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Bridging the gap: Overcoming the 85 mm railway gauge difference between Ukraine and Europe using principles of circular economy and European service quality standards

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Abstract: The ongoing railway reforms in Ukraine are crucial for the country's integration into the European Union's transportation network. A major challenge lies in the difference in track gauge widths: Ukraine predominantly uses a 1520 mm gauge, while European countries utilize a 1435 mm gauge. This 85 mm difference presents significant logistical and operational barriers, hindering smooth cross-border trade and travel. The study examines the current state of Ukraine's railway system, highlighting the urgent need for infrastructure modernization to meet European standards. Methods include a comparative analysis of Ukraine's railway network with those of EU member states, focusing on integration challenges and potential solutions. Results indicate that aligning Ukraine's railway with European standards could substantially enhance connectivity, reduce transit times, and foster economic growth. However, "Ukrzaliznytsia's" slow adaptation to these necessary changes is a major roadblock. The study concludes that the construction of a standard-gauge railway linking Ukraine to the EU is vital not only for improving trade routes but also for supporting Ukraine's broader political and economic aspirations towards EU membership. Circular economy principles, such as resource optimisation, extending the life cycle of existing infrastructure and reusing materials from dismantled railway facilities, can offer a cost-effective and sustainable approach. This infrastructural change will serve as a catalyst for deeper integration, strengthening Ukraine's position within the European transportation network.

Keywords: circular economy; economic integration; gauge difference; logistics; railway reform; track gauge alignment; transportation infrastructure; Ukrzaliznytsia

1. Introduction

1.1. Path to Europe—Historical context and challenges of Ukraine's railway integration

Ukraine’s railway infrastructure, which utilizes the 1520 mm gauge inherited from the Soviet Union, presents logistical and operational challenges for integrating with the European Union, where the standard 1435 mm gauge, known as the “Stephenson gauge,” is prevalent. This difference in track width hinders seamless cross-border transport, impacting Ukraine’s aspirations for economic and political integration with Europe. Moving to the 1435 mm gauge would represent a strategic step away from the former Soviet infrastructure, bringing Ukraine closer to the European standards critical for aligning with EU transport policies (Gerhátová et al., 2021; Grushevska et al., 2016).

Since the late 20th century, the EU has gradually liberalized its railway sector, creating a foundation for competition and uniformity in infrastructure (Stefanović et al., 2020). This began with Directive 91/440, which mandated the separation of railway management and operations (European Commission, 1991), followed by Directive 95/18 (introducing licensing for railway undertakings) (European Commission, 1995a) and Directive 95/19 (regulating infrastructure access and fee structures) (European Commission, 1995b). In 1996, Directive 96/49 established common safety standards for transporting hazardous materials (European Commission, 1996; Howkins, 2005). The early 2000s saw the implementation of the “First Railway Package” with Directives 2001/12, 2001/13, and 2001/14, further opening access to railway infrastructure across Europe by setting fair usage and safety standards (European Commission, 2001a, 2001b, 2001c), helping create a cohesive and safe European rail network (Benoliel et al., 2023; Lundström et al., 2003; Nikitinas and Dailydka, 2016).

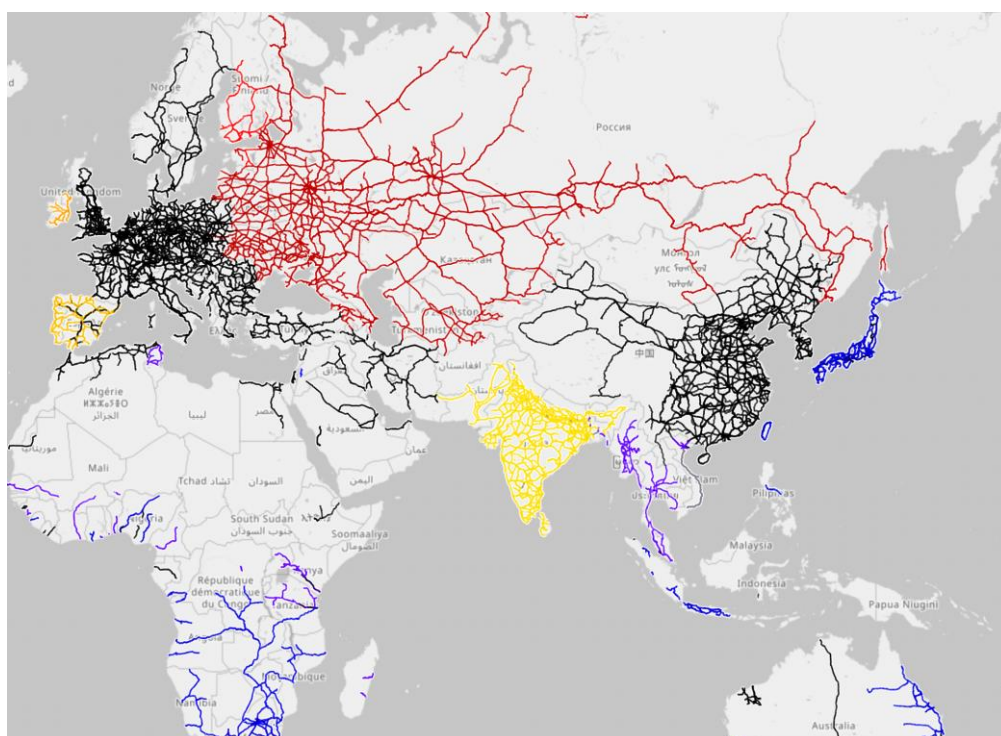


Figure 1. The width of the railway track.

