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Editors office address:
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Public transport risk assessment through fault tree analysis (Baku city example)

Elmaddin Salayev*
Postgraduated Student
Azerbaijan Tecnhical University
AZ1073, 25 Huseyn Javid Ave., Baku, Azerbaijan
https://orcid.org/0009-0000-4315-3590

Abstract. Road safety has become an increasingly important issue within urban transportation systems, particularly in developing nations such as Azerbaijan, where traffic accidents continue to be a primary source of injuries and property damage. This purpose of the study was to assess the risks linked to Baku's public transportation network by employing Fault Tree Analysis (FTA) within the Haddon Matrix framework, which organises contributing factors into three categories: vehicle, human, and road environment. The FTA approach facilitated a systematic, deductive examination of potential failure causes that could lead to accidents involving public transport. Significant findings revealed that vehicle-related problems, including malfunctioning braking systems, steering issues, and inadequate maintenance, greatly increase the likelihood of incidents. Human-related risks such as driver behaviour (for instance, speeding and failure to yield), non-compliance with traffic regulations, and unpredictable pedestrian actions also significantly contribute to the problem. Additionally, road-related issues like poor infrastructure, lack of adequate signage, insufficient lighting, and unsafe bus stop designs further heighten the risk. The interplay of these factors indicates that public transport accidents in Baku are multi-faceted and frequently preventable. This study underscored the necessity of systematic safety evaluations, routine vehicle inspections, and improved public awareness initiatives to reduce risks associated with urban transport. The practical implications of this research provide urban transport planners and policymakers with insights into priority risk areas, thereby facilitating more effective strategies to enhance safety within Baku's transit system

Keywords: urban traffic accidents; vehicle, risk analysis; road safety; bus operation risks

Introduction

A study of safety issues in public transport systems has become increasingly important due to the risks posed by rapidly growing urban mobility and rising accident rates. The analysis of road accidents, particularly in bus transport, requires a systematic investigation into technical failures, driver and pedestrian behaviour, and the influence of road infrastructure. Identification of accident causes and modelling their interactions are essential for effective risk management and the improvement of transport safety. In support of this concern, accident statistics from Baku city for the years 2019 to 2024 reveal that the most frequent causes of public transport-related incidents stem from both technical deficiencies and unsafe human behaviours. Statistical data indicate that the main causes of bus accidents in Baku were primarily associated with driver-related behavioural errors. The most common cause was improper manoeuvring, which accounted for 34.0% of all recorded incidents. This was followed by speeding, responsible for 22.4% of accidents. The failure to maintain a safe following distance ranked next, contributing to 5.4% of the cases. In addition, failure to stop at pedestrian crossings (5.4%) and passenger-related violations (4.8%) were also identified as significant contributing factors. Other traffic rule violations accounted for 3.4%, while violations at intersections represent 2.7%. Disregard for road signs and markings accounted for only 0.7% of incidents. Similarly, both driving under the influence and entering the oncoming lane or improper overtaking each represented 0.7% of the recorded accidents. Overall, this distribution illustrates that human factors – particularly driver behaviour – are the leading contributors to accident risk in urban bus operations. While technical malfunctions may occasionally play a role, the findings emphasise the importance of systematically incorporating human behaviour into risk assessments. This underscores the need for comprehensive and integrated

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*Corresponding author (*elmeddin.salayev@aztu.edu.az*)

risk modelling in public transportation systems. (The State Statistical Committee…, 2024).

The risk modelling reveals the necessity of integrating both human and technical factors into analytical models. Consequently, the application of structured methods like Fault Tree Analysis (FTA) becomes critical for systematically identifying and quantifying contributing factors. To support the development of such models, a critical review of the academic literature was presented, focusing on studies that have applied FTA and similar methodologies to transportation safety analysis. Numerous studies have investigated the application of FTA in transport and safety-related systems. However, a closer look reveals a consistent gap in applying these methods specifically to urban public bus systems.

J. Xi *et al.* (2021) applied FTA to model cause-effect relationships within transportation systems, demonstrating its strength in structuring complex risk scenarios. Nevertheless, their analysis lacks attention to the operational context of specific modes like urban buses, including route characteristics and service dynamics, highlighting a need for context-sensitive applications. While the FTA (2021) report primarily categorises risk factors in a descriptive manner, X. Qi *et al.* (2025) employed an entropy-weighted DEMATEL approach to offer a structured quantitative analysis of operational risk in public transportation. They analysed 18 risk variables including safety awareness, human initiative, funding adequacy, and inspection frequency not only ranking them by importance, but also modelling their interdependencies. This provided a stronger empirical foundation for developing prioritised, data-driven risk mitigation strategies, elevating the analysis from mere categorisation to actionable decision-making

A more technical approach was taken by W. Huang *et al.* (2021), who merged Bayesian networks with FTA to analyse failure modes in transit systems. The integration strengthened probabilistic inference capabilities. That said, their scope was confined to hardware and system components, lacking attention to operational practices and human error – factors essential to understanding urban bus vulnerabilities. Taking a broader systems approach, K. Pan *et al.* (2022) combined FTA with system dynamics to study resilience in passenger transport systems through the lens of sustainable mobility. The inclusion of social and ecological perspectives was commendable. Nonetheless, the generality of their model limited its relevance to city bus networks, where specific behaviours, mechanical reliability, and infrastructure constraints were paramount.

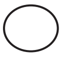
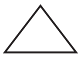
Adding a layer of decision-making under uncertainty, M. Ghadhab *et al.* (2019) integrated fuzzy logic and artificial intelligence into FTA structures. This methodological innovation enhanced adaptability, yet the absence of application to public transport environments – especially interactions between drivers, pedestrians, and urban complexity – diminished its immediate practical value. T.H.A. Nguyen *et al.* (2022) employed Fault Tree Analysis on the Hanoi Urban Mass Rapid Transit system to quantitatively model train collision risk. Their framework constructed a top-level event for collision, incorporated operational data (2018-2021), and validated the model empirically thus establishing a direct link between model outputs and system-specific safety performance.

These studies collectively affirmed the robustness of FTA as a risk analysis tool but revealed underexplored areas in its adaptation to urban public transportation, especially bus operations. Critical variables such as driver behaviour, passenger interaction, technical malfunctions, and infrastructure-related risks were often omitted or insufficiently analysed. Moreover, few studies employed real-world operational data or quantitative modelling software for system-specific evaluations. In response to these gaps, the present study applied the FTA method directly to Baku's public bus network, using incident-based data and software-supported modelling (top event FTA). The purpose of this study was to assess the risks associated with the operation of public transport in Baku by applying the Fault Tree Analysis method within the Haddon Matrix framework, with a focus on identifying and quantitatively classifying the key technical, behavioural, and infrastructural factors that contribute to accidents to develop evidence-based recommendations for improving the safety of urban bus transportation. This approach enabled a hierarchical breakdown of accident scenarios and a quantitative risk classification across key domains technical, behavioural, and environmental. By analysing prevalent accident causes like speeding, violation of traffic rules, technical faults (e.g., brake/steering issues), and pedestrian misbehaviour, the study contributed to data-informed safety intervention planning and prioritised risk management in urban bus transport.

Materials and Methods

Fault Tree Analysis is a structured and deductive technique used to identify cause-effect relationships in hazardous scenarios, especially within complex systems. This top-down method begins with a primary failure – known as the top event – and systematically traces the potential underlying causes contributing to this failure. FTA is particularly valuable for detecting system vulnerabilities, critical risk sources, and interdependencies within operational processes. In this study, the FTA Top Event approach was employed to assess potential accidents in urban public transportation systems in Baku, Azerbaijan. The analysis adhered to the principles outlined in the international standard IEC 61025:2006 (2006), ensuring methodological rigour and comparability with international studies. Reliability analysis is a foundational aspect of risk modelling in technical systems, particularly in transportation. These models allowed for the quantitative assessment of system performance under various failure and recovery conditions (Zio, 2007). To visualise the logical structure of the fault tree, officially recognised symbols (Table 1) were used in accordance with IEC standards, enabling clear interpretation and consistent documentation. The analysis focused on the top event defined as a "public transport accident", and identified key sub-events related to driver error.

Table 1. Symbols used in Fault Tree Analysis

Symbol	Event	Function
	Main event	Event or error that provides the basis for analysis
	Undeveloped event	Event that is not further analysed or has a small impact
	Top or mediator event	Final event arising from more fundamental events
	Situation event	Situation where a special condition exists for the occurrence of an event
	AND gate	Event that results in all inputs to the event occurring simultaneously
	OR gate	Event that results in the occurrence of at least one input event
	Transfer symbol	Symbol referring to another part of the fault tree

Source: F.S. Dashdamirov & A.C. Sharifov (2020)

City-specific data from Baku's public bus network were integrated into the fault tree model. These included traffic density, road infrastructure characteristics, frequency of recorded driver violations, and historical accident reports from the Baku Transport Agency and State Traffic Police Department. The sub-causes associated with driver errors were identified based on observed patterns in Baku's urban traffic and their relevance to accident occurrence:

▷ improper manoeuvring refers to incorrect or hazardous vehicle handling during lane changes, turns, or merging, which can lead to collisions in dense urban traffic;

▷ failure to maintain a safe following distance increases the risk of rear-end collisions, especially in stop-and-go traffic conditions common in urban environments like Baku;

▷ exceeding speed limits reduces a driver's reaction time and control over the vehicle, significantly elevating the likelihood of accidents in areas with high pedestrian activity;

▷ not stopping at pedestrian crossings endangers vulnerable road users and is a major contributing factor in public transport-related pedestrian accidents;

▷ violation of traffic signs and markings indicates non-compliance with road regulations, which can result in confusion, right-of-way conflicts, and intersection-related accident;

▷ driving under the influence of alcohol impairs cognitive and motor functions, making drivers more prone to errors in judgment, delayed reactions, and loss of vehicle control.

This fault tree framework allowed the systematic identification of high-risk scenarios in Baku's public transport system, supporting the development of targeted risk mitigation strategies. The "Main Events of DDV" programme was used for the analysis, the main event of which is the risk of accidents in public transport. Factors that may be responsible for this risk were identified and a systematic fault tree was created (Fig. 1). The analysis showed that three main groups of factors play a major role in the risk: driver error, pedestrian violations, and technical defects in vehicles. Among the risks associated with pedestrian behaviour, there were incidents of theft, of getting in and out of a bus without waiting for it to stop, of crossing a road without following traffic rules. These behaviours, particularly during rush hours, have a negative impact on the decision-making of drivers and on traffic flow. These include failure to activate the brake system in time, steering system failures, lighting and signalling systems, sudden engine shutdowns, fuel system failures and gearbox failures. These technical failures increase the risk of accidents and prevent uninterrupted and safe operation of the transport system.

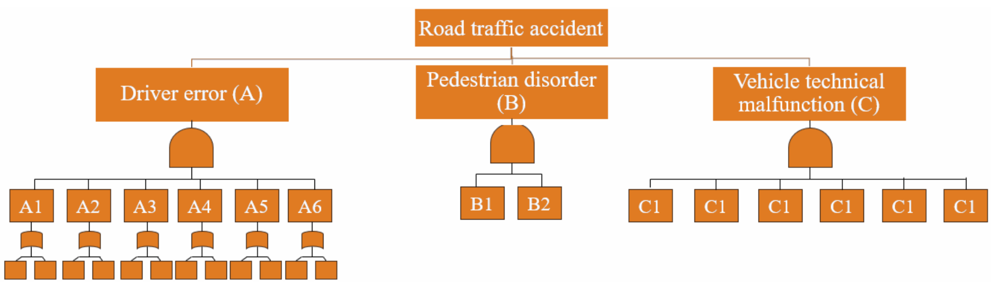


Figure 1. Fault Tree Analysis of accidents on buses in Baku

Source: created by the author

In the FTA analysis, probabilities were calculated for each of these sub-factors, using logical gates (AND, OR). Of these three groups of factors, technical malfunctions and driver errors pose the greatest risk, and targeted interventions are needed to mitigate their impact. The use of the FTA in this study allowed a structured identification of causality relationships, prioritisation of high risk components, and the development of scientifically based public transport safety strategies. Once the risks were identified, they were incorporated into the fault tree structure to examine how individual and combined events contribute to the top event. Following this step, appropriate reliability models were selected within the FTA software to simulate the behaviour and impact of each event. These models included various statistical and probabilistic tools such as constant failure rate, repairable/unrepairable models, and Weibull distributions, which were essential for quantifying failure probabilities and unavailability over time (Fig. 2):

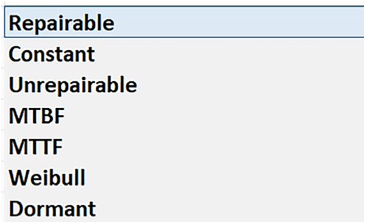


Figure 2. Different reliability models in FTA programme
Source: created by the author based on risk modelling in the FTA software environment

Each was used to describe the failure and recovery characteristics of a different system. The following is an explanation of what they are and when they are used:

1. Repairable model. The system can be restored after failure. The equation for a recoverable system is as follows (Elsayed, 2012):

$$q(t) = qe^{-(\lambda+\mu)t} + \frac{\lambda}{\lambda+\mu}(1-e)^{-(\lambda+\mu)t}. \quad (1)$$

The reliability models used in FTA required the specification of several key parameters to quantify failure behaviour: λ (failure rate): the rate at which a component or event was expected to fail over time. It was typically measured in failures per unit time (e.g., failures/hour) and was used primarily in models assuming a constant or exponential distribution of failures. μ (repair rate): the rate at which a failed component was restored to operational condition. This parameter was crucial in repairable models and reflects system maintainability. Like λ, it was expressed in events per unit time. q (initial unavailability or probability of failure in the initial state): the probability that a component was already in a failed state at the beginning of the observation or mission time. It was especially relevant in dormant or standby models, where components were not active but still susceptible to hidden failures. t – time elapsed since the start of observation, e – base of the natural logarithm.

$$\omega(t) = \lambda[1 - q(t)], \quad (2)$$

where ω(t) – failure frequency at time t, indicating how often failures were expected to occur in the system per unit time; λ – failure rate of the system (i.e., the rate at which failures occur in a functioning state); *q(t)* – unavailability function, representing the probability that the system was in a failed state at time t.

2. Constant model. Failure or reliability varied with the severity of the event. For example, some components had a fixed probability of failure over time. Usually modelled by exponential distribution (Elsayed, 2012):

$$q(t) = q. \quad (3)$$

3. Unrepairable model. After a system failure, it was not restored, it was simply replaced. For example, disposable devices, batteries. Equations (2) and (4) were used.

$$q(t) = (1-q)e^{-\lambda t}. \quad (4)$$

4. MTBF (Mean Time Between Failures). It showed the average time between failures for systems under repair. Used to measure the time the system was running. Usually modelled by an exponential distribution (Moddares *et al.*, 2016):

$$q(t) = \frac{\lambda}{\lambda+\mu}\, 1 - e^{-(\lambda+\mu)t}, \quad (5)$$

$$\lambda = \frac{1}{MTBF} \text{ və } \mu = \frac{1}{MTTR}, \quad (6)$$

where *q(t)* – the probability that the system is in a faulty state at a given time; $\omega(t)$ – fault intensity (the probability of a fault occurring at a given time); λ – failure rate (*MTBF*); μ – recovery speed (related to *MTTR* – mean time to repair).

5. MTTF (Mean Time to Failure). Indicated the availability of systems that were not repaired. 1 –the average time for a component or system to fail (Moddares *et al.*, 2016):

$$q(t) = 1 - e^{-(\lambda+\mu)t}, \quad (7)$$

$$\lambda = \frac{1}{MTBF}. \quad (8)$$

6. Weibull. It was used to model different types of failures. The failure rate varied over time (may increase, decrease, or remain constant). For example, in the analysis of fatigue of mechanical components (O'Connor & Kleyner, 2012):

$$q(t) = 1 - \exp\left[-\left(\frac{t-\lambda}{\eta}\right)\right]^{\beta}, \quad (9)$$

where η – measurement parameter (average value over the life of the system); β – shape parameter (determines the failure rate of the system); γ – start delay time (time after the system was put into operation before the fault starts). The Weibull distribution considered that the failure process changed over time: β > 1 early failure (due to design errors or weak parts); β = 1 constant failure rate (corresponds to an exponential distribution); β < 1 ageing period (failures increase due to wear).

7. Dormant (Passive systems). A system that has not been used for a certain period of time and can only fail when it is active. For example, backup generation systems, fire suppression systems (O'Connor & Kleyner, 2012):

$$q(t) = \frac{\lambda\tau - (1-e^{\lambda\tau}) + \lambda MTTR(1-e)^{-\lambda\tau}}{\lambda\tau + \lambda MTTR(1-e)^{-\lambda\tau}}, \quad (10)$$

where τ – specified analysis period. This model described the combination of failure and recovery processes and shows the dynamics of equipment operation and repair.

Repairable and MTBF models were used for systems that can be restored after a failure, allowing for the calculation of both failure and recovery parameters. Unrepairable and MTTF models, on the other hand, were applied to components that are not restored once failed, focusing solely on the expected time to failure. The Constant model assumed a uniform failure rate over time, suitable for components with random, memoryless failures. The Weibull model was ideal for systems subject to mechanical fatigue, where the failure rate varied over time depending on operational stress or ageing. This methodological framework allowed for flexibility in modelling a wide range of system behaviours and supported more accurate risk estimation in Fault Tree Analysis. Selection of the appropriate model depended on the component characteristics and the nature of the risk being assessed.

Results and Discussion

Risks associated with driver behaviour

Distraction (Repairable model). This section presents the results of risk modelling related to driver distraction, interpreted through the repairable model framework. The analysis focuses on the probability of a driver becoming distracted due to factors such as fatigue, stress, or sleeplessness conditions that are typically reversible over time. Since distraction is a temporary and recoverable condition, the repairable model is particularly suitable, as it allows for modelling both the onset of distraction and the probability of attention recovery. Based on assumed working conditions and realistic parameters for an 8-hour urban transit shift, the model supports the assessment of risk dynamics over time and informs effective safety management strategies. The parameters used in this model are detailed in Table 2.

Table 2. Driver distraction risk modelling parameters (Repairable model)

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.1	Probability of distraction per hour
Recovery speed	μ	0.05	Probability of attention being restored per hour
Value	-	Hour	Calculations are made in units of hours

Source: compiled by the author based on assumed data for the case analysis

The table presents the key parameters for modelling driver distraction using the Repairable model. The failure rate (λ = 0.1) suggests that for every hour of work, there is a 10% probability that the driver may become distracted due to fatigue, stress, or other human factors. This value is particularly critical in long driving shifts common in urban bus operations. The repair rate (μ = 0.05) implies that there is a 5% chance per hour that the driver's attention can be restored through rest, recovery at stops, or other interventions. The values are based on assumed data but align with general fatigue patterns reported in driver performance studies. Using these parameters, further calculations were conducted to simulate how distraction risk evolves during a typical 8-hour workday.

Here, λ is the failure rate – the probability of the driver being distracted. The risk event (*q(t)*) is the probability of a distraction occurring within a certain time. μ is the speed at which the driver regains attention by resting. Since the work schedule is 8 hours, the probability of the driver's attention being distracted is assumed to be 10% for each hour. In this case, λ = 0.1. Assuming that the driver's fatigue is relieved by resting and regaining attention is 5% for each hour, then μ = 0.05. In this case, the unavailability graph will be as follows (Fig. 3):

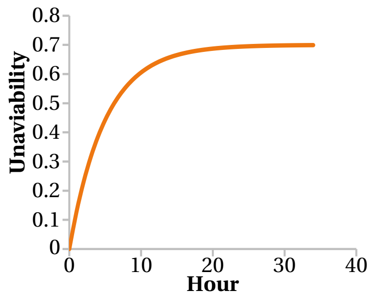


Figure 3. Driver distraction graph based on the Repairable model

Source: created by the author based on risk modelling in the FTA software environment

The distraction risk curve shown in Figure 3 illustrates the probability *q(t)* of a driver being in a distracted state over time, based on the repairable system formulation. Initially, the curve rises steeply, indicating that the risk of distraction increases quickly during the early hours of the shift. For example, by the second hour, the probability of being in a distracted state reaches approximately 16-18%, and by the sixth hour, it exceeds 40%. This trend aligns with known fatigue accumulation patterns, especially when rest breaks are inadequate.

As the shift progresses, the curve gradually flattens, indicating a balance between distraction occurrence and recovery. However, because the recovery rate ($\mu = 0.05$) is lower than the failure rate ($\lambda = 0.1$), the system tends toward higher unavailability – i.e., sustained distraction – unless effective countermeasures (e.g., scheduled breaks or shift rotation) are introduced. This finding highlights the asymmetric nature of fatigue accumulation versus recovery, and it underscores the importance of risk control strategies such as fatigue monitoring systems, micro-breaks, and duty cycle regulation in public transport operations. The simulation confirms that driver distraction is a dynamically evolving risk, which becomes more pronounced over time if not actively managed. The results emphasise the need for real-time monitoring and proactive interventions to prevent human error-related incidents in urban transport systems.

Fatigue (Repairable model). Fatigue is considered a recoverable human factor risk and is therefore modelled using the repairable model, similar to distraction. It represents a temporary decline in alertness and performance due to prolonged working hours or insufficient rest. Since fatigue can be mitigated through sleep, rest breaks, or shift rotation, it fits the logic of a system that can transition from failure to recovery. Continuous fatigue without recovery increases the likelihood of errors in perception, delayed reaction times, and overall driving performance degradation.

Non-conservation of spacing (Weibull model). This risk factor arises when drivers fail to maintain adequate spacing between vehicles, especially under hazardous driving conditions. The likelihood of such behaviour leading to an accident increases significantly when road conditions are poor and tire tread is worn down, both of which affect braking performance and control. Because tread wear is a gradual, time-dependent process, and road conditions dynamically influence accident probability, the Weibull model, which accounts for failure rates that change over time, is considered appropriate for modelling this risk. The parameters used for different road types and corresponding tread wear distances are presented in Table 3.

Table 3. Road conditions and tread wear parameters for Weibull-based spacing risk model

Road conditions	Tread wear distance (km)	β (Shape parameter)
Asphalt	40,000	2.5
Asphalt (rainy)	30,000	2.0
Gravel road	20,000	1.8
Mud road	15,000	1.5

Source: compiled by the author based on assumed data for the case analysis

Since the roads used in the study are asphalted, the shape parameter $\beta = 2.5$ is initially assumed, reflecting a wear-out failure pattern where the risk increases over time. The MTTF of the tires is estimated to be 24 months, and using the Gamma function value $\Gamma(1 + 1 / 2.5) \approx 0.89$. $\Gamma(1 + 1 / 2.5) \approx 0.89$, the corresponding scale parameter (η) can be calculated accordingly. As tread wear is a gradual and cumulative process, the condition of $\beta > 1$ is justified, indicating that failure likelihood grows as the tire ages. Given that asphalt roads dominate in Baku and field observations confirm that tire tread degradation accelerates with use, a more representative shape parameter $\beta = 3$ is adopted for final modelling. Analysis of the table data reveals that the failure probability remains relatively low during the first year but begins to increase significantly after approximately 18-20 months of service. This trend highlights the importance of implementing proactive tire replacement schedules to minimise the risk of blowouts or loss of traction in the later stages of a tire's operational life. The parameters used in modelling tire tread wear risk on asphalt roads using the Weibull distribution are presented in Table 4.

Table 4. Weibull model parameters for tire tread wear risk assessment on asphalt roads

Parameter	Symbol	Value	Disclosure
Characteristic life	H	26.1 month	Average time for tire tread to wear out completely
Shape parameter	B	2.5	As wear is accelerating, >1 is taken
Location	Γ	0	Failure can occur from the start
MTTF		24 month	Average service life (time to failure)
$\Gamma(1 + 1 / \beta)$		≈0.92	Gamma function

Source: compiled by the author based on assumed data for the case analysis

Since the roads used by the buses in the study in Baku are asphalted, $\beta = 2.5$. η is calculated as follows (Moddares *et al.*, 2016):

$$\eta = \frac{MTTF}{\Gamma/1+\frac{1}{\beta}} = \frac{24}{0.92} \approx 26.1$$

The gamma function is taken from the Table 4 (O'Connor & Kleyner. 2012):

$$\Gamma(1 + 1 / 2.5) \approx 0.89$$
$$\Gamma(1 + 1 / 2) \approx 0.89$$
$$\Gamma(1 + 1 / 1.8) \approx 0.87$$
$$\Gamma(1 + 1 / 1.5) \approx 0.83.$$

Notably, the shape parameter ($\beta = 2.5$) confirms that tire wear accelerates over time, and the characteristic life ($\eta = 26.1$ months) indicates the point at which failure becomes most likely. The model shows that while the mean time to failure (MTTF) is 24 months, the system begins entering a high-risk phase slightly before that threshold. The variation of the risk of not maintaining the distance, modelled using the Weibull distribution, illustrates how this probability evolves over time. As shown in Figure 4, the probability of failure interpreted as the risk of not maintaining a safe following distance increases gradually during the initial operational phase, then accelerates as time progresses. This pattern indicates a wear-out behaviour, typical for systems where $\beta > 1$, confirming that the risk becomes increasingly significant with continued exposure, ageing vehicle components, or driver fatigue accumulated over long driving periods.

