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DEVELOPMENT OF AN INNOVATIVE DIGITAL MODEL FOR THE DEVELOPMENT OF RAILWAY TRANSPORT ENTERPRISES

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The article determines that the turbulence of the operating environment of railway transport enterprises, caused by digitalization processes, increased interspecific competition, as well as crisis and war risks, actualizes the need to form a new model of development of the industry. Based on the analysis of the activities of railway transport enterprises, it is determined that the depleted material and technical base, intensification of competition from other types of transport, digital transformation of transport systems, increased requirements for environmental friendliness and energy efficiency, socio-economic challenges and post-war recovery, the importance of integration into international transport corridors require innovative and digital transformation of the system of functioning of enterprises in the industry. A system of key factors that determine the expediency of their innovative transformation is determined. It is argued that political, economic, socio-cultural, technological and environmental factors comprehensively determine the directions of innovative transformation of railway transport enterprises, forming requirements for modernization, digitalization and greening of the industry. A theoretical model for ensuring the innovative and digital

development of railway transport enterprises has been formed, which defines the goal, principles, tasks and tools for implementing innovative and digital transformations in order to transform enterprises in the industry into an integrated and highly automated platform that provides world-class logistics and passenger services. The key tasks of innovative and digital development of railway transport enterprises within the framework of the model are: creation of a modern, effective and sustainable transport system; digital transformation of management; innovative renewal of production processes and funds; integration into the international transport space; ensuring sustainability and safety; personnel management and HR transformation. It has been proven that the implementation of this model at railway transport enterprises will create an opportunity not only to optimize business processes, increase operational efficiency and safety, but also to increase the competitiveness of Ukraine in the international transport services market.

***Keywords:* model, innovative and digital development, railway transport enterprises, factors, tools.**

РОЗРОБЛЕННЯ ІННОВАЦІЙНО-ЦИФРОВОЇ МОДЕЛІ РОЗВИТКУ ПІДПРИЄМСТВ ЗАЛІЗНИЧНОГО ТРАНСПОРТУ

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У статті встановлено систему ключових факторів, що визначають доцільність інноваційно-цифрової трансформації підприємств залізничного транспорту. Сформовано теоретичну модель забезпечення інноваційно-цифрового розвитку підприємств залізничного транспорту, що визначає мету, принципи, завдання та інструментарій реалізації інноваційно-цифрових трансформацій задля перетворення підприємств галузі в інтегровану та високоавтоматизовану платформу, що надає логістичні та пасажирські послуги світового рівня. Доведено, що реалізація даної моделі на підприємствах залізничного транспорту створить можливість не лише для оптимізації бізнес процесів, підвищення операційної ефективності і безпеки, а й дозволить підвищити конкурентоспроможність України на міжнародному ринку транспортних послуг.

Ключові слова: модель, інноваційно-цифровий розвиток, підприємства залізничного транспорту, фактори, інструменти.

Problem statement. In the context of global digitalization and rapid intensification of intermodal competition in the transportation market, the need for systemic modernization of railway transport in Ukraine and the world is becoming an unalternative vector of development. Railways, being the strategic foundation of the national economy, responsible for population mobility, energy security and international logistics integration, in modern conditions face challenges that cannot be overcome within the framework of outdated management approaches. The lack of innovative activity is becoming a critical barrier to realizing the transit potential of the state and ensuring sustainable economic growth.

The current realities of the functioning of domestic railway transport enterprises are characterized by a critical level of technological wear and tear of fixed assets, which leads to an increase in operating costs and a decrease in the quality of service. At the same time, there is an aggressive increase in competition from road and air transport, which are adapting faster to the requirements of the

"speed economy". In this context, Ukraine's European integration aspirations and the need to synchronize with the European Transport Area (TEN-T) require not just an update of the technical base, but a complete transformation of business processes based on unified digital standards. Traditional hierarchical management methods and linear planning models have finally exhausted their resource, which necessitates an urgent need to transition to a new innovative and digital paradigm by implementing intelligent systems based on Big Data, deploying networks of "digital twins" of infrastructure and using blockchain technologies in automated logistics platforms, which allow not only to radically optimize operating costs, but also to form a high adaptability of the industry to unpredictable crisis phenomena and military risks.