Note: Black: 1435 mm, red: 1520 mm, yellow: 1668 mm, blue: 1067 mm.

The map on **Figure 1** illustrates the global distribution of different railway track gauges. The colors represent specific track widths:

Black: 1435 mm (standard gauge), widely used across Europe, North America, and parts of Asia.

Red: 1520 mm (Russian gauge), prevalent in Russia, former Soviet states, and parts of Eastern Europe.

Yellow: 1668 mm (Iberian gauge), primarily used in Spain and Portugal.

Blue: 1067 mm (Cape gauge), seen in Japan and parts of Africa.

This distribution highlights the regional preferences for track gauges, which pose challenges for seamless cross-border railway operations, especially between regions with different standards, such as between Europe (1435 mm) and former Soviet states (1520 mm) (Yakymenko and Petrushov, 2015).

Projects such as Rail Baltica demonstrate how Baltic nations, which also used the 1520 mm gauge, are making the shift toward European standards. This transition serves as a critical example for Ukraine's infrastructure goals, especially within the National Transport Strategy 2030, which includes building 1435 mm gauge routes to connect major cities like Kyiv, Odessa, Lviv, and Dnipro (Gao and Xu, 2024; Habrel et al., 2024). Additionally, the recent reconfiguration of export routes due to the war has intensified Ukraine's focus on western border connections, underscoring the urgency of increasing capacity and standardization for more efficient export logistics.

Ukraine is also taking steps to align its railway system with European standards under the National Transport Strategy 2030. Meanwhile, the blockade of Ukraine's seaports has made western border crossings a critical route for exporting grain and ore, though their capacity remains limited, especially for large volumes of cargo, which decreases export efficiency (Chou et al., 2024; Wang et al, 2023; Yuan et al., 2022).

The transition to the European standard gauge is not only a technological step but also a geopolitical decision that will allow Ukraine to accelerate trade with the EU and gradually reduce dependence on post-Soviet transport standards, strengthening its integration into the European transport system.

1.2. Challenges related to the track gauge difference

The reform of railway infrastructure, particularly the transition to a different track gauge, involves both technological and organizational challenges. On a technological level, this includes the implementation of automatic track gauge-changing systems such as "Talgo-RD" in Spain and "SUW 2000" in Poland, which have proven effective in ensuring uninterrupted train movement between regions with different track standards (Bureika et al., 2019; Pittman et al., 2020).

Organizationally, close coordination between regulatory authorities is required to harmonize standards and ensure efficient interaction between countries. Spain's experience with the "Talgo-RD" system, which significantly improved the speed and convenience of cross-border rail transport, and Poland's successful integration of the "SUW 2000" system for traffic between Poland and Lithuania, demonstrate the importance of such initiatives. These measures have contributed to increased freight and passenger flow, especially in cross-border regions (Kurhan and Kurhan, 2018).

The transition to a new track gauge also impacts loading operations, requiring infrastructure modernization, including the construction of specialized platforms and terminals. For instance, in Poland, the “SUW 2000” automatic track gauge-changing system has reduced wagon downtime at borders, significantly improving the efficiency of logistics processes (Chornopyska and Stasiuk, 2020; Massel, 2019). However, such innovations require substantial investments. While the initial costs of modernization and technology implementation are high, long-term savings are achieved by reducing transshipment costs and minimizing delays (Szkoda, 2014).

To minimize costs, it is recommended to integrate circular economy principles, including material reuse, resource optimization, and waste minimization. Investments in workforce training are also critical, as the adoption of new technologies requires highly skilled personnel to effectively manage the upgraded infrastructure (Giunta 2023; Kurhan and Kurhan, 2018).

The difference in track gauge between Ukraine’s 1520 mm standard and the European Union’s 1435 mm gauge represents a major barrier to Ukraine’s integration into the European transport network. Converting the entire Ukrainian railway network to the European gauge is an unrealistic undertaking due to the substantial cost and logistical challenges. Such a shift would require not only a complete overhaul of the track infrastructure but also a replacement of the rolling stock. Estimates indicate this would demand investments exceeding \$100 billion, as it involves updating not only the rail tracks but also all switchgear and connecting lines (Villalba Sanchis et al., 2021).

A more practical approach involves developing cross-border corridors with 1435 mm gauge and utilizing existing segments of European track gauge infrastructure for expansion towards major cities in regions bordering the EU. For instance, existing 1435 mm tracks, such as sections in the Zakarpattia region connecting Chop to Mukachevo, hold significant potential for reactivation and expansion. Another project has focused on constructing a 1435 mm gauge track from Vadul-Siret at the Romanian border to Chernivtsi, allowing passenger trains from Romania to reach Ukraine’s Bukovina region and establishing a freight hub for transloading between different gauges (Lemoine-Rodríguez et al., 2024; Pittman et al., 2020; Rosal, 2022).

