

GLOBAL INITIATIVES ON DIGITAL TRANSFORMATION OF RAILWAYS: EXPERIENCE IN IMPLEMENTING THE CONCEPT OF “RAILWAY 4.0”

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The article examines the prerequisites for the formation of the “Railway 4.0” concept and determines that its emergence is caused by increased competition in the transportation market, increased requirements for their quality and safety, and the aggravation of geopolitical and environmental crises. It is determined that the European model of the “Railway 4.0” concept is based on technological integration, automation (robotization) of processes and predictive management and is focused on increasing the interoperability of the railway network, the development of customer-oriented services and the formation of a single digital space of the transport system. International initiatives in the field of digital transformation of railways, in particular FRMCS and Horizon Europe, are analyzed, and it is argued that these projects of digitalization of railway transport ensure the creation of a digital railway ecosystem, thereby creating conditions for the safety, efficiency and environmental sustainability of the industry. Global projects of digital transformation of railways and the results of the integration of digital solutions into the activities of railway transport in the world are characterized.

Keywords: digitalization, rail transport, world experience, the concept of “Railway 4.0”, digital transformation projects.

ГЛОБАЛЬНІ ІНІЦІАТИВИ З ЦИФРОВОЇ ТРАНСФОРМАЦІЇ ЗАЛІЗНИЦЬ: ДОСВІД ВПРОВАДЖЕННЯ КОНЦЕПЦІЇ «ЗАЛІЗНИЦЯ 4.0»

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У статті досліджено передумови становлення концепції «Залізниця 4.0» і визначено, що її поява викликана посиленням конкуренції на ринку перевезень, підвищенням вимог до їх якості та безпеки, загостренням геополітичних та екологічних криз. Аргументовано, що концепція «Залізниця 4.0» передбачає повну цифрову трансформацію залізничної системи шляхом інтеграції передових технологій та фундаментальної перебудови операційних процесів, що забезпечує перехід від традиційної аналогової моделі до Smart-залізниці. Визначено, що європейська модель концепції «Залізниця 4.0» ґрунтується на технологічній інтеграції, автоматизації (роботизації) процесів та предиктивному управлінні і зорієнтована на підвищення інтероперабельності залізничної мережі, розвиток клієнтоорієнтованих сервісів та формування єдиного цифрового простору транспортної системи. Проаналізовано міжнародні ініціативи у сфері цифрової трансформації залізниць, зокрема FRMCS та «Горизонт Європа», і аргументовано, що ці проекти цифровізації залізничного транспорту забезпечують формування цифрової екосистеми залізниць, створюючи цим самим умови для безпеки, ефективності та екологічної стійкості галузі. Охарактеризовано світові проекти цифрової трансформації залізниць та результати інтеграції цифрових рішень в діяльність залізничного транспорту у світі.

Визначено, що предиктивне обслуговування, ERTMS-стандартизація, екологізація за принципами «Green Rail» та впровадження систем автоматизації на базі штучного інтелекту формують системну основу трансформаційних змін у залізничній галузі, створюючи передумови для становлення інтегрованої Smart-інфраструктури і забезпечуючи перехід до якісно нової моделі функціонування залізничного транспорту, заснованої на принципах даноорієнтованого управління, високого рівня автоматизації та безшовної інтеграції у глобальні транспортно-логістичні системи.

Ключові слова: *цифровізація, залізничний транспорт, світовий досвід, концепція «Залізниця 4.0», проекти цифрової трансформації.*

Problem statement. The current stage of the world economy is characterized by the rapid spread of digital technologies that radically change traditional industries, forming new models of management and organization of business processes. The transport sector is no exception, in particular the railways, which were among the first to embark on the course of digitalization, implementing strategies for the implementation of digital solutions to increase efficiency, environmental friendliness, energy efficiency and the creation of qualitatively new services for passengers and businesses. Global trends in the implementation of a digital strategy for the innovative development of railway transport revolve around the concept of “Railway 4.0”, which consists in the complete digital and technological transformation of railway transport in order to increase its safety, efficiency, reliability and integration into the global digital economy. This is not just modernization, but a transition from a traditional, mainly analog system, to a Smart system, where all processes are data-driven and automated [1-3].