Analysis of recent research and publications. The scientific community pays significant attention to the search for tools for innovative development of enterprises, including railway transport enterprises, in the context of the emergence of a digital paradigm. Among Ukrainian scientists, a significant contribution to solving the problem of developing railway transport enterprises on an innovative and digital basis was made by Dykan V., Zaporozhets V., Zalesky O., Kalycheva N., Korin M., Martsenyuk L., Obruch H., Ovchinnikova V., Ozerska G., Tokmakova I., Yanovska V. and others [1-8].

At the same time, the turbulence of the operating environment of railway transport enterprises, caused by digitalization processes, increased interspecific competition, as well as crisis and war risks, actualizes the need to form a new model of industry development. It is the innovative digital paradigm that is able to ensure high adaptability and sustainability of enterprises, cost optimization, integration into the European transport space and creation of prerequisites for the long-term competitiveness of railway transport in Ukraine.

The purpose of the article is to study the operating environment of railway transport enterprises and develop an innovative digital model of their development in turbulent conditions.

Presentation of the main material. Railway transport enterprises operate in a highly regulated and capital-intensive sector, which requires constant adaptation to global and local changes. In addition, the need to establish an innovative path of development at enterprises of the railway industry of Ukraine is caused by the following circumstances.

Firstly, the material and technical base is largely outdated. Most of the rolling stock and infrastructure require modernization, which is impossible without innovative solutions. The overall level of depreciation of fixed assets of JSC "Ukrzaliznytsia" before the start of the full-scale invasion was a critical 80% and above. The war only accelerated physical depreciation and increased the load. Although JSC "Ukrzaliznytsia" regularly carries out write-offs and modernization, a significant part of its own fleet (over 60-70% by 2022, according to various estimates) was operated beyond the standard service life (over 30-40 years). The depreciation of the fleet of mainline locomotives exceeds 90%. The average age of diesel and electric locomotives is 35-45 years, with a standard service life of 20-25 years. This leads to high fuel costs, more frequent failures and low reliability. About 35-40% of the tracks need major repairs or replacement. The poor quality of the track limits the speed of movement (in many sections the speed is reduced to 40-60 km/h) and creates safety risks. The vast majority of electric centralization (EC) systems are analog and outdated [10-12]. This makes it practically impossible to integrate systems with European standards and implement high-speed digital technologies. Overcoming such large-scale obsolescence requires not just replacement, but innovative renewal with a focus on digitalization, energy efficiency and safety.

Secondly, competition from other modes of transport is growing. Road and air transport are actively implementing the latest technologies, so the railway must meet modern standards. Road transport is actively modernizing through the use of intelligent

transport systems, GPS navigation, digital platforms for logistics and route optimization. This allows you to reduce delivery times, reduce costs and ensure flexibility in transportation. Air transport is introducing modern reservation technologies, electronic tickets, automated passenger service systems, as well as new aircraft models with increased energy efficiency. This makes aviation attractive for fast and comfortable travel. In such an environment, railway transport cannot remain on the sidelines. It must meet modern standards by: modernizing rolling stock (high-speed trains, energy-efficient locomotives); digitalizing processes (electronic tickets, online services, automated traffic management); improving the level of service for passengers (convenience, comfort, safety); optimization of freight transportation (logistics centers, integration with other modes of transport).