While it is technically feasible to adapt part of Ukraine’s freight wagons by replacing bogies, this solution remains partial. Ukraine’s rail cars are considerably larger and bear higher axle loads (up to 23.5 tons) than those permitted in many European countries (18–20 tons), creating operational restrictions. This limitation means that in countries like Hungary, Slovakia, and Poland, only European-sized wagons with lower axle loads can typically be used (Havârneanu et al., 2022; Milan, 1997). Historically, Ukrainian-gauge wagons had access through a corridor extending from Yagodyn to Berlin, but both Germany and Poland have since discontinued support for this corridor.

In light of the recent blockade of Ukraine’s seaports, there has been a critical need to increase the capacity of western border train crossings, especially loading activities. This adaptation is essential to ensure stable export volumes and reduce dependence on limited transloading capabilities (Pittman, 2007).

1.3. Purpose and significance of the study: The benefits of track adaptation to facilitate cross-border trade, logistics and economic development, taking into account the principles of the circular economy and EU quality standards

The objective of this study is to assess the impact of adapting Ukraine's railway gauge to facilitate cross-border trade, logistics, and economic development by adopting the principles of a circular economy and meeting EU quality standards. With over 70% of Ukraine's exports previously transported through seaports, the current blockade of these ports has intensified the need for alternative routes. Railways, which previously handled only around 11% of exports, have now become essential. However, the discrepancy between Ukraine's 1520 mm track gauge and the EU's 1435 mm gauge significantly limits railway throughput at border crossings and raises logistical costs (Hasselwander et al., 2022; Miltiadou et al., 2017; Zheng et al., 2024).

The European Union is particularly interested in facilitating the adaptation of Ukrainian railways to the European gauge. Such a transformation would enable faster and more efficient cargo movement, reducing congestion at border crossing points and enhancing the connectivity between Ukraine and EU markets. The construction of European-gauge lines within Ukraine could potentially increase transshipment capacity by 30%–40% and support additional container shipments, estimated at around 37,000 containers annually (Deutschmann et al., 2023). This would not only strengthen food security by ensuring the stable export of essential Ukrainian goods but also reinforce EU supply chains that have been disrupted by the current geopolitical situation.

Applying circular economy strategies enables efficient resource utilization by prioritizing the recycling and reuse of materials from outdated infrastructure and opting for durable, eco-friendly materials in the modernization of tracks, platforms, and rolling stock (Bressi et al., 2021). For example, implementing resource recovery systems can significantly reduce waste and reliance on virgin resources, thus aligning with EU environmental priorities.

Transitioning from diesel-powered to battery-operated locomotives, with operational ranges up to 200 km, serves as a key measure in decarbonizing rail transport. Such efforts not only contribute to achieving noise reduction targets (–3 to –8 dB) but also minimize vibration impacts, ensuring compliance with EU environmental standards. Additionally, integrating energy-saving technologies could lead to a 30% reduction in energy consumption and greenhouse gas emissions, addressing critical climate action objectives (Wang et al., 2022).

Economic advantages can also be realized through lifecycle cost optimization. By reducing lifecycle costs (LCC) by 5%–10%, Ukraine can lower maintenance expenses and extend the usability of railway components. Innovations like regenerative braking and modular design further enhance cost-effectiveness and environmental sustainability (Bocken et al., 2016).

Enhancing resilience to global challenges, such as climate change and pandemics, is vital for sustaining operations. Modular designs and digital monitoring systems can bolster the railway's adaptability and ensure seamless integration with EU transport

systems. Harmonization with EU interoperability standards will enable streamlined border operations and boost cross-border trade efficiency (Krezo et al., 2023).

Moreover, integrating Ukrainian railways with the EU's standard gauge would benefit passenger transportation. A direct rail connection with Poland, for example, could significantly reduce travel times and increase mobility for workers, students, and business travelers, aligning with the EU's goals of enhancing regional integration. This study underscores the strategic need for gauge adaptation as a solution to technical barriers and as a catalyst for sustainable economic development and improved logistics networks, which align with EU interests and standards.

2. Materials and methods

The study aims to conduct a systematic review of current literature on the circular economy within the context of railway transport. The objectives include identifying critical research areas, key institutions, and prominent scientists contributing to this domain. The methodology integrates bibliometric approaches, ensuring objective analysis of a significant volume of publications, inspired by the approach used by Delehan (Delehan and Malychkovich, 2024). Data was sourced from reputable academic databases, including Web of Science and Scopus, to ensure access to peer-reviewed journals and reliable media sources. The search utilized specific keywords: circular economy, railways, sustainable transport, resource efficiency, carbon footprint, and rail infrastructure. Selection Criteria:

Publication Period: 2014–2024, focusing on contemporary research and advancements.

Publication Type: Articles in peer-reviewed journals, books, book chapters, and media articles.

Language: English and Ukrainian, ensuring a diverse and coherent analysis.

Subject: Relevance to railway transport, circular economy principles, and sustainable development practices.

