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1 Executive Summary

This document offers an analysis and research of innovation directions in the field of decarbonization of a railway company using the example of the Joint-Stock Company "Ukrainian Railways" (UZ) at the current stage, as well as the development of this process in the medium term. The organizational structure of UZ is considered and the structural units responsible for the company's innovative activities in the field of decarbonization are identified. The main areas of UZ activity, as well as the areas of decarbonization, are identified. It is noted that the military conflict led to the rapid adaptation of UZ, railway operating companies and businesses related to the activities of UZ. It is important to emphasize, that using UZ as an example, the general conclusions correspond to European and international practices of implementing railway innovations under more stable conditions.

The status and progress of the implementation of three areas of decarbonization that are widespread in the EU are analyzed: electrification of tracks, use of alternative traction and digitalization of transportation. Four main barriers to the slow implementation of innovations in UZ are identified. These barriers are ranked according to three criteria: the strength of of influence, the scale of coverage and the complexity of overcoming. Five key conditions have been identified for increasing the pace of innovation implementation in UZ. The condition "active digitalization" has been identified as the highest priority.

Three general scenarios for implementing innovations in the field of decarbonization in UZ in the medium term have been developed. The most realistic is the adaptive scenario, which consists in the gradual modernization of the structure and functions of UZ, including in the field of decarbonization.

2 Abbreviations and acronyms

GHG – greenhouse gases.

UZ – Joint Stock Company "Ukrainian Railways".

CAPEX – capital expenditures.

OPEX – operational expenditures.

NPV – net present value.

IRR – internal rate of return.

CO_2 – carbon dioxide.

GHG – greenhouse gases.

RAMS – reliability, availability, maintainability and safety .

3 Objective/Aim

The objective of this deliverable is to determin responsibility in the structure of the companies using as example the State company "Ukrainian Railway" (UZ) for research, implementation of innovations intending decarbonization. And also to identify barriers to slow innovation implementation and determine ways of their overcoming. To improve the quality (reliability and validity) of the research results, the methodology takes into account the experience of other railway administrations and European approaches to decarbonization, financial assessment, safety, certification, and interoperability.

4 Background

The railway industry is often criticized for not being innovative enough and for being too slow to implement research results. Several reasons are identified and they are characteristic of rail transport in different countries: a fragmented industry structure, high aversion to risk, the priority given to safety means that innovative systems require thorough testing when implementing new technologies, and others (Nash & Smith, 2019).

However, the decarbonization of railway transport today is one of the highest priorities of European policy. The adoption of the Green Deal and the Fit for 55 package (European Commission, 2019) requires a 55% reduction in greenhouse gas emissions by 2030 and achieving climate neutrality by the middle of the 21st century. Rail has the lowest specific emissions among transport modes, but meeting such commitments requires a profound change in existing practices, namely: large-scale electrification, the deployment of hydrogen and battery trains, the digitalisation of traffic control systems, the creation of flexible financial and regulatory incentives, etc.

In this context, the analysis of the reasons for the slow implementation of innovations in railway transport becomes particularly relevant, including the identification of effective mechanisms for their acceleration under modern conditions.

5 Data gathering and analysis of measures and mechanisms to support implementation of rail technical innovations supporting the decarbonization of transport

5.1 Introduction

In international and European practice, railway transport is considered as one of the key platforms of decarbonization. According to IEA data, railway transport provides about 7% of global passenger-kilometers and 6% of tonne-kilometers and forms only 1% of transport emissions (International Energy Agency, 2024). The European Union Agency for Railways emphasizes that railway transport has some of the lowest emissions among land transport.

Joint Stock Company "Ukrainian Railways" (hereinafter abbreviated as UZ) is the national railway operator of Ukraine, which has the legal status of a joint-stock company with 100% state ownership. The characteristics of UZ in the periods before 24.02.2022 (the beginning of the full-scale military invasion of the Russian Federation into Ukraine, which is referred to in Ukraine as a war) and after this date until the current moment are very different. Until 24.02.2022, UZ carried out about 70% of freight transportation and more than 50% of passenger transportation. Over the last 5 years, there has been a tendency towards a decrease in the share of rail transportation in the freight transportation market and the passenger transportation market (Non-governmental organization “Railway Without Corruption”, 2022). The structural reforming of UZ was carried out, preparation for integration with the EU was underway, while the biggest problem is an outdated locomotive and wagon fleet.

Today, the key priorities of UZ include restoration of infrastructure and rolling stock after destruction, provision of social transportation, and reduction of personnel due to mobilization; the number of employees has decreased by about 30% compared to 2021 (Joint Stock Company “Ukrainian Railways”, 2025).

Nevertheless, it should be emphasized that most business processes have been preserved, although in a form adapted to the conditions of wartime. A relevant confirmation of this is the arrival in Kyiv of high-level international delegations by railway during the war, under conditions of the absence of domestic and international air transport in Ukraine.

As mentioned above, most business processes operate, adapting to the wartime environment. At the same time, freight and passenger transportation indicators have naturally significantly decreased (Fig. 1).

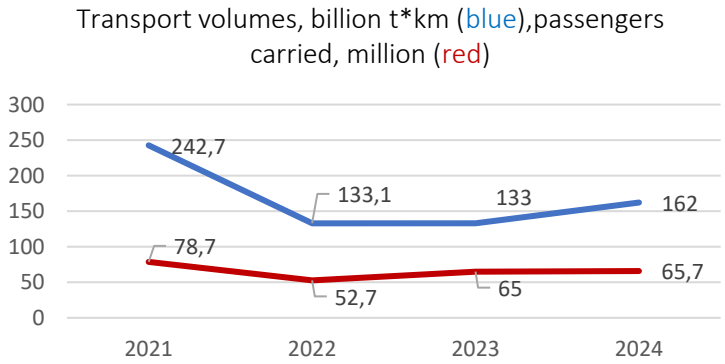

Figure 1 – Dynamics of transportation in UZ during wartime (Joint Stock Company “Ukrainian Railways”, 2025)

Relatively small fluctuations in the volumes of passenger transportation are explained by large flows of people into evacuation and resettlement from the combat zone and the occupied territories. The large-scale phase of the war, which has been going on for four years, naturally made serious adjustments to the directions of activity of UZ, including the direction of innovative activity.