Thirdly, the digital transformation of the transport system is taking place. It involves the implementation of automated transportation management systems that allow real-time control of transport traffic, optimize schedules and quickly respond to changes. This applies to both passenger and freight transportation: electronic tickets, mobile applications for booking, electronic invoices and logistics control systems are becoming the standard. Big data analytics plays an important role. Collection and processing of information on passenger flows, freight routes, technical condition of rolling stock make it possible to forecast demand, increase resource efficiency and identify problems in a timely manner. The use of machine learning algorithms helps to find optimal solutions and reduce risks. Integration into European digital platforms is no less important. This ensures the compatibility of transport systems, simplifies cross-border transportation and allows Ukrainian carriers to work according to uniform standards. A single digital space opens up opportunities for creating shared services - for example, a single ticket for multiple modes of transport or integrated logistics solutions.

Fourth, the requirements for environmental friendliness and energy efficiency are increasing. The growth of requirements for environmental friendliness and energy efficiency in the transport sector is a natural result of global trends – the fight against climate change, reducing the use of fossil resources and the desire for a “green” economy. Railway transport has significant potential to become the most environmentally friendly mode of transport. Already today, it demonstrates a lower level of greenhouse gas emissions compared to road and air transport. However, in order to fully realize this potential, it is necessary to introduce innovative technologies in the field of energy saving and alternative energy. This includes the use of modern locomotives and wagons that consume less energy due to lightweight materials and optimized design, the use of energy recovery systems during braking, as well as automated traffic control systems that allow reducing electricity costs by optimizing speed and schedules. An important direction is the transition to alternative energy sources: the use of electricity from renewable sources, the introduction of hydrogen trains, as well as the integration of railways into “green” energy clusters. This not only reduces the negative impact on the environment, but also increases the competitiveness of railway transport compared to other types of transportation.

Fifth, socio-economic challenges and post-war recovery. The destruction of infrastructure and the need for rapid restoration of logistics chains actualize the innovative approach as the basis of the development strategy. The destruction of infrastructure – railway tracks, bridges, stations, logistics centers – leads to serious problems in transportation and requires rapid restoration. This is especially important for ensuring economic stability, humanitarian transportation and supporting international trade relations. Restoring logistics chains is becoming a priority, as traditional routes are often destroyed or blocked. Therefore, it is necessary to create new, more flexible and sustainable transportation systems that can

quickly adapt to changes. An important direction is integration with the European transport network, which ensures the continuity of international transportation and opens up new opportunities for economic cooperation. An innovative approach is the basis of the development strategy. This means the use of modern technologies in restoration – digital modeling for reconstruction planning, "smart" traffic management systems, automated logistics platforms. During construction and repair, new materials and energy-efficient solutions are used, which allow creating infrastructure that is more resilient to crisis situations.

Sixth, the need for integration into international transport corridors. Ukraine strives for European integration, and this requires the implementation of modern standards of safety, speed and quality of transportation. Ukraine's integration into international transport corridors is a strategic task that is directly related to the process of European integration. This means that railway transport and the entire transport system of the country must meet modern standards of safety, speed and quality of transportation that operate in the European Union.

This is about harmonizing technical standards: compatibility of railway tracks, signaling systems, rolling stock and infrastructure with European requirements. This will ensure the continuity of transportation without the need for additional technical procedures at the border. It is important to increase the level of security. Ukrainian carriers must implement modern traffic control systems, automated management and monitoring tools that meet European standards. This guarantees the protection of passengers and cargo, and also increases the trust of international partners. Integration involves increasing the speed and quality of transportation.

This requires the modernization of rolling stock, the development of high-speed railway lines, the improvement of passenger service and the creation of modern logistics centers for freight transportation.

Based on the analysis of the study of the operating environment of railway transport enterprises, it is worth highlighting the following key factors that confirm the feasibility of establishing an innovative path for the development of the industry (table 1).

Political decisions and legislation have a direct impact on the investment climate, and accordingly on the attractiveness of innovative projects. A key factor is the process of restructuring the state monopolist and unbundling (separation of the infrastructure component from the transport component).