Post data collection, the study employed a qualitative analysis to adapt existing methods to the specificities of railway transport. The study conducted a double peer-review process with industry experts, ensuring the inclusion of accurate and relevant publications. The reliability of thematic clustering and content categorization was verified using the Krippendorff reliability coefficient (≥ 0.8), confirming the robustness of the analysis framework.

The comparative analysis between Ukraine's and the EU's railway systems focuses on key infrastructure and operational aspects. Using multi-criteria analysis, this study evaluates factors such as track gauge width, network density, interoperability, and technical standards. The analysis incorporates data from both Ukrainian and European sources to assess the differences and challenges posed by the 1520 mm gauge in Ukraine compared to the 1435 mm standard in Europe. This methodological approach enables a comprehensive understanding of integration barriers and highlights necessary modifications for alignment with the European transport network, as well as its economic and logistical implications (Camillo et al., 2013; Fitzová and Nash, 2024; Wang et al., 2021; Yin et al., 2024).

To address the high costs associated with adapting railway infrastructure, the study integrates circular economy principles. This involves resource efficiency strategies, such as recycling materials from decommissioned tracks, utilizing refurbished components for maintenance, and implementing energy-efficient practices. By examining case studies where circular economy frameworks have been applied within railway systems, this study provides a pathway for Ukraine to optimize resource use and reduce infrastructure costs. (Chaves Franz et al., 2024; D'Amato et al., 2024; Koohmishi et al., 2024; Lin et al., 2024; Liu et al., 2024).

The final aspect of the methodology assesses the feasibility of implementing European service quality standards in Ukraine's railway system. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) (Rodríguez et al., 2024) analysis is employed to evaluate the operational and logistical challenges of adopting EU safety, reliability, and customer service standards. This approach helps identify Ukraine's current service gaps and potential improvements by benchmarking against EU practices. By exploring existing EU regulations and assessing Ukraine's capacity to meet these standards, the study provides insights into the potential impact on passenger experience and freight reliability, thus supporting integration with EU markets (Cherchye et al., 2024; Padovano et al., 2024; Versluis et al., 2024).

3. Results

3.1. Experience of the Rail Baltica project in standardizing railway infrastructure of Ukraine

The Rail Baltica project stands as a model for EU-driven efforts to create a cohesive and standardized railway network, linking key Baltic cities with Poland and potentially extending toward Germany and Italy (Pomykała and Engelhardt, 2023; Vaičiūnas and Steišūnas, 2017). Funded predominantly through the Connecting Europe Facility (CEF), the project aims to establish a high-speed, 1435 mm gauge railway corridor to improve both freight and passenger transport capabilities. With an estimated budget of €5.8 billion, this project underscores the strategic importance of integrating Eastern European countries into the EU's larger transportation framework, thus reinforcing connectivity across member states. Key factors include track gauge width, interoperability, and technical standards. While Ukraine operates on a 1520 mm gauge, the Rail Baltica uses the EU-standard 1435 mm gauge. This comparative analysis highlights the logistical complexities and integration barriers Ukraine faces, as adapting to EU standards would involve substantial infrastructure and operational modifications.

To mitigate the financial and resource-intensive nature of such large-scale infrastructure projects, the Rail Baltica initiative incorporates circular economy principles. Resource efficiency strategies, such as recycling and reusing decommissioned track materials, are central to the project's sustainable approach. Additionally, the integration of energy-efficient technologies aligns with the EU's environmental goals, presenting a model that Ukraine could replicate to reduce costs and environmental impact as it aligns its infrastructure with European standards. Case

studies of circular economy applications within the Rail Baltica project demonstrate long-term cost savings and sustainability benefits.

The Rail Baltica project also emphasizes adherence to European service quality standards, ensuring high levels of safety, reliability, and customer service. This is particularly relevant for Ukraine, where adopting similar standards could enhance passenger and freight experiences. Using a SWOT analysis, the Rail Baltica initiative evaluates the strengths, weaknesses, opportunities, and threats associated with applying these standards. By benchmarking against EU service levels, Ukraine could address existing service gaps and optimize its rail system for better integration into the European network, thereby facilitating economic growth and strengthening cross-border mobility. The Rail Baltica project's infrastructure, environmental sustainability, and service quality focus provide a comprehensive framework that Ukraine can adopt for its own integration into the EU's transportation network. By prioritizing gauge compatibility, leveraging circular economy principles, and enhancing service quality, Ukraine could facilitate more efficient trade routes and stabilize its export capacities, especially through Baltic ports like Tallinn and Riga. This adaptation is critical for minimizing delays associated with gauge changes at border points, particularly in the face of current logistical disruptions caused by the ongoing war with Russia.

3.2. Analysis of Ukraine's recovery plan and its connection to infrastructure development

The Recovery Plan for Ukraine outlines a strategic approach to rebuilding and modernizing Ukraine's critical infrastructure using principles of circular economy, which has been severely impacted by the ongoing war. The plan prioritizes enhancing resilience, increasing connectivity, and aligning with European Union (EU) standards to support integration efforts and economic recovery. Key initiatives include developing transport corridors, modernizing railway systems, and strengthening logistics networks to facilitate efficient trade and reduce the dependency on vulnerable seaports.