Despite the national guidelines for the digitalization of key sectors of the economy, the railway industry of Ukraine is currently implementing digital solutions in a fragmented manner, limited to the automation of individual functions and processes in the field of transport and logistics services. The local nature of initiatives for the digitalization of Ukrainian railways does not provide a systemic transformation effect and is caused by the action of institutional, financial and technological barriers to ensuring a comprehensive digital transformation of the industry. Chronic lack of investment resources, high level of depreciation

of fixed assets, fragmentation of information systems, lack of a single digital architecture for railway transportation management, together with the low level of digital competencies of personnel and institutional inertia of the management system limit the ability of the industry to develop on a digital basis and determine the objective need to study the world experience of implementing digital transformations in railway transport.

Analysis of recent research and publications. The issue of railway transport development based on the application of digitalization technologies is quite actively discussed in scientific circles. Among Ukrainian researchers, the following scientists have devoted their research to the study and development of models and tools for railway digitalization: Dykan V. L., Zalesky O. V., Korin M. V., Mnykh O. B., Obruch H. V., Ovchinnikova V. O., Tokmakova I. V., Toropova V. I., Yanovska V. P. and others [4-10].

It is worth noting that despite the considerable attention of scientists to the problem of digital development of railway transport in Ukraine, currently the pace of digitalization of the industry lags significantly behind global initiatives to implement the concept of “Railway 4.0”, which necessitates the need to study the features of the formation of a digital model of railway growth in developed countries of the world.

The purpose of the article is to study the world experience of implementing digital transformations in railway transport and to establish the features of the global concept of “Railway 4.0”.

Presentation of the main material. In

the modern developed world, the emergence of the concept of “Railway 4.0” is caused by the pressure of external and internal factors that require an immediate structural restructuring of the global system of organizing railway transportation.

Firstly, the need for digital transformation of the global railway system is due to the need to increase economic competitiveness. Today, railway transport faces fierce competition, especially from road transport. Digitalization is the only way to achieve the same flexibility and reliability that customers expect. Predictive maintenance reduces maintenance costs, and route optimization using AI (Eco-driving) reduces energy consumption, providing a sustainable economic advantage [11].

Secondly, safety requirements have increased significantly. Aging infrastructure and increasing freight traffic create an increased risk of accidents. It is the concept of “Railway 4.0” that offers solutions that minimize the human factor and provide round-the-clock monitoring of critical facilities, which makes rail transportation the most reliable and safe.

Thirdly, the implementation of digital railway technologies is also a geopolitical and environmental necessity. After all, for Ukraine, integration into the European transport network (TEN-T) is possible only if it complies with ERTMS standards and full digital interoperability [12]. In addition, today rail transport is positioned as a key player in the fight against climate change. AI traffic management systems allow us to significantly reduce the carbon footprint by optimizing energy consumption, meeting the global requirements of the Green Deal. Therefore, the concept of “Railway 4.0” should be recognized as a strategic response to the challenges of modernity, because its tools make it possible to transform the railway from an infrastructure facility into an intelligent, self-regulating system. For Ukraine, in the conditions of post-war reconstruction, this is not just modernization, but a fundamental condition for ensuring economic stability, security and full integration into the European space.

Thus, the concept of “Railway 4.0” is a strategic paradigm for the development of global railway transport, reflecting its transition to the Smart-system model. Its content consists in a complete digital transformation, integration of advanced technologies and fundamental restructuring of operational processes, and its relevance is due to the need to respond to the key economic, security and environmental challenges of the 21st century [12].

It is also worth noting that “Railway 4.0” is not just the purchase of new equipment, but, above all, it is a systemic integration of information and operational technologies. On Europe's railways, the network is based on three key pillars.

1 Technological integration (IoT and Big Data). The core of the transformation is the constant collection and analysis of data. The railway network is equipped with millions of IoT sensors on rolling stock, infrastructure and management objects. These sensors feed Big Data platforms, ensuring the creation of a “digital twin” of the railway. The use of cloud technologies provides resilience and scalability, which is critical for such a complex and geographically distributed system as railways [13].

2 Automation and predictive management, which are key tools for increasing efficiency. Thanks to artificial intelligence and machine learning, railways are moving to predictive maintenance. AI algorithms analyze IoT data to predict breakdowns of rolling stock and infrastructure before they actually occur, which allows replacing rigid repair schedules with repairs on demand, and accordingly, minimizing downtime, operating costs and, most importantly, increasing traffic safety [13].