The innovation strategy should take into account the transition to a competitive transport market, where private operators may demand innovative solutions, for example, in the field of electronic data exchange and access to infrastructure. The implementation of European Union requirements (EU Directives) requires the unification of technical standards, in particular, the introduction of the European Rail Traffic Management System (ERTMS) and the transition to European track at key border crossings. These innovations are mandatory, not voluntary. The presence or absence of state innovation support programs and guarantees for foreign investors directly affects the ability to finance long-term, capital-intensive projects, such as electrification and renewal of traction rolling stock.

Economic factors shape financial opportunities and demand for rail transport services. The high level of depreciation of fixed assets (about 80%) requires significant investments, which requires a clear strategy for attracting capital through loans from international banks, foreign investments and public-private partnerships. Volatility of tariffs and exchange rates actualizes the need to reduce the cost of transportation through innovative technologies that quickly pay for themselves, for example, energy-efficient locomotives. Forecasting demand in key customer industries (metallurgy, agricultural sector) requires the implementation of digital logistics systems that can adapt to changes in cargo flows. Sociocultural factors relate to

personnel and end consumers. Modern innovations require highly qualified engineers and IT specialists, so the strategy should include innovations in the field of education – corporate universities, cooperation with technical universities, internship programs. At the same time, customers are putting forward new requirements: passengers expect comfort, speed and digital services (online tickets, Wi-Fi, accurate information), and shippers – transparency, reliability and integration through electronic document management and GPS tracking.

Table 1

Key factors determining the feasibility of innovative transformations at railway transport enterprises

Factor category	Key aspects	Impact detail
Political decisions and legislation	Industry reform	Unbundling of the state monopoly, transition to a competitive market, need for electronic data exchange and access to infrastructure
	European integration	Implementation of EU directives, unification of standards, implementation of ERTMS, transition to European track at border crossings
	State investment policy	Innovation support programs, guarantees for investors, financing for electrification and rolling stock renewal
Economic factors	Investment attractiveness	Depreciation of funds ≈80%, need for large investments, attraction of international capital and public-private partnership
	Tariff and currency volatility	Purchase of equipment in foreign currency, need for quick payback technologies, energy-efficient locomotives
	Demand forecasting	Dependence on metallurgy and the agricultural sector, the need for flexible digital logistics systems
Sociocultural factors	Staff shortage	The need for highly qualified engineers and IT specialists, innovations in education, corporate universities, internships
	Customer requirements	Passengers: comfort, speed, digital services. Shippers: transparency, reliability, GPS tracking, electronic document management
Technological factors	Digitalization and automation	IoT for monitoring, Big Data for traffic optimization, AI for predictive maintenance
	High-speed movement	Development of high-speed corridors, renewal of rolling stock
	Competing technologies	Taking into account the development of motor transport (unmanned trucks), disruptive solutions (Hyperloop)
Environmental factors	Energy efficiency	Regenerative braking, hybrid locomotives, transition to electric traction
	Noise and emission reduction	Innovations in rolling stock and infrastructure design: screens, modernized braking systems

Technological factors are determining the global development vector. The main trend is digitalization and automation: the implementation of IoT for asset monitoring, Big Data for traffic optimization and artificial intelligence for predictive maintenance. The strategy should take into account the development of high-speed corridors and

rolling stock renewal, as well as competitive technologies such as driverless trucks or promising disruptive solutions such as Hyperloop.

Environmental factors are associated with the growing pressure to reduce the carbon footprint. This requires the introduction of "green" innovations: regenerative braking, hybrid locomotives, switching to electric traction instead of diesel, where economically feasible. It is also important to reduce noise and emissions through innovations in the design of rolling stock and infrastructure, for example, the use of special screens or modernized braking systems.

Thus, political, economic, socio-cultural, technological and environmental factors comprehensively determine the directions of innovative transformation of railway transport, forming requirements for modernization, digitalization and greening of the industry.