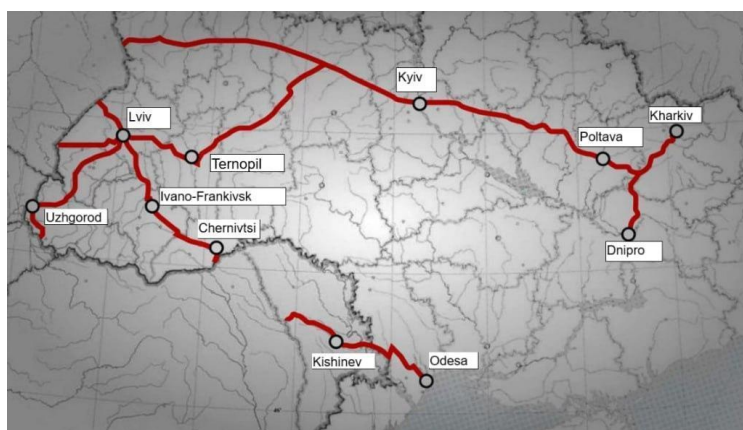


Figure 2. A project for a network of European railways presented in July 2023 by the European Commission and the EIB.

Figure 2 depicts a project for establishing a European railway network, published by the European Commission and the European Investment Bank (EIB) in July 2023.

The project outlines the expansion of railway infrastructure in Ukraine and Moldova to meet TEN-T standards, aiming to strengthen connections with the European Union. Specifically, the new corridors are intended to enhance export capacity, improve access to European markets, and increase the resilience of the transport network against challenges such as port blockades due to military actions (Council of the European Union, 2024).

Key Areas of Focus:

- 1) **Transport Resilience and Railway Modernization**—The plan emphasizes the modernization of Ukraine’s railway infrastructure, particularly by addressing the track gauge difference between Ukraine (1520 mm) and the EU (1435 mm). This adaptation is critical for smoother cross-border transit, reducing logistical bottlenecks, and enhancing trade efficiency. Such developments align with projects like Rail Baltica and serve as an integration tool within the EU’s Trans-European Transport Network (TEN-T) framework, thus reinforcing Ukraine’s Euro-integration aspirations.
- 2) **Multimodal Logistics and Trade Facilitation**—Given the ongoing maritime blockades, the plan prioritizes developing multimodal logistics hubs near western borders, allowing for a diversified transport strategy that includes rail, road, and river routes. This diversification helps secure export channels, particularly for agricultural products, metals, and other key exports. By increasing border-crossing capacity and facilitating seamless movement of goods, Ukraine aims to mitigate the current congestion challenges and enhance its role as a transit country within Europe.
- 3) **Digital and Green Infrastructure**—The plan includes ambitions to incorporate digital technologies and green infrastructure practices. Integrating smart logistics and digital monitoring systems will optimize infrastructure use, minimize energy consumption, and reduce emissions, aligning with EU standards for sustainable development. Moreover, green energy solutions and eco-friendly materials will play a role in rebuilding efforts, fostering a circular economy within the infrastructure sector.
- 4) **Funding and International Collaboration**—Much of the recovery funding is expected to come from international sources, with substantial contributions from EU initiatives such as the Connecting Europe Facility (CEF) and private investments. International collaboration is essential for mobilizing resources, sharing best practices, and ensuring adherence to international quality and safety standards. This funding structure emphasizes accountability and transparency, which are necessary for the efficient use of resources and successful project implementation.

By aligning infrastructure redevelopment with EU norms, Ukraine’s recovery strategy is poised to strengthen regional stability, stimulate economic growth, and create jobs. Improved infrastructure will enhance trade capacities and reduce transit times, benefitting both Ukraine and its European partners. This alignment not only addresses immediate recovery needs but also positions Ukraine as a critical transport and logistics hub in Eastern Europe, supporting broader EU objectives for regional connectivity.

3.3. EU Support for railway projects in Ukraine under the Connecting Europe Facility (CEF)

The European Union has prioritized financial and technical support for Ukraine's railway infrastructure under the Connecting Europe Facility (CEF), especially following the challenges posed by the ongoing conflict. CEF's support in Ukraine is aimed at enhancing cross-border connectivity, optimizing logistics corridors, and aligning Ukraine's rail infrastructure with European standards. Notably, CEF has provided funding for projects that address critical infrastructure gaps, support gauge compatibility, and build resilience into the Ukrainian transport system to facilitate smoother integration into the Trans-European Transport Network (TEN-T).

Funding for gauge standardization and compatibility between Ukraine's 1520 mm gauge and the EU's 1435 mm gauge represents a critical step towards aligning Ukraine's railway system with European standards. Investments made under the Connecting Europe Facility (CEF) prioritize infrastructure at border crossings and multimodal hubs, which serve as the logistical nexus for freight and passenger transit. By funding rapid-change gauge systems, these projects aim to mitigate the financial and time costs traditionally associated with gauge changes at borders. This effort reduces logistical bottlenecks, allowing for smoother cross-border operations and improved integration into the EU transport network (Shah et al., 2021; Zhao et al., 2020). The application of circular economy principles in this context enhances efficiency by reusing materials and optimizing resource allocation, which further minimizes costs and environmental impact (Kisielińska et al., 2021; Kraus and Proff, 2021).