5.2 Methodology

The general methodology of this study consists of the following components:

I. Review of literary scientific sources and websites regarding the peculiarities of activities, as well as regulatory documentation of UZ.
II. Analysis of statistical data of transportation of UZ for the last four years. Methods of information collection: review on the Internet of the websites of UZ, mass media and specialized information sources, student excursions to the enterprises of UZ, participation in meetings, personal business contacts.
III. Formulation of the peculiarities of the functioning of UZ on the basis of: review and analysis, use of the practical experience of the members of the PhD1 team during work in UZ, results of interviews with railway workers and representatives of the company management.
IV. Substantiation and determination of barriers in the innovative activity of the UZ in the field of decarbonization. To strengthen the justification of the results, a ranking of the main barriers to the implementation of innovations in the field of decarbonization.
V. Determination of ways to reduce the impact of barriers and shortcomings in the UZ.

The main scientific methods of this study were system analysis and structural-functional analysis of systems.

The process of innovation in the field of decarbonization is considered as the result of the interaction of organizational, technical-economic and external factors.

The methodology shows that UZ are used as a practical example under crisis conditions, whereas the assessment methods, the list of barriers, and the decision-making tools can be adapted by other railway administrations under stable conditions.

5.3 Results

The results are based on outcomes of a qualitative analysis of official corporate publications, policy documents, analytical reports and recent scientific studies concerning the functioning of UZ under wartime conditions and the implementation of decarbonization-related innovations.

Recently, the activities of UZ have been covered mainly in Ukrainian academic publications, industry reports and professional media sources.

The main source of information dedicated to the activities of UZ under conditions of military actions in Ukraine is the Press Center of UZ. There are also several other sources that often duplicate the publications of the Press Center or provide industry commentary. In 2022, UZ electrified 82 km of tracks, and 470 km of lines were reconstructed and overhauled (Joint Stock Company “Ukrainian Railways”, 2023). This is the highest value of the indicator in the last 10 years. A significant reduction in costs at UZ has been achieved due to the implementation of energy efficiency measures (Joint Stock Company “Ukrainian Railways”, 2024). The company reduced diesel fuel consumption rates and increased the share of transportation by electric traction, which is 2-3 times cheaper than diesel traction. UZ is actively working on updating the locomotive fleet (Joint Stock Company “Ukrainian Railways”, 2024). The purchase of up to 80 modern electric locomotives reduces the use of diesel fuel, and accordingly reduces emissions in 2024. It is indicated that UZ will receive 10 modern battery-powered shunting locomotives (Joint Stock Company “Ukrainian Railways”, 2025). The transition to battery-powered shunting locomotives also reduces the

consumption of diesel fuel and accordingly – harmful emissions. UZ has published corporate environmental policy documents, this in turn confirms that the environmental and climate goals of UZ are formalized at the level of internal rules and principles (Joint Stock Company "Ukrainian Railways", 2022). UZ is among the TOP-5 largest distribution companies in Ukraine in terms of network length and electricity transmission volumes. The company has announced the establishment of a new entity, "UZ Energo", noting that current electricity consumption limits cover only about 75% of its actual needs (Joint Stock Company "Ukrainian Railways", 2024). As a distribution system operator, it plays a critical role in ensuring electricity supply, and such decisions indicate a shift in the priorities of its innovative activity. Regarding public investments and priorities – there are state documents of strategic and investment planning that show the creation of large transport projects (Ministry of Economy of Ukraine, 2025). For 2026 – 2028, the Ukrainian strategic goals are energy efficiency, response to climate change, gender equality, and digitalization, defined as one of the priority directions of investments.

Today, more and more scientists are studying the issue of decarbonization, which is discussed below. Researchers Samsonkin et al. (2025) devoted their study to EU policies and legislation regarding the implementation of the European Green Deal in the transport sector. Proposals are provided regarding the decarbonization of various types of transport in Ukraine, as well as recommendations regarding joining the European Green Deal. The researchers proposed the development of a common vision of the ways of decarbonization of the transport sector of Ukraine, in particular railway transport. This indicates a divergence between the decarbonization goals and the practical tools for their implementation in Ukraine.

In addition to the information sources, a Ukrainian Government document approved a plan of the National Transport Strategy and its implementation for the coming years (Cabinet of Ministers of Ukraine, 2024). The information is presented regarding the restoration of infrastructure, which should be at the highest level of quality, taking into account European integration requirements, safety and decarbonization. The document records the current characteristics and condition of UZ, namely: the operational length of railway tracks; describes the consequences of the war, damaged and destroyed infrastructure facilities and rolling stock; it is noted that the renewal of tracks and rolling stock is mainly financed by UZ's own funds; provides estimates of losses and recovery needs; describes various transport problems; forms strategic directions and tasks for the future. Based on the analysis of this document, it can be concluded that the strategic priorities are generally consistent with the European principles of decarbonization.

The current state of functioning of railway transport in Ukraine is described in an analytical report (Transparency International Ukraine, 2023). It proposes actions for reforming of UZ taking into account the EU requirements. The key problems of railway transport in Ukraine are described: outdated technologies with a high degree of wear such as signaling systems, traffic safety, logistics and dispatching of transportation, etc. It is predicted that the main problem of railway transport for the period of reconstruction of the country will be the transition from outdated and worn infrastructure and outdated standards to modern European ones (Transparency International Ukraine, 2023). The scientists claim that the recovery and the role of the railway in post-war Ukraine will strongly depend on the rapid preparation and implementation of new reforms. Such reports are useful in that they propose specific steps for reforming and reconstruction of the railway, which can be compared, for example, with the National Transport Strategy and make optimal decisions (Cabinet of Ministers of Ukraine, 2024).