It is worth noting that railway transport enterprises have significant innovative potential, but its implementation requires a systemic approach: overcoming internal weaknesses, using external opportunities and minimizing risks. This should become the basis for the formation of an effective innovative model of industry development, based on the large-scale implementation of digital solutions.

The model of innovative and digital development of railway transport enterprises aims to transform traditional railways into a modern high-tech smart system. It involves the integration of digital solutions into all levels of activity – from the management of rolling stock and infrastructure to interaction with customers (Figure 1). The basis of the model is the implementation of Industry 4.0 technologies. The Internet of Things and sensors allow you to create a "digital twin" of the railway network, collecting data on the condition of tracks, wagons and locomotives in real time. Big Data and artificial intelligence provide breakdown prediction, optimization of traffic schedules and increased safety. Cloud technologies guarantee the resistance of systems to physical damage and cyberattacks, and also make it possible to scale computing resources. In the freight sector, digitalization has the greatest economic effect. The creation of a single digital portal for cargo owners provides transparency, electronic document management and online ordering of transportation. Automated wagon flow management systems based on artificial intelligence minimize downtime and idling, reducing costs. Modernization of infrastructure and rolling stock is aimed at increasing safety and compliance with European standards. Predictive maintenance allows for repairs based on the actual condition of the equipment, and the implementation of the ERTMS system ensures integration with the EU transport network. Digitalization of the depot through electronic passports of wagons and locomotives allows for accurate accounting of resources. No less important is personnel management. The transition to electronic document management simplifies personnel processes, and the use of VR/AR technologies in training allows for improving the qualifications of employees and reducing the number of errors. As a result, such a model of innovative and digital development of railway transport becomes a key tool for economic reconstruction. It increases efficiency, reduces costs, ensures safety and creates conditions for the integration of Ukraine into the European transport space, turning the railway into a powerful logistics hub of Eastern Europe.

This model involves a comprehensive digital transformation of the industry and its transformation into an intelligent transport system. Transforming railway transport enterprises into an integrated, transparent and highly automated platform that provides world-class logistics and passenger services, using data as the main asset, is possible by implementing the following key areas.

Intelligent traffic and infrastructure management (operational domain) is the basis for increasing throughput and safety. In particular, it involves:

Model for ensuring innovative and digital development of railway transport enterprises

Goal: creating a modern, efficient and sustainable transport system through the comprehensive implementation of digital technologies that ensure innovative renewal of production processes, increased competitiveness, integration into the international transport space and orientation towards customer needs

Principles

systematicity	innovativeness	efficiency and sustainability	international integration	customer orientation

Guidelines for digital innovative development of railway transport enterprises

Task	Toolkit	Content of transformations
Creating a modern, efficient and sustainable transport system *optimizing operations, reducing costs, increasing productivity*	Internet of Things (IoT) and sensors	installation of sensors on tracks, wagons, locomotives; real-time data collection; creation of a "digital twin" of the railway
	Big Data and AI	processing IoT data with algorithms; predicting breakdowns, optimizing traffic schedules, identifying dangerous areas
	Cloud technologies	migration of systems to secure cloud environments; resistance to attacks and damage; capacity scaling
Digital transformation of management *automation of business processes and document flow, transparency and speed of management decisions*	Single Digital Interface	online transportation orders, electronic documents, cargo tracking, transparency and reduction of corruption
	Automated train traffic management	AI optimizes car distribution, minimizes idling and downtime, and reduces costs
Innovative renewal of production processes and assets *reducing accidents, increasing safety*	Predictive maintenance	repairs based on the actual condition of the equipment; sensors detect early signs of wear; reduced accident rates
	Depot digitalizatio	electronic passports of locomotives and wagons; accurate accounting of repair history and resources
Integration into the international transport space *compatibility with international systems*	European Rail Traffic Management Systems	implementation of European traffic management standards; integration with the EU network; interoperability
Ensuring stability and security *data protection, network stability*	Cybersecurity systems, blockchain, SCADA	cyber defense and infrastructure monitoring
Human Resources Management and HR Transformation *increasing the efficiency of human resources management and creating an innovative, customer-oriented corporate culture*	Electronic accounting and document management	digitalization of personnel processes (vacation, sick leave, contracts)
	Digital training and simulators (VR/AR)	virtual training of drivers and repairmen; advanced training; reduction of errors