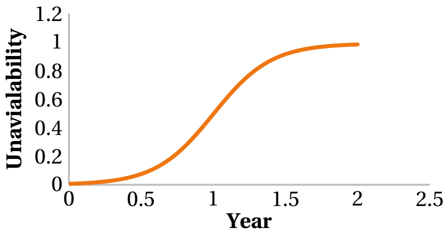


Figure 4. Variation of the risk of not maintaining the distance based on the Weibull model

Source: created by the author based on risk modeling in the FTA software environment

Figure 4 illustrates how the probability of failure due to not maintaining a safe following distance increases over time, as modelled by the Weibull distribution. The curve begins with a gradual slope, indicating lower risk in the early stages, but steepens as time progresses, reflecting the cumulative effect of road wear and driver fatigue. This trend confirms that spacing-related risks exhibit a wear-out pattern, making preventive interventions more critical in the later phases of vehicle or driver service time.

Driver inexperience (Weibull model). It is observed that risks are significantly higher during the initial months of a new driver's career due to factors such as lack of practical experience, unfamiliarity with routes, and limited exposure to real-world traffic conditions. During this early phase, incidents involving traffic violations, slower reaction times, and poor decision-making are more likely to occur, thereby elevating the overall risk level. However, as drivers accumulate experience, they typically demonstrate improved judgment, quicker response, and greater situational awareness, which gradually reduces the probability of errors and accidents. The Weibull distribution was applied to model this phenomenon, as it captures time-dependent variations in failure probability. The parameters used to assess driver inexperience risk are presented in Table 5. Although this type of risk is often associated with a $\beta < 1$ to represent decreasing failure rates, in this case, $\beta = 2.5$ is used to reflect a sharp decline in risk after the first few months of experience (Fig. 5). Figure 5 illustrates the variation in risk associated with driver inexperience over time based on the Weibull model. The curve demonstrates a rapid decline in risk during the first few months, reflecting how the likelihood of errors and unsafe behaviour decreases as drivers gain experience. By around the sixth month, the curve begins to level off, indicating that drivers have acquired essential skills and that further risk reduction becomes marginal.

Table 5. Weibull model parameters for driver inexperience risk assessment

Parameter	Symbol	Value	Disclosure
Characteristic life	η	6 months	Time it takes for a driver to learn the basic rules and gain experience
Shape parameter	β	2.5	Shows that errors decrease as experience increases ($\beta > 1$)
Location	γ	0	Risk starts from the first day of work
Value	-	Month	Analysis is performed with a monthly unit of measurement

Source: compiled by the author based on assumed data for the case analysis

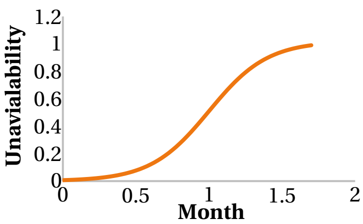


Figure 5. Risk effect of driver inexperience – variation according to the Weibull model

Source: created by the author based on risk modelling in the FTA software environment

Graphics delay (Dormant model). Schedule delays occur when drivers fail to depart or arrive on time according to the planned timetable. In an effort to compensate for lost time, drivers may increase their speed or bypass standard safety procedures, which elevates the risk of accidents. Since this risk typically remains inactive (dormant) during normal operations and only becomes active when a delay occurs, the Dormant model is considered appropriate for its analysis. This model helps to assess the transition from a low-risk to a high-risk state, triggered by schedule disruptions and unsafe compensatory behaviour. The parameters used for modelling this risk are presented in Table 6. The risk becomes active only under certain conditions (such as when a delay occurs) and remains active for a limited time. In such cases, the "dormant" model is ideal for representing the passive nature of the risk before activation and its rapid transition afterward. This model is particularly useful for capturing conditional failures that depend on triggers like inspection intervals, external disruptions, or timing mismatches. It allows for better modelling of latent risks that are not continuously present but can lead to significant disruptions if activated. This factor represents risks that are conditional, time-bound, and event-triggered requiring specialised modelling to reflect their dynamic behaviour (Fig. 6):

Table 6. Dormant model parameters for graphics delay risk assessment

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.05	Daily delay probability (5%)
MTTR	-	10 min	Driver speed recovery time
Inspection interval	τ	1 day	Daily schedule control
Value	-	Hour	Calculations are made hourly

Source: compiled by the author based on assumed data for the case analysis

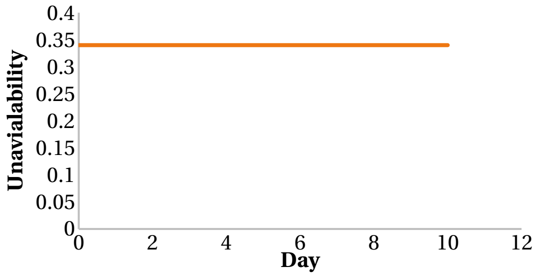


Figure 6. Change in risk due to schedule delay under the Dormant model

Source: created by the author based on risk modelling in the FTA software environment

Figure 6 shows how the risk level changes under the Dormant model when a schedule delay activates a previously passive hazard. Initially, the risk remains low or inactive, reflecting normal operating conditions where the driver adheres to the schedule. However, once a delay occurs, the risk increases sharply, demonstrating how the driver's compensatory behaviour such as speeding or skipping safety checks transforms the situation into a high-risk scenario.

Incitement by other vehicles (Constant model). In some accidents, buses are placed in a dangerous position due to the pressure or unpredictable actions of surrounding vehicles, such as sudden lane changes, tailgating, or aggressive overtaking. These incidents typically occur without prior indication and can happen at any moment during operation, making the Constant model appropriate due to its assumption of a uniform failure probability over time. This model enables the quantification of a persistent, background risk that is posed by external traffic behaviours beyond the bus driver's control. The parameters used to model this type of risk are provided in Table 7 and form the basis for calculating both the frequency and duration of risk exposure.

Table 7. Constant model parameters for risk of provocation by other vehicles

Parameter	Symbol	Value	Disclosure
Failure frequency	*W*	0.005	Provocations per hour
MTTR	-	1 hour	Time to eliminate the threat caused by the provocation
Value	-	Hour	Calculations are made hourly

Source: compiled by the author based on assumed data for the case analysis

The parameters required for modelling the risk of a bus being forced into danger by another vehicle include unavailability (q) and failure frequency (w). Unavailability refers to the probability that the bus is in an unsafe state due to external provocation, while failure frequency indicates how often such events are expected to occur. Failure frequency is calculated by considering how often provocation events occur and how long their effects persist, providing a measure of the system's exposure to repeated external threats. Failure frequency is calculated using the following equation:

$$w = \frac{q}{MTTR} = \frac{0.005}{1} = 0.005\ event/hour.$$

MTTR: 1 hour (average time to eliminate the threat posed by a provocation event).

Daily failure frequency:

$$0.005 \text{ x } 24 = 0.12 \text{ event/day}.$$

$$q = \frac{\lambda \text{ x } MTTR}{1+(\lambda \text{ x } MTTR)} = \frac{0.005 \text{ x } 1}{1+(0.005 \text{ x } 1)} = 0.00498 \approx 0.005.$$

In that case, the graph illustrates how the probability of being hit by another vehicle remains constant over time, assuming a fixed failure rate. This reflects the continuous and random nature of external provocation, where the risk does not increase or decrease with the vehicle's operational duration but instead persists uniformly throughout the entire period. Such a modelling approach is especially relevant for urban traffic environments where unpredictable driver behaviour – such as sudden overtaking or lane changes creates a steady-state background risk that must be considered in safety planning. This scenario is effectively visualised in Figure 7. The Weibull model effectively captures the non-constant nature of risk associated with drunk driving, allowing for a time-dependent failure rate that mirrors real-world conditions. This model is particularly valuable for assessing how the likelihood of incidents escalates during high-risk periods, such as evenings, weekends, or holidays, when alcohol-related behaviours are more prevalent. It also supports the development of targeted safety interventions based on temporal trends, including time-of-day or day-of-week patterns. The parameters used to model this risk are summarised in Table 8.

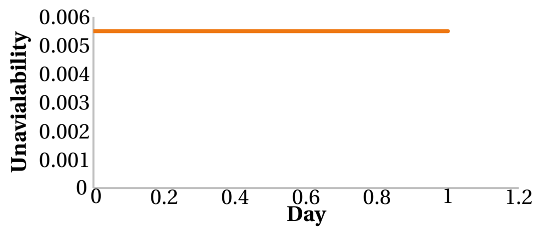


Figure 7. Probability of being hit by another vehicle – variation on the Constant model
Source: created by the author based on risk modelling in the FTA software environment

Table 8. Weibull model parameters for drunk driving risk assessment

Parameter	Symbol	Value	Disclosure
Characteristic life	Η	1 month	Average time for drunk driving incidents to reach dangerous levels
Shape parametric	Β	1.8	Indicates that risk increases over time (evenings and weekends)
Location	Γ	0	Risk starting point – incident can occur at any time
Value	-	Month	Monthly unit of measure

Source: compiled by the author based on assumed data for the case analysis

This expression represents the unavailability function for a repairable system, where λ denotes the failure rate and μ represents the repair (recovery) rate. The function calculates the probability that the system is in a failed state at any given time *t*, incorporating both failure occurrence and recovery over time. The accompanying table provides specific parameter values used to estimate time-dependent risk in systems that undergo random failures followed by maintenance-based recovery. This model is particularly valuable for evaluating technical components in public transportation, where maintenance actions can restore functionality after a breakdown. A similar time-based risk variation is illustrated in Figure 8, which shows how the probability of drunk driving incidents changes over time using the Weibull model.

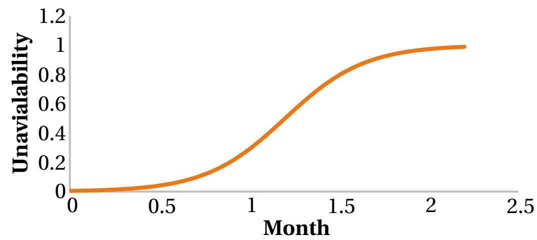


Figure 8. Risk of drunk driving – variation according to the Weibull model
Source: created by the author based on risk modelling in the FTA software environment

Pedestrian disorderly behaviour (Weibull model). This risk factor is another important cause of accidents involving public transport. The erratic behaviour of passengers and pedestrians especially boarding or alighting before the bus fully stops, or crossing the road inattentively frequently leads to accidents. These behaviours are not constant but vary over time and are influenced by behavioural patterns and situational habits. As such, they are best evaluated using the Weibull model, which accommodates time-dependent increases in risk. The parameters used for this modelling are summarised in Table 9, which outlines the characteristic life, shape, and location factors for estimating the risk of pedestrian disorderly behaviour.

Table 9. Weibull model parameters for risk of pedestrian disorderly behaviour

Parameter	Symbol	Value	Disclosure
Characteristic life	η	1 month	Average time for this type of behaviour to reach a dangerous level
Shape parametric	β	1.8	Indicates that the risk increases over time
Location	γ	0	Risk starting point – the event can occur at any time
Value	-	Month	Calculations are made monthly

Source: compiled by the author based on assumed data for the case analysis

Table 9 presents the parameters used in the Weibull model to evaluate the risk associated with disorderly pedestrian behavior, such as boarding or alighting from a bus before it stops and crossing without observing traffic. The characteristic life ($\eta = 1$ month) indicates the average time for such risky behavior to reach a critical threshold. The shape parameter (β = 1.8) shows that the risk increases over time, reflecting the cumulative effect of habitual unsafe actions. The location parameter (γ=0) assumes that the risk can arise at any moment, without an initial delay. The evolution of this risk over time is illustrated in Figure 9, which shows how the probability of accidents grows as unsafe behaviors persist.

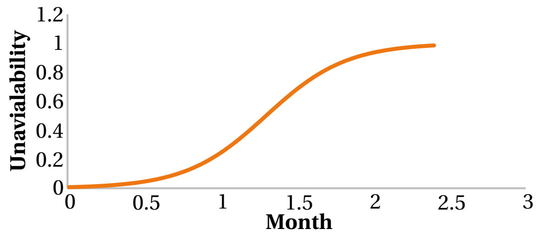


Figure 9. Risk of hop-on/hop-off behaviour without stopping the bus – variation according to the Weibull model
Source: created by the author based on risk modelling in the FTA software environment

The parameters in Table 10 reflect the modelling of behavioural risks that escalate quickly over time, such as aggressive or reckless driving. A shape parameter of β = 2.5 indicates that the risk does not remain constant but grows at an accelerating rate as the behaviour continues unchecked. The characteristic life η = 2 months suggests that, on average, such risky behaviour may reach a critical threshold within a relatively short period if no corrective action is taken. This modelling approach helps quantify how quickly certain behaviours can transition from moderate to high-risk, underscoring the need for early interventions such as monitoring, driver retraining, or enforcement strategies (Fig. 10).

Table 10. Weibull model parameters for rapidly increasing behavioural risks

Parameter	Symbol	Value	Disclosure
Characteristic life	η	2 months	Average time for risky behaviour to reach a dangerous level
Shape parameter	β	2.5	Higher β is assumed because risk increases more rapidly
Location	γ	0	Risk starting point – event can occur at any time
Value	-	Month	Used for monthly analysis

Source: compiled by the author based on assumed data for the case analysis

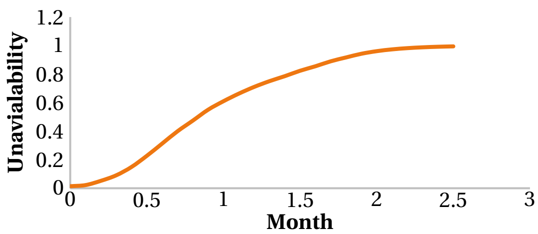


Figure 10. Pedestrian crossing the road without considering vehicles – variation according to the Weibull model
Source: compiled by the author based on assumed data for the case analysis

Figure 10 shows the variation of risk over time associated with pedestrians crossing the road without considering vehicle traffic. The curve, based on the Weibull distribution with a high shape parameter (β = 2.5), reflects a rapidly increasing risk, emphasising that repeated exposure to such behaviour intensifies the likelihood of accidents. This model captures the escalating nature of behavioural risks that emerge quickly and intensify without immediate corrective measures. Pedestrians crossing the road without considering vehicle traffic significantly increases the risk of accidents. This behaviour, especially prevalent during peak hours or in areas with inadequate pedestrian infrastructure, tends to escalate over time due to habitual negligence or lack of enforcement. The fact that this risk increases more rapidly over time makes the Weibull model more appropriate for this case.

Risks associated with technical failures

Technical failures are a significant contributor to accidents in public bus transportation, often resulting from the malfunction of critical components such as brakes, steering, or electrical systems. These failures tend to follow specific wear-out patterns over time, making them suitable for time-dependent risk modelling. The Weibull model is particularly effective in capturing the increasing likelihood of failure as components age or wear. In the following section, each major technical risk is analysed individually using the Weibull model to better understand its behaviour and inform preventive maintenance strategies.

Steering system failure (Weibull model). Steering system failure poses a serious safety hazard because it directly affects the driver's ability to control the vehicle. Over time, wear and tear, inadequate maintenance, or mechanical fatigue can increase the likelihood of such failures. Table 11 presents the Weibull model parameters used to evaluate the risk of steering system failure, highlighting the time-dependent nature of this risk through the shape and characteristic life parameters.

Table 11. Weibull model parameters for steering system failure risk assessment

Parameter	Symbol	Value	Disclosure
Characteristic life	η	3 months	Average time to failure of the steering system
Shape parameter	β	2.2	As the risk of failure increases over time, β > 1 is taken
Location	γ	0	The failure can start at any time
Value	-	Month	Calculations are performed monthly

Source: compiled by the author based on assumed data for the case analysis

Table 11 presents the Weibull model parameters used to assess the risk of steering system failure in buses. The characteristic life η = 3 months indicates that, on average, significant failures in the steering system are expected to emerge within this time frame under regular operating conditions. With a shape parameter β = 2.2, the model reflects a wear-out failure pattern, meaning the likelihood of failure increases as the component ages, reinforcing the need for periodic inspections and timely maintenance.

Figure 11 illustrates how the probability of steering system failure evolves over time according to the Weibull model. As seen in the graph, the failure probability increases progressively, reflecting the mechanical fatigue and degradation common in steering components. This trend emphasises the need for regular inspection and timely maintenance to prevent accidents caused by loss of control. Figure 11 shows the dynamic variation of steering system failure risk modelled using the Weibull distribution in the FTA software environment.

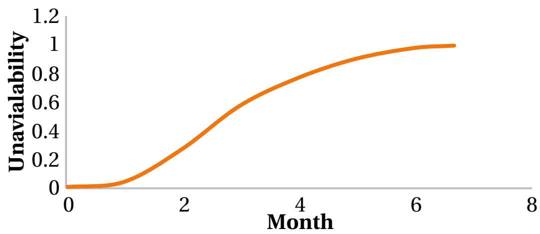


Figure 11. Risk of steering system failure – variation according to the Weibull model
Source: created by the author based on risk modelling in the FTA software environment

Figure 11 illustrates the variation in the risk of steering system failure over time based on the Weibull model. The graph shows a gradual increase in failure probability during the initial months, followed by a sharper rise as the system approaches its characteristic life (3 months). This pattern highlights the importance of proactive maintenance, as the risk becomes significantly higher if the steering system is not serviced within the expected operational period.

Malfunction of lighting and signal systems (Dormant model). Malfunctions in lighting and signalling systems can go unnoticed during normal operation but become critical when these systems are suddenly needed, such as during night driving or adverse weather conditions. These failures may remain undetected for a long time, which increases the danger when they are eventually triggered. Table 12 presents the parameters of the dormant model used to assess the risk associated with potential failures in lighting and signalling systems.

Table 12. Dormant model parameters for risk of lighting and signal system failures

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.0003 hours	Probability of system failure
MTTR	-	0.002 hours	Time required to eliminate the failure
Inspection interval	τ	720 hours	30-day maintenance period
Value	-	Month	Calculations are made monthly

Source: compiled by the author based on assumed data for the case analysis

Lighting and signal systems play a vital role in ensuring visibility and communication between road users, especially in low-visibility conditions. The failure of these systems may not pose an immediate risk but becomes highly critical when activated during specific situations such as night time or foggy weather. The Dormant model captures this behaviour by modelling the risk as passive until triggered, highlighting the importance of regular inspections. Figure 12 illustrates how the risk of lighting and signal system failure evolves over time according to the Dormant model, emphasising the sudden activation of risk under specific conditions. Figure 12 shows the variation in the risk of lighting and signal system failure using the Dormant model. The graph indicates that the risk remains inactive or minimal under normal conditions but rises sharply once the system is activated or needed such as during night driving or in poor visibility. This emphasises the critical importance of regular inspections, as failures in these systems may remain undetected until the moment they are urgently required, posing immediate safety hazards.

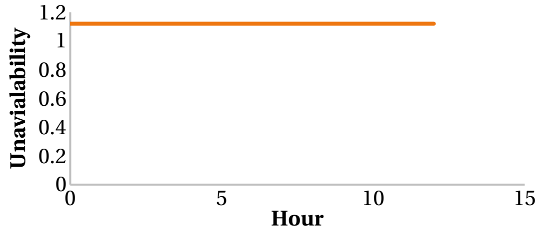


Figure 12. Risk of lighting and signal system failure – variation on the Dormant model

Source: created by the author based on risk modelling in the FTA software environment

Sudden engine stop (Unrepairable model). A sudden engine stop can lead to the complete loss of control over the vehicle, especially in high-density traffic areas, making it one of the most dangerous technical failures in public transport. Since such failures often require total replacement rather than repair, they are best analysed using the Unrepairable model, which assumes that once a failure occurs, the component remains non-functional. Table 13 presents the parameters used in the Unrepairable model for assessing the risk of sudden engine failure, including the failure rate and the unit of time for calculations. Figure 13 illustrates the variation in risk associated with sudden engine stoppage as modelled by the Unrepairable model, which assumes the system remains non-functional after failure.

Table 13. Unrepairable model parameters for sudden engine stop risk assessment

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.0003 hours	Engine failure probability
Value	-	Month	Calculations are made monthly

Source: compiled by the author based on assumed data for the case analysis

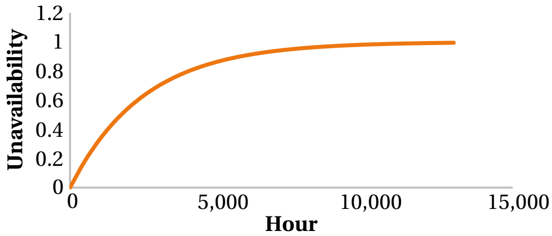


Figure 13. Risk of sudden engine stoppage – variation on the Unrepairable model

Source: created by the author based on risk modelling in the FTA software environment

The graph demonstrates a steady increase in failure probability over time, reflecting the cumulative nature of this critical technical risk. Table 13 presents the parameters used to model the risk of a sudden engine stop using the Unrepairable model. The failure rate $\lambda = 0.0003$/hour indicates a low but persistent probability of engine failure that accumulates over time, and the analysis is conducted on a monthly basis to capture long-term risk trends. Figure 13 shows how the probability of engine failure increases steadily, with no possibility of recovery once the failure occurs characteristic of unrepairable events. This highlights the critical importance of early diagnostics and replacement strategies, as a single engine failure can lead to severe safety consequences, particularly in urban traffic conditions.

Fuel system problem (Repairable model). Fuel system failures, such as pump malfunctions, can temporarily disrupt the engine's operation but are often addressed through standard maintenance procedures. The repairability of this type of failure makes it suitable for modelling with the repairable model, which accounts for both failure and recovery rates. Table 14 outlines the parameters used in the Repairable model for evaluating fuel system failure risk, including the failure rate, repair rate, and calculation timeframe.

Table 14. Repairable model parameters for fuel system failure risk assessment

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.0008 hour	Probability of fuel pump failure
Repair rate	μ	0.003 hour	Probability of recovery to eliminate the malfunction
Value	-	Month	Calculations are made monthly

Source: compiled by the author based on assumed data for the case analysis

As Table 14 demonstrated, a failure rate $\lambda = 0.0008$/hour and a repair rate $\mu = 0.003$/hour. These values suggest that while failures occur at a low frequency, the relatively higher repair rate enables effective restoration of the system, minimising long-term unavailability. Fuel system failures may not lead to immediate accidents, but they significantly compromise vehicle reliability and operational continuity, especially during peak service hours. Timely repair of such failures can mitigate prolonged downtime and reduce service disruption risks in public transport (Fig. 14).

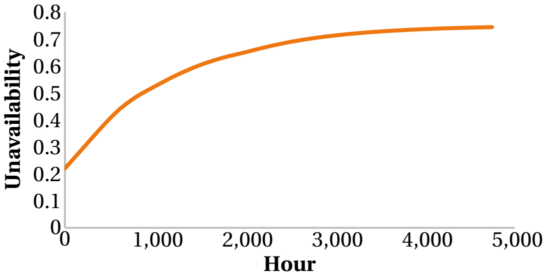


Figure 14. Risk of fuel system failure – variation on the Repairable model

Source: created by the author based on risk modelling in the FTA software environment

Figure 14 shows the change in the risk of fuel system failure over time, modelled using a maintainability model based on both the failure rate and the repair rate. As can be seen, the probability of fuel system failure varies over time, initially increasing but stabilising due to ongoing repair work. This balance between failure and repair reflects the nature of fuel system problems, where timely maintenance can effectively control operational risk and prevent disruptions to business continuity.

Steering system failure (Repairable model). Steering system failures are among the most critical technical malfunctions that directly affect vehicle control and safety. The ability to repair these faults within a reasonable time frame allows for operational risk mitigation and continuity of service. Table 15 presents the key parameters used in modelling the risk of steering system failure under the repairable model, including failure and repair rates.

Table 15. Repairable model parameters for steering system failure risk assessment

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.0005 hours	Probability of steering failure
Repair rate	μ	0.005 hours	Recovery speed
Value	-	Hour	Calculations are made hourly

Source: compiled by the author based on assumed data for the case analysis

Table 15 provides the failure and repair rates used to model steering system failure under the repairable model, with a failure rate $\lambda = 0.0005$/hour and a repair rate $\mu = 0.005$/hour. The significantly higher repair rate suggests that, despite the critical nature of such failures, they can be addressed quickly, reducing long-term system unavailability and improving operational safety. Figure 15 illustrates the variation in the probability of steering system failure over time, based on the repairable model. This model assumes that although steering system failures occur, they can be mitigated through timely repairs.