The researchers Abuselidze et al. (2023) analyze the decarbonization policy of all transport of Ukraine and state that the current measures and mechanisms of decarbonization are not sufficient. They grounded the statement that the structural redistribution of transportation from the road transport to the rail transport gives the best decarbonization effect. By comparing Ukraine with countries similar in terms of the length of the railway network they emphasized that the reduction of emissions by the Ukrainian Railways was a consequence of a fall in transportation volumes, and not modernization, in contrast to some EU countries. These scientists show different scenarios of investments in the railway transport and how the transition from road transport to railway transport

will change transport CO_2 emissions by 2030 in Ukraine. Such sources emphasize that railway transport is a key tool for decarbonization of the whole transport complex of the country.

Regarding shunting operations, researchers Goolak et al. (2023) write that UZ uses more than 1200 shunting diesel locomotives ЧМЭ3 with 100% actual wear. UZ uses the power of the diesel generator set of shunting diesel locomotives only partially; which require low traction efforts. This means that a significant part of the diesel fuel costs during shunting operations are formed due to the operation of the power plant in modes with increased relative fuel consumption. Technical and organizational measures aimed at improving the operation of shunting diesel locomotives can ensure a reduction in diesel fuel costs. Regarding increasing the fuel efficiency of diesel traction, in (Riabov et al, 2024) the use of an electric energy storage system is considered. The system stores part of the braking energy and then uses it for traction on a two-section freight diesel locomotive. These investigators show that the use of such a system makes it possible to reuse a significant share of the energy spent on the operation of the locomotive, which leads to a reduction in fuel consumption. It is emphasized that the result depends on the specific type of locomotive and operating conditions. It is important that reducing diesel fuel consumption with the same amount of work means a proportional reduction in CO_2 emissions.

Such solutions which were considered earlier also correspond to modern international trends. Latest studies show (Domínguez et al., 2025) that energy storage systems in railway transport can be used for stabilization of energy consumption and increase of energy efficiency of both rolling stock and infrastructure. These systems make this a promising direction for UZ.

In addition to academic sources, it is worth noting the EU view on the state of reforming the railway sector of Ukraine in the context of European integration. In (European Commission, 2024) it is noted that as of 2023 the progress of railway reform is slow, even despite the approximation of technical standards to the EU requirements. In the conclusion, gaps are emphasized, namely: an independent regulator is needed as a separate state body in the market, which has an independent organization and is not subordinate to UZ and the bodies that finance transportation; there is no independent national safety authority; separation of the functions of infrastructure management and operational work is necessary; the need to strengthen the system of safety and accident investigations.

5.3.1 Areas of activity of UZ

It should be emphasized that the activities of structural units and branches are constantly changing according to the military situation. The main areas of activity of UZ is presented in a summarized manner Based on analysis and observation, the following priority areas of activity of JSC "UZ" for the current period were identified:

I. Adaptation of technological processes and personnel behavior to the conditions of military actions, restoration of infrastructure and production assets after their destruction due to missile and bomb strikes.
II. Inter-state train traffic in inter-state communication to the aggressor states on the track gauge of 1520 mm has been stopped, preparation is underway to reorient the movement of freight and passenger trains to the west, to the network of EU states, namely: step-by-step construction of the Euro gauge of 1435 mm (traffic has been launched on the Chop–Uzhhorod section, the Medyka–Lviv section is being modernized, etc.), design of 1435 mm gauge infrastructure on other sections.
III. The strategic structural reforming of the company continues: liquidation of regional branches-railways (until 2028); instead of the locomotive department a branch “Locomotive Company” has been created; organizational reforming of the passenger sector has been completed; the train traffic management

department has been reformed; the freight wagon department has been liquidated, and its functions have been transferred to other departments; in 2026 a branch "UZ-Cargo" will be organized, etc.

IV. Preparation is underway for the implementation of the EU legislative and regulatory framework in accordance with the "Association Agreement between Ukraine and the European Union" (Cabinet of Ministers of Ukraine, 2025): a draft law "On safety and interoperability of Ukraine railway transport " is prepared and has passed to the Parliament of Ukraine.

It should be noted that after 2022 the role of UZ in the transport market significantly increased. UZ became an important part of the transport resilience of Ukraine and Europe. The European Commission directly calls Solidarity Lanes a "lifeline for the Ukrainian economy". As of February 2026 Ukraine exported almost 209 million tons of goods, including almost 90 million tons of grain, oilseeds, products, and also imported about 95 million tons of goods (European Commission (2025a). The value of trade through Solidarity Lanes is estimated at approximately €260 billion. This confirms that UZ is an important element of European supply chains. The role of UZ in the European transport system is also emphasized by European investments. The EU has attracted more than €2.3 billion for the development of Solidarity Lanes, of which €1.55 billion constitutes grant support (European Commission (2025b). These funds are directed to 38 transport projects: modernization of border crossings, improvement of connections with Ukraine, gradual integration into the European 1435 mm network and others.

5.3.2. Crisis situation as a factor of adaptation of a railway company

Military actions in Ukraine should be considered as a long-term crisis. According to crisis management research, the concept of a crisis encompasses not only immediate conflict but also related phenomena such as energy crises, shortages of fuel and electricity, disruptions of supply chains, large-scale cyberattacks, technological accidents, natural disasters, climate change, epidemics, and general instability in the market environment (Boin et al., 2016).