Infrastructure development and modernization are equally critical components of the CEF-supported initiatives, which target aging railway infrastructure to ensure compliance with EU regulations. These projects focus on enhancing speed, safety, and operational standards, particularly at key border-crossing points with Poland, Romania, and Hungary. Modernizing these nodes is essential to managing increased freight volumes, a direct consequence of restricted maritime access due to geopolitical tensions. Through these efforts, Ukraine can strengthen its role as a critical transport corridor linking Europe with Asia while simultaneously adhering to EU transport and safety standards.

CEF's commitment to environmental sustainability and the integration of circular economy principles represents another layer of its multifaceted support. These principles emphasize recycling and reusing materials, particularly in track renewal projects and energy-efficient railway operations. Such practices align with the European Green Deal, showcasing Ukraine's commitment to sustainable development (Lee et al., 2017). By adopting circular economy approaches, CEF projects not only conserve resources but also reduce the carbon footprint of railway modernization, positioning Ukraine as a leader in regional sustainability initiatives and enhancing its reputation as an environmentally responsible transport hub.

Below on **Figure 3** is a summary chart of CEF funding allocations by project focus (e.g., gauge compatibility, infrastructure modernization, sustainability) and estimated impact on border-crossing efficiency.

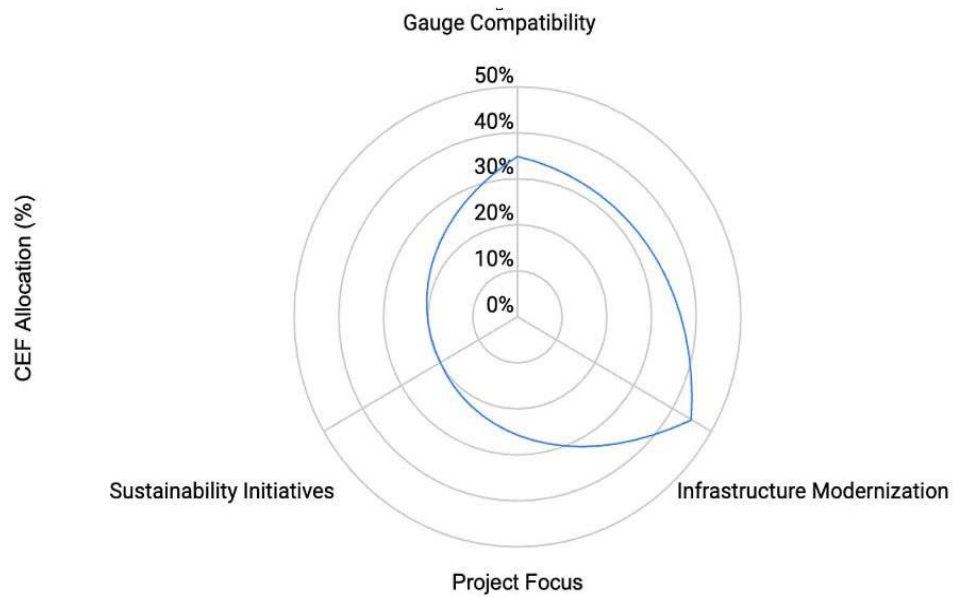


Figure 3. Visual data of the project focus taking into account CEF allocation (%).

The chart on **Figure 3** shows that the bulk of the CEF funding is directed towards infrastructure modernisation (45%), which is strategically important to increase the speed and capacity of the Ukrainian railway system. This will significantly reduce waiting times at the border, as more efficient infrastructure will be able to handle higher volumes of freight and passengers, facilitating access to EU markets.

Investments in track interoperability account for 35% of the total funding. This is critical as it ensures the smooth crossing of borders with the EU, in particular with Poland, Slovakia and Romania, where the European 1435 mm gauge is used. The harmonisation of gauges between Ukraine and the EU will help to remove technical barriers, reducing dependence on additional wagon adaptation operations, which will significantly increase the efficiency of transporting goods and passengers.

Finally, 20% of the funding is earmarked for environmental initiatives. This is particularly important for the EU, which aims to achieve climate neutrality by 2050. The implementation of environmental measures within the Ukrainian railway system, such as the introduction of energy-efficient technologies and material recycling, increases the overall environmental sustainability of the region and reduces the environmental footprint of international transport.