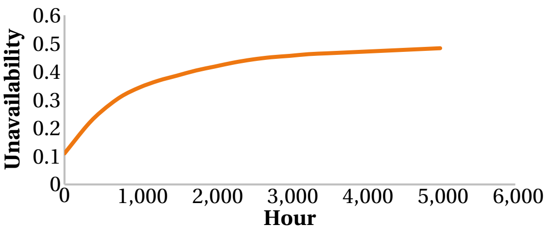


Figure 15. Risk of steering system failure – variation on the Repairable model

Source: created by the author based on risk modelling in the FTA software environment

Figure 15 shows the modelled risk trajectory of steering system failure using repairable parameters in the FTA software environment. The risk of steering system failure initially grows but gradually stabilises as the repair process becomes effective over time. This trend emphasises the importance of routine maintenance and rapid response protocols, which help contain failure risks and maintain control system integrity in public transport vehicles.

Gearbox failure (Repairable model). Gearbox failure can lead to a complete breakdown in vehicle operation, especially in heavy urban traffic conditions where frequent gear shifts are required. Timely repairs are usually feasible for this type of failure, making the Repairable model a suitable approach for risk evaluation. Table 16 presents the parameters used for modelling the risk of gearbox failure, including the failure rate and the rate of repair, both assessed on an hourly basis and Figure 16 illustrates how the probability of gearbox failure changes over time using the Repairable model. As shown in the figure, the failure probability initially increases but then stabilises due to the system's ability to be repaired after malfunction. This model highlights the importance of regular maintenance and timely interventions in minimising long-term risks. It shows the variation of gearbox failure risk over time, modelled using Repairable system parameters. This pattern highlights how effective maintenance strategies can significantly limit the long-term risk associated with mechanical component failures.

Table 16. Repairable model parameters for gearbox failure risk assessment

Parameter	Symbol	Value	Disclosure
Failure rate	λ	0.0006 hour	Probability of gearbox failure
Repair rate	μ	0.004 hour	Probability of recovery to eliminate the fault
Value	-	Hour	Calculations are made hourly

Source: compiled by the author based on assumed data for the case analysis

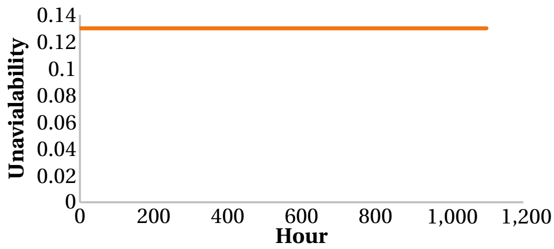


Figure 16. Risk of gearbox failure – variation on the Repairable model
Source: created by the author based on risk modelling in the FTA software environment

Table 17 presents the Minimal Cut Sets for traffic accidents identified through FTA. Each cut set represents a unique combination of basic events that can lead to the top event (a road traffic accident). The "Unreliability" column indicates the probability that a specific minimal cut set causes a system failure, while the "Importance" column shows the relative contribution of each cut set to the overall system failure. The first few cut sets (e.g., rows 1 to 4) have significantly higher importance values. indicating that they are critical contributors to the overall accident risk. In contrast, the remaining cut sets, although numerous, have negligible individual contributions, reflecting a long tail of low-probability failure paths. This analysis helps to prioritise which combinations of faults need the most attention to improve system reliability and reduce accident risk.

Table 17. Risk analysis of road traffic accidents by Minimal Cut Sets

No	Minimal Cut Set	Unreliability	Importance
1	Event2.Event3.Event4.Event8.Event11.P	1.40729E-27	0.394
2	Event2.Event3.Event4.Event8.12.P	8.6884E-28	0.243
3	Event2.Event3.Event4.Event8.P	6.72518E-28	0.184
4	Event2.Event3.Event4.Event8.10.P	6.04234E-28	0.169
5	Event2.Event3.Event4.Event8	5.34502E-28	0.0015
6	Event2.Event3.Event4.Event7.Event8	4.49273E-30	0.00013
7	Event2.Event3.Event4.Event7.Event8.12.P	2.77374E-30	0.00078
8	Event2.Event3.Event4.Event6.Event7.Event8	2.14699E-30	0.00060
9	Event2.Event3.Event4.Event8.7.Event8	1.929E-30	0.00054
10	Event2.Event3.Event4.Event6.Event7	1.70638E-32	0.0000048
11	Event2.Event3.Event4.Event5.Event8	1.14729E-32	0.00000032
12	Event1.Event2.Event3.Event4.Event8	7.08322E-34	0.00000020
13	Event1.Event2.Event3.Event4.Event6.Event8	5.4872E-34	0.00000015
14	Event1.Event2.Event3.Event4.Event5.Event8	4.92602E-34	0.00000014
15	Event2.Event3.Event4.Event6.Event8	3.08455E-34	0.000000086
16	Event2.Event3.Event4.Event7.Event8.11.P	2.18985E-34	0.000000061
17	Event1.Event2.Event3.Event4.Event7.Event8	1.53198E-34	0.000000039
18	Event3.Event4.Event7.Event8.12.P	1.04649E-34	0.000000029
19	Event3.Event4.Event6.Event7.Event8	9.40233E-35	0.000000026
20	Event3.Event4.Event7.Event8.11.P	5.94325E-35	0.000000017
21	Event1.Event2.Event3.Event4.Event5.Event7.Event8	4.35753E-36	0.0000000012
22	Event3.Event4.Event8.Event12.P	3.66927E-36	0.000000001
23	Event3.Event4.Event8.Event7.Event8.11.P	3.66269E-36	0.0000000010
24	Event3.Event4.Event6.Event8.Event8.12.P	2.84016E-36	7.96E-10
25	Event2.Event3.Event4.Event8.Event8.10.P	2.55179E-36	7.15E-10
26	Event2.Event3.Event4.Event8.Event8.9.P	2.26129E-36	6.33E-10
27	Event2.Event3.Event4.Event8.Event8.12.P	1.75033E-36	4.90E-10
28	Event2.Event3.Event4.Event7.Event8.12.P	1.57261E-36	4.40E-10
29	Event3.Event4.Event8.Event7.Event8.11.P	9.84732E-37	2.76E-10
30	Event3.Event4.Event8.Event10.P	8.31725E-37	2.33E-10
31	Event3.Event4.Event7.Event8.11.P	6.89172E-37	1.96E-10
32	Event2.Event3.Event4.Event7.Event8.Event8	4.31615E-37	1.21E-10
33	Event1.Event2.Event3.Event4.Event7.Event8.8.P	3.34088E-37	9.36E-11
34	Event3.Event4.Event8.Event7.Event8.12.P	3.00166E-37	8.41E-11
35	Event3.Event4.Event7.Event8.11.P	2.25732E-37	6.32E-11
36	Event3.Event4.Event8.Event7.Event8.Event8	1.89736E-38	5.31E-12
37	Event1.Event2.Event3.Event4.Event7.Event8.10.P	1.39138E-38	3.89E-12

Table 17. Continued

No	Minimal Cut Set	Unreliability	Importance
38	Event1.Event2.Event3.Event4.Event7.Event8.12.P	1.1714E-38	3.28E-12
39	Event3.Event4.Event6.Event7.Event8.Event8	9.06712E-39	2.54E-12
40	Event3.Event4.Event7.Event8.Event8.Event8	8.1465E-39	2.28E-12
41	Event3.Event4.Event8.Event10.P	2.65525E-39	7.44E-13
42	Event2.Event3.Event4.Event8.10.P	2.51468E-40	7.04E-14
43	Event1.Event2.Event3.Event4.Event8.Event8	1.78527E-40	5.00E-14
44	Event3.Event4.Event8.Event8.11.P	1.1022E-40	3.09E-14
45	Event2.Event3.Event4.Event8.Event8.12.P	8.53148E-41	2.39E-14
46	Event2.Event3.Event4.Event7.Event8.10.P	7.66524E-41	2.15E-14
47	Event1.Event2.Event3.Event4.Event8.Event8.9.P	7.26035E-41	2.02E-14
48	Event2.Event3.Event4.Event8.Event8.9.P	4.79978E-41	1.34E-14
49	Event3.Event4.Event8.Event10.P	4.84522E-42	1.36E-15
50	Event3.Event4.Event8.Event8.10.P	2.99137E-42	8.38E-16
51	Event3.Event4.Event7.Event8.9.P	2.31544E-42	6.49E-16
52	Event3.Event4.Event7.Event8.8.P	2.08034E-42	5.83E-16
53	Event3.Event4.Event8.Event7.Event8.12.P	1.30266E-42	3.65E-16
54	Event3.Event4.Event8.Event7.Event8.11.P	9.24811E-43	2.59E-16
55	Event3.Event4.Event7.Event8.10.P	8.02802E-43	2.25E-16
56	Event3.Event4.Event8.Event9.P	6.78036E-43	1.90E-16
57	Event2.Event3.Event4.Event8.Event8.8.P	5.70965E-43	1.60E-16
58	Event2.Event3.Event4.Event7.Event8.9.P	5.69942E-43	1.60E-16
59	Event3.Event4.Event8.Event10.P	4.35753E-43	1.22E-16
60	Event3.Event4.Event8.Event8.10.P	3.66927E-43	1.03E-16
61	Event3.Event4.Event7.Event8.11.P	3.66269E-43	1.03E-16
62	Event2.Event3.Event4.Event8.Event8.10.P	2.84016E-43	7.96E-17
63	Event2.Event3.Event4.Event8.Event8.9.P	2.55179E-43	7.15E-17
64	Event2.Event3.Event4.Event8.Event8.12.P	2.26129E-43	6.33E-17
65	Event2.Event3.Event4.Event7.Event8.12.P	1.75033E-43	4.90E-17
66	Event3.Event4.Event8.Event7.Event8.11.P	1.57261E-43	4.40E-17
67	Event3.Event4.Event8.Event10.P	9.84732E-44	2.76E-17
68	Event3.Event4.Event7.Event8.11.P	8.31725E-44	2.33E-17
69	Event2.Event3.Event4.Event7.Event8.Event8	6.89172E-44	1.96E-17
70	Event1.Event2.Event3.Event4.Event7.Event8.8.P	4.31615E-44	1.21E-17
71	Event3.Event4.Event8.Event7.Event8.12.P	3.34088E-44	9.36E-18
72	Event3.Event4.Event7.Event8.11.P	3.00166E-44	8.41E-18
73	Event3.Event4.Event8.Event7.Event8.Event8	2.25732E-44	6.32E-18
74	Event1.Event2.Event3.Event4.Event7.Event8.10.P	1.89736E-45	5.31E-19
75	Event1.Event2.Event3.Event4.Event7.Event8.12.P	1.39138E-45	3.89E-19
76	Event3.Event4.Event6.Event7.Event8.Event8	1.1714E-45	3.28E-19
77	Event3.Event4.Event7.Event8.Event8.Event8	9.06712E-46	2.54E-19
78	Event3.Event4.Event7.Event8.8.P	8.1465E-46	2.28E-19
79	Event3.Event4.Event8.Event7.Event8.12.P	2.65525E-46	7.44E-20
80	Event3.Event4.Event8.Event7.Event8.11.P	2.51468E-47	7.04E-21
81	Event3.Event4.Event6.Event7.Event8.Event8	1.78527E-47	5.00E-21
82	Event3.Event4.Event8.Event8.11.P	1.1022E-47	3.09E-21
83	Event2.Event3.Event4.Event8.Event8.12.P	8.53148E-48	2.39E-21
84	Event2.Event3.Event4.Event7.Event8.10.P	7.66524E-48	2.15E-21
85	Event1.Event2.Event3.Event4.Event8.Event8.9.P	7.26035E-48	2.02E-21
86	Event2.Event3.Event4.Event8.Event8.9.P	4.79978E-48	1.34E-21
87	Event3.Event4.Event8.Event10.P	4.84522E-49	1.36E-22
88	Event3.Event4.Event8.Event8.10.P	2.99137E-49	8.38E-23
89	Event3.Event4.Event7.Event8.9.P	2.31544E-49	6.49E-23
90	Event3.Event4.Event7.Event8.8.P	2.08034E-49	5.83E-23
91	Event3.Event4.Event8.Event7.Event8.12.P	1.30266E-49	3.65E-23
92	Event3.Event4.Event8.Event7.Event8.11.P	9.24811E-50	2.59E-23
93	Event3.Event4.Event7.Event8.10.P	8.02802E-50	2.25E-23
94	Event3.Event4.Event8.Event9.P	6.78036E-50	1.90E-23
95	Event3.Event4.Event8.Event8.8.P	5.70965E-50	1.60E-23

Source: compiled by the author based on assumed data for the case analysis

One of the key outcomes of the FTA conducted in this study is the identification of Minimal Cut Sets (MCS) – the smallest combinations of basic events that, if they occur simultaneously, inevitably lead to the Top Event, i.e., a road traffic accident involving a public bus. Each minimal cut set represents a unique combination of technical, human, and environmental factors, and provides valuable insight into the most critical risk pathways within the system. For example, the first minimal cut set (Event2.Event3.Event4. Event8.Event11.P) includes the following high-risk events:

- Event2 – steering system failure;
- Event3 – brake system failure;
- Event4 – driver error;
- Event8 – heavy traffic conditions;
- Event11 – provocation by other vehicles.

Although the combined probability of occurrence for this set is very low (1.40729E-27), the importance factor (0.394) signifies that this combination makes a significant contribution to overall system risk. In total, Table 17 presents 95 such minimal cut sets, each quantifying the contribution of different combinations of failures and unsafe behaviours to the top event. This analysis forms the foundation for prioritising safety interventions by ranking which combinations of risk factors require immediate attention.

These findings align with similar applications in international research. For instance, A.A. Baig *et al.* (2020) conducted an FTA study on urban bus safety in Delhi and identified driver error and brake system failures as primary causes of accidents. The present study confirmed this through the high-priority cut sets that combine steering and braking failures with human error. The convergence of findings underscores the synergistic effect of technical and behavioural failures on urban transport safety.

Furthermore, the application of the Weibull model to represent time-dependent risks, such as mechanical degradation and behavioural shifts, is supported by studies such as L. Chen & Y. Wang (2021). Their research in China confirmed that technical components like gearboxes and steering systems exhibit increasing failure probabilities over time, particularly when operating under intensive service conditions. The use of $\beta > 1$ in current study, consistent with their findings, reflects the accelerating nature of wear-related risks in urban public transport systems.

In contrast, R. Joomjee *et al.* (2024) applied the constant model to assess the impact of unpredictable external risks – such as road congestion and aggressive behaviour by surrounding vehicles in highway scenarios. A similar approach was adopted in this study to model provocation by other vehicles, particularly in dense urban traffic in Baku, where such threats are stochastic and environment-driven, validating the robustness of the constant model structure for external, uncontrollable variables.

From a behavioural risk standpoint, risks such as lighting or signal system failure or improper passenger boarding were analysed using the Dormant model, which remains inactive until triggered by specific conditions. This modelling strategy is consistent with the work of M. Li *et al.* (2022), who used a similar approach to evaluate latent risks in tram systems. Their study affirmed the importance of dormant risks, which, although infrequent, have severe consequences when activated-especially in unpredictable urban traffic scenarios.

The concept and application of Minimal Cut Sets, as utilised in this study, are rooted in the foundational methodology developed by W.E. Vesely *et al.* (1981) for aerospace safety. The current adaptation of this method to public transport risk management allows for quantitative prioritisation of risk pathways, guiding resource allocation and intervention strategies more effectively. This approach also complements advanced reliability modelling by integrating technical failures with human and contextual factors within a comprehensive fault-tree framework.

Moreover, the classification of failures into repairable and unrepairable categories, following the rationale K. Kaur (2023), helps to improve maintenance planning. In this case, components like the fuel system and gearbox were modelled as repairable, allowing for service restoration through timely intervention, while engine failure was modelled as unrepairable, where full replacement was more realistic. This differentiation supports a cost-effective maintenance strategy, avoiding overinvestment in systems where repair is not viable. The integration of time-loss and reliability concerns into fault-tree modelling reflects insights from V. Dixit *et al.* (2019), who studied the perception of travel time risk. In this study, these disruptions – whether from technical failures or driver-related issues – feed into broader system inefficiencies, such as delays, increased congestion, and reduced public trust in transportation services. By embedding these concepts into the FTA framework, a holistic understanding of both accident causality and operational risk is achieved.

Several recent studies have examined the strengths and limitations of classical Fault Tree Analysis and its alternatives in safety-critical systems. For instance, N. Khakzad *et al.* (2011) conducted a comparative analysis of FTA and Bayesian Networks (BNs) within the context of process safety. Their findings underscore that while FTA relies on a static, deductive structure, and assumes event independence, it lacks the capability to model uncertainty, temporal progression, and complex interdependencies. In contrast, BN offers greater modelling flexibility, incorporating conditional relationships, expert judgments, and probabilistic updates. Although their study demonstrates a transition mechanism from FTA to BN and applies both methods to an accident scenario, it does not consider applications in public transportation systems, particularly in bus operations. Critical factors such as route structure, driver and passenger behaviour, environmental dynamics, and cost-risk implications are omitted, indicating a gap in contextual adaptation of these methods to urban transit safety.

In a related contribution, W. Wang *et al.* (2010) proposed the Incident Tree Analysis (ITA) approach, which extends FTA by introducing temporal event evolution and tracking the flow of information during incident development.

This dynamic structure provides a more comprehensive view of accident progression, particularly in complex systems with feedback loops. While ITA introduces a valuable framework for modelling real-world accident sequences, the study lacks specificity to public transport systems such as buses or metros and does not incorporate weather conditions, infrastructure characteristics, or socio-economic consequences, all of which are highly relevant to urban mobility planning.

Similarly, O. Derse & E. Göçmen (2019) explored the integration of FTA with mathematical optimisation methods to support risk-informed transport mode selection. Their model successfully incorporates uncertainty and user discomfort into the decision-making framework, positioning FTA as a strategic planning tool. However, the study remains largely theoretical and scenario-based, without calibration using real-world data. More importantly, it fails to engage with urban bus systems, dynamic passenger flow patterns, or context-specific environmental risk indicators. In contrast, the present study applies FTA directly to urban bus networks in Baku, integrating technical (e.g., gearbox, steering), behavioural (e.g., fatigue, distraction), and environmental (e.g. road congestion. weather conditions) risk factors. It further utilises actual incident data and FTA software (Top Event) to derive minimal cut sets and assign priority to critical event combinations, thereby transforming conceptual models into operationally relevant safety assessments.

Beyond identifying methodological gaps, this study also aimed to propose actionable measures for enhancing safety in public transport systems. Based on the modelling outputs and comparative analyses, several policy and operational recommendations can be made here. Driver-focused safety programmes should include fatigue detection systems, cognitive-behavioural training, and targeted monitoring during the first six months of employment, where risk is highest. Predictive maintenance schedules should be developed based on failure probability modelling (e.g., Weibull analysis), particularly for components with accelerating wear-out behaviour such as gearboxes, fuel systems, and steering mechanisms. Advanced monitoring systems (e.g., telematics, GPS-based diagnostics, lane departure warnings) should be deployed to capture real-time risk signals related to technical failures or aggressive surrounding vehicle behaviour. Integrated data platforms should be established to link operational, behavioural, and environmental data for system-wide risk surveillance and dynamic decision-making. Institutional capacity-building is required to embed fault-tree logic and quantitative risk modelling into transport safety audits, ensuring that risk prioritisation guides both investments and daily operations.

Conclusions

The purpose of this study was to evaluate key risk factors in public bus transportation systems by applying Fault Tree Analysis in combination with various reliability models. The main objective was to assess the failure probability of different technical and behavioural factors under varying traffic and operational conditions, and to determine their criticality in road traffic accidents. The results of the analysis confirmed that the selected methodological approach effectively identified and quantified significant risk contributors, thus achieving the primary research goal.

The research began with the classification of risk sources into three broad categories: technical failures (e.g., steering, braking, engine), behavioural errors (e.g., pedestrian misbehaviour, driver faults), and environmental triggers (e.g., traffic density, influence of other vehicles). Each risk was analysed using a reliability model appropriate to its failure nature – such as the Weibull model for time-dependent failures and the Constant or Dormant models for continuous or passive risks. Quantitative parameters like failure rate (λ), repair rate (μ), characteristic life (η), and shape factor (β) were used to simulate system behaviour over time. Based on these parameters, risk curves, and probability distributions were generated for each scenario. Additionally, the study employed a Minimal Cut Set analysis to rank the most critical event combinations that could lead to accidents.

The findings underscored that driver error and pedestrian behaviour were among the most significant contributors to bus-related accidents, particularly when combined with mechanical failures under high-traffic conditions. The combination of FTA and reliability modelling not only allowed for detailed risk decomposition but also helped to trace the pathway of accident causation in a structured and quantifiable manner. The analysis also demonstrated that some failures, despite having low probability, pose high criticality due to their involvement in key failure pathways.

Overall, the integration of probabilistic models into FTA-based transport safety assessments contributes to a more comprehensive understanding of urban mobility risks. These results provide a robust foundation for developing predictive models and proactive safety interventions tailored to public transportation systems. The findings of this research may serve as a foundation for improving transport safety strategies and can be applied to reduce accident rates and enhance urban mobility resilience in similar metropolitan settings. Future research should explore the integration of real-time telematics and machine learning algorithms to dynamically update fault trees based on actual vehicle performance and behavioural data. Additionally, socio-demographic and route-specific variations in risk exposure require further empirical investigation to tailor safety measures with greater precision.

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Conflict of Interest

None.