So the experience of adaptation of UZ to the military environment may become important and useful for EU practice. It should be noted that the military conflict has led to rapid adaptation of UZ, railway operating companies and businesses that are connected with the activity of UZ. This conflict has forced rapid adaptation and the adoption of rational managerial decisions. Shortage of personnel, damage to infrastructure led to changes in train formation plans, and the necessity of continuous provision of passenger and freight transportation. What in peacetime could be discussed for a long time, in crisis conditions is implemented much faster.

Personnel shortage is a factor that pushes toward modernization of business processes and implementation of innovations. Transport-forwarding companies that carry out transportation by railway transport, for example Euro Logistic Trade LLC – (Euro Logistic Trade, 2026), under conditions of personnel shortage radically change work models. Personnel are not limited to performing standard logistics functions but independently develop automation tools, study programming, and create software modules, bots, and decision-support systems. This allows them to analyze the transportation market (including in Poland and Germany), maintain continuity of operational activity, and reduce dependence on external suppliers of digital solutions. As a result, digitalization becomes a practical response to personnel shortage and activity during crises.

In European countries a similar tendency is also observed: shortage of personnel in the railway sector stimulates digitalization, automation, development of systems for monitoring the condition of equipment and new approaches to transportation management.

Researchers Bureika et al. (2026) have also examined this trend, analyzing the relationship between technological innovations in railway transport and the engineering competencies of logistics specialists. Using the Analytic Hierarchy Process (AHP) method, they demonstrated that the implementation of modern technologies,

particularly digitalization and automation, enhances transport logistics efficiency and contributes to the development of logistics professionals' competencies (Bureika et al., 2026).

Analytical reports (CER & ETF, 2022) state that in many countries up to 50% of the current workforce may leave by 2030. At present EU railway sector already faces a significant shortage of personnel in many professions, and digitalization and automation radically change the requirements for the workforce. The report of the European Labour Authority (European Labour Authority, 2025) notes that in the railway sector digitalization, automation, predictive maintenance, and the implementation of ERTMS are already advancing. This is exactly what forms demand for a more technologically prepared workforce.

UZ also develops digital services in the passenger and freight sectors. In 2024 the UZ application reached 2 million authorized users, the share of online tickets in total sales amounted to 89%, and the share of the mobile application increased from 25% to 38% (Joint Stock Company "Ukrainian Railways", 2026). Electronic systems "e.Portal UZ-Cargo" are being implemented in freight transportation, which are used to reduce the time of document processing, decrease resource costs and transfer part of operations into digital format. Although UZ directs its efforts more toward modernization than toward large-scale infrastructural innovations, digitalization develops quite quickly. In the future some such solutions may be of interest for the EU.

5.3.3 Analysis of the UZ's structural divisions responsible for innovation activities

Today, in UZ the variant of the organizational structure that was approved in November 2025 (Joint Stock Company "Ukrainian Railways", 2026).) is relevant. The concept of building the organizational structure has a vertically integrated nature. The current organizational structure has seven verticals. In Fig.2 a fragment of the organizational structure of UZ is provided, in which the structural subdivisions that take direct part in solving the problem of decarbonization are shown. These subdivisions belong to the integrated vertical "Chairman of the Management Board" and "Freight transportation".

Innovation activity in UZ is the responsibility of the Department of Innovation, Technical Development and Quality Management (abbreviated as CIR).

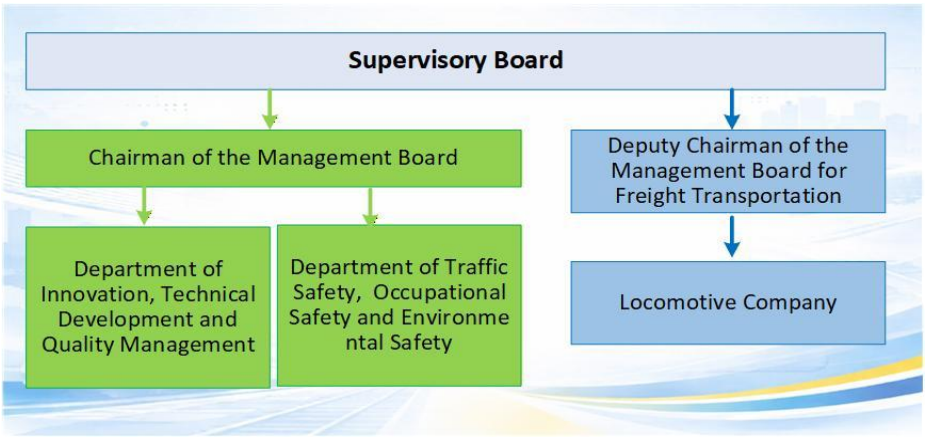

Figure 2 – Fragment of the organizational structure of the management of UZ (Joint Stock Company "Ukrainian Railways", 2026)

The main tasks of CIR include:

- organization of innovation activity;
- ensuring the efficient use of electrical energy, diesel fuel, natural gas and coal;
- control over the use of all types of fuel and energy resources;

- organization of implementation of energy-saving programs.

In accordance with the tasks, the CIR department performs the following functions:

- implementation of technical policy in the company;
- formation of reports on innovation activity;
- ensuring overall management and support for the implementation of innovative technical solutions and providing conclusions on the possibility of their scaling.

5.3.4 Overview of decarbonization trends in UZ

Today, the following initiatives related to innovation in the field of decarbonization are being implemented.