3 Interoperability and customer orientation. The concept also includes external integration. The implementation of a single European traffic management system ERTMS is key to ensuring the interoperability of national networks. At the same time, digital platforms provide transparency for freight owners (online tracking, electronic document management) and multimodality for passengers (integration of tickets and schedules with other modes of

transport) [13].

It should be noted that today, global projects for the digital transformation of railways are aimed at the implementation of 5G communications, automation of traffic management and the use of innovative technologies to improve safety and efficiency. Key international initiatives include the following projects and programs.

FRMCS (Future Railway Mobile Communication System) is a European project for the transition from GSM-R to a new communication system based on 5G, ensuring the digital transformation of the transport system, increasing the safety, efficiency and environmental friendliness of railway transport. FRMCS is a key European innovation project aimed at replacing the current GSM-R railway communication standard with a new unified system based on 5G technology. This transition is a necessary condition for the complete digital transformation of railway transport, increasing its safety, efficiency and competitiveness. The GSM-R system, introduced in the 1990s, has now reached the limits of its capabilities, as [14]:

- has limited bandwidth: GSM-R operates on 2G technology, which has a low data rate, which is sufficient for voice communication and basic ETCS (European Train Control System) functions, but not sufficient for modern digital applications (video, IoT, Big Data);

- is based on outdated technologies: equipment suppliers are gradually phasing out support for GSM-R, which makes its maintenance expensive and complex;

- insufficient for ERTMS Level 3: for the implementation of highly automated traffic control systems (ERTMS Level 3 and above), which require constant exchange of large amounts of data, the bandwidth of GSM-R is insufficient.

FRMCS, based on 5G, solves these problems by offering ultra-high speed (up to 10 Gbps), low latency (up to 1 ms) and significantly higher connection density. FRMCS provides integration of three key classes of services that were separated in GSM-R [14]:

1) Mission-critical services, namely:

- train traffic control (ETCS/ATO): FRMCS is the basic platform for data transmission for ETCS and ATO (Automatic Train Operation). Due to its low latency, the system allows for safe reduction of train intervals;

- voice communication: providing high-quality and priority voice communication between the driver, the dispatcher and the maintenance staff, with the possibility of group calls;

- cybersecurity: using modern encryption and authentication protocols, which is critical for protecting traffic control systems from cyber threats.

2) Business-Critical services:

- Predictive Maintenance (PdM): real-time collection and transmission of large amounts of data from IoT sensors on the track, bridges and rolling stock, which allows for the implementation of repairs based on the actual condition, which reduces operating costs by 10-20%;

- Video surveillance and diagnostics: transmission of high-resolution video streams from driver cabins, platforms and marshalling yards to increase safety and operational control;

- Accessory management: remote control of doors, heating, ventilation and air conditioning (HVAC) systems on rolling stock;

3) Commercial and passenger services:

- Passenger Wi-Fi: provision of high-speed Internet to passengers (thanks to excess 5G bandwidth);

- Information systems: transmission of schedule data, delays and interactive services to on-board screens and mobile devices;

- digital logistics: transmission of cargo data (temperature, humidity, location) for integration with customer logistics platforms.

Therefore, FRMCS is not a separate network, but uses the 3GPP architecture and protocols standardized for 5G. The implementation of FRMCS provides a multiplier effect for innovation: the possibility of implementing ERTMS Level 3, where there are no track devices, and information about the train's location is transmitted directly, and accordingly, helps reduce infrastructure costs,

contributes to the creation of a single digital backbone, allows for the full integration of all IT systems, from personnel management to logistics, thanks to precise monitoring and traffic management through FRMCS, ATO systems can optimize the train speed profile, minimizing energy consumption. FRMCS is not just a replacement for the radio system, but a digital highway that opens the door to all next-generation Smart Railway technologies [14].