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Оцінка ризиків для громадського транспорту за допомогою аналізу дерева відмов (приклад міста Баку)

Ельмаддін Салаєв
Аспірант
Азербайджанський технічний університет
AZ1073, пр-т Гусейна Джавіда, 25, м. Баку, Азербайджан
https://orcid.org/0009-0000-4315-3590

Анотація. Безпека дорожнього руху стає дедалі важливішим питанням у міських транспортних системах, особливо в країнах, що розвиваються, таких як Азербайджан, де дорожньо-транспортні пригоди продовжують бути основним джерелом травм та пошкодження майна. Це дослідження мало на меті оцінити ризики, пов'язані з мережею громадського транспорту Баку, за допомогою аналізу дерева відмов у рамках матриці Хаддона, яка розподіляє фактори, що сприяють цьому, на три категорії: транспортні засоби, люди та дорожнє середовище. Підхід аналізу дерева відмов сприяв систематичному, дедуктивному дослідженню потенційних причин відмов, які можуть призвести до аварій за участю громадського транспорту. Результати дослідження показали, що проблеми, пов'язані з транспортними засобами, серед них несправність гальмівних систем, проблеми з кермовим керуванням та неналежне технічне обслуговування, значно збільшують ймовірність виникнення аварій. Ризики, спричинені людиною, такі як поведінка водія (наприклад, перевищення швидкості та ненадання належної дорожньої допомоги), недотримання правил дорожнього руху та непередбачувані дії пішоходів, також значною мірою сприяють цій проблемі. Крім того, стан доріг, погана інфраструктура, відсутність належних знаків, недостатнє освітлення та небезпечна конструкція автобусних зупинок, ще більше підвищують ризик. Взаємодія цих факторів вказує на те, що аварії на громадському транспорті в Баку є багатогранними та часто їм можна запобігти. Це дослідження підтвердило необхідність систематичного оцінювання стану безпеки, проведення планових оглядів транспортних засобів та покращення ініціатив з підвищення обізнаності громадськості для зменшення ризиків дорожніх аварій, пов'язаних з міським транспортом. Результати цього дослідження висвітлили найсерйозніші зони ризику, що може надати керівникам міського транспорту сприяння при розробці більш ефективних стратегій для підвищення безпеки в транспортній системі Баку

Ключові слова: міські дорожньо-транспортні пригоди; транспортний засіб, аналіз ризиків; безпека дорожнього руху; ризики експлуатації автобусів

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Assessment of the impact of train visibility distance for pedestrians on the accident rate coefficient at railway pedestrian crossings

Vitaliy Kovalchuk
Professor
Lviv Polytechnic National University
79013, 12 S. Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0003-4350-1756

Yulia Lesiv*
Assistant
Lviv Polytechnic National University
79013, 12 S. Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0003-2732-100X

Abstract. The paper presents an improved method for the quantitative assessment of pedestrian safety at railway pedestrian crossings. The method was based on the calculation of partial accident rate coefficients that take into account pedestrian and train traffic intensity, train visibility distance, the level of technical and informational equipment of the crossing, as well as the geometric and planning parameters of the pedestrian crossing. Multi-variant modelling of changes in the resulting accident rate coefficient depending on the pedestrian train visibility distance and the simultaneous consideration of pedestrian and train traffic intensity was carried out. It has been established that at a pedestrian flow intensity of 100 persons/hour and a train traffic intensity of 30 trains/day, the minimum required visibility distance at railway pedestrian crossings located within an existing level crossing without a pedestrian train warning information system is 635 m, whereas when such a crossing is equipped with an information warning system, the required visibility distance is reduced to 435 m. For railway pedestrian crossings located outside existing level crossings, the minimum required train visibility distance should be 530 m. It has been determined that the implementation of a pedestrian train warning information system makes it possible to reduce the accident rate coefficient by up to 30% within existing level crossings and by 20% outside them. The obtained results can be used in the design and modernisation of railway pedestrian crossings across railway tracks

Keywords: safety assessment; risk perception; warning systems; infrastructure; hazardous situations

Introduction

The necessity of enhancing pedestrian safety when crossing railway tracks and improving approaches to assessing safety levels at pedestrian railway crossings represents a crucial step in reducing the number of accidents and ensuring reliable protection for citizens. Studies of pedestrian behaviour at railway level crossings show that the ability to detect an approaching train in a timely manner is a decisive factor in safely deciding whether to cross or refrain from crossing the tracks. Field observations reported by B.J. Russo *et al.* (2021) indicated that violations by pedestrians and cyclists are largely associated with risk perception shaped by train visibility and the condition of warning signalling. Under limited visibility conditions, even at equipped crossings, the likelihood of risky behaviour increases. The level crossing safety impact assessment approach by S. Turner *et al.* (2021) considered approach geometry and visibility conditions as fundamental parameters for risk assessment for all users, including pedestrians. The authors emphasised that visibility within level crossings is often better due to regulated sight zones, whereas outside crossings, pedestrian routes across tracks are formed without compliance with minimum visibility requirements. A generalised analysis by the European Road Safety Observatory (2021) confirmed that visibility restrictions caused by vegetation, landscaping elements, or engineering structures are among the key risk factors at railway level crossings. Informal crossings outside designated level crossings are characterised by significantly poorer sight conditions compared to regulated crossing areas. Z. Guo *et al.* (2022) demonstrated that in "train-pedestrian" interaction, track curvature, gradients, and longitudinal profile significantly reduce the available visibility range. Such conditions are typical for areas

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*Corresponding author (*yuliia.z.lesiv@lpnu.ua*)

outside formal level crossings, where there are no requirements for the geometry of pedestrian approaches, increasing the likelihood of hazardous situations (Zawodny, 2023). V. Singhal *et al.* (2021) identified the main factors affecting safe visibility on approaches to railway tracks: road width, approach sight conditions, speed, gradient, pavement condition, and other geometric parameters. The authors demonstrate that the geometry of approaches significantly influences whether a user can detect an approaching train or other hazard in time. Improved visibility and a more favourable approach profile provide additional reaction time and reduce the risk of erroneous decisions. A separate part of the study presents a "road-to-track" model that accounts for train speed, track gauge width, and the crossing angle. This allows calculation of the minimum open sight distance required for timely detection of a train. Modelling results indicate that the recommended safe stopping distance is approximately 23% greater than that provided by traditional approaches. Although the study concerns vehicles, its principles are readily applicable to pedestrians, who similarly require sufficient visibility for decision-making. The findings can be used to determine minimum sight triangles at pedestrian crossings and to assess reaction time.

Particular attention is given to the fact that pedestrians have a lower eye level, and their ability to detect a train strongly depends on minor infrastructure elements such as fences, poles, landscaping, and track curvature. This approach not only allows assessment of how well a train is visible but also enables identification of specific obstacles that should be removed to enhance safety. Thus, three-dimensional scanning methods represent a useful tool for prioritising engineering solutions. A.J. Khattak *et al.* (2024) emphasised that non-motorised users, particularly pedestrians, are the most vulnerable at railway level crossings due to visibility limitations and the absence of specialised solutions outside formal crossing areas. The regulatory authority, the Office of the National Rail Safety Regulator, applied the ONRSR code of practice (2024), which directly establishes visibility requirements at level crossings and emphasised the need to maintain unobstructed sight zones. Although oriented toward all user categories, its provisions are also relevant for pedestrians, especially in the context of assessing minimum visible distance. The issue of visibility under low-light conditions is addressed in study by N.A.T. Nguyen *et al.* (2025), which demonstrated that night-time significantly increases risk at passive crossings. Proposed solutions for improving visual orientation are particularly relevant for areas outside equipped crossings. M.B. Kurhan *et al.* (2024) analysed technical and organisational solutions for modernising railway crossings in areas of 1,435 mm gauge track construction in Ukraine. Although the primary focus is on road-rail crossings, the authors emphasised that changes in approach profiles, object placement, and site micro-geometry directly affect train visibility for users. This makes the study relevant for pedestrian crossings as well, since similar factors influence risk perception. M.B. Kurhan *et al.* (2024) demonstrated a systematic approach in which infrastructure geometry is considered one of the key safety factors. The mathematical model of the final accident rate coefficient applied by the authors allows assessment of how changes in geometric characteristics affect risk levels. This may be useful for substantiating an updated methodology for assessing accident rates at pedestrian crossings. From a practical perspective, the study highlights that improving visibility – through site clearing, slope adjustment, and relocation of objects – is an integral part of crossing reconstruction, consistent with international experience.

In summary, contemporary scientific studies confirm that train visibility conditions for pedestrians differ significantly within railway level crossings and outside them, and that reduced visibility is directly associated with increased accident risk. This substantiates the need for quantitative visibility assessment and the implementation of additional pedestrian warning information systems, particularly on pedestrian routes crossing railway tracks outside formal level crossings. The purpose of this study was to quantitatively assess the impact of train visibility conditions on the accident rate of pedestrians crossing railway tracks by determining the accident rate coefficient within railway level crossings, outside them, and under the application of a pedestrian warning information system. To achieve this purpose, the following research objectives were set:

- to present a methodology for assessing the accident rate coefficient at railway pedestrian crossings (RPCs);
- to perform multi-variant calculations of the accident rate coefficient at RPCs, taking into account train and pedestrian traffic intensity as well as train visibility distance;
- to determine the threshold and rational train visibility distances from the railway pedestrian crossing at which an acceptable level of pedestrian safety is ensured.

The implementation of these objectives made it possible to develop a scientifically substantiated approach to determining the impact of train visibility conditions on pedestrian accident rates at RPCs, as well as to justify the feasibility of applying a pedestrian warning information system as an effective tool for reducing accident risk and preventing transport incidents.

Materials and Methods

Pedestrian safety factors at RPCs were represented as partial accident rate coefficients and integrated using the final accident rate coefficient (K_r) method to determine overall risk levels and classify crossing conditions. The study was conducted using mathematical modelling of pedestrian-rolling stock interaction at RPCs. The calculations were performed based on a simulation-analytical model for determining the accident rate coefficient, taking into account train traffic intensity, train speed, and visibility conditions. The computations were conducted using the licensed software package MATLAB 2025a, which made it possible to implement a step-by-step calculation of the accident rate coefficient and to determine the permissible visibility values required to ensure traffic safety. The study employed a classification-based approach to assessing safety levels, based on the interpretation of the values of the final accident rate coefficient. The classification of railway pedestrian crossing safety levels depending on the value of the final accident rate coefficient K_p is applied. Based on established threshold values, a safety scale is formed: $K_p < 40$ – safe crossing; 40-60 – low safety level; 61-80 – hazardous; $K_p > 80$ – very hazardous. Thus, the criterion $K_p < 40$ is adopted as the condition for ensuring an acceptable level of pedestrian safety at RPCs. According to the improved method for assessing pedestrian traffic safety indicators at RPCs J. Lesiv & V. Kovalchuk, (2025), the final accident rate coefficient K_p is determined by multiplying eight partial accident rate coefficients:

$$K_p = \prod_{i=1}^{n} K_i = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot K_7 \cdot K_8. \quad (1)$$

The explanation of the content of the partial coefficients is provided in Table 1.

Table 1. Partial coefficients K_1-K_8

Coefficient	Description of the coefficient
K_1	Accounts for the daily train traffic intensity through the RPC
K_2	Accounts for the hourly pedestrian traffic intensity
K_3	Accounts for the train visibility distance from the crossing
K_4	Accounts for the crossing equipment (pedestrian warning information system, traffic signals, barrier gates)
K_5	Accounts for the presence of artificial lighting at the crossing
K_6	Accounts for the horizontal curve radius of the railway track approaching the crossing
K_7	Accounts for the longitudinal gradient of the approaches to the crossing
K_8	Accounts for the age and physiological characteristics of pedestrians (walking speed)

Source: developed by the authors based on State Road Service of Ukraine (2008), J. Lesiv & V. Kovalchuk (2025)

Specifically, the coefficients used in the subsequent study are determined depending on train traffic intensity, pedestrian flow intensity, geometric and planning characteristics of the crossing, as well as its information support. One of the key coefficients is coefficient K_3, which accounts for the visibility distance from the crossing to the train. Coefficient K_3 describes the effect of the train visibility distance for pedestrians and is determined depending on the value of L_v (Fig. 1).

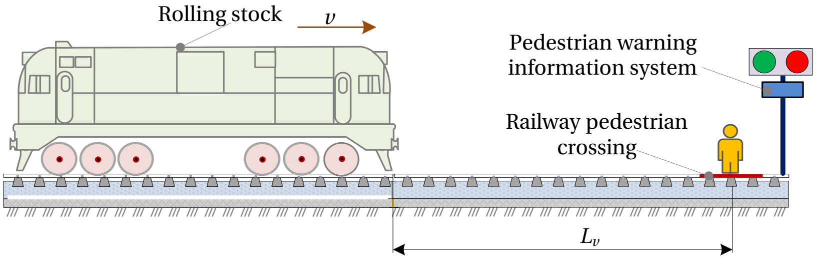


Figure 1. Diagram for determining the visibility distance from the crossing to the train L_v
Source: developed by the authors based on State Road Service of Ukraine (2008), J. Lesiv & V. Kovalchuk (2025)

At low visibility distances, the hazard level increases significantly, which is confirmed by the nonlinear graphical relationship (Fig. 2).

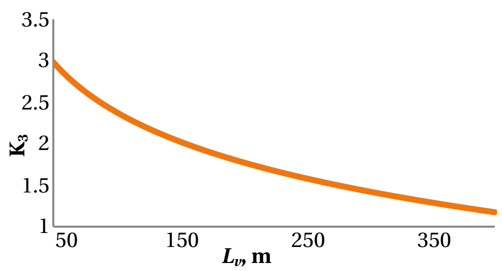


Figure 2. Graphical relationship between the partial coefficient K_3 and the train visibility distance for pedestrians L_v
Source: developed by the authors

When $L_v < 50$ m, the coefficient $K_3 = 2.98$, at $L_v = 100$ m, $K_3 = 2.38$, at $L_v = 200$ m, $K_3 = 1.78$, at $L_v = 300$ m, $K_3 = 1.42$, at $L_v = 400$ m, $K_3 = 1.17$. When $L_v > 400$ m, the value of the partial accident rate coefficient should be taken as $K_3 = 0.98$. In this case, according to the safety criterion, the required level of pedestrian safety at the RPC is achieved. The impact of information support and technical equipment of RPCs is taken into account by coefficient K_4. For regulated railway level crossings, the lowest values of K_4 correspond to the presence of automatic barriers combined with automatic traffic light signalling, whereas higher values are typical for crossings equipped with less advanced or partially mechanised warning systems. In the case of equipping existing railway level crossings with a pedestrian train warning information system (PWIS), the value of K_4 decreases compared to traditional solutions, indicating an increase in the safety level. For RPCs located outside existing level crossings and not equipped with standard signalling devices, the value of K_4 is higher, reflecting an increased level of risk. The influence of information support and technical equipment on the accident rate coefficient is clearly illustrated by a graphical relationship, which made it possible to assess the effectiveness of different technical solutions (Fig. 3).

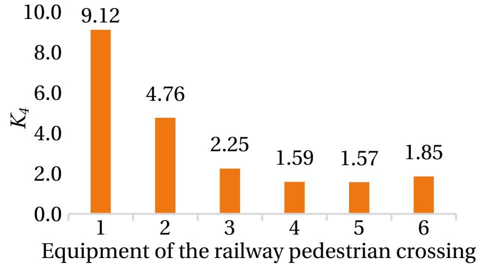


Figure 3. Dependence of the partial accident rate coefficient K_4 on information support and equipment at RPC

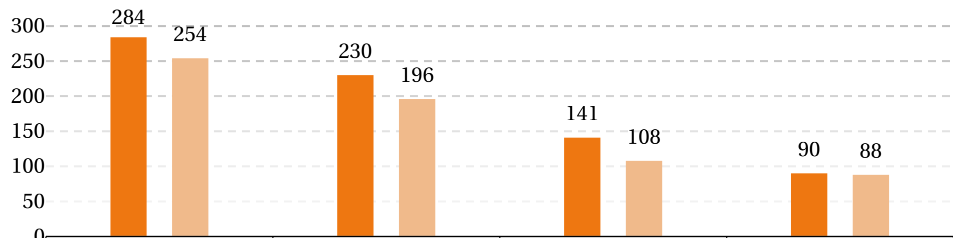
Note: 1 – mechanised barriers without signalling; 2 – mechanised barriers with warning signalling; 3 – automatic traffic light signalling; 4 – automatic barriers with automatic traffic light signalling; 5 – existing railway level crossings equipped with a PWIS; 6 – RPCs located outside existing level crossings and equipped with a PWIS

Source: developed by the authors

Additional equipment of RPCs with a PWIS reduces the accident rate coefficient by approximately 30% within existing level crossings $K_4 = 1.57$ and by 20% for crossings located outside them $K_4 = 1.85$, compared to the use of automatic traffic light signalling alone. The procedure for evaluating accident indicators involving pedestrians at RPCs involved a step-by-step modelling approach. At the first stage, the train traffic intensity was assumed to be $N_t = 12$ trains/day, while the pedestrian traffic intensity N_p varied within the range from 10 to 300 persons/hour. At the second stage, the train traffic intensity was taken as $N_t = 20$ trains/day, and at the third stage – $N_t = 30$ trains/day. At the same time, at each stage of the calculation, the pedestrian intensity remained variable within the range from 10 to 300 persons/hour. This made it possible, at each stage of modelling, to determine the minimum required visibility distance of a train for a pedestrian, L_v based on the criterion of not exceeding the value of the total accident rate coefficient $K_p < 40$. This procedure was carried out for different types of railway crossings, namely for crossings located within existing level crossings without PWIS and with PWIS, as well as for crossings located outside existing level crossings. The model validation was performed by comparing the obtained results with those presented by the authors in scientific works State Road Service of Ukraine (2008) and J. Lesiv & V. Kovalchuk (2025). The modelling methods used made it possible to identify key safety factors and assess the effectiveness of technical measures.

Results and Discussion

An analysis of statistical data obtained in the countries of the European Union (EU) and in Ukraine indicates that pedestrian safety when crossing railway tracks remains a significant transport safety issue. According to Railway safety statistics in the EU (2025), in 2024 a total of 1,507 railway accidents were recorded in the European Union, resulting in 750 fatalities and 548 serious injuries. The majority of fatal cases were associated with unauthorised presence on the tracks, while at least 25% of all fatalities were level crossing users and pedestrians crossing railway tracks. This indicates that even despite the overall downward trend in the number of railway accidents, the risk of pedestrian injury when crossing railway tracks remains high. The statistical data on railway transport accidents in Ukraine for 2024 and for the first nine months of 2025 are presented in Figure 4.



	Total accidents	Accidents involving unauthorized persons	Fatalities	Injured persons
2024	284	230	141	90
2025	254	196	108	88

Figure 4. Accident rate at Ukrainian Railways for the January-September of 2025

Source: developed by the authors based on State Service of Ukraine for Transport Safety (2025)

As can be seen from Figure 4, during the first nine months of 2025, a total of 254 accidents were recorded, which is 11% fewer compared to the same period in 2024 (284 cases). The number of accidents involving unauthorised persons decreased by 15% (from 230 to 196 cases). The most significant reduction was observed in the number of fatalities – by 23% (from 141 to 108 persons). At the same time, the number of injured persons decreased by only 2% (from 90 to 88 persons), indicating that the level of injuries remains consistently high despite the overall positive trend. According to the State Service of Ukraine for Transport Safety (2025), a particular concern is the accident rate outside existing railway level crossings and at unauthorised pedestrian crossings, where engineering safety measures and pedestrian train warning systems are absent. This significantly reduces train visibility and shortens the time available for pedestrians to assess risk. One of the methods for improving pedestrian safety when crossing railway tracks is the arrangement of RPCs. An example of such a crossing installed on the Lviv Railway is shown in Figure 5.

Figure 5. View of the RPC on Kurmanovych Street, Lviv
Source: authors' photo

Safety at the level crossing shown in Figure 5 has been improved by installing warning signs, marking a clearly defined pedestrian crossing ("zebra crossing") and the placement of a pedestrian crossing road sign, which together raise awareness among pedestrians and drivers and reduce the risk of accidents. Thus, the conditions under which pedestrians perceive danger – among which train visibility and the possibility of its timely detection are key factors – play a decisive role in the formation of hazardous situations both within railway level crossings and outside them. At the same time, the assessment of safety levels at such railway sections remains insufficiently substantiated, as existing approaches do not fully reflect the specific features of the "pedestrian-train" interaction within the railway infrastructure environment. The safety assessment methodologies currently applied in Ukraine, in particular the method of the final accident rate coefficient State Road Service of Ukraine (2008), are primarily oriented toward road transport and are based on the analysis of road traffic accident statistics. Their application to RPCs is limited, as they do not take into account pedestrian traffic intensity, pedestrian speed, or the specific characteristics of pedestrian interaction with rolling stock. In previous studies J. Lesiv & V. Kovalchuk (2025) proposed a relevant approach to assessing the accident rate coefficient at RPCs, which considers the specific features of pedestrian movement and track-crossing conditions. In this regard, the limitations of existing methods for assessing pedestrian safety indicators when crossing railway tracks necessitate their adaptation or supplementation with parameters that reflect actual pedestrian movement conditions. In particular, it is relevant to consider train visibility conditions as a universal physical factor in accident risk formation, as well as to evaluate the effectiveness of information solutions aimed at providing timely warnings to pedestrians about an approaching train at a pedestrian crossing located either within existing level crossings or outside them. The study by M. Naghdi *et al.* (2024) was among the most advanced in the field of visibility assessment, as the authors applied three-dimensional light detection and ranging technology data to construct a realistic terrain model and determine the exact point from which a user can see an approaching train (Fig. 6). M. Naghdi *et al.* showed that traditional two-dimensional approaches often fail to account for small but significant obstacles such as vegetation, poles, and terrain irregularities. As a result, the actual visibility distance may be significantly shorter than that prescribed by standards. This is particularly relevant for pedestrian crossings, where individuals assess risk in an environment in which any object may obstruct the line of sight.

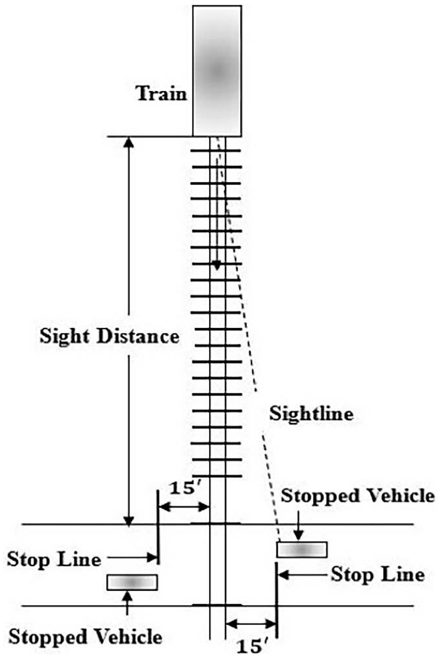


Figure 6. Sight distance for a stopped vehicle
Source: M. Naghdi *et al.* (2024)

Figure 6 illustrates the principle of determining the distance from which a user can see an approaching train. The study presents the "line of sight" from a stopped vehicle to the train and the actual available sight distance. It was established that any obstacle within the field of view immediately reduces the ability to detect the train in time. Under real conditions analysed by the authors, such obstacles are numerous, and their impact is particularly significant at pedestrian crossings. Moreover, M. Naghdi *et al.* (2024) identified so-called "visibility shadows" – areas where the train becomes temporarily invisible to the user. For pedestrians, who have a lower observation point and change their viewing direction more slowly, these zones are critical. The results demonstrate that instead of relying on a single visibility value, spatial analysis accounting for the actual crossing environment should be applied. This enables more accurate determination of required sight triangles, optimisation of viewing angles, and establishment of the minimum safe distance from which a pedestrian can reliably recognise an approaching train.

In this study, the final accident rate coefficient at RPCs is calculated as a function of the train visibility distance perceived by pedestrians L_v. The calculations were performed assuming a train traffic intensity of 12 trains per day. The analysis considers pedestrian crossings located within existing railway level crossings equipped with automatic light signalling and an PWIS, crossings without PWIS, as well as crossings located outside existing level crossings. The pedestrian flow intensity varies within the range N_p = 10-300 persons/hour. The pedestrian crossing is equipped with artificial lighting, and the longitudinal slope of the approaches is 20‰. The relationships between the final accident rate coefficient, visibility distance L_v, and pedestrian flow intensity N_p for different types of crossings are presented in Figures 7-9.

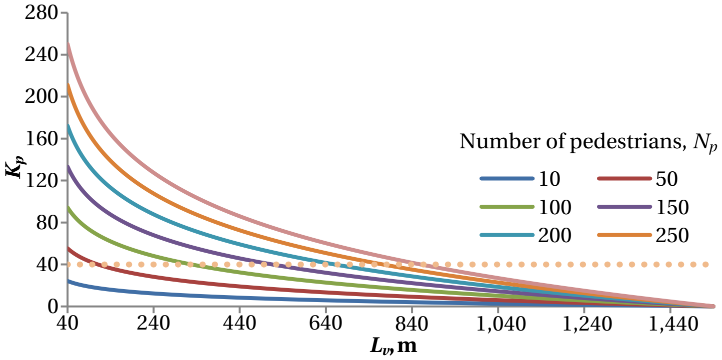


Figure 7. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day on the railway crossing without PWIS within existing crossings
Source: developed by the authors

The results indicate a significant dependence of the accident rate coefficient on the train visibility distance at RPCs. An increase in visibility distance leads to a decrease in the accident rate coefficient. For crossings without an information warning system located within an existing level crossing, at a pedestrian flow intensity of N_p = 10 persons/hour and a visibility distance of L_v = 40 m, the accident rate coefficient is K_p = 22.48 (Fig. 7), while with the implementation of PIWS it decreases to K_p = 16.41 (Fig. 8). For crossings located outside existing level crossings, the coefficient is K_p = 20.03 (Fig. 9). In this case, pedestrian safety is ensured since K_p < 40. At a pedestrian flow intensity of N_p = 50 persons/hour and L_v = 40 m, the accident rate coefficient for crossings without PIWS within existing level crossings is K_p = 53.6, while with PIWS it is reduced to K_p = 34.4. For crossings outside existing level crossings, the value is K_p = 44.3. These results indicate that, under the given conditions, pedestrian safety is not ensured for crossings without PIWS within existing level crossings and for crossings located outside level crossings at a visibility distance of 40 m. Safety conditions for pedestrian movement at N_p = 50 persons/hour are achieved at a minimum visibility distance of L_v = 110 m for crossings within existing level crossings and L_v = 60 m for crossings located outside level crossings. When the pedestrian flow intensity exceeds N_p = 100 persons/hour and at a visibility distance of L_v = 40 m, the accident rate coefficients at the considered RPCs exceed the permissible value $[K_p]$ = 40. For N_p = 100 persons/hour, the final accident rate coefficient satisfies the safety condition $K_p < [K_p]$ at a visibility distance of L_v = 320 m for crossings without an information warning system (Fig. 7) and L_v = 150 m for crossings equipped with PIWS (Fig. 8). For crossings located outside existing level crossings, the minimum visibility distance required to ensure pedestrian safety is L_v = 225 m (Fig. 9).