These initiatives include both innovative technological solutions and rail vehicle modernization aimed at improving energy efficiency and reducing greenhouse gas emissions:

A. *Modernization of the engine on 21 diesel locomotives of the 2TE116 series* with the aim of reducing GHGs. In the context of the Ukrainian railways sector, such modernization represents a practical approach to decarbonization through technological upgrading of the existing locomotive fleet. A similar decision was also made in 2016, at a meeting of the Public Council under the Ministry of Infrastructure of Ukraine, where it was directly indicated that it was planned to carry out modernization of diesel locomotives 2TE116 in the amount of €1.95 million (Ryabov at al., 2024). Also now, in the medium-term plan of priority public investments of the state for 2026 - 2028, the target number of 21 modernized diesel locomotives of the 2TE116 series is indicated. In addition to rolling stock modernization, some researchers propose innovative solutions to increase the fuel efficiency of 2TE116 (Ryabov at al., 2024), through optimization of load distribution between sections of diesel-generator units. This will ensure a reduction in fuel consumption and CO_2 emissions.
B. Modernization of freight electric traction through the procurement of new electric locomotives. In 2024, an international tender was announced for the supply of up to 80 mainline dual-system electric locomotives (CFTS Ukraine, 2024), within the framework of the project “Restoration of Main Logistics Infrastructure and Network Connectivity” (RELINC). It is also noted that UZ submitted an application for financing to the European Bank for Reconstruction and Development. Such a strategic step reflects UZ commitment to attract external sources of financing to support new projects and initiatives for modernization and improving the efficiency of railway infrastructure of Ukraine.
C. *Electrification of the Kovel–Yahodyn and Chop–Uzhhorod directions.* By 2030, a complete reconstruction and technical re-equipment of the railway border crossing point Kovel–Yahodyn is planned. It is planned to rebuild the track from 1520 mm to 1435 mm and to electrify the railway from Kovel to the state border of Poland. Such information is presented in the strategy for the development and construction of border infrastructure with the countries of the European Union and the Republic of Moldova until 2030 (Cabinet of Ministers of Ukraine., 2024, December 24). Modernization of the railway infrastructure between Liuboml, Maciej (Poland) and Kovel is also envisaged.
D. *Reduction of the comparative consumption of energy resources by locomotives* in order to save them and increase train weights. One of the directions of decarbonization at UZ, directly connected by a cause-and-effect and systemic relationship. Increasing the average weight of freight trains can often be economically justified, as it increases carrying capacity and can lead to reduced fuel and electricity consumption and transportation costs (Ukrainian State University of Railway Transport, 2021). The Press Center of UZ (Joint Stock Company “Ukrainian Railways”, 2024) writes about the improvement of

operational indicators: “improved locomotive turn-around and increased section speed”. Specific data on the increase in the average weight of a freight train are also provided: from 2,832 tons to 2,910 tons, and in parallel, the increase in locomotive productivity from 1,053 to 1,188 thousand gross tkm is shown. This is an indicator that UZ is increasing the weight of trains and increasing traction productivity. An increase in the energy efficiency of locomotive traction due to a reduction in mechanical friction between the wagon and the track is considered in (Zlenko, 2022).

E. *Reduction of the metal intensity of metal structures* in order, including, to reduce welding costs and the corresponding load on the environment. In (Baranovskyi et al., 2022), researchers propose to reduce the metal intensity of a freight wagon through a change in the floor structure. They propose a different shape so that the floor is stiffer and bends less under load. The proposed floor shape will make it possible to reduce material consumption by 1–2%, which will increase the carrying capacity by 1.4–1.7 t. It is noted that in this way it is possible to reduce the number of wagons in the consist while maintaining the total train mass. It is worth mentioning that UZ in contracts for 100 new passenger cars declares a service life of 50 years due to stainless steel bodies and extended overhaul intervals (Joint Stock Company “Ukrainian Railways”, 2025).

F. *Implementation of technical means* for accounting of fuel consumption on existing diesel locomotives in order to reduce fuel volumes for train operations. A mechanism for reducing the specific consumption of energy resources through improvement of standardization and automated control of diesel fuel consumption for train operations is shown in (Diatel, 2022) and the savings are associated with an increase in train weights and the conditions of their operation. As a result, if there is less diesel fuel or electricity per 10 thousand tkm, then CO_2 emissions are also proportionally reduced. Tools for reducing energy consumption for diesel traction and fuel consumption control systems are described in the scientific work (Ananieva & Chervenko, 2024). It is emphasized that such systems can be part of decarbonization measures if they are integrated into global decarbonization strategies.

G. *Transition to a predictive concept of monitoring the condition of locomotives* in order to reduce repair costs and increase the life cycle duration. The transition from diagnostics where response already occurs after a failure to predictive diagnostics, through intelligent systems for monitoring the condition of locomotives is stated in article (Fomin et al., 2025). The researchers note that they have developed a conceptual model of an intelligent diagnostic system. A model visualizes the condition of the locomotive in real time and provides data for managerial decision-making. Such a solution makes it possible to optimize maintenance schedules and reduce operating costs. On the website of UZ it is possible to find standards and technical conditions regarding repairs and maintenance of locomotives (Joint Stock Company “Ukrainian Railways”, 2026). There are technical conditions regarding the extension of the service life of the diesel locomotive 2TE116 during overhaul and modernization, which constitutes a documentary basis for extending the life cycle. The press center of UZ writes that the repair and production block in 2023–2024 saved more than €8 million due to cost optimization, implementation of technologies and expansion of its own production of spare parts (Joint Stock Company “Ukrainian Railways”, 2025). It can be concluded that UZ nevertheless reduces resource and energy costs in the repair and production sector, in order to spend fewer resources on repairs, which ultimately leads to lower emissions.

5.3.5. European decarbonization practices useful for UZ

Decarbonization of railway transport in the EU is part of the general transport policy. Decarbonization of railways is carried out simultaneously in several directions, which in their essence coincide with the directions of UZ. Three key directions can be identified for further consideration: track electrification, the use of alternative traction

technologies, and the digitalization of transportation processes: electrification of tracks, use of alternative traction and digitalization of transportation.