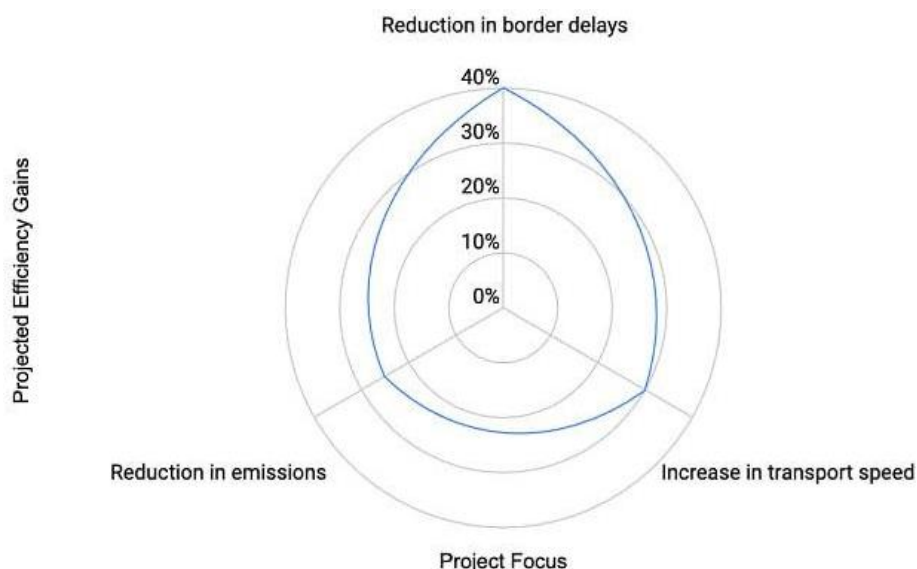


Figure 4. Visual data of the project focus taking into account projected efficiency gains.

The diagram on **Figure 4** shows an estimate of the expected efficiency gains from implementing these areas. In particular, the modernisation of infrastructure can reduce delays at the borders by 40%, which is key to optimising logistics processes between Ukraine and the EU. It also facilitates access for Ukrainian goods to European markets, supporting economic development on both sides.

Investments in environmental projects lead to an expected 25% reduction in emissions, which is in line with the EU’s environmental goals and helps reduce pollution associated with long-distance transport of goods. For the EU, this means less environmental impact at the border with Ukraine and the possibility of applying common standards of environmental responsibility in the transport network.

In addition, the improved infrastructure helps to increase the speed of traffic flows by 30%, which reduces transport costs for businesses on both sides and contributes to the growth of trade between Ukraine and the EU. For the European Union, this means a stable supply of goods and improved transport resilience, which is especially important in cases of geopolitical risks.

This structured support through CEF not only aids in overcoming immediate logistical challenges but also positions Ukraine’s railway network for long-term growth and integration with European systems.

4. Discussion

4.1. SWOT analysis of the Ukrainian railway industry in the context of European integration and military conditions

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) is a highly effective tool in strategic planning, enabling organizations to evaluate internal strengths and weaknesses alongside external opportunities and threats. Its implementation enhances an organization’s ability to understand the current landscape and develop well-informed strategies for future growth.

Deepening the SWOT analysis by incorporating empirical data and referencing relevant literature significantly increases its reliability and practical value. This approach allows not only the identification of key factors but also an in-depth understanding of their impact on organizational operations. For example, research published in *Sustainability* demonstrates the use of SWOT analysis to formulate strategies for sustainable water resource management, considering social, economic, and environmental dimensions (Wang et al., 2017).

Another study, featured in *Frontiers in Sustainability*, integrates SWOT and PESTEL approaches to evaluate renewable energy development. This combined methodology provides deeper insights into the internal and external factors influencing the sector and highlights the importance of interdisciplinary tools for comprehensive analysis (Kansongue et al., 2023). Thus, a detailed and nuanced SWOT analysis supported by empirical data and literature is critical for crafting effective strategies and making informed managerial decisions. This approach not only strengthens strategic outcomes but also ensures a holistic understanding of both opportunities and challenges in a given context.

SWOT analysis at **Table 1** demonstrates that Ukraine’s railway industry faces many challenges related to the war, but also has opportunities for adaptation and integration into the European transport network.

Table 1. SWOT analysis of the Ukrainian railway industry in the context of European integration and military conditions.

Internal	Strengths	Weaknesses
	Geographical location as a strategic transit corridor	Targeted destruction of infrastructure
	Extensive railway infrastructure network	Incompatibility with EU standards
	Experience in crisis management during wartime	Outdated service processes
	Need for modernization provides an opportunity for upgrades	Dependence on seaports, limiting logistics flexibility
External	Opportunities	Threats
	Modernization potential according to EU standards	Ongoing military aggression posing infrastructure threats
	Diversification of logistic routes to reduce dependency	Incompatibility with EU infrastructure (track gauge differences)
	Enhanced coordination with EU transport processes	High costs for modernization and upgrades
	Technological improvements for greater efficiency	Uncertainty in the restoration of industrial enterprises

Ukraine’s railway sector presents a complex interplay of strengths, weaknesses, opportunities, and threats that demand a nuanced and evidence-based SWOT analysis. Positioned as a vital transport corridor between Europe and Asia, Ukraine’s geographical location offers strategic advantages for the transit of goods, especially as global supply chains increasingly seek alternative routes to enhance resilience. This advantage is supported by the country’s extensive railway network, which, despite wartime destruction, remains a vast logistical framework capable of adapting to evolving transportation needs. Moreover, the railway industry’s demonstrated ability to operate under crisis conditions, as evidenced by its pivotal role in evacuation, military logistics, and humanitarian transport during the ongoing conflict, underscores its resilience and adaptability. Importantly, the need for modernization within the sector offers a unique opportunity to integrate advanced technologies and EU

standards during reconstruction, including improved accessibility for individuals with disabilities.