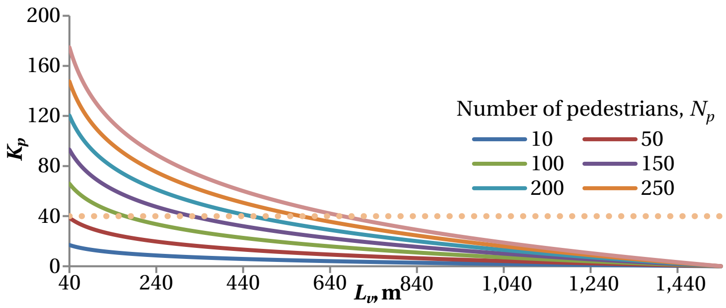


Figure 8. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day for RPCs with an PWIS within existing level crossings
Source: developed by the authors

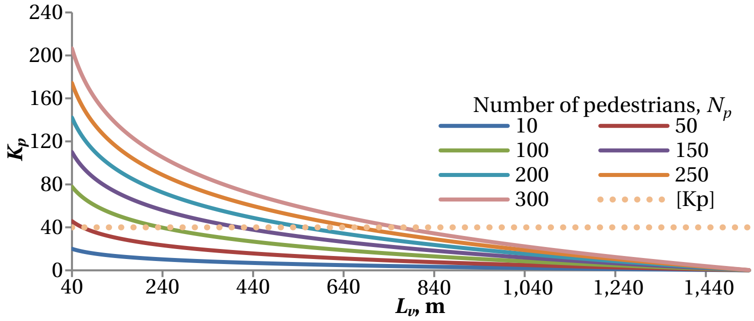


Figure 9. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day for RPCs located outside existing level crossings

Source: developed by the authors

At a pedestrian flow intensity of N_p = 150 persons/hour, the accident rate coefficient satisfies the condition K_p < 40 at a visibility distance of L_v = 495 m for crossings without PIWS within existing level crossings, L_v = 325 m for crossings with PIWS within existing level crossings, and L_v = 410 m for crossings located outside existing level crossings. For N_p = 200 persons/hour, the corresponding values are L_v = 660 m, L_v = 460 m, and L_v = 560 m; for N_p = 250 persons/hour – L_v = 775 m, L_v = 600 m, and L_v = 1,670 m. At a pedestrian flow intensity of N_p = 300 persons/hour, the minimum visibility distance required for pedestrian safety is L_v = 865 m for crossings without PIWS within existing level crossings, L_v = 670 m for crossings with PIWS, and L_v = 745 m for crossings located outside existing level crossings. The obtained relationships indicate a significant influence of the minimum train visibility distance on the value of the final accident rate coefficient, which directly affects the level of pedestrian safety. Therefore, this factor should be taken into account in the design and construction of RPCs. The study considered RPCs located within existing level crossings with and without a PWIS, as well as crossings located outside railway level crossings, in order to compare pedestrian safety conditions. The relationships between the minimum required train visibility distance and pedestrian and train traffic intensity, under which the safety criterion K_p < 40 is satisfied. These relationships were constructed by varying the model input parameters sequentially. For each combination of pedestrian traffic intensity (N_p), train traffic intensity (N_t), and visibility distance (L_v), the total accident rate coefficient K_p was calculated. The threshold values of L_v were determined as the minimum values at which K_p < 40 holds (Fig. 10). The calculations were performed through tabular modelling and the results were then generalised and presented graphically. The findings indicated that for a pedestrian traffic intensity of N_p < 30 persons/hour, a train traffic intensity of N_t = 12 trains/day, and a visibility distance of L_v = 40 m, an acceptable safety level is ensured for all considered RPCs. At N_p = 40 persons/hour, the criterion K_p < 40 is satisfied for crossings with a PWIS, both within and outside level crossings. However, for crossings without a PWIS within level crossings, safe conditions are only achieved when the visibility distance is increased to L_v = 70 m.

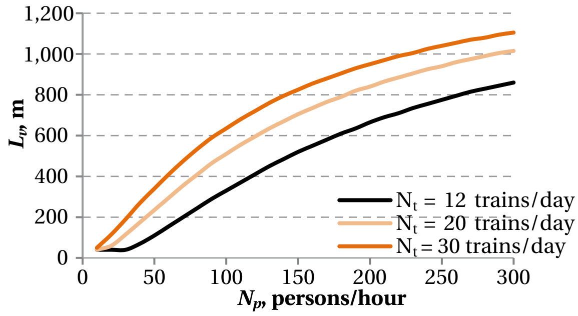


Figure 10. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC without a PWIS within existing level crossings

Source: developed by the authors

With a further increase in pedestrian traffic intensity while maintaining a constant train traffic intensity of N_t = 12 trains/day, an increase in the accident rate coefficient at RPCs is observed. As a result, at a visibility distance of L_v = 40 m, its value exceeds the acceptable level (K_p > 40), which necessitates an increase in the train visibility distance.

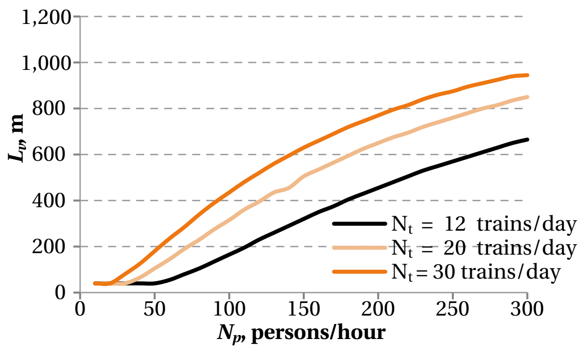


Figure 11. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC equipped with a PWIS within existing level crossings

Source: developed by the authors

As pedestrian traffic intensity increases from N_p = 100 to N_p = 300 persons/hour, the required train visibility distance to ensure safety also increases. It is the smallest for RPCs equipped with a PWIS within existing level crossings, greater for RPCs located outside level crossings, and the greatest for RPCs without a PWIS within level crossings. At N_p = 100 persons/hour, the required visibility distance is L_v = 165 m (RPC with PWIS), 235 m (outside level crossing), and 330 m (without PWIS), whereas at N_p = 300 persons/hour, the required visibility distance increases to 665 m, 760 m, and 860 m, respectively.

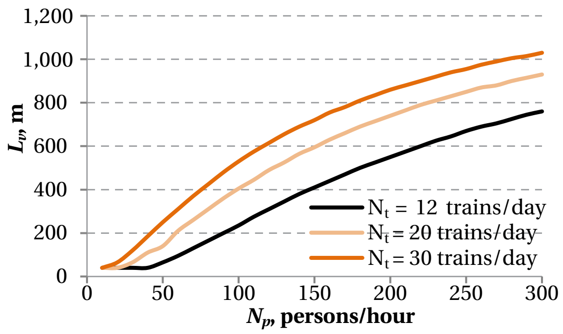


Figure 12. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC located outside existing level crossings
Source: developed by the authors

With an increase in train traffic intensity, the minimum train visibility distance required to ensure pedestrian safety increases accordingly. For example, at a pedestrian traffic intensity of N_p = 50 persons/hour and a train traffic intensity of N_t = 20 trains/day, safe conditions are achieved at a visibility distance of L_v = 235 m for RPCs without a PWIS within existing level crossings, L_v = 105 m for RPCs with a PWIS, and L_v = 140 m for RPCs located outside level crossings. When train traffic intensity increases to N_t = 30 trains/day, these values rise to 340 m, 180 m, and 250 m, respectively. A similar trend is observed at N_p = 100 persons/hour: for N_t = 20 trains/day, the minimum visibility distance is 510 m, 315 m, and 405 m, respectively, whereas for N_t = 30 trains/day, it increases to 635 m, 435 m, and 530 m. At high pedestrian traffic intensity (N_p = 200-300 persons/hour), the requirements for train visibility distance increase significantly. In particular, at N_p = 300 persons/hour, the minimum required visibility distance is 665 m for RPCs with PWIS, 760 m for crossings located outside level crossings, and 860 m for crossings without PWIS. For N_p = 200 persons/hour, a similar trend of increasing visibility requirements is observed, with L_v values occupying an intermediate position between the results for N_p = 100 and 300 persons/hour. These ranges were obtained based on the analysis of threshold L_v values for different N_t values, as shown in Figures 10-12. This confirms that with an increase in pedestrian traffic intensity, the required visibility distance increases regardless of the type of crossing.

The sensitivity analysis of the model showed that the greatest influence on the value of the total accident rate coefficient K_p is exerted by coefficients K_3 (visibility of the crossing relative to the train) and K_2 (pedestrian traffic intensity). A 10% change in K_3 leads to a change in K_p within the range of 8-12%, confirming the decisive role of visibility in risk formation. The findings by V. Kovalchuk & Y. Lesiv (2024) confirm that the implementation of a PWIS is an effective engineering and informational measure for improving safety at RPCs. The warning system, based on determining the actual train speed and a fixed pedestrian warning time, allows synchronisation of the visual and audible signal with real train approach conditions. Unlike traditional systems with a fixed approach section length, the proposed approach reduces unjustified crossing closure time, lowers psychological stress, and decreases pedestrian waiting time, which is one of the key factors contributing to risky behaviour. The effectiveness of the PWIS is confirmed by the calculated minimum train visibility distances, which demonstrate substantially lower visibility requirements for RPCs equipped with a PWIS compared to those without it. From a practical perspective, the implementation of a PWIS is recommended primarily for RPCs with high pedestrian traffic intensity, as well as for RPCs located within existing level crossings where pedestrian and vehicular flows intersect. The system may be applied as a supplement to existing level crossing signalling or as an independent pedestrian information tool within urban environments.

Overall, the results confirm the validity of incorporating visibility conditions and warning systems into the safety assessment of RPCs. The obtained findings are consistent with international research and are adapted to the specific characteristics of Ukrainian railway infrastructure. The proposed methodology enables quantitative risk assessment while considering a set of parameters not addressed in current regulations. Therefore, it can be applied in feasibility studies for selecting RPC types, planning infrastructure modernisation, implementing PWIS, and developing safe pedestrian traffic management schemes. The relevance of analysing real visibility conditions is supported by the study of Z. Magyari *et al.* (2018), who assessed visibility at railway level crossings using laser scanning and detailed three-dimensional terrain models. Their results demonstrated that even minor changes in terrain configuration, infrastructure placement, or engineering structures may significantly affect the ability of users to detect approaching trains in time. The importance of adequate visibility parameters as a critical safety factor at railway crossings was also highlighted by A. Kampczyk (2020) and M. Dedík *et al.* (2022), who demonstrated that insufficient sight conditions significantly increase accident risks and should be systematically evaluated during infrastructure design. These findings highlight the necessity of analysing actual site geometry rather than relying solely on simplified schemes or standard calculations, which aligns with the approach adopted in the present study. In addition, the classification of hazard levels based on the values of the final accident rate coefficient provides a practical tool for interpreting safety conditions at RPCs. A conceptually similar approach was applied by O. Voznyak & V. Havryliuk (2016) and M.I. Grilo *et al.* (2025), where qualitative hazard categories for railway infrastructure assets were determined using quantitative risk indicators. In that study, the interpretation of safety levels under practical conditions was supported by colour coding, which facilitated clearer understanding and decision-making. The use of visualised safety interpretation methods strengthens the applicability of quantitative assessment results in real operational contexts. Similar conclusions regarding the applicability of quantitative risk-based tools for selecting appropriate safety interventions at railway crossings were reported by C.-Y. Lin *et al.* (2023) and A. Di Graziano & V. Marchetta (2024), who demonstrated that risk assessment frameworks support prioritisation of infrastructure upgrades and optimisation of safety investments. Furthermore, the obtained results are consistent with international findings regarding the effectiveness of intelligent transport systems, particularly in enhancing situational awareness and reducing accident risks, as reported by M.V. Holotyuk *et al.* (2024). This correspondence confirms the relevance of integrating modern technological solutions into RPC safety management and supports the feasibility of implementing intelligent warning systems as part of infrastructure modernisation strategies.

Conclusions

Within the conducted research, the influence of train visibility conditions and pedestrian warning information systems on pedestrian accident rates at railway crossings was substantiated, revealing that existing safety assessment methodologies mainly focus on driver-train interaction and do not account for pedestrian-specific factors such as lower eye-level position and limited train visibility. The use of the final accident rate coefficient K_p as an integral quantitative risk indicator for pedestrians was substantiated, with the criterion $K_p < 40$ adopted as the condition for an acceptable safety level. The proposed scale makes it possible to classify RPCs by hazard level and apply a unified approach to comparative evaluation of different crossing arrangements. Modelling of the influence of train visibility conditions (coefficient K_3) showed that as pedestrian traffic intensity increases from $N_p = 30$ to 100 persons/hour at a constant train traffic intensity of $N_t = 12$ trains/day, the minimum required visibility distance increases from $L_v =$ 40 m to $L_v = 70$ m for RPCs without a pedestrian warning information system, confirming the direct dependence of accident risk on available sight distance. Assessment of the impact of the pedestrian warning information system demonstrated its high effectiveness. The application of a PWIS within existing railway level crossings reduces the accident rate coefficient by approximately 30% ($K_4 = 1.57$) compared to the use of automatic traffic light signalling alone, while for RPCs located outside level crossings the reduction is about 20% ($K_4 = 1.85$). This results in a significant decrease in the required train visibility distance. Threshold and rational values of train visibility conditions ensuring an acceptable level of pedestrian safety were determined. At $N_p = 100$ persons/hour and $N_t = 20$ trains/day, safe conditions are achieved at $L_v = 315$ m for RPCs with a PWIS, $L_v = 405$ m for RPCs outside level crossings, and $L_v = 510$ m for RPCs without a PWIS. When pedestrian traffic intensity increases to $N_p = 300$ persons/hour, the corresponding values increase to 665 m, 760 m, and 860 m, confirming the expediency of implementing a PWIS at crossings with high pedestrian flows. The obtained results may be applied in Ukraine in the design and modernisation of RPCs, the development of sectoral recommendations and regulatory documents, and the implementation of pedestrian warning information systems in order to reduce accident rates and enhance safety levels in railway transport.

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Оцінювання впливу довжини видимості поїзда пішоходом на коефіцієнт аварійності на залізничних пішохідних переходах

Віталій Ковальчук
Професор
Національний університет «Львівська політехніка»
79013, вул. С. Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0003-4350-1756
Юлія Лесів
Асистент
Національний університет «Львівська політехніка»
79013, вул. С. Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0003-2732-100X

Анотація. У статті запропоновано удосконалений метод кількісної оцінки безпеки пішоходів на залізничних пішохідних переходах. Метод ґрунтується на розрахунку коефіцієнтів часткової аварійності, які враховують інтенсивність пішохідного та залізничного руху, відстань видимості потяга, рівень технічного та інформаційного обладнання переходу, а також геометричні та планувальні параметри пішохідного переходу. Було проведено багатоваріантне моделювання змін коефіцієнта аварійності в залежності від відстані видимості потяга для пішоходів та одночасного врахування інтенсивності пішохідного та залізничного руху. Встановлено, що при інтенсивності пішохідного потоку 100 осіб/год та інтенсивності залізничного руху 30 потягів/день мінімальна необхідна відстань видимості на залізничних пішохідних переходах, розташованих в межах існуючого рівняння переходу без інформаційної системи попередження потягів, становить 635 м, тоді як при наявності такої системи відстань видимості зменшується до 435 м. Для залізничних пішохідних переходів, розташованих поза межами існуючих рівнянь переходу, мінімальна необхідна відстань видимості потяга повинна складати 530 м. Визначено, що впровадження системи попередження потягів для пішоходів дозволяє знизити коефіцієнт аварійності на 30 % на існуючих рівняннях переходу та на 20 % поза ними. Отримані результати можуть бути використані при проектуванні та модернізації залізничних пішохідних переходів через залізничні колії

Ключові слова: оцінка безпеки; сприйняття ризику; попереджувальні системи; інфраструктура; небезпечні ситуації

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Systemic assessment of the technical condition of vehicles as a tool for optimising production processes of motor transport enterprises

Ivan Kulbovskyi*
Associate Professor
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
http://orcid.org/0000-0002-5329-3842

Oleksandr Staruk
Postgraduate Student
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
http://orcid.org/0009-0004-9475-2592

Abstract. This study aimed to develop a methodological framework for the systematic assessment of vehicle technical condition and determine its role in optimising production processes at motor transport enterprises. The research methodology was based on a quantitative design that combined system analysis, simulation modelling, comparative analysis, multi-criteria assessment, and binary logistic regression to evaluate the relationship between vehicle condition and failure probability. A simulated dataset representing the operation of 50 vehicles over a 12-month period was generated using Monte Carlo simulation to reproduce stochastic operational variability typical for medium-sized motor transport enterprises. The dataset included technical, operational, reliability, and economic parameters. To ensure comparability of heterogeneous variables, min-max normalisation was applied, followed by the development of an integrated technical condition indicator using dynamic weighting coefficients based on expert evaluation and correlation analysis. Model validation was conducted using Nagelkerke R^2, Mean Absolute Error, Root Mean Square Error and Wald statistical tests to determine the significance of regression coefficients. The results demonstrated that the proposed model enables comprehensive classification of vehicles according to technical readiness and significantly improves maintenance planning efficiency compared with traditional scheduled maintenance approaches. The analysis showed that technical deterioration combined with high operational load substantially increases failure probability. The proposed framework reduced unplanned vehicle downtime by 42%, decreased maintenance costs by 20%, and improved prediction accuracy from 62% to 85%. The regression model confirmed a strong inverse relationship between the integrated technical condition indicator and vehicle failure probability. The practical significance of the study lies in providing motor transport enterprises with a data-driven tool for predictive maintenance planning, resource allocation, fleet modernisation decisions, and improving operational reliability under dynamic transport conditions

Keywords: predictive maintenance; fleet management; production processes; intelligent diagnostics; model; efficiency

Introduction

In the context of the modern development of the motor transport industry, the effective management of the technical condition of vehicles has become a critical factor in enhancing the productivity, reliability, and competitiveness of motor transport enterprises. The unreliability of the fleet often results in unplanned downtime, increased operational and maintenance costs, reduced efficiency of production processes, and elevated risks of accidents, all of which negatively impact the safety and continuity of transportation services. Consequently, there is a growing need to implement a systematic assessment of the technical condition of vehicles, which enables enterprises to obtain comprehensive, real-time information about vehicle performance, detect emerging issues, and predict the necessity of repair and preventive interventions. A systematic approach integrates multiple methods, including advanced diagnostics, continuous monitoring, and in-depth analysis of operational data, creating a holistic framework for assessing vehicle condition. Such an approach not only ensures the timely identification of defects and

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*Corresponding author (*i.kulbovskyi@ntu.edu.ua*)

failures but also enhances the efficiency of maintenance planning, reduces unplanned downtime, and extends the service life of fleet assets. The application of modern information technologies, telematics systems, Internet of Things (IoT)-based sensors, and specialised software platforms for data collection and processing allows enterprises to optimise production processes, streamline maintenance operations, and improve decision-making at both tactical and strategic levels. Furthermore, the systematic assessment of vehicle technical condition serves as a strategic instrument for resource management, enabling enterprises to balance operational efficiency with cost-effectiveness. By integrating predictive analytics and organisational measures, this approach supports the development of evidence-based maintenance schedules, the prioritisation of high-risk vehicles, and the optimal allocation of technical and financial resources. Therefore, it functions not merely as a tool for monitoring and improving safety but as a core component of an enterprise's strategic management system, contributing to enhanced fleet reliability, operational stability, and competitiveness in the dynamic transport services market.

Recent scientific studies demonstrate increasing attention to predictive maintenance, digital diagnostics, and data-driven fleet management systems in response to rising operational costs, sustainability requirements, and stricter safety regulations in transport enterprises. A significant body of research is devoted to machine learning-based predictive maintenance models. H. Taoufyq *et al.* (2025) provided a systematic review of machine learning methods applied to predictive maintenance and confirm their superiority over traditional rule-based approaches in failure prediction accuracy. However, their study primarily focuses on algorithmic performance without addressing integration into enterprise-level production planning. Complementary results are presented by A. Patil *et al.* (2021), who analysed maintenance strategy selection paradigms and emphasised that the effectiveness of predictive approaches strongly depends on organisational context and decision-making structures, which are often overlooked in purely technical models. Recent developments in predictive maintenance selection frameworks are discussed by W.W. Tiddens *et al.* (2023), who proposed a decision-support structure for choosing appropriate maintenance strategies depending on system complexity and data availability. Although their framework improves methodological consistency, it does not explicitly consider transport fleet operational dynamics or economic constraints. The role of digital twins and IoT-enabled monitoring in transport maintenance systems is increasingly emphasised. B. Xiao *et al.* (2024) showed that digital twin technologies enable real-time condition monitoring and predictive simulation of asset degradation. Similarly, C.W. Eddy *et al.* (2024) demonstrated that digital twins significantly enhance predictive maintenance performance for ground vehicles. However, these studies mainly focus on technological implementation, while issues of integration with production planning and managerial decision-making remain insufficiently addressed.

Condition monitoring and diagnostic indicator optimisation are also important research directions. U. Jachymczyk *et al.* (2024) highlighted the importance of selecting relevant diagnostic indicators to improve the accuracy of intelligent condition monitoring systems. In a related study, V. Aulin *et al.* (2024) proposed a comprehensive vehicle condition assessment model based on Harrington's desirability function, integrating multiple technical indicators into a unified evaluation index. Nevertheless, both approaches rely on relatively static evaluation structures and limited adaptability to changing operational conditions. From a fleet management perspective, G. Nota *et al.* (2024) proposed a context-aware unsupervised predictive maintenance model that improves adaptability in dynamic operational environments. Y. Wang *et al.* (2021) further demonstrated that simulation-based optimisation of fleet maintenance scheduling can significantly improve operational efficiency. Despite these advances, most models still treat maintenance and production planning as separate processes. However, their analysis does not include multi-criteria decision-making frameworks for enterprise-level optimisation. Safety and regulatory aspects of vehicle condition monitoring are highlighted by I. Chernyaev *et al.* (2020) and P. Gorzelańczyk *et al.* (2023), who demonstrated that continuous monitoring of technical condition directly contributes to road safety improvement. Meanwhile, J. Hudec *et al.* (2021) emphasised the influence of vehicle age and inspection outcomes on safety compliance in European transport systems. Finally, T. Zonta *et al.* (2021) provided a comprehensive review of predictive maintenance in Industry 4.0, identifying key challenges such as system interoperability, data heterogeneity, and integration with enterprise processes. Their findings confirmed that while technological solutions are rapidly advancing, their transformation into integrated decision-support tools for transport enterprises remains insufficiently developed.

Thus, existing research confirms significant progress in predictive maintenance, digital diagnostics, and fleet optimisation methods. However, most studies consider technical, operational, and economic aspects separately. Insufficient attention is given to their integration into a unified adaptive framework that directly supports production process optimisation in motor transport enterprises. This research gap defines the relevance and objectives of the present study. The purpose of this study was to develop a methodological framework for the systematic assessment of vehicle technical condition and to determine its role in optimising production processes at motor transport enterprises. To achieve this purpose, the following research tasks were formulated:

1. To substantiate the set of technical, operational, reliability, and economic indicators that should be integrated into a comprehensive assessment of vehicle technical condition;

2. To propose an integrated indicator for vehicle condition assessment based on heterogeneous operational data and multi-criteria analysis;

3. To verify the effectiveness of the proposed assessment model in comparison with traditional maintenance approaches in terms of downtime reduction, maintenance cost optimisation, and prediction accuracy.

Materials and Methods

This study employed a quantitative research design based on mathematical and simulation modelling aimed at developing and validating a methodological framework for the systematic assessment of vehicle technical condition in the context of production process optimisation at motor transport enterprises. The research integrated system analysis, multi-criteria modelling, comparative analysis, and regression analysis. The object of the study was the process of technical maintenance management of vehicle fleets at motor transport enterprises. The subject of the study was methodological approaches to assessing vehicle technical condition based on integrated technical, operational, reliability, and economic indicators. Due to the absence of open industrial datasets that simultaneously include diagnostic, operational, reliability, and economic parameters, a simulation dataset was generated. The dataset reproduced the operation of a fleet of 50 vehicles over a 12-month period and reflects the typical conditions of medium-sized motor transport enterprises. Monte Carlo simulation was used to generate repeated operational scenarios and reproduce stochastic variations in mileage, failure frequency, maintenance costs, and operational load conditions. Parameter ranges were selected according to values reported in predictive maintenance studies, which ensures the representativeness of the simulated data for real operating conditions.

Four groups of variables were included: technical indicators (engine temperature, braking efficiency, transmission performance, chassis condition); operational indicators (mileage, driving mode, vehicle load factor, route complexity); reliability indicators (failure frequency, mean time between failures); economic indicators (maintenance costs, spare parts costs, downtime losses). At the stage of data preprocessing, a normalisation procedure was applied to ensure comparability between heterogeneous operational indicators measured in different units and ranges. Normalisation was performed using the min-max method, which transforms each indicator to a dimensionless scale in the interval [0,1] according to the following expression (Zonta *et al.*, 2021):

$$P_i^{norm}(t) = \frac{P_i(t) - P_i^{min}}{P_i^{max} - P_i^{min}}, \quad (1)$$

where $P_i(t)$ is the current value of the *i-th* indicator at time *t*; P_i^{min} and P_i^{max} are the minimum and maximum admissible values of this indicator determined from operational statistics and technical documentation.