Electrification of tracks has been applied in UZ for quite a long time, and today Ukraine has one of the largest percentages of electrified lines in Europe (Joint Stock Company "Ukrainian Railways", 2024).

The use of alternative traction on non-electrified sections, such as battery and hydrogen locomotives, may be effective on low-activity lines and in shunting work. Studies in the EU show (Domínguez et al., 2025) that traction without combustion of diesel fuel and without direct CO_2 emissions during movement does not have a universal solution for all types of transportation. The choice between battery, hydrogen or other alternative traction depends on the length of the section, traffic intensity and life-cycle cost. For UZ this means that such solutions are advisable to consider primarily for shunting work, non-electrified sections.

Regarding digitalization of transportation, the measures of diminishing of GHGs depend not only on the type of traction, but also on the organization of transportation, train formation plan, choice of routes, etc. That is, part of the decarbonization effect is achieved through the efficiency of the transportation process (Hernandez et al., 2024). Notably, in EU countries significant attention is paid to energy-efficient train driving, digital control of energy consumption and optimization of the timetable. For UZ such an approach is especially useful, since through increasing the efficiency of operation of the existing fleet emissions are reduced and the use of resources is reduced.

In general, the experience of the EU shows that decarbonization of railways is not one separate activity, but a combination of electrification, alternative traction, digitalization and innovative approaches in general (Ahsan et al., 2023). Such an approach makes it possible to consider innovations in the field of decarbonization as a complex of interconnected solutions for UZ.

5.3.6 Identifying the causes and barriers to slow innovation adoption in UZ

The pace of implementation of innovations at UZ cannot be considered satisfactory. Along with the traditional features of railway transport in Western and Central Europe (conservatism, the need to scale innovations, large volumes of capital investments for the latest equipment and technologies), there are also individual features characteristic specifically of Ukraine.

To determine the reasons and prerequisites for the lag in the pace of innovations, it is necessary to analyze the company's activities over the last 30 years. The fact is that until the end of the 1990s, Ukrainian railways either were part of the railway transport of the Soviet Union de jure, or in the first years after the cessation of its existence – de facto. Practically independent strategic management of railway transport in Ukraine, and consequently the development of innovations, has been taking place for approximately the last 30 years.

Based on an analysis of the background and current situation, the following reasons and barriers to the slow implementation of innovations can be identified:

I. Insufficient volumes of financing of research and development (R&D) and experimental design studies during the last 25 years (about 0.5% of the total expenditures of railway transport of Ukraine) and insufficient attention to scientific research.
II. Absence or critical insufficiency of organizational and technical infrastructure for conducting multifactor testing of new equipment and technologies (test ranges, specialized testing structures, bench equipment, etc.)
III. Ignoring by the bodies of state power of Ukraine of urgent problems of railway transport during the 2000s – beginning of the 2020s of the 21st century, related to financing the renewal of rolling stock fleet. The fact is that, in accordance with the "Law on Railway Transport" of those times, the state had to finance the renewal of rolling stock of railway transport *(Verkhovna Rada of Ukraine, 1996)*.

IV. Absence of a strategic program for the implementation of new technologies, including regarding decarbonization.

Proposed ranking of barriers according to three criteria:

1) the strength of influence;
2) the scale of coverage;
3) the complexity of overcoming.

The evaluation was carried out according to a five-point scale: 1 point – weak influence of the barrier, 5 points – very strong influence of the barrier. For the generalized assessment of the significance of each barrier an integral assessment according to the formula was used:

$$\text{Integral Assessment} = 0.5 \times \text{strength of influence} + 0.3 \times \text{scale of coverage} + 0.2 \times \text{complexity of overcoming.} \quad (1)$$

The coefficients in Formula (1) were determined by the method of expert evaluation. The greatest significance was given to the criterion of the strength of the barrier's influence, because it shows how strongly this barrier slows down innovative development. The scale of coverage shows how widely the barrier manifests itself in the activity of the company. The complexity of overcoming shows how difficult it is to eliminate or weaken the effect of this barrier in practice.

The results of barrier ranking (Table 1) show that the most critical criteria for UZ are insufficient financing of research activity, long-term underfunding of rolling stock renewal and the absence of a strategic program for the implementation of new technologies.

Table 1. Ranking of barriers

Barrier	Degree of impact	Scale of coverage	Difficulty of overcoming	Summarised assessment
Insufficient R&D funding	5	5	5	5
The state's disregard for the need to renew rolling stock	5	4	5	4.7
Absence of a strategic programme for the implementation of new technologies, including decarbonization	4	5	4	4.3
Insufficient organisational and technical infrastructure for testing	4	3	4	3.7

The obtained results (Table 1) prove that the main constraining factors are systemic financial and organizational-strategic limitations. This means that acceleration of the innovative activity of UZ requires a more consistent state and corporate policy in the field of investments, strategic planning and modernization.

5.3.7 What can improve the decarbonization situation in the UZ?

Several key conditions are identified for accelerating the implementation of innovations at UZ:

1. Termination of the active phase of military actions by the Russian Federation and transition to intensive planning and management of the company's development.
2. Effective reforming of UZ. This term denotes: (a) continuation of the process of structural reforming in order to improve socio-economic performance indicators of activity; (b) use of wartime experience in the period of restoration of the company after a possible termination of the active phase of the war ("rollback forward", and not backward – to the state as of 24.02.2022); (c) departure from shortcomings in the behavior of the management and personnel of the company, which were a matter of concern in the EU, for example, the actual reduction of the level of corruption, which is referred to in the relevant program (Joint Stock Company "Ukrainian Railways", 2024); (d) formation of effective management of the company, including with the invitation of railway experts from EU states.
3. Accession of Ukraine to the EU or/and implementation of EU acquis and other documents that regulate the activity of railway transport.
4. Improvement of personnel training and renewal of the system of professional education.