Fig. 1. Key provisions of the model for ensuring innovative and digital development of railway transport enterprises (formed by the authors)

− joining the European Traffic Management System (ERTMS), namely the gradual implementation of the ERTMS/ETCS level 2 or 3 standard, which provides continuous communication between the train and the control center, increasing the speed and safety of movement, and, accordingly, is critical for integration with the European network;

− implementing predictive maintenance: using IoT sensors on the track, bridges, switch points and rolling stock to collect data. Analysis of this data using Artificial Intelligence allows predicting equipment failures, moving from planned and preventive to maintenance based on the actual state;

− automated control of marshalling yards: implementation of automated systems for regulating the speed of train separation and formation, which minimizes the human factor and downtime.

Digitalization of rolling stock (technological domain), namely the implementation of:

− smart wagons and locomotives: equipping wagons with GPS trackers and cargo status sensors (temperature, humidity, vibration), which ensures end-to-end transparency of the logistics chain;

− digital twins: creating virtual copies of critical assets (new locomotive, key bridge) for load simulation, testing new components and optimizing operation before physical implementation;

− traction automation: implementation of driver assistance systems that, based on data on the schedule, track profile and tariffs, offer the optimal train driving mode for maximum energy efficiency.

Customer and logistics platforms (customer-oriented domain) by creating:

− a single electronic platform: creating a single online cabinet for shippers and passengers, integrating all services: ordering transportation, tariff calculation, real-time cargo tracking, electronic document management;

− Big Data and dynamic pricing: using Big Data analysis to forecast demand for freight and passenger transportation. This allows for the implementation of flexible tariffs, optimizing capacity utilization and maximizing revenue;

− integration with the ecosystem: integrating IT systems of railway transport enterprises with systems of seaports, customs, border guards and logistics operators (3PL/4PL) to create a single seamless transport corridor.

For the successful implementation of digital solutions, a solid foundation is needed, the foundation of which will be the following supporting elements.

Information and cybersecurity. With the increase in the level of digitalization, the risk of cyberattacks is critically increasing. Protection of critical infrastructure can and should be ensured by creating a multi-level system of protection of operational technologies and traffic management systems, implementing an incident management system, as well as implementing a 24-hour cyber threat response center and regular audits and exercises.

A data management subsystem that will ensure data centralization by creating a single corporate data repository for aggregating information from all operational, financial and client systems, as well as data quality, ensuring reliability, accuracy and relevance of data, which is the basis for decision-making based on AI and Big Data

A subsystem of personnel and innovation culture that requires retraining of personnel through the creation of training programs for engineers and operators, the creation of digital offices as a separate structural unit responsible for accelerating and coordinating all digital initiatives, the implementation of an agile approach, namely flexible project management methodologies instead of the traditional "waterfall" for the rapid development and implementation of IT solutions.

The model of innovative and digital development of railway transport enterprises

is a key tool for the modernization of the industry and its integration into the global transport system. It is aimed at creating a Smart Railway – an intelligent, transparent and highly automated platform that ensures effective traffic management, digitalization of rolling stock, development of client and logistics services.

The successful implementation of this model is possible only if a solid foundation is formed:

- ensuring cybersecurity and protection of critical infrastructure;

- creating a data management system for high-quality analytics and decision-making;

- development of human resources and innovation culture, which will ensure the adaptation of personnel to new technologies.

Thus, the digital transformation of railway transport will not only increase its efficiency and safety, but also ensure Ukraine's competitiveness in the international transport services market, creating conditions for sustainable development and integration into global logistics chains.

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