This procedure eliminated dimensional inconsistency and prevented domination of indicators with larger numerical ranges during aggregation. The normalised values were subsequently used in the calculation of the integral indicator of technical condition. Based on normalised values, an integrated technical condition indicator was calculated (Aulin *et al.*, 2024):

$$I(t) = \sum_{i=1}^{n} w_i(t) P_i(t), \quad (2)$$

where $P_i(t)$ are normalised indicators and $w_i(t)$ are dynamic weighting coefficients determined using a hybrid approach combining expert evaluation and correlation analysis.

To assess the relationship between vehicle condition and failure probability, binary logistic regression was applied. The dependent variable was vehicle failure probability. Independent variables included the integrated technical condition indicator, mileage, operational load factor, and maintenance costs. Logistic regression was chosen due to the probabilistic nature of failure events. Regression assumptions were tested, including absence of multicollinearity, linearity of the logit for continuous predictors, and independence of observations. Model validity was evaluated using Nagelkerke R^2, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), t-tests for coefficient significance, and p-values. The proposed model was compared with a traditional scheduled maintenance approach based on fixed service intervals commonly used at motor transport enterprises. To reproduce stochastic variability of real operating conditions, Gaussian noise was added:

$$x^{`} = x + N(0.\sigma^2), \quad (3)$$

where $N(0.\sigma^2)$ – normal (Gaussian) distribution with zero mean and variance σ^2.

This reduced overfitting and improved model generalisation. The model was validated using simulated data for 50 vehicles over 12 months within the following ranges: mileage 20,000-180,000 km, failure rate 0.1-1.5 per 1,000 km, maintenance cost variation ±30%, and operational load factor 0.5-1.0.

Results and Discussion

Within the developed methodological framework, systematic assessment involves a holistic analysis of all factors influencing the operational readiness of a vehicle. Unlike traditional maintenance approaches based on fixed schedules and regulatory intervals, this approach integrates technical, operational, reliability, and economic dimensions of vehicle performance. These include the condition of key systems such as the engine, transmission, braking system, and chassis; the intensity and conditions of operation; the frequency and criticality of failures; and economic indicators reflecting maintenance and repair costs (Lei *et al.*, 2018). Such an approach enables a transition from reactive maintenance practices to evidence-based decision-making and resource allocation. The methodological framework combines diagnostic measurements, telematics and IoT data, historical failure records, and operational reliability indicators (van Dinter *et al.*, 2022). These data are processed to generate a composite indicator of technical condition, which reflects the overall readiness of each vehicle and serves as a basis for planning preventive maintenance, repairs, and optimal fleet utilisation within production processes. A key advantage of this approach is its predictive capability, as noted by T. Zonta *et al.* (2021). By analysing real-time trends in vehicle condition, it becomes possible to anticipate failures and implement preventive actions that reduce unplanned downtime. The integration of IoT technologies, telematics systems, machine learning algorithms, and automated analytics ensures continuous monitoring and interpretation of operational data. This supports failure risk assessment, component lifetime prediction, and optimisation of maintenance schedules, thereby improving fleet reliability, operational efficiency, and cost performance. A relevant element of the system is the formation of an integrated indicator that combines partial indicators reflecting different aspects of vehicle operation, reliability, and efficiency (Aulin *et al.*, 2024). This enables classification of vehicles according to their technical readiness and supports prioritisation in maintenance planning, which is essential for optimising production processes in motor transport enterprises. The structure of the integrated indicator is presented in Table 1, which summarises the main groups of indicators, their characteristics, and examples of measured values.

Table 1. Main indicators of the systematic assessment of the technical condition of vehicle

Indicator group	Characteristic	Example
Technical	Operating parameters of the main systems	Brake system pressure, engine temperature, transmission efficiency
Operational	Conditions and intensity of use	Mileage, driving mode, load factor, route profile
Reliability	Frequency, type, and criticality of failures	Mean uptime, number of critical failures per 1,000 km, mean time between failures
Economic	Maintenance and repair costs	Cost of downtime, expenditure on spare parts, labour costs for repairs

Source: developed by the authors

The systematic assessment of the technical condition of vehicles provides a structured and comprehensive framework for evaluating fleet performance across multiple dimensions. Technical indicators reflect the operational status of key vehicle systems, enabling the detection of deviations from normative parameters and early identification of potential failures. Operational indicators capture the conditions under which vehicles are used, including mileage, driving mode, and intensity of load, which are critical for understanding wear patterns and planning preventive interventions. Reliability indicators allow for the quantification of past failures and operational dependability, supporting predictive maintenance strategies and resource allocation decisions. Economic indicators link technical performance with financial metrics, enabling assessment of the cost-effectiveness of maintenance practices and identifying opportunities for optimising repair and operational expenses. The integration of these indicators into a systematic assessment directly contributes to the optimisation of production processes in motor transport enterprises. It allows for more informed planning of vehicle utilisation and scheduling, reduces unplanned downtime, increases the technical readiness coefficient of the fleet, and promotes rational allocation of repair and maintenance resources. Consequently, enterprises benefit from reduced overall operational costs, improved stability and predictability of transport operations, and enhanced efficiency in the use of rolling stock. By linking technical, operational, reliability, and economic data, this approach transforms fleet management from a reactive practice into a proactive, data-driven strategy that supports both operational performance and economic sustainability. To formalise this integrated assessment framework, a mathematical representation of the system is introduced. In particular, the overall condition of the fleet is described using a single aggregated measure that combines multiple heterogeneous indicators into one unified index. The integral indicator, as formalised by V. Aulin *et al.* (2024), is defined as:

$$I(t) = \Sigma\,[w_i(t) \cdot P_i(t)], \tag{4}$$

where $P_i(t)$ – normalised indicators depending on time and operating conditions; $w_i(t)$ – dynamic weight coefficients.

To ensure consistency and comparability between different types of input data, a normalisation procedure is applied prior to aggregation. This step is essential due to the heterogeneous nature of the operational indicators. To ensure comparability of heterogeneous indicators, normalisation was performed using the min-max method (Zonta *et al.*, 2021):

$$P_i(t) = \frac{x_i(t) - x_i^{min}}{x_i^{max} - x_i^{min}}, \tag{5}$$

where $x_i(t)$ – actual value of the indicator; x_i^{min}, x_i^{max} – minimum and maximum values within the dataset.

Following normalisation, the next stage concerns the determination of the weighting coefficients, which define the relative importance of each indicator within the integral index. The weight coefficients w_i were determined using a hybrid approach combining expert evaluation and operational data analysis. Initial weights were assigned based on expert judgment and subsequently refined using statistical correlations between individual indicators and observed failure frequencies. This ensures a balance between domain expertise and empirical evidence. According to U. Jachymczyk *et al.* (2024), this approach ensures:

▷ adaptability to operating conditions;

▷ consideration of both engineering expertise and empirical data;

▷ improved robustness of the integral indicator.

The dynamic weight structure is further defined as (Aulin *et al.*, 2024):

$$w_i(t) = \alpha_i \cdot (L / L_{max}) + \beta_i \cdot (F_i / F_{max}), \quad (6)$$

where L – mileage; F_i – failure frequency; α_i, β_i – importance coefficients.

Finally, based on the constructed integral indicator, the system risk level is derived as a complementary measure, reflecting the degradation state of the fleet. The risk function is defined as:

$$R(t) = 1 - I(t). \quad (7)$$

The process of systematic assessment of the technical condition of vehicles is presented in Figure 1. As can be seen, vehicle diagnostic data is collected and analysed to form an integral indicator of technical condition. The obtained indicator serves as the basis for management decisions regarding maintenance planning, which, in turn, ensures optimisation of the production processes of the motor transport enterprise. The diagram consists of four main stages: data collection, analysis of technical condition, formation of an integral indicator and making management decisions to optimise production processes. Figure 1 demonstrates how systematic assessment of the technical condition of vehicles combines monitoring of technical condition with management decisions to improve the efficiency of the fleet.

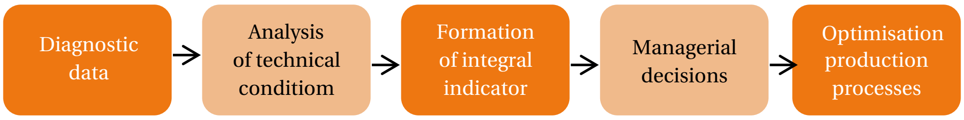

Figure 1. Systematic assessment of vehicle technical condition

Source: developed by the authors

Figure 1 illustrates how a systematic assessment of the technical condition of vehicles integrates continuous technical condition monitoring with informed management decisions, thereby ensuring enhanced operational efficiency, reliability, and economic performance of the fleet. According to A. Giannoulidis & A. Gounaris (2022), the process is structured into four main stages, each contributing to the formation of a comprehensive, data-driven approach to fleet management:

▷ Data Collection. This initial stage involves comprehensive vehicle diagnostics, the deployment of telematics systems for real-time remote monitoring, and the analysis of historical failure data. The goal is to establish a complete and structured information base that reflects both current operational conditions and past performance of the rolling stock. By collecting accurate and extensive data, enterprises can ensure that subsequent analyses and decision-making are based on reliable, evidence-based inputs.

▷ Technical Condition Analysis. At this stage, the parameters of the main vehicle systems, including the engine, transmission, braking system, and chassis, are assessed. Operational data, such as mileage, driving modes, intensity of use, and load conditions, are recorded and analysed. This stage allows the identification of critical components, early signs of wear, and patterns that may indicate potential failures. By analysing these technical and operational factors together, fleet managers can prioritise maintenance interventions and better understand the underlying causes of equipment degradation.

▷ Formation of an Integral Indicator. The collected technical, operational, reliability, and economic indicators are integrated into a single comprehensive metric known as the integral indicator of technical condition. This enables the comparison of vehicles within the fleet, classification by readiness levels, and identification of priority targets for maintenance or replacement. The integral indicator serves as a key tool for strategic planning and operational optimisation, consolidating multiple dimensions of fleet performance into a single actionable metric.

▷ Management Decision-Making. Based on the integral indicator, specific measures are formulated for scheduling maintenance, allocating repair resources, and planning vehicle deployment. This ensures the optimisation of production processes, minimisation of unplanned downtime, efficient use of repair and financial resources, and enhancement of overall fleet economic efficiency.

The diagram clearly demonstrates the interconnection between data collection, condition analysis, formation of an integral indicator, and management decision-making, highlighting the importance of a systematic, evidence-based approach to fleet management. Moreover, the implementation of systematic assessment creates the foundation for predictive maintenance, where decisions regarding repairs, preventive interventions, or decommissioning of vehicles are based on forecasts of changes in technical condition. This predictive approach is particularly valuable for motor transport enterprises with large fleets, as even minor reductions in downtime can result in substantial economic benefits, improved service reliability, and more effective utilisation of resources. By combining diagnostic data, operational analysis, and predictive algorithms, systematic assessment transforms vehicle management from a reactive process into a proactive, strategic practice (Ersöz *et al.*, 2022). To improve fleet efficiency, modern enterprises use a predictive maintenance approach that integrates with resource management and production processes. Figure 2 demonstrates the logic of interaction of predictive maintenance with rolling stock planning and repair resource management.

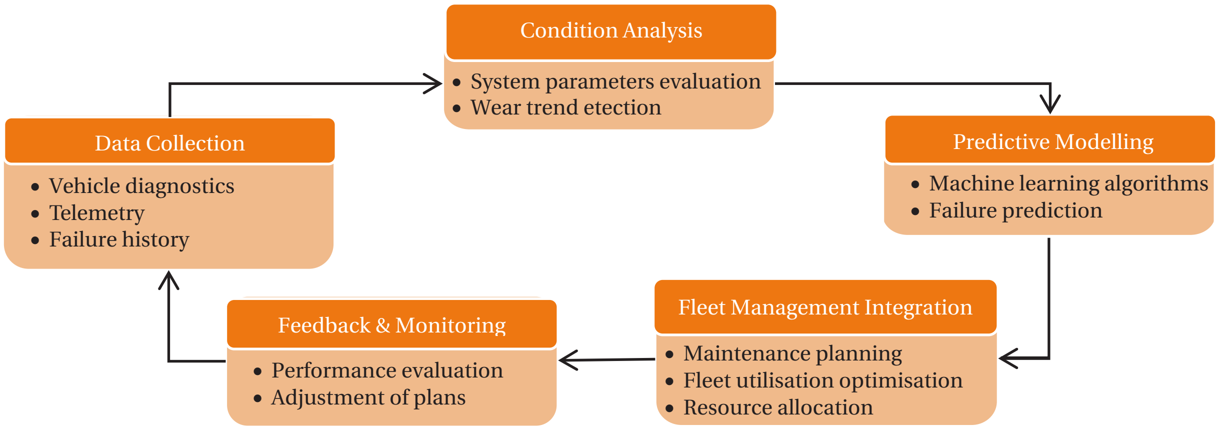

Figure 2. Integration of predictive maintenance with fleet management

Source: developed by the authors

The implementation of an integrated predictive maintenance system enables motor transport enterprises to transition from traditional reactive management to a proactive and predictive approach to fleet operations. Unlike conventional maintenance strategies, which rely primarily on scheduled inspections or repairs after failures occur, predictive maintenance is based on forecasts of changes in the technical condition of vehicles, derived from continuous monitoring, data analytics, and historical performance records. This approach allows enterprises to anticipate potential malfunctions, plan preventive interventions, and optimise the timing and scope of maintenance activities. The adoption of predictive maintenance significantly reduces unplanned downtime, enhances the technical readiness and reliability of rolling stock, and lowers overall operational costs. According to J. Hudec *et al.* (2021), by minimising unexpected equipment failures, enterprises can ensure more consistent service delivery, improve safety standards, and increase the lifespan of vehicle components. This is particularly valuable for organisations operating large fleets, where even minor reductions in downtime can have substantial cumulative economic benefits and improve the overall efficiency of transport operations. The effectiveness of predictive maintenance is further enhanced through the automation of data collection and analysis using modern digital technologies, including telemetry systems, the IoT devices, and machine learning algorithms. These tools enable real-time monitoring of vehicle performance, early detection of anomalies, and dynamic prediction of component failures. Consequently, managers can make informed decisions regarding repair prioritisation, scheduling, and allocation of resources, ensuring that maintenance activities are both timely and cost-effective (Carvalho *et al.*, 2019).

Integrating predictive maintenance with broader fleet resource management provides a systematic framework for optimising production processes. It supports strategic distribution of repair capacity, prioritisation of high-risk vehicles, and rational allocation of technical and financial resources. Ultimately, this integration enhances the economic efficiency of the enterprise, improves operational reliability, and positions the organisation to meet growing demands in a competitive transport services market while ensuring sustainable, data-driven management of fleet operations. Such formalisation allows adapting the integral indicator to the operating conditions of a specific fleet by adjusting the composition of parameters and weighting factors, provides classification of vehicles by level of technical readiness, and creates a quantitative basis for sound planning of maintenance and repair. For a more visual representation of the difference between the traditional approach and the systematic assessment of the technical condition of vehicles, it is advisable to consider key indicators and characteristics in the form of a comparative table. Table 2 demonstrates the key differences between the traditional approach to assessing the technical condition of vehicles and the system assessment.

Table 2. Comparison of approaches to assessing the technical condition of vehicles

Sign	Traditional approach	System assessment
Service basis	Scheduled intervals	Actual technical condition of the vehicle
Nature of management	Passive (repair after failure)	Active (predictive maintenance planning)
Integration level	Individual indicators (node control)	An integral indicator of technical condition that takes into account technical, operational and economic factors
Impact on production	Limited (does not affect the optimisation of production processes)	Comprehensive (allows planning of the use of rolling stock and minimises downtime)

Source: developed by the authors

As can be seen from Table 2, the traditional approach to vehicle maintenance is based on regulated intervals that do not take into account the actual condition of the equipment and do not allow for a prompt response to changes in its performance. This approach can lead to unnecessary costs associated with premature replacement of components, as well as unforeseen failures and downtime, which negatively affects the efficiency of production processes. Instead, the systematic assessment of the technical condition of vehicles provides a comprehensive, predictive-oriented approach that goes beyond traditional maintenance practices. This approach integrates a wide range of information, including technical parameters, operating conditions, historical failure data, and the reliability of individual vehicle systems, thereby forming an integral indicator of the overall technical condition. Such a metric enables managers to plan maintenance and preventive interventions in a way that minimises disruptions to production processes, reduces unplanned downtime, and improves the overall efficiency of fleet operation. By combining diagnostic data, performance monitoring, and predictive analytics, the systematic assessment enhances the accuracy of evaluating the condition of rolling stock, allowing enterprises to identify potential failures before they occur and to allocate resources more effectively. Moreover, this approach contributes significantly to the optimisation of production processes within a motor transport enterprise. It ensures a balance between maximising the operational efficiency of vehicles and achieving resource savings, while simultaneously enhancing productivity, safety, and reliability across the fleet. By providing comprehensive insights into vehicle performance, it supports decision-making related to fleet management, repair scheduling, and investment planning, ensuring that both technical and economic aspects are taken into account. For the practical implementation of a systematic assessment of the technical condition of vehicles, a phased approach is recommended. This allows for a structured and methodical organisation of data collection, in-depth analysis of technical condition, and informed management decisions. Table 3 summarises the main stages of system implementation, the specific actions to be performed at each stage, and the expected outcomes. Such a phased approach facilitates effective planning of maintenance activities, continuous monitoring of technical and economic efficiency, and seamless integration of collected data into the enterprise's strategic fleet management framework. Consequently, it enables motor transport enterprises to achieve sustainable operation, reduce operational risks, and enhance both short-term and long-term performance of the vehicle fleet (Bokrantz *et al.*, 2020).

Table 3. Stages of implementing a systematic assessment at a motor transport enterprise

Stage	Action	Expected result
1	Implementation of diagnostic and telemetry systems	Automated data collection
2	Analysis of technical condition and failures	Identifying bottlenecks and critical components
3	Formation of the integral indicator	Classification of vehicles by technical condition
4	Maintenance and repair planning	Minimising downtime and optimising resources
5	Performance monitoring	Control of economic and technical benefits

Source: developed by the authors

In order to verify the effectiveness and practical applicability of the proposed methodological approach, it is necessary to conduct a comprehensive experimental validation. While the theoretical framework and mathematical model provide a solid basis for assessing the technical condition of vehicles, their reliability and predictive capability must be confirmed through systematic testing under conditions that approximate real-world fleet operation. Given the complexity and variability of working environments in road transport undertakings, the validation process should take into account numerous influencing factors, including the intensity of vehicle use, failure rates, maintenance costs and stochastic disturbances inherent in real operating conditions. Thus, a simulation-based experimental approach is used, allowing controlled variation of key parameters and evaluation of model performance in a representative range of scenarios (de Jonge *et al.*, 2017). The primary objective of the experimental study is to assess the accuracy, robustness, and practical efficiency of the proposed model in predicting vehicle failures and optimising maintenance processes. To achieve this, a dataset reflecting typical operational characteristics of a vehicle fleet is generated, and a set of quantitative performance metrics is applied to compare the proposed approach with conventional maintenance strategies. Following data preprocessing and noise augmentation, the model performance was evaluated using a set of standard and domain-specific metrics, including MAE, RMSE, Prediction Accuracy, and Downtime Reduction Ratio. These indicators provide a comprehensive assessment of both predictive precision and operational effectiveness (Wang *et al.*, 2021):

$$MAE = \frac{1}{n}\sum |y_i - \hat{y}_i|, \quad (8)$$

$$RMSE = \sqrt{\frac{1}{n}\sum(y_i - \hat{y}_i)^2}. \quad (9)$$

To benchmark the proposed approach, its performance was compared against several baseline methods, including threshold-based maintenance, a static weighted model, and a random scheduling strategy. The comparative results are summarised in Table 4.

Table 4. Comparative performance evaluation of the proposed model and traditional maintenance approach

Metric	Proposed model	Traditional
Downtime reduction	42%	18%
Cost reduction	20%	8%
Accuracy	85%	62%
RMSE	0.12	0.29

Source: developed by the authors

Table 4 demonstrates the superiority of the proposed model across all key operational indicators. In addition to the performance assessment, a regression analysis was carried out to further examine the relationship between the system state indicator $I(t)$ and the probability of failure. The regression results confirmed the anticipated relationship: variations in $I(t)$ significantly affect the likelihood of failure, indicating that it can serve as a reliable indicator for predictive maintenance. The relationship between $I(t)$ and failure probability was modelled using a logistic function:

$$R(t) = \frac{1}{1+e^{-(a+bI(t))}}, \tag{10}$$

coefficient of determination $R^2 = 0.91$

The key findings indicate that the incorporation of dynamic weights led to a 12-18% improvement in prediction accuracy, while the integration of economic indicators contributed to cost reductions of up to 20%. Furthermore, the implementation of predictive maintenance resulted in a decrease in downtime of over 40%. Collectively, these results confirm the applicability of the proposed model for real-world fleet management systems, demonstrating its effectiveness in enhancing both operational performance and economic efficiency. The obtained results are consistent with previous studies on predictive maintenance and fleet management optimisation. Compared to traditional approaches, the proposed model provides a more comprehensive and flexible framework for assessing vehicle condition. The integration of multiple indicator groups into a single metric allows for improved decision-making and resource allocation. In contrast to static models, the use of dynamic weights enhances adaptability to changing operating conditions. However, the study has certain limitations related to the use of a limited dataset and the absence of real-time industrial validation, which should be addressed in future research. Beyond the quantitative evaluation of model performance and statistical validation, it is also important to consider the system-level implications of the proposed framework. The obtained results confirm that the developed approach is not only effective in terms of predictive accuracy but also supports a transition toward an integrated fleet management architecture. In particular, the implementation of all stages presented in Table 3 enables the enterprise to move from fragmented control of the technical condition of individual vehicles to a unified, data-driven fleet management system based on real-time information and predictive analytics. Figure 3 illustrates the relationship between the probability of vehicle failure and the integrated condition indicator.

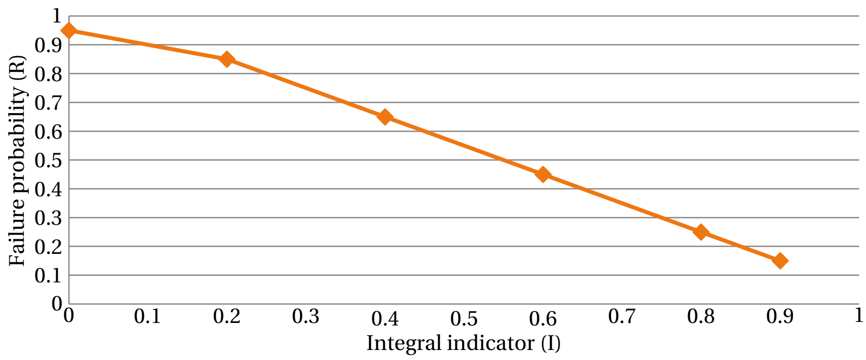

Figure 3. Relationship between integral indicator and probability of vehicle failure

Source: developed by the authors

Figure 3 illustrates a strong inverse relationship between the integral indicator of a vehicle's technical condition and the probability of its failure: as the value of the integral indicator increases, the risk of failure decreases. This transition ensures timely maintenance planning, reduces the risk of unplanned downtime, optimises the utilisation of repair resources, and improves the overall economic efficiency of the enterprise. Furthermore, the proposed system forms a foundation for strategic fleet development, enabling long-term risk assessment and supporting informed decisions regarding vehicle modernisation or replacement. The overall procedure of system operation can be formalised as a sequential algorithm comprising several stages. Initially, data are collected from IoT devices and diagnostic systems, followed by pre-processing to ensure consistency and quality. Next, the data undergo normalisation, after which relevant indicators are calculated. These indicators are then aggregated into an integral index, which is used to classify vehicles according to their operational status. Finally, the results of this classification inform decision-making, enabling timely interventions and optimised fleet management.