To activate a digitalization – one of the fastest tools for accelerating innovations in UZ. Digitalization optimizes the work of the entire UZ, due to this new solutions are implemented and scaled faster across the entire railway.

To determine the priority of the five key conditions for improving the situation with decarbonization presented above, it is advisable to make a ranking according to the criteria: expected impact on the pace of implementation of innovations, possibility of practical implementation and speed of obtaining the result. For summarizing the results an integral assessment of priority is used, which is calculated according to the formula:

$$\text{Priority} = 0.5 \times \text{expected impact} + 0.3 \times \text{possibility of implementation} + 0.2 \times \text{speed of obtaining the effect.} \quad (2)$$

The results of the measure ranking are presented in Table 2. The numerical values in Table 2 were determined on the basis of the content of the studies, analysis of the current state of UZ, practical experience and evaluation of the realism of implementation of the corresponding measures. The evaluation was carried out according to a five-point scale: 1 point – weak manifestation of the criterion, 5 points – very strong manifestation. The criterion "expected impact" shows how strongly a particular condition can accelerate innovative development. The criterion "possibility of implementation" shows how realistic it is to implement this measure in the current conditions. The criterion "speed of obtaining the effect" shows how quickly after implementation the first results can be seen.

Table 2. Priority of conditions and measures for accelerating innovation implementation in UZ

Condition / measure	Expected impact	Feasibility of implementation	Speed of effect	Summarised assessment
Active digitalisation of processes	5	5	5	5
Effective reform of UZ	5	4	3	4.3
Ukraine accession to the EU and/or implementation of EU acquis and other relevant documents	5	3	3	4
Improvement of staff training	4	4	3	3.8
Reduction / cessation of the active phase of the war	5	1	2	3.2

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The condition “active digitalization” received the highest score, since it provides a high impact on the pace of implementation of innovations, high controllability within the company and a fast practical effect. Effective reforming of UZ also has a high potential impact, however it requires more time to obtain the effect. Accession to the EU and rapprochement with the European system were assessed as a strategically important direction, but the speed of implementation here is low due to political, legislative and external limitations. Improvement of personnel training is an important condition; however this occurs not quickly. Termination of the active phase of the war has a maximally high potential impact, but this key condition does not depend on UZ.

5.3.8. Methodological tools and digital platforms to improve the efficiency of PhD research

Development of the Innovative Process of Decarbonization in the Railway Sector under Post-Crisis and Stable Conditions

Based on crisis management literature (Boin, ’t Hart, Stern, & Sundelius, 2016), two primary directions of recovery are typically distinguished following a crisis: “as it was" (i.e. do as it was before the crisis), and “do differently” (which entails adapting in response to lessons learned during the crisis). However, most EU railway administrations operate under stable conditions and have the opportunity to implement innovations in the field of decarbonization in a planned manner. Therefore, the authors proposed scenarios for implementing innovations based on the assessment of current implementation conditions (Table 3). The authors identified 10 aspects for assessing implementation conditions (general logic, implementation conditions, nature of innovations, etc.) and proposed three generalized scenarios: the inertial scenario (“as it was”), the adaptive scenario (“doing differently”), and the scenario of accelerated integration (“adaptive-accelerated”), which involves the systematic implementation of innovations, harmonization with EU standards, digitalization of processes, etc. This approach is broadly applicable, since it is suitable both for crisis conditions, as illustrated by UZ and for stable operating conditions of railway companies.

Table 3. Generalized Scenarios for the Implementation of Emission-Reduction Innovations in Railway Transport

Assessment aspect	**Inertial scenario**	**Adaptive scenario**	**Accelerated integration / transformation scenario**
General development logic	Continuation of the existing operating model and local improvements without substantial technological change	Gradual modernisation through the selection of the most realistic and effective innovations	Systemic renewal of the railway system based on long-term investment, digitalisation and alignment with European standards
Implementation conditions	Crisis or resource-constrained conditions; the main priority is to maintain basic system functionality	Partial stabilisation, limited resources for modernisation and the possibility to select priority projects	Stable or recovery-oriented conditions, access to investment, international programmes and long-term planning
Nature of innovations	Individual energy-efficiency measures, repairs, maintenance of existing rolling	Electrification of selected routes, traction modernisation, digitalisation of processes, reduction of energy	Alternative traction, large-scale digitalisation, interoperable systems,

	stock and infrastructure	consumption and operational losses	automation and integrated decarbonization programmes
Justification of decarbonization effects	Mainly qualitative or simplified quantitative assessment based on available statistical data	Calculation of energy consumption, CO_2 emissions, specific indicators and comparison of several options	Full modelling of emissions, energy mix, life cycle, implementation scenarios and scaling effects
Financial evaluation	Simplified cost assessment; focus on minimising immediate costs	CAPEX/OPEX analysis, payback period, cost-benefit analysis for priority measures	Full life-cycle cost assessment, NPV, IRR, payback period, cost of avoided CO_2 and sensitivity analysis
Safety, certification and interoperability	Compliance with minimum existing requirements; innovations are limited by the current regulatory framework	Verification of compatibility with operational requirements, safety, technological readiness and infrastructure	Systemic alignment with European standards, safety case, RAMS, interoperability assessment and certification support
Digital readiness and data	Fragmented data, limited automation and a high share of manual decision-making	Use of digital data for monitoring, planning, effect assessment and implementation control of selected measures	Integrated digital platforms, decision-support systems, dashboards, audit trail and data-quality models
Managerial feasibility	Decisions are mostly reactive; responsible units and implementation stages are not always formalised	Decision owners, data sources, implementation stages, control criteria and pilot potential are identified	A full innovation management cycle is formed: data — assessment — decision — pilot — scaling — monitoring
Role of personnel	Personnel mainly maintain current system operation; involvement in innovation is limited	Gradual training of personnel for new technologies, digital tools and changed processes	Systemic renewal of competences, development of digital skills, work with data and personnel involvement in innovation implementation
Expected result	Slow emission reduction and continued dependence on existing technologies	Realistic emission reduction through priority measures, modernisation and improved operational efficiency	Significant emission reduction, technical compatibility with the EU, higher efficiency, resilience and controllability of the railway system