Horizon Europe Programme. Horizon Europe has become a key instrument supporting the digital transformation of rail transport in the European Union. Its grant mechanisms allow consortia of operators, equipment manufacturers and research institutions to receive funding of up to €700,000 for the implementation of innovative projects. The programme focuses on several strategic areas. Firstly, it is the modernization of infrastructure – from the renewal of tracks and signaling systems to the introduction of new mobile communication standards, such as FRMCS, which replaces the outdated GSM-R. Secondly, the digitalization of transport processes: the creation of platforms for passenger and freight traffic management, the use of artificial intelligence and sensor technologies to monitor the technical condition of trains [15]. No less important is the environmental aspect. Horizon Europe supports projects that contribute to the reduction of energy consumption and emissions, making railways more sustainable and competitive compared to other modes of transport. The duration of such projects is usually from two to four years, and their implementation should ensure the creation of new business models and technologies that can change the future of European mobility. Thus, Horizon Europe acts not only as a source of funding, but also as a strategic platform for the formation of a single digital railway ecosystem that meets the challenges of the 21st century.

Unlike Europe, Japan focuses on robotics and artificial intelligence. JR East uses automated track maintenance and fault prediction systems, which reduces the risk of accidents and optimizes maintenance costs.

China demonstrates a different

approach: large-scale investments in high-speed lines are accompanied by the creation of “smart stations” with digital monitoring of passenger traffic and the integration of mobile services. Here, digitalization is combined with an infrastructure boom, making railways a key element of the national transport strategy [16].

The United States focuses on safety and freight logistics. The use of big data and IoT sensors helps to optimize routes, reduce delays and increase the efficiency of freight transportation, which is critical for the country's economy [16].

Thus, although all countries are moving towards the digital transformation of railways, their priorities differ: Europe is betting on environmental friendliness and standardization, Japan on robotics and AI, China on scalability and "smart" infrastructure solutions, and the United States on logistical efficiency. This indicates the multifaceted nature of the global digitalization process, which adapts to national needs and development strategies.

So, summing up, it is worth highlighting the following main areas of strategies for managing the digitalization of railway transport in the world:

- digital integration of processes, which is reduced to the use of unified platforms for managing passenger and freight transportation, which ensures transparency and speed of decision-making;

- transition to intelligent monitoring systems, namely the use of IoT sensors and big data to predict the technical condition of infrastructure and rolling stock;

- automation of traffic management through the implementation of artificial intelligence systems for dispatching, route optimization and prevention of emergency situations;

- environmental strategy: digital solutions are being implemented that allow reducing energy consumption, optimizing resource use and forming a "green" transport policy [16].

Table 1 presents global projects for the digital transformation of railways.

Table 1

Global projects for the digital transformation of railways [16]

Country / Operator	Key project	Main trend	Description and purpose
Germany (Deutsche Bahn)	Digital Rail for Germany	Automation and ERTMS	A large-scale initiative to transition to a fully digital signalling and control system (DSD). The aim is to increase network capacity and improve safety through the implementation of ETCS (Level 2/3).
Germany (Deutsche Bahn)	Siemens Railigent	Predictive maintenance	A comprehensive cloud platform that uses IoT sensors and AI to monitor the technical condition of trains, predicting component failures (e.g., wheelsets) before they occur.
Switzerland (SBB)	ETCS implementation	Interoperability	Switzerland is one of the leaders in Europe in terms of ETCS network coverage. This is critical for integration with neighboring countries and ensuring safe cross-border traffic.
USA (Wabtec)	Trip Optimizer	Green Rail and AI	A system that uses AI algorithms to analyze the route profile and train weight, providing the driver with recommendations on the optimal driving mode (so-called Eco-driving). Goal: significant fuel/energy savings and reduced wear.
France (SNCF)	Digital twin of the network	Automation and AI	Creating a virtual model of the entire railway infrastructure. Used to simulate the impact of repairs, schedule changes and weather conditions, allowing for optimized operational decisions.
Singapore (SMRT)	REAMS (Rail Enterprise Asset Management System)	Predictive maintenance	A digital asset management system equipped with analytical capabilities for automatic monitoring of the condition of rolling stock and metro infrastructure in real time.
Northern Europe	Automation in ports	Logistics 4.0	Implementing AI to optimize the interaction between rail, sea and road transport in large logistics hubs, ensuring full transparency and speed of cargo transshipment.

The implementation of these projects is driven by the following interrelated factors.

Firstly, the growth of technological maturity of companies. The mass availability of inexpensive and reliable sensors has made it cost-effective to place them on every wagon and critical infrastructure node. The power of computing resources allows you to instantly process gigabytes of data, revealing hidden patterns (for example, small changes in vibration), which makes predictive maintenance economically viable.