However, these strengths are counterbalanced by significant weaknesses. Persistent targeted attacks on railway infrastructure have not only caused widespread damage but also exacerbated the burden of repair and maintenance. Additionally, much of Ukraine's rail infrastructure and operational procedures remain incompatible with EU standards, limiting cross-border integration and reducing overall efficiency. Outdated processes further hinder service quality, while the reliance on maritime logistics has been disrupted by port blockades, forcing freight flows to pivot to western border crossings, thereby intensifying pressure on these nodes.

Opportunities for Ukraine's railway sector lie in its potential for modernization and alignment with European standards. Post-conflict reconstruction offers a chance to introduce cutting-edge technologies, improve safety measures, and establish EU-compliant systems. Diversifying logistics routes through the development of western border crossings could mitigate reliance on maritime pathways, thereby expanding export capabilities and enhancing resilience. Furthermore, closer coordination with EU nations on logistics and transportation processes would foster integration into the European transport network, facilitating smoother cross-border operations. The adoption of advanced digital transport management systems and other innovative technologies could further boost efficiency, reducing delays and optimizing resource utilization.

Despite these opportunities, significant threats loom. The ongoing military aggression continues to jeopardize infrastructure, personnel, and transportation services, delaying recovery efforts and hampering normal operations. The gauge incompatibility between Ukraine and the EU remains a critical challenge, necessitating additional transshipment capacity that complicates logistics and reduces efficiency. Furthermore, the high financial demands of modernizing and reconstructing transshipment facilities present an obstacle, particularly in the context of martial law and economic strain. Additionally, uncertainty regarding the recovery of industrial production complicates the prediction and planning of cargo flows, undermining the ability to optimize logistics and infrastructure planning effectively.

In sum, the SWOT analysis of Ukraine's railway sector underscores the dynamic interplay of strategic advantages and pressing challenges. While the sector's resilience and geographical importance lay a strong foundation, addressing its weaknesses and mitigating threats will require strategic investment, international cooperation, and the integration of modern technological and operational standards. By leveraging these opportunities, Ukraine can enhance its transport sector's role as a critical link between Eastern and Western Europe, contributing to its broader economic recovery and integration into the European Union.

4.2. Railway transport in Ukraine: Opportunities, challenges, and strategic insights

The study, aimed at conducting a systematic review of literature on the principles of the circular economy in the context of railway transport, highlights the significant potential of this field for integrating sustainable practices. The application of

bibliometric methods allowed for an objective analysis of a substantial body of academic publications, identifying critical research areas, key institutions, and leading scholars. The findings demonstrate that adopting circular economy principles can substantially contribute to railway infrastructure modernization, reducing restoration costs and minimizing environmental impacts.

However, the analysis reveals several limitations that may influence the scalability of the findings. One major limitation lies in the reliance on accessible academic publications, which are predominantly focused on developed countries. This creates an imbalance in addressing the specific conditions of transition economies, such as Ukraine. Furthermore, while qualitative analysis and validation of results through the Krippendorff reliability coefficient enhanced the robustness of the methodology, questions about the representativeness of the sample remain, particularly given the limited inclusion of non-English language publications.

The findings emphasize key areas for development, including the integration of digital technologies, resource optimization, and infrastructure standardization to meet European Union requirements. These elements are critical for reducing cross-border transportation costs, improving logistics flows, and achieving environmental sustainability. However, implementing these changes requires significant financial investment and international collaboration, which may be hampered by economic uncertainties and ongoing military conflict.

Moreover, applying circular economy principles in Ukraine holds considerable promise but depends on the engagement of public and private investors to fund innovative solutions. The lack of a clear policy framework supporting such initiatives and the absence of comprehensive legislative measures could slow the adoption of sustainable practices. Additionally, the need for large-scale reconstruction of railway infrastructure underscores the importance of strategic planning that considers not only short-term economic benefits but also long-term environmental objectives.

The study also opens avenues for future research, particularly in the development of multi-criteria models for prioritizing infrastructure investments and exploring the impact of digital technologies on the efficiency of transport system management. At the same time, its limitations highlight the necessity for further research that incorporates local characteristics and the specific needs of diverse regions. Such efforts would deepen understanding of the potential for the circular economy in railway transport and provide practical tools for implementing these principles in response to real-world challenges.

5. Conclusions

The integration of Ukraine's railway infrastructure into the European network is not only a strategic priority for Ukraine but also a pressing need for the European Union, particularly in light of current geopolitical dynamics. This study has shown that addressing the 85 mm gauge difference between Ukrainian and European railways, along with implementing principles of the circular economy and EU service quality standards, could greatly enhance cross-border connectivity and logistical efficiency. This alignment supports EU goals of minimizing dependence on non-EU infrastructure, particularly by developing direct, stable, and secure transit routes that

bypass adversarial regions. For Europe, Ukraine's alignment with EU rail standards could mitigate risks associated with external threats by strengthening intra-European resilience and reducing reliance on external logistical networks.

Implementing these changes will require targeted investment and collaboration between EU member states and Ukrainian stakeholders to enhance infrastructure compatibility, efficiency, and sustainability. In the long term, achieving these standards is essential for Ukraine's economic stability and EU integration, as well as for the EU's own strategic interests in building a robust, autonomous logistics network that reinforces both economic and geopolitical stability.

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