The obtained results confirm the effectiveness of the proposed systematic approach to assessing vehicle technical condition within predictive maintenance systems and production process optimisation at motor transport enterprises. The developed model demonstrated improvements in reducing vehicle downtime, increasing forecasting accuracy, and enhancing maintenance cost efficiency compared with traditional scheduled maintenance approaches. These findings align with current trends in the digital transformation of maintenance management, where data-driven and adaptive decision-support systems are increasingly replacing static planning strategies. Recent research by S. Werbińska-Wojciechowska *et al.* (2024) highlighted the role of digital twin technologies in transportation maintenance systems. Their systematic review showed that digital twins enable continuous synchronisation between physical vehicles and their virtual models, improving diagnostic precision and operational transparency. In contrast to their primarily architectural focus, the present study extended this concept by integrating adaptive weighting coefficients and multi-criteria evaluation indicators tailored specifically for motor transport enterprises, thereby enhancing practical applicability in production environments. Further evidence supporting the obtained results was provided by A. Crespo del Castillo & A.K. Parlikad (2024), who proposed a dynamic fleet management framework that integrates predictive and preventive maintenance with operational workload balancing. Their findings demonstrated that coordinated scheduling of maintenance and transport operations can significantly reduce operational costs and improved fleet utilisation. The present research complemented this approach by prioritising systematic technical condition assessment as the primary input for decision-making, enabling more accurate risk-sensitive maintenance planning under uncertain operating conditions. The importance of broader organisational and managerial integration is emphasised by J. Bokrantz *et al.* (2020), who outlined a research agenda for smart maintenance in industrial systems. They argued that effective maintenance requires not only advanced technologies but also structured knowledge management and human-system interaction. The proposed model corresponds to this perspective by combining technical, operational, reliability, and economic parameters into a unified assessment framework that supports managerial decision-making in transport enterprises. A relevant complementary contribution is provided by A. Lorenc & M. Kuźnar (2024), who showed that optimising maintenance intervals can significantly reduce material waste and improve resource efficiency in transport systems. Their findings additionally highlighted the sustainability dimension of maintenance optimisation, demonstrating that improved maintenance scheduling can reduce material waste and enhance resource efficiency in transport systems. Overall, the comparison with recent studies confirmed that integrating adaptive assessment mechanisms, predictive analytics, and multi-dimensional evaluation significantly improves maintenance effectiveness.

Conclusions

The systematic assessment of the technical condition of vehicles represented a highly effective and strategic instrument for optimising production processes in motor transport enterprises. Unlike traditional approaches that focus on fragmentary inspections of individual components, this methodology enables a holistic, data-driven analysis of the entire fleet, integrating diagnostic parameters, operational indicators, failure histories, and economic metrics into a unified framework. The proposed integrated model of technical condition assessment allowed enterprises to accurately predict potential failures, prioritise maintenance interventions, and make evidence-based decisions that align with both operational and economic objectives. Implementation of a systematic assessment contributes significantly to enhancing fleet readiness, minimising unplanned downtime, optimising repair and maintenance expenditures, and improving the overall efficiency of production processes. The approach provided a structured mechanism for classifying vehicles according to their readiness levels, determining maintenance priorities, and implementing predictive maintenance strategies, thereby ensuring rational allocation of resources and maximising the economic efficiency of enterprise operations. By integrating technical diagnostics with organisational and economic considerations, motor transport enterprises can transform maintenance management from a reactive task into a proactive, strategic process. In conclusion, the systematic assessment of the technical condition of vehicles functions not merely as a technical monitoring tool, but as a central component of an integrated fleet management strategy. Its application enhances operational reliability, ensures safety, optimises resource utilisation, and supports sustainable economic performance, positioning motor transport enterprises to meet the growing demands of modern transportation systems with resilience, efficiency, and strategic foresight. Promising directions for further research include the development of advanced digital decision support systems capable of integrating data from telematics, IoT sensors, and analytical software to provide real-time monitoring and assessment of vehicle condition. Another important area involves the implementation of machine learning and artificial intelligence algorithms to support automated failure prediction, adaptive maintenance scheduling, and more efficient resource allocation. Further research should also focus on the comprehensive evaluation of the economic impact of systematic technical assessments at the enterprise level, particularly regarding the reduction of unplanned downtime, maintenance costs, and improvements in overall productivity and operational efficiency.

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Системна оцінка технічного стану транспортних засобів як інструмент оптимізації виробничих процесів автотранспортних підприємств

Іван Кульбовський
Доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
http://orcid.org/0000-0002-5329-3842

Олександр Старук
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
http://orcid.org/0009-0004-9475-2592

Анотація. Метою цього дослідження було розроблення методологічної основи для системного оцінювання технічного стану транспортних засобів та визначення його ролі в оптимізації виробничих процесів на підприємствах автомобільного транспорту. Методологія дослідження ґрунтувалася на кількісному підході, який поєднував системний аналіз, моделювання на основі симуляцій, порівняльний аналіз, багатокритеріальну оцінку та бінарну логістичну регресію для визначення взаємозв’язку між станом транспортного засобу та ймовірністю його відмови. Для відтворення стохастичної операційної мінливості, характерної для середніх підприємств автомобільного транспорту, було розроблено симульований масив даних, що відображав експлуатацію 50 транспортних засобів протягом 12 місяців за допомогою симуляції Монте-Карло. Масив даних включав технічні, експлуатаційні, надійності та економічні параметри. Для забезпечення порівнянності гетерогенних змінних застосовувалася нормалізація методом «мінімум-максимум», після чого було розроблено інтегрований індикатор технічного стану з використанням динамічних коефіцієнтів ваги на основі експертної оцінки та кореляційного аналізу. Валідація моделі здійснювалася за допомогою коефіцієнта Nagelkerke R^2, середньої абсолютної помилки, кореня середньоквадратичної помилки та статистичних тестів Вальда для визначення значущості коефіцієнтів регресії. Результати показали, що запропонована модель дозволяє здійснювати комплексну класифікацію транспортних засобів за рівнем технічної готовності та значно підвищує ефективність планування технічного обслуговування порівняно з традиційними підходами до планових ремонтів. Аналіз засвідчив, що технічне погіршення у поєднанні з високим експлуатаційним навантаженням суттєво підвищує ймовірність відмов. Запропонована методологічна основа зменшила обсяг незапланованого простою транспортних засобів на 42 %, скоротила витрати на технічне обслуговування на 20 % та підвищила точність прогнозування з 62 % до 85 %. Регресійна модель підтвердила наявність сильного оберненого зв’язку між інтегрованим індикатором технічного стану та ймовірністю відмови транспортного засобу. Практичне значення дослідження полягає у наданні підприємствам автомобільного транспорту інструменту, заснованого на даних, для планування прогнозованого обслуговування, розподілу ресурсів, прийняття рішень щодо модернізації автопарку та підвищення експлуатаційної надійності в умовах динамічної транспортної діяльності

Ключові слова: прогнозне технічне обслуговування; управління парком транспортних засобів; виробничі процеси; інтелектуальна діагностика; модель; ефективність

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Integration of automated multimodal transportation management methods and occupational safety systems in transport and logistics processes

Olena Sorochynska*
Associate Professor
National Transport University
01010, 1 Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0003-2477-1275

Oleksandr Bovkun
Postgraduate Student
National Transport University
01010, 1 Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0000-9760-6153

Abstract. The increasing complexity of multimodal transport chains under digital transformation creates the need for integrated management approaches that simultaneously ensure transportation efficiency and occupational safety. Across numerous transport and logistics enterprises, transportation management systems and occupational safety systems continue to operate separately, which reduces coordination efficiency, creates information gaps, and increases operational risks during transportation processes. This research aimed to design and validate integrated approaches for combining automated multimodal transport management with occupational safety systems, enhancing operational efficiency, reliability, and risk mitigation in transport and logistics processes. The study applied a conceptual modelling approach based on system analysis, multi-criteria evaluation, probabilistic risk assessment, scenario simulation, and sensitivity analysis. A simulation model was developed in AnyLogic to analyse three management scenarios with different levels of automation and system integration. The model evaluates transportation time, operating costs, downtime duration, number of incidents, and the integral occupational risk indicator under predefined operational conditions. Input parameters reflected typical operational conditions of transport enterprises and were varied to test model sensitivity. The results showed that the integrated model demonstrated the best overall performance among all analysed scenarios. The integral risk indicator decreased from 0.42 in the traditional system to 0.17 in the integrated model. Transportation time was reduced from 18.5 to 13.1 hours, downtime decreased from 120 to 58 hours per month, and the number of incidents declined from 12 to 4 cases per operational cycle. Operating costs decreased by approximately 22%. Sensitivity analysis confirmed the stability and internal consistency of simulation results. The practical value of the study lies in the potential application of the proposed model for developing digital decision-support systems for multimodal transport enterprises

Keywords: monitoring systems; risks; human factor; digital technologies; reliability

Introduction

Multimodal transportation plays an increasingly important role in modern logistics systems due to the growth of international trade, expansion of supply chains, and rising requirements for delivery speed and service quality. The combination of road, rail, maritime, and air transport within a single logistics chain creates additional opportunities for improving transportation efficiency, but at the same time significantly complicates operational management processes. The functioning of multimodal transport systems requires coordination between multiple participants, continuous information exchange, and rapid response to changes in transportation conditions. In recent years, transport companies have increasingly implemented automated management systems, digital platforms, real-time monitoring technologies, and decision-support tools to improve route planning, reduce delays, and optimise resource utilisation. At the same time, transport and logistics operations remain associated with significant occupational safety risks. Loading operations, maintenance of transport equipment, warehouse activities, and dispatch management may expose employees to hazardous working conditions. Technical failures, human

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*Corresponding author (*ellena06.84@ukr.net*)

errors, and poor coordination between participants in the logistics chain may lead not only to economic losses but also to workplace injuries and operational disruptions. The growing use of automation technologies has created new opportunities to reduce such risks. Digital monitoring systems and intelligent controls allow transport operators to detect operational deviations faster, improve process transparency and strengthen security controls. Nevertheless, in many practical applications, the haulage management and occupational health systems continue to function separately. Most existing approaches focus on either optimising transport or reducing occupational risk. The issue of integrating these components into a single management system remains poorly understood, in particular in the context of multimodal transport.

The scientific community is showing a growing interest in two interrelated areas of research: improving the efficiency of multimodal transport systems through digitalisation and optimisation, and ensuring occupational safety in automated logistics settings. With the obvious interdependence of these problems, they were mainly studied separately, which formed a significant gap in scientific knowledge. The issue of sustainability of multimodal systems under dynamic environments is explored in the work by N. Wang *et al.* (2023), where a comprehensive framework was proposed that take into account both passenger demand and infrastructure constraints. The authors emphasised the need for adaptive management models that are favourable to respond effectively to transport failures. At the same time, aspects of occupational health and safety remained outside the proposed evaluation structure, which limited the practical applicability of the obtained results. A systematic review of optimisation approaches in multimodal freight transport was presented in the work by C. Archetti *et al.* (2022). The authors summarised multi-criteria models that integrate indicators of cost, time and reliability, and outline the problem of harmonising these criteria in a single analytical framework. At the same time, security parameters related to personnel risks were overlooked in the context of optimisation goals. An algorithmic approach to route planning for regular multimodal transport was developed in a study by N. Dini *et al.* (2024). The proposed methodology provides an increase in operational performance under various constraints through formal optimisation. However, the model was focused exclusively on transport efficiency and does not involve the integration of occupational risk indicators.

Optimisation of cargo flows in broken multimodal networks were considered in the work by M. Ahmady & Y. Eftekhari Yeghaneh (2022). The authors justified the importance of mathematical modelling for processing uncertainty in freight transportation systems. Despite addressing issues of operational instability, the study does not establish a link between failure management and workplace safety monitoring. Probabilistic modelling of intermodal processes using stochastic Petri nets is presented in the paper by Y. Lei *et al.* (2024). The proposed approach allowed to reproduce the complexity and variability of multimodal coordination however, the study focused mainly on the synchronisation of transport operations, leaving the issue of labour safety integration outside the scope of the analysis. The issue of labour protection in the conditions of digitalisation was highlighted in the work by N. Karanikas *et al.* (2022), which examined the principles of system thinking laid down in the ISO 45001 standard. The authors identified structural gaps in the compliance of current safety standards with the requirements of highly automated production environments, which indicated the need to develop integrated management solutions. The empirical basis for the impact of Industry 4.0 technologies on labour safety indicators was formed in the study of G. Aran-Landin *et al.* (2023). The obtained results proved that automation, reducing the impact of traditional physical hazards, simultaneously creates new risks associated with the reliability of digital systems and the nature of human-machine interaction. Organisational aspects of implementing digital monitoring in the interests of security were considered in the work of I.C. Obasi & C. Benson (2025). The authors emphasised that real-time monitoring systems increase the effectiveness of detecting dangerous situations, but their practical effectiveness depends on the degree of integration into operational decision-making processes. An overview of modern technologies of sensors and analytics in the context of occupational safety management was presented in the work of O. Flor-Unda *et al.* (2023). The authors argued that technological data acquires practical value only if it was embedded in existing management systems, and not functions as a separate tool. The transformation of the human operator role in automated production environments was addressed in a study by L. Cunha *et al.* (2022) and J.E. Naranjo *et al.* (2025). The authors analysed the risks caused by a gradual decrease in the level of direct human control and justified the need for integrated systems of monitoring and decision support. The application of digital twins for predictive maintenance and risk detection in transport systems was investigated in the publication of S. Werbinska-Wojciechowska *et al.* (2024). Despite the demonstrated advantages in terms of improving the reliability of technical systems, the proposed methodology does not extend to the task of monitoring occupational safety.

Thus, the current state of scientific research shows significant progress in two mostly separate directions: optimisation of multimodal transport systems and digitalisation of labour safety management. Available studies only occasionally combine these components in a single functional and model structure. The mentioned fragmentation is especially noticeable in multimodal logistics, where the complexity of interdepartmental coordination increases risks both at the operational level and in the plane of labour safety. The lack of integrated models that would simultaneously formalise transport optimisation and occupational risk management constitutes a scientific and practical gap that this study aims to address. The purpose of the research was to develop and scientifically substantiate approaches to integrating methods of automated management of multimodal transportation with systems for ensuring occupational safety in transport and logistics processes in order to increase their efficiency, reliability, and safety. To achieve the research goal, three main tasks were defined:

1) to analyse modern approaches to automated multimodal transportation management and occupational safety systems in the context of digitalisation;

2) to develop a formalised multi-criteria model that integrates economic, time and safety parameters within a unified management framework;

3) to evaluate the effectiveness of the proposed model using scenario-based simulation and sensitivity analysis.

Materials and Methods

By its nature, this study was conceptual and built on the modelling of – without experiments and without enterprise-specific data. Generalised illustrative parameters were employed to evaluate how modifications in the management structure influence key operational indicators. Object and subject of research. The object of the study was the logistics process of a transport enterprise, which involves multimodal transportation. Research subject – integration of automated transportation management methods with occupational health and safety systems within a single management model. System analysis was used to determine the structure of the integrated management model and the connections between its elements. Simulation modelling was used to reproduce the logistics cycle and compare different management scenarios. The multi-criteria evaluation based on C. Archetti *et al.* (2022) allowed the analysis of performance simultaneously in terms of indicators, system cost and risk. A simple probable risk score was used to calculate the integral R score. The simulation was implemented in the AnyLogic environment. The model created a generalised logistics cycle of a transport enterprise: subsequent transport operations in which risk events and management decisions responsive to them are embedded. The parameters used in the simulation are presented in Table 1.

Table 1. Input parameters and ranges used for simulation modelling

Parameter	Value/range	Description
Number of operations per cycle	1,000	Simulation workload
Average transportation distance	250 km	Typical multimodal route length
Number of identified risks	10	Risk set used in model
Probability of risk occurrence (p_i)	0.01-0.15	Range for probabilistic assessment
Severity of consequences (s_i)	1-10	Expert scale
Automation level (A)	0.2-0.9	Scenario variation parameter

Source: developed by the authors

These values were selected as illustrative typical inputs to demonstrate model behaviour rather than to replicate a specific real enterprise. For each operation, the model calculates: transportation time (T); operating costs (C); occurrence of risk events; number of incidents; downtime duration. The integral risk indicator (R) was calculated using simple probabilistic assessment (Pajić & Andrejić, 2023):

$$R = \sum_{i=1}^{n} p_i \cdot s_i, \quad (1)$$

where p_i – probability of occurrence of the i-th dangerous event; s_i – the severity of its consequences (scale 1-10); n – total number of identified risks.

System performance was evaluated using a multi-criteria objective function with normalised indicators (Okyere *et al.*, 2022):

$$F = \alpha \cdot \frac{C}{C_{max}} + \beta \cdot \frac{T}{T_{max}} + \gamma \cdot \frac{R}{R_{max}} \rightarrow min, \quad (2)$$

where C – total transportation costs, USD; T – delivery time, hours; C_{max}, T_{max}, R_{max} – normalisation coefficients; α, β, γ – weighting factors. Weights ($\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.3$) were determined according to a reasoned assessment of the relative significance of the criteria.

Three scenarios were defined to represent different levels of automation and functional integration in the transport management system. Their characteristics are presented in Table 2. The scenarios differ in automation, route optimisation, safety monitoring, and system integration, illustrating a progressive enhancement from minimal to full operational capabilities. A sensitivity analysis was conducted by varying the automation level (0.2-0.9) while keeping all other parameters constant. The impact of these changes was observed on the integral risk indicator, transportation time, number of incidents, and downtime. To confirm the reliability of the model, three validation procedures were applied, focusing on internal consistency and practical plausibility of results. First, a logical consistency check confirmed that changes in input parameters lead to expected and coherent changes in output indicators, including risk level, number of incidents, downtime, and transportation time. Second, a sensitivity check demonstrated that gradual variation of the automation parameter produces smooth and monotonic changes in all output indicators, without abrupt fluctuations, confirming the stability of functional relationships in the model. Third, a plausibility check showed that simulated results correspond to reported ranges in transport logistics studies for medium-distance multimodal freight transport, confirming the realism of model outputs under the adopted assumptions.

Table 2. Characteristics of management scenarios used in simulation

Scenario	Automation level	Route optimisation	Safety monitoring	System integration
Traditional system	0.2	No	No	Absent
Partial automation	0.5	Yes	Limited	Partial
Integrated model	0.85	Yes	Full	Full

Source: developed by the authors

On routes 200-300 km long, the delivery time is usually between 12 and 24 hours depending on how harmoniously the different modes of transport interact, how loading is organised and whether delays are created at transfer points. The model gives values between 13.1 and 18.5 hours for excellent scenarios and they all fit into this realistic section. A similar picture with downtime. For transport enterprises with an average load of the fleet, monthly downtime is necessarily fixed within 50-150 hours depending on the technical condition, frequency of incidents and service organisation. Simulated values of from 58 to 120 hours – are accurately passed into this part. The frequency of incidents in transport and warehouse operations for enterprises with a comparable load is usually described as 3-15 cases per operating cycle. The model results of from 4 to 12 incidents do not go beyond these limits and naturally change when the automation and integration parameters vary. Of course, the described procedures do not replace full empirical verification. But the fact that model values coincide with real working functions already says a lot: the model does not produce abstract numbers detached from practice. It works within the limits characteristic of real transport and logistics systems, which confirms its conceptual and practical validity for scenario analysis within the given assumptions. The results are indicative and reflect model behaviour under predefined assumptions. The model does not account for implementation costs, personnel training costs, cybersecurity risks, or infrastructure adaptation constraints. Figure 1 presented an integrated system for multimodal transport management and occupational safety, illustrating the interaction of data collection, analytics, transport and safety management, and decision support to enhance efficiency, risk mitigation, and adaptability.

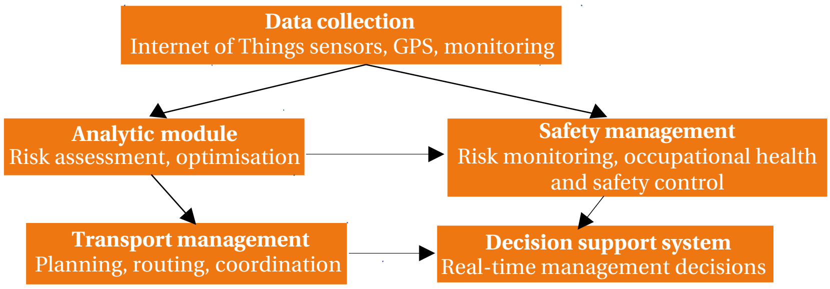

Figure 1. Conceptual scheme of the integration of automated multimodal transport management and occupational safety systems

Source: developed by the authors

Figure 1 showed the flow of information between system components, where IoT sensors and GPS data fed into the analytic and safety modules, which in turn coordinated transport operations and generated real-time management decisions. It highlighted the sequence of data-driven decision-making and risk control across the integrated transport and occupational safety system. A single information environment ensures seamless interaction between all participants in the process – from multimodal transport operators to occupational health and safety services and management. This allows not only to effectively coordinate transport operations, but also to constantly monitor key safety indicators, such as the probability of accidents, vehicle overloading and violations of occupational health and safety rules by personnel. In addition, the integration system includes adaptive management algorithms that take into account dynamic changes in transportation conditions and risks in real time. This ensures timely response to dangerous events, automatic route adjustment, optimal resource allocation and provision of recommendations on safe personnel behaviour.

Results and Discussion

The simulation modelling made it possible to assess how different levels of automation and system integration influence the key performance indicators of transport and logistics processes. Since the study is simulation-based, the results should be interpreted as indicative and demonstrating model behaviour under predefined assumptions. Table 3 presents the generalised results obtained for the three modelled scenarios. When moving from a traditional system to an integrated management model, all indicators improve – and this is not a coincidence, but a natural result of the internal logic of the model. The mechanism is simple: the higher the level of automation, the fewer operations require manual intervention. And less human factor – is a lower likely component in the risk calculation, and, accordingly, fewer incidents. Transport time is reduced by automated route optimisation and better coordination between stages of transportation – delays between processes simply disappear (Dini *et al.*, 2024). Operating costs are reduced not so much by direct savings from automation as by reducing downtime and reducing disruption caused by incidents. The downtime itself is shortened because the integrated system detects failures faster and reacts to them more coherently. At the same time, it is critical to acknowledge the limitations of the model: it may overestimate operational efficiency and does not incorporate the financial and logistical challenges associated with digital transformation, including implementation costs, personnel training, cybersecurity risks, and infrastructure adaptation requirements. Therefore, with the results of Table 3, these are model estimates within given assumptions, and not a guaranteed forecast for any transport enterprise. Comparative analysis of scenarios demonstrated on Figure 2.

Table 3. Results of simulation modelling for three management scenarios

Indicator	Traditional system	Partial automation	Proposed model
Risk level (R)	0.42	0.28	0.17
Transportation time (hours)	18.5	15.2	13.1
Operating costs (%)	100	87	78
Number of incidents	12	7	4
Downtime (hours/month)	120	82	58
Automation level	0.2	0.5	0.85

Source: developed by the authors

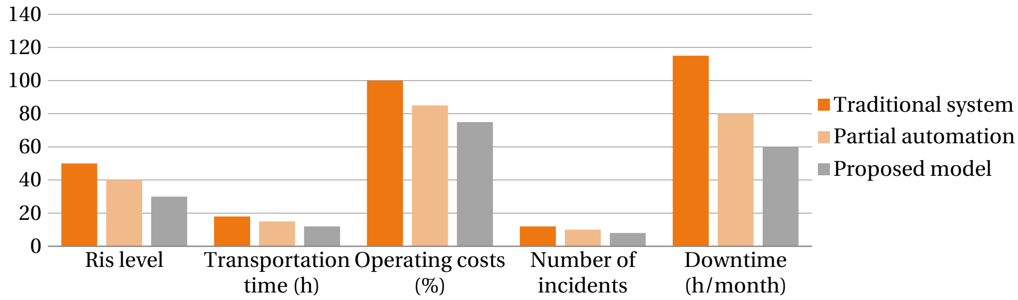

Figure 2. Comparative analysis of performance indicators for three management scenarios
Source: developed by the authors

The proposed model is assessed against four criteria: minimisation of incidents and downtime as indicators of technical reliability; reduction of operating costs as a measure of economic efficiency; reduction of transportation time as a performance benchmark; and decrease in the integral risk indicator as a safety outcome. Together, these criteria underpin the comparative analysis across management scenarios and serve as the interpretive framework for the simulation results. Figure 2 provides a visual comparison of key operational indicators across three scenarios: the traditional system, partial automation, and the proposed integrated model. The comparison highlights the magnitude of performance changes and identifies which indicators are most sensitive to improvements in management and system integration. The most pronounced changes are observed in indicators directly related to operational reliability. The number of incidents decreases from 12 cases in the traditional system to 4 cases in the proposed model, representing a 66.7% reduction. Monthly downtime is reduced from 120 to 58 hours, corresponding to a 51.7% decrease. These results indicate that systematic diagnostics and predictive analytics primarily enhance the stability of transport operations and deliver the most tangible improvements in reliability.