Secondly, increasing regulatory pressure and integration processes. In the EU countries (and for Ukraine, which is striving for integration), there is a direct regulatory requirement to implement ERTMS to ensure interoperability. This forces operators to invest in digital modernization regardless of current financial indicators. Stricter safety requirements force them to abandon outdated analog control systems that depend on the human factor.

Thirdly, changing customer expectations and behavior patterns. Freight owners demand transparency and reliability.

Systems like Trip Optimizer, which reduce delays and ensure accurate delivery times, are a key competitive advantage over road transport. Passengers expect real-time information, convenient e-ticketing and personalized services, which forces them to invest in digital interfaces.

In addition, the implementation of the «Railway 4.0» concept is also due to the need to solve a number of global challenges and use new opportunities that are emerging in the environment of large-scale digital transformations, namely (table 2):

Table 2

Key results of the integration of digital solutions into the activities of railway transport in the world [16]

Trend	The main factor	Security tools
Predictive maintenance	Economic feasibility (cost reduction) and technological progress.	The availability of cheap sensors (IoT) capable of collecting huge amounts of data, and the development of powerful AI/Machine Learning algorithms for their analysis.
ERTMS (Standardization)	Regulatory requirement and Geopolitical integration (EU).	International standards establishing uniform communication protocols (GSM-R/FRMCS) and traffic control are mandatory for cross-border transport.
Green Rail (Environmental friendliness)	Environmental regulations and public demand for decarbonization.	Digital Eco-driving systems to optimize energy consumption and investments in renewable power sources for traction.
Automation and AI	The need for speed, security, and compensation for staff shortages.	Development of computing power, Digital Twins for modeling and testing, as well as the development of autonomous control systems.

– to successfully counteract competitive pressure from road transport in the freight segment, the railway must carry out a digital transformation. The implementation of innovative digital solutions, in particular, predictive maintenance, is a key lever for minimizing operating costs. At the same time, digitalization ensures increased speed and reliability of transportation, which is a decisive factor for attracting and retaining business customers;

– increasing load on the network and wear of fixed assets lead to an increase in the accident rate. Therefore, modernization aimed at safety is an absolute priority. Key innovative solutions, such as the unified European ERTMS system and intelligent monitoring systems based on artificial intelligence, allow technologically securing the transportation process, increasing reliability and reducing dependence on the human factor;

– responding to the global trend to reduce the harmful impact on the environment, railways, as an ecological mode of transport,

must strengthen their «green» advantages. This requires strategic innovations aimed at energy efficiency. The use of artificial intelligence to optimize energy consumption (Eco-driving) is a key tool for further reducing the environmental load and meeting the highest standards of sustainable development;

International integration of railways and the formation of key transport corridors (for example, TEN-T) are impossible without the unification of management systems. Therefore, ERTMS is a technological response to the need for standardization, as it removes technical barriers and ensures seamless interoperability between different national railway networks.

Thus, the innovative development of the railway is a response to the challenges of the 21st century, where technology is used to achieve higher standards of safety, efficiency and environmental friendliness.

Global trends in the implementation of a digital strategy for the innovative development of rail transport revolve around the concept of “Railway 4.0” and focus on automation, safety

and environmental friendliness using artificial intelligence and IoT.

Conclusion. Thus, the concept of “Railway 4.0” appears as a strategic response to the modern challenges of the global economy, caused by increased competition, increasing requirements for the quality and safety of transportation, as well as geopolitical and environmental crises. Its implementation involves a comprehensive digital transformation of the railway system by integrating advanced technologies, automation and predictive management, which ensures the transition from an analog model to a Smart Railway. International initiatives in the field of digital transformation of railways, in particular FRMCS and Horizon Europe, are analyzed, and it is argued that these projects of digitalization of railway transport ensure the creation of a digital railway ecosystem, thereby creating conditions for the safety, efficiency and environmental sustainability of the industry. Global projects of digital transformation of railways and the results of the integration of digital solutions into the activities of railway transport in the world are characterized. It has been determined that predictive maintenance, ERTMS standardization, greening according to the principles of Green Rail, and the implementation of automation systems based on artificial intelligence form the systemic basis of transformational changes in the railway industry, creating the prerequisites for the formation of an integrated Smart infrastructure and ensuring the transition to a qualitatively new model of railway transport operation, based on the principles of data-oriented management, a high level of automation, and seamless integration into global transport and logistics systems.

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