Table 3 summarizes the scenarios by implementing decarbonization innovations by railway administrations. The difference between the scenarios lies primarily in the level of justification for making management decisions. The more complex and large-scale scenario, the more important it is to assess in advance the technical effect, emissions, cost, safety, certification, data quality, and the possibility of scaling the innovation. For example, for UZ

in the medium term, the adaptive scenario is the most realistic, since it makes it possible to combine post-crisis recovery with gradual modernization, digitalization, reform, personnel training, and adjustment to European requirements. For other railway administrations, this scenario framework can be used as a tool for comparing modernization paths. Under such conditions, the key issue is the selection of economically feasible, safe, and interoperable innovations. Therefore, the adaptive scenario or the accelerated integration scenario can serve as a basis for planning decarbonization priorities.
In further research, such a scenario framework can be expanded into digital tools for supporting management decision-making. This will make it possible to move from the description of innovations to the comparison of specific measures and the further dissemination of solutions in railway companies.

The most realistic scenario in the medium term seems to be the adaptive scenario.

5.4 Conclusion and discussion

The following four key conclusions summarize the main findings of this study regarding the innovative development and decarbonization. Each point reflects both observed facts and their implications for the company's strategic development:

1. Slow implementation of innovations at UZ, in addition to barriers traditional for the railway sector, is explained by insufficient financing of scientific activity, lack of experience in strategic planning of the development of railway transport due to the short period of independence of Ukraine, ignoring by the state authorities of Ukraine during the 2000s–2020s of the 21st century the necessity of renewal of railway rolling stock, and the absence of a strategic program for the implementation of innovations. The conducted ranking showed that the most significant barriers to the innovative development of UZ are insufficient financing of research activity, underfunding of rolling stock renewal and the absence of an integral strategic program for the implementation of new technologies.
2. The main directions of innovation in the field of decarbonization at JSC "Ukrainian Railways" are electrification of certain routes, modernization of diesel locomotive engines in order to reduce emissions, reduction of the metal intensity of metal structures, development and implementation of technical means for accounting of fuel consumption on traction rolling stock, and transition to a predictive concept of monitoring the condition of locomotives.
3. The key conditions for increasing the pace of implementation of innovations at JSC "Ukrainian Railways" are the termination (at least for some period) of the active phase of military actions of the Russian Federation against Ukraine, effective reforming of the company, actual accession of Ukraine to the EU or/and active implementation of EU regulatory documents in Ukraine regarding the railway sector.
4. The experience of UZ in crisis conditions is valuable for Europe, since it is considered as a practical example of rapid adaptation of a railway system to catastrophically changed conditions of the environment of existence: prolonged external pressure, shortage of personnel, damaged infrastructure, etc. In such conditions digitalization, automation, transition to more flexible managerial decisions and development of new approaches to the resilience of the transportation process are accelerated.

The decarbonization directions from the 2nd paragraph are of a historical nature of the last 15–20 years. They were formed even before the "era of decarbonization". Among modern European innovations in the field of decarbonization (hydrogen traction, battery trains, use of biofuels), unfortunately, there are no examples of their permanent application at UZ. Partly this can be explained by the war with the Russian Federation, which actually began in 2014.

The prospect of a short-term cessation of the military operations referenced in paragraph 3 appears highly unlikely at present. Ukrainians hope that this low probability can be realized according to the principle of bifurcation from catastrophe theory. Also, the integration of Ukraine into the EU looks like a long-term perspective. This perspective has both supporters and opponents in EU states. Therefore, the most realistic scenario is the gradual implementation of the EU regulatory framework in Ukraine, construction of 1435 mm gauge track to the western borders of Ukraine, and step-by-step integration into the TEN-T network. However, there is a probability that in the future, during post-war reconstruction, development will go sharply upward. Rapid deployment of the latest systems, increase in investments in science and technologies, and growth of modernization rates are possible. Therefore, in the medium term, the most appropriate option for UZ is to combine an adaptive development scenario with a priority on digitalization, reform, personnel training, and gradual approximation to European approaches in the field of decarbonization.

5. For the most EU railway administrations, the proposed scenario approach can be used to compare development options: from maintaining existing practices to adaptive modernization and accelerated implementation of interoperable, financially justified, and safe innovations.

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2. Rohovyi, O., Samsonkin, V., Yurchenko, O., Bureika, G. (2025) A Single AI Platform for the Unification of Railway Transport Logistics Processes. *20th European Dependable Computing Conference Companion Proceedings (EDCC-C), Lisbon, Portugal, 2025, 96-101*. doi: 10.1109/EDCC-C66476.2025.00039 https://ieeexplore.ieee.org/document/11144878
3. Rohovyi, O. Decarbonization of Railway Diesel Traction: A Comparative Analysis of Renewable Diesel Fuels. (Accepted in February 2026 in the Collection of Scientific Papers of the Ukrainian State University of Railway Transport, tentative publication in No. 215 in 2026).
4. Samsonkin, V., Rohovyi, O., Yurchenko, O., Strelko, O., Bureika, G. (2025) Justification of a rational strategy for the decarbonization of EU rail transport as a solution to a multi-criteria problem. *6th International Scientific and Technical Conference "Intelligent Transport Technologies", Kharkiv, November 24–26, 2025: Abstracts of reports. – Kharkiv: UkrDUZT, 2025. 19-21.* chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://kart.edu.ua/wp-content/uploads/2025/12/zbirnik-tez-dopovidej-itt2025-.pdf