutional constraints such as data privacy regulations (de Wijs et al., 2016).

With the increasing demand for and adoption of smart city initiatives, it is essential to plan railway infrastructure adequately. If properly integrated, it can have a major positive impact. Given the complexity involved, systems thinking provides a useful framework for railway transport planning (Okonta et al., 2023).

5. CONCLUSION

The development of the smart railway concept is the result of dynamic transformations in the fields of information and communication technologies, the Internet of Things (IoT), and digital infrastructure. The modernization and implementation of advanced railway traffic management systems contribute to the enhanced safety, efficiency, reliability, and sustainability of the railway system, thereby improving the overall user experience. In this context, railways are positioned as an environmentally friendly and mobile mode of transport, with smart railways emerging as one of the foundational elements of the future smart city.

As demonstrated in this paper, the integration of smart railways into the smart city concept enables the achievement of key urban and societal goals—improved quality of life, increased mobility, economic growth, and optimal resource utilization. Railway stations, in particular, stand out as central infrastructural hubs within the broader frameworks of sustainable and digitally supported urban development.

However, the development and implementation of smart railways are accompanied by certain challenges: high initial implementation and maintenance costs, complex integration with existing systems, the need for a high level of cybersecurity and data protection, and potential resistance from certain demographic groups to technological innovations.

Despite these challenges, global trends in digital transformation and the widespread adoption of smart city initiatives indicate that the future of railways is inextricably linked with further digitalization and open innovation. In this regard, infrastructural and urban development plans for smart railways must be aligned with the strategic directions of smart city development. Only then can synergistic effects be achieved, enabling the full potential of the smart railway as a vital service of the smart city to be realized.

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