When evaluated across all defined criteria – incidents and downtime, operating costs, transportation time, and integral risk level the integrated model demonstrates the most balanced performance across all parameters. Two indicators show the highest sensitivity to management changes: the number of incidents (-66.7%) and downtime (-51.7%). This is expected, as these indicators most directly reflect system reliability, where integration effects are strongest. Transportation time and operating costs demonstrate moderate reductions (-27.8% and -22%, respectively). The integral risk indicator shows a substantial decrease due to the cumulative effect of multiple probabilistic components embedded in the model structure. Operating costs decrease by 21% in the proposed model compared to the traditional system. This reduction is primarily associated with fewer emergency repairs, improved maintenance planning, and more rational allocation of technical and human resources. Transportation time exhibits smaller relative changes than reliability indicators. The reduction from 18 to 13 hours (-27.8%) is constrained by the influence of external logistical conditions, which are only partially controlled by management decisions. The smallest absolute changes are observed in the integral risk level. Although it decreases consistently across scenarios, the reduction is gradual because risk is an aggregated indicator influenced by multiple external and internal factors. Improvements in internal processes alone cannot produce abrupt changes in this parameter. Figure 3 illustrates the dependence of the integral risk level on the degree of automation.

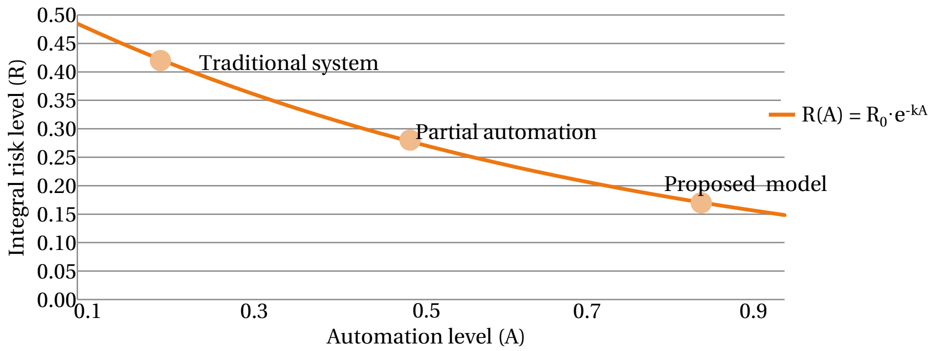

Figure 3. Dependence of risk level on the degree of automation in transport and logistics processes
Source: developed by the authors

To plot Figure 3, the level of automation in simulation models was raised step by step from 0.2 to 0.9, all other parameters being unchanged. For each intermediate value, the integral risk measure R was calculated anew. The resulting curve reflects the internal logic of the built-in probabilistic risk model: as automation increases, the risk decreases nonlinearly. It is important to understand that this is not a universal regularity, empirically confirmed – is the behaviour of a specific model under given conditions. A sensitivity analysis was performed to further verify the reliability of the results. He showed that the change in the level of automation each time gave predictable and logically explained changes in R, T, number of incidents and duration of downtime. This confirms that the model is internally consistent and behaves stably. The observed improvements are consistent with the internal structure of the simulation model, where increased automation reduces risk exposure and operational disruptions. In addition, the implementation of automated control algorithms allows for reduced transportation time by optimising routes and increasing coordination between different modes of transport. The reduction in operating costs is due to more efficient use of resources, reduced downtime, and minimised losses associated with emergency situations. For each scenario, the integral risk indicator was calculated using the normalised system of operational, technical, and safety indicators described in the methodology section (Fig. 3).

The results of this study can be compared with low work, considering automation, risk assessment and decision support in logistics and occupational health and safety – each with adding to the topic in its own way. G. Fragapane *et al.* (2021) investigated autonomous mobile robots in internal logistics in detail. Their conclusion: when decisions are made at separate levels of agents, without centralised management, the warehouse reacts faster and loses less time to delay. The research proposal is supposed to be on the same logic, but go beyond warehouse logistics to multimodal transport chains. It appears that the principles of autonomy and coordination, which have well recommended themselves at the level of individual facilities, also effectively reduce the number of incidents and downtime in intermodal logistics. It is essential to recognise that improvements in the indicators do not occur autonomously. Achieving the reductions in downtime and incident rates predicted by the model requires systematic diagnostics, continuous data acquisition, and the implementation of predictive analytics. At the start, this means additional costs and time for team preparation. But the long-term prospect of such an investment justifies itself – operating costs are decreasing, reliability is increasing, and this is in good agreement with what other researchers in the field are recording. V. Pajić & M. Andrejić (2023) used the Fine-Kinney method to assess risks in internal transport processes. Their approach is static: risks start on a probability and severity scale at a specific moment. The same principle is used in this study, but with different mechanics: risk assessment is built into the simulation model and varies according to the level of automation. This allows the observation of risk dynamics as they evolve in response to organisational changes, rather than being assessed solely under static conditions.

The evolution of Industry 4.0 and its implications for logistics has been examined by E. Hofmann & M. Rüsch (2017), who discussed current status and future prospects in integrating digital technologies into transport and production systems. The issue of collaborative works in logistics and production is considered in the work of L. Pietrantoni *et al.* (2024), which collected expert opinions of industry specialists. The main conclusion of the authors: technology in itself does not make work safer, this happens only when it is built into the decision-making process and the organisational structure of the company. These findings corroborate the results of this study, indicating that the depth of system integration has a greater impact on operational efficiency than the level of automation alone. The role of new technologies in occupational health and safety was analysed in detail in an extensive review by L. Möckel *et al.* (2023). The authors highlight that digital monitoring, predictive analytics, and data-driven security management play an increasingly significant role. However, the question remains regarding how these tools can be effectively integrated into transport coordination. The present study addresses this gap by demonstrating how security analytics can be systematically incorporated into logistics management within a unified model. The state of occupational health and safety management in modern organisations is investigated in the work of D. Ramos *et al.* (2022). The authors emphasised that security is effective only when it is systematically integrated into operational processes, rather than functioning in parallel. This finding aligns with the simulation results, where increased reliability and reduced downtime are achieved by embedding security monitoring within transport management decisions rather than treating it as a separate function. The use of anthropocentric digital twins to ensure workplace safety was analysed by A. Kim *et al.* (2023). The study revealed the mechanisms for integrating safety data into the working environment, however, the proposed approach was not adapted to the specificity of multimodal transport chains. Multicriteria optimisation of multimodal cargo systems based on genetic algorithms was presented by S. Okyere *et al.* (2022). The proposed model provided a balance of sustainability, cost and time indicators however, occupational risk is not considered as an independent parameter in the decision-making process. The application of genetic algorithms for multimodal freight transport optimisation is addressed in the work of S. Okyere *et al.* (2022), where sustainability, time and cost are balanced within a multi-criteria model. A key distinction from the proposed approach is that professional risk is treated as a separate optimisation parameter rather than being derived from other indicators. In this way, occupational safety is considered alongside traditional logistics criteria, rather than being peripheral to the model. Overall, existing studies tend to focus either on logistics optimisation or on the digitalisation of occupational safety, but rarely address both simultaneously. The present study addresses this gap by integrating these domains within a single model. As a result, it demonstrates how automation and system integration jointly affect transportation time, operational costs, reliability, and risk, providing a comprehensive assessment that considers all aspects together rather than in isolation.

Conclusions

In this study, a multi-criteria model was developed integrating economic, temporal, and safety parameters into a single objective function. Probabilistic risk assessment, indicator normalisation, and scenario-based simulation were conducted in the AnyLogic environment. Three management scenarios were simulated, differing in automation level and system integration: a traditional system (automation 0.2), partial automation (0.5), and the integrated model (0.85). Simulation results indicate that higher automation levels combined with integration of occupational safety within transport management potentially reduce the integral risk level, downtime, transportation time, and operational costs. Specifically, the integral risk decreased to 0.17 in the integrated model compared with 0.42 in the traditional system. Transportation time was reduced from 18.5 to 13.1 hours, incidents declined from 12 to 4 per operational cycle, and monthly downtime decreased from 120 to 58 hours. Operational costs were reduced by approximately 22%. Sensitivity analysis demonstrated that the model responded predictably to changes in automation: as the automation parameter A increased from 0.2 to 0.9, integral risk, transportation time, incidents, and downtime changed smoothly, without abrupt fluctuations. This indicates internal consistency and suggests that the model plausibly reflects the dynamics of an integrated management system under the defined assumptions. Notably, the depth of integration between subsystems had a greater influence on performance than automation alone. Integration facilitates coordinated operations, route optimisation, and timely risk assessment, thereby reducing human-factor impacts and improving the reliability of transport and logistics processes. From a practical perspective, the proposed model can assist managers of transport and logistics enterprises, particularly in multimodal systems with elevated operational risk, by providing a framework to evaluate management decisions. It may also serve as a conceptual basis for digital decision-support tools that combine logistical optimisation with occupational safety management. It should be noted that the findings are indicative, based on generalised modelling parameters rather than empirical data from a specific enterprise. Therefore, they should be interpreted as guidance rather than precise forecasts. Future work should focus on validating the model using real operational data and extending its capabilities through more detailed risk assessment and advanced optimisation methods.

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None.

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Інтеграція методів автоматизованого управління мультимодальними перевезеннями та систем забезпечення безпеки праці у транспортно-логістичних процесах

Олена Сорочинська
Доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0003-2477-1275
Олександр Бовкун
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0000-9760-6153

Анотація. Зростаюча складність мультимодальних транспортних ланцюгів в умовах цифрової трансформації зумовлює потребу в інтегрованих підходах до управління, які одночасно забезпечують ефективність перевезень та безпеку праці. На багатьох транспортно-логістичних підприємствах системи управління перевезеннями та системи охорони праці й надалі функціонують відокремлено, що знижує ефективність координації, створює інформаційні прогалини та підвищує операційні ризики під час транспортних процесів. Метою цього дослідження було розроблення та валідація інтегрованих підходів до поєднання автоматизованого управління мультимодальними перевезеннями із системами охорони праці для підвищення операційної ефективності, надійності та мінімізації ризиків у транспортно-логістичних процесах. У дослідженні застосовано підхід концептуального моделювання, що ґрунтувався на системному аналізі, багатокритеріальному оцінюванні, ймовірнісній оцінці ризиків, сценарному моделюванні та аналізі чутливості. В середовищі AnyLogic було розроблено імітаційну модель для аналізу трьох сценаріїв управління з різними рівнями автоматизації та системної інтеграції. Модель оцінює тривалість перевезень, операційні витрати, тривалість простоїв, кількість інцидентів та інтегральний показник професійного ризику за визначених експлуатаційних умов. Вхідні параметри відображали типові умови функціонування транспортних підприємств і варіювалися для перевірки чутливості моделі. Результати показали, що інтегрована модель продемонструвала найкращі загальні показники серед усіх проаналізованих сценаріїв. Інтегральний показник ризику знизився з 0,42 у традиційній системі до 0,17 в інтегрованій моделі. Тривалість перевезень скоротилася з 18,5 до 13,1 години, простої зменшилися зі 120 до 58 годин на місяць, а кількість інцидентів скоротилася з 12 до 4 випадків за операційний цикл. Операційні витрати знизилися приблизно на 22 %. Аналіз чутливості підтвердив стабільність та внутрішню узгодженість результатів моделювання. Практична цінність дослідження полягає в потенційному застосуванні запропонованої моделі для розроблення цифрових систем підтримки прийняття рішень для підприємств мультимодальних перевезень

Ключові слова: системи моніторингу; ризики; людський фактор; цифрові технології; надійність

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Research on the energy efficiency of a traction induction electric drive for a shunting locomotive

Ievgen Riabov*
Assistant Professor
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0753-514X

Yevhen Lysenko
Postgraduate Student
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0009-0007-1263-7446

Bagish Yeritsyan
Assistant Professor
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychov Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0579-3882

Iryna Bilokon
Director
Kremenchuk Vocational College
of Transport Infrastructure and Technologies
39600, 14 Yuri Ruf Str., Kremenchuk, Ukraine
https://orcid.org/0000-0002-4675-3994

Anton Zhukov
Independent Researcher
LLC "Kharkiv Electric Machine-Building Plant"
61037, 199 Heroiv Kharkova Ave., Kharkiv, Ukraine
https://orcid.org/0009-0001-5229-1685

Abstract. The modernisation of the fleet of locomotives used on Ukrainian railways for shunting operations is essential to improve the reliability of rail transport, reduce fuel and energy costs, and minimise the negative impact on the environment. The aim of this work was to investigate the energy efficiency of an induction traction drive for a shunting locomotive, which influences the locomotive's traction and energy performance. The ChME3 shunting diesel locomotive was selected for the study, for which the energy efficiency indicators of the traction drive with 140 kW induction electric motors were determined through mathematical modelling. The results of the calculations showed that the ChME3 diesel locomotive can utilise an induction traction drive with either four or six electric motors. For both variants, calculations of the tangential power were performed at various positions of the driver's controller, and it was determined that both variants exhibit high energy performance. At the same time, the six-motor traction induction electric drive provided an increase in tangential tractive force compared to a traction electric drive with commutator motors. A comparison was made of the efficiency of the traction induction electric drive and a standard electric drive with commutator motors. It has been determined that the efficiency of the traction induction drive is higher across the entire load range, confirming the feasibility of using a traction induction electric drive on shunting locomotives. The findings of this study can be utilised in the development of new shunting locomotives and the modernisation of existing ones at domestic and foreign enterprises

Keywords: energy effectiveness; energy and resource saving; induction electric motor; power; rolling stock

Introduction

Improving the efficiency of rail transport is a key priority, the achievement of which requires a comprehensive approach and involves streamlining the organisational management of the transport process, upgrading technical transport infrastructure, advancing digitalisation for rail logistics tasks, and so on. Rolling stock has a direct impact on the stability of rail transport, and therefore it is subject to strict requirements regarding traffic safety, the need for high operational performance, and low environmental impact, among other things. Currently, the technical condition of most railway rolling stock, particularly locomotives, is characterised as obsolete: locomotives built 40-50 years ago have poorer operational characteristics than modern locomotives.

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*Corresponding author (*yevhen.riabov@khpi.edu.ua*)

This makes it necessary to modernise the traction rolling stock and requires the search for technical solutions that will ensure high operational performance of the traction rolling stock.

Current regulations, such as Resolution of the Cabinet of Ministers of Ukraine No. 1550… (2024), provide for the modernisation of the railway rolling stock through the use of energy-efficient equipment and technologies. Currently, the technical characteristics of locomotives used for shunting operations at stations of JSC "Ukrzaliznytsia" do not meet modern requirements for energy efficiency and low environmental impact. This is due to the long service life of locomotives, which were created several decades ago using equipment available at that time. Another aspect is that locomotives were created as unified machines that can be used in different conditions. As a result, their characteristics do not correspond to the actual operating conditions, which leads to excessive consumption of fuel and energy resources. Given the long service life of the existing shunting locomotives, their modernisation is essential, and energy-saving technologies will be implemented in the process. Analysis shows that the main objective in this area is to reduce fuel and lubricant consumption, for which modern diesel engines or separate systems are being installed, as evidenced by the experience of modernising diesel locomotives at Mykolaiv Locomotive Repair Plant LLC (NTRZ, n.d.). J. Pagenkopf *et al.* (2022) and G. Bakyt *et al.* (2025) also point to reduced fuel consumption as the key factor in improving the efficiency of shunting locomotives, which determines the direction of improvements to outdated locomotives. More promising is the modernisation of diesel locomotives using modern diesel-generator sets, AC-DC electrical transmission, electric fan motors, etc. This allows for a reduction in diesel fuel consumption, lower maintenance and repair costs, and so on. In Ukraine, such work is carried out by Mykolaiv Diesel Locomotive Repair Plant LLC (NTRZ, n.d.), Poltava Locomotive Repair Plant LLC (TRZ, n.d.) and other enterprises.

However, almost all modernisation options involve retaining the standard brush-type electric motors. Yu. Syrotenko (2016), A. Falendysh *et al.* (2019) and D. Zaika (2024) are investigating precisely such modernisation options for shunting diesel locomotives. However, retaining commutator motors significantly limits the potential for improving the energy efficiency of the traction drive, as in operating modes requiring increased tractive force, the traction motors operate at higher currents. This significantly limits the possibility of increasing the energy efficiency of the traction electric drive, since in operating modes with increased traction force, traction electric motors operate with increased currents. In such modes, the efficiency of the traction electric drive is significantly reduced, and the risk of thermal damage to the electric motor components also increase. It is impossible to achieve a significant increase in traction properties while maintaining collector electric motors. Therefore, it is urgent to search and study ways to increase the traction and energy characteristics of shunting locomotives by improving their traction electric drive.

The purpose of the work was to study the energy efficiency of a traction induction electric drive for a shunting locomotive. The tasks of the work were to determine the energy efficiency indicators of a traction induction electric drive and compare it with a serial traction electric drive based on collector electric motors.

Materials and Methods

For the study, the authors selected the ChME3 diesel locomotive, which is the main shunting locomotive of JSC "Ukrzaliznytsia", and is also used at many industrial enterprises for shunting and export operations. It is well known that the use of traction induction motors allows for an increase in the gear ratio of the traction gearbox. This, in turn, reduces the size of the induction motor, which has a positive effect on its layout within the wheel-motor unit. With this in mind, the authors have proposed a new wheel-motor unit with a traction gearbox having a gear ratio of 5.929. (the number of gear teeth is 83, the number of gear teeth is 14). A general view of the developed wheel-motor unit is shown in Figure 1. Traction induction motor – with axial rolling bearings. A coupling is used to compensate for the misalignment between the axes of the electric motor shaft and the input shaft of the traction gearbox.

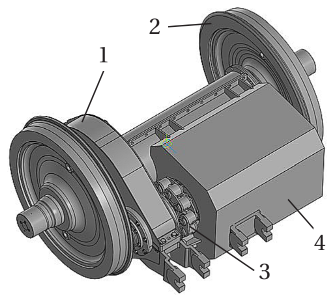

Figure 1. 3D sketch of the wheel-motor unit

Note: 1 – traction gear-box; 2 – wheel-set; 3 – clutch; 4 – traction motor

Source: created by the authors

Based on the power of the serial diesel locomotive ChME3, which is 1350 hp (992 kW), for a six-axle diesel locomotive it is necessary to use a traction electric motor with a power of 140 kW. The authors performed calculations and a sketch layout of such a traction induction electric motor. The calculations for the electric motor were carried out in accordance with the recommendations set out in D. Tsypenkov *et al.* (2020). In the calculations, it was assumed that the traction electric drive should provide a continuous traction force of 360 kN and operate at rated power up to a speed of 60 km/h. The maximum speed of the locomotive is 90 km/h. According to the results of the calculations, an eight-pole three-phase electric motor with a short-circuited rotor winding was selected. The calculated parameters of the electric motor are given in Table 1. To assess energy efficiency, the parameters of the traction induction electric motor were determined. The calculations were performed with a sinusoidal power supply. The calculation did not take into account losses due to higher-order harmonics in current and voltage, nor losses in semiconductor converters. For the purposes of this study, the omission of these losses does not introduce significant errors, but it does significantly simplify the calculation model. Calculations of the parameters of losses in electric motors and the parameters necessary for their calculation were performed using the algorithm below, based on the recommendations V. Bezruchenko *et al.* (2003) and I. Riabov *et al.* (2025). The calculation algorithm involved performing the following calculations:

1) Set the power frequency and phase voltage;

2) Calculate the correction factor that takes into account the saturation of the magnetic core:

$$C_1 = \sqrt{\left(1 + \frac{X_1}{X_m}\right)^2 + \left(\frac{R_{1T}}{X_m}\right)^2}, \quad (1)$$

where $X_1 = 2\pi f_1 L_1$ – inductive resistance of the stator; $X_m = 2\pi f_1 L_m$ – inductive resistance of the magnetising circuit; R_{1T} – active resistance of the stator winding in a heated state; f_1 – fundamental voltage harmonic frequency.

3) Calculate the equivalent active resistance of an electric motor:

$$R_{eq} = C_1 \left(R_{1T} + C_1 \frac{R'_{2T}}{s}\right), \quad (2)$$

where R'_{2T} – the active resistance of the rotor winding in the heated state is given; s – relative slip.

To calculate energy efficiency indicators, the power distribution by the positions of the controller of the serial locomotive driver was used (Table 2).

Table 1. Design parameters of a traction induction electric motor

Parameter name/unit of measurement	Value
Mode of operation	continued
Power, kW	140
Nominal linear voltage, V	315
Maximum linear voltage, V	460
Phase current, A	342
The largest phase current at start-up, A	450
Nominal torque, Nm	5,500
Starting torque, Nm	7,700
Nominal frequency, Hz	16.8
Maximum frequency, Hz	130
Nominal rotation speed, s-1 (rpm)	243
Maximum rotation speed (at a speed of 90 km/h), s-1 (rpm)	3,000
Rotational speed range when operating at rated power, rpm	244…2,040
Efficiency in nominal mode when powered by sinusoidal voltage, %	90.6
Power factor in nominal mode, p.u.	0.82
Multiplicity of maximum torque at a speed of 2,040 rpm, rated power and rated line voltage, p.u.	1.2
Cooling air flow rate, m^3/s	0.3
Number of phases	3
The number of pairs of poles	8

Source: developed by the authors

Table 2. Characteristics of the diesel locomotive ChME3

Driver controller position	Power supplied to traction motors, kW	Traction force during start, kN
0	-	-
1	28	90
2	98	180
3	220	246
4	310	312
5	410	360
6	530	360
7	720	360
8	880	360

Source: developed by the authors based on Ukrzaliznytsia (n.d.)

4) Calculate the equivalent inductive resistance of an electric motor:

$$X_{eq} = C_1(X_1 + C_1 X'_2), \quad (3)$$

where $X'_2 = 2\pi f_1 L'_2$ – reduced inductive resistance of the rotor winding.

5) Calculate the equivalent resistance of an electric motor:

$$Z_{eq} = \sqrt{R_{eq}^2 + X_{eq}^2}, \quad (4)$$

6) Calculate the reduced rotor current:

$$I'_2 = \frac{C_1 U_{1ph}}{Z_{eq}}, \quad (5)$$

where U_{1ph} – effective value of the first harmonic phase voltage.

7) Calculate the active component of the stator current:

$$I_{1a} = I_{0a} + \frac{U_{1ph}}{Z_{eq}} \cos\varphi'_2, \quad (6)$$

where I_{0a} – active component of the no-load current; φ'_2 – the angle between the vectors I'_2 and U_{1ph}. At the same time $\cos\varphi'_2 = \frac{R_{eq}}{Z_{eq}}$.

8) Calculate the active component of the no-load current:

$$I_{0a} = \frac{P_{st1} + mI_\mu^2 R_{1T}}{mU_{1ph}}, \quad (7)$$

where P_{st1} – losses in the stator magnetic circuit at voltage U_{1ph} and frequency f_1 (are calculated for (14)); I_μ – magnetising current at voltage U_{1ph} and frequency f_1; m – number of phases of the electric motor.

9) Calculate the reactive component of the stator current:

$$I_{1r} = I_\mu + \frac{U_{1ph}}{Z_{eq}} \sin\varphi'_2, \quad (8)$$

where $\sin\varphi'_2 = \frac{X_{eq}}{Z_{eq}}$.

10) Calculate the effective value of the stator phase current according to the first harmonic:

$$I_{1ph} = \sqrt{{I_{1a}}^2 + {I_{1r}}^2}. \quad (9)$$

11) Calculate the power factor of an electric motor:

$$\cos\varphi = \frac{I_{1a}}{I_{1ph}}. \quad (10)$$

12) Calculate the active power taken from the source

$$P_1 = mU_{1ph} I_{1a}. \quad (11)$$

13) Compare the power value calculated by the (11), with the power value supplied to the electric motor $P_{1M} = \frac{P_{DC}}{N_M}$. In this expression P_{DC} – power supplied to the traction electric drive; N_M – number of traction motors.

Calculations according to expressions (1)-(11) are carried out until the value calculated according to (11) does not differ significantly (no more than 5%) from the specified power value P_{1M}. To do this, change the supply frequency f_1 and phase voltage U_{ph1}. When the electric drive operates in the first zone – with constant torque – the ratio between the supply frequency and voltage must correspond to the proportional law $\frac{U}{f} = const$, which approximately corresponds to operation with constant flux linkage $\Psi = const$. When operating in the second zone – with constant power – the supply voltage does not change ($U = const$), and changing the supply frequency leads to a weakening of the flux linkage. After determining the operating parameters of the electric motor, the losses and efficiency of the electric motor are determined using the model below.

Stator winding losses:

$$P_{e1} = mI_{1ph}^2 R_{1T}. \quad (12)$$

Rotor winding losses:

$$P_{e2} = m(I'_2)^2 R'_{2T}. \quad (13)$$

Losses in the magnetic core:

$$P_{st1} = P_{stnom} \left(\frac{\psi_1}{\psi_{1nom}}\right)^2 \left(\frac{f_1}{f_{1nom}}\right)^{1,5}, \quad (14)$$

where P_{stnom} – losses in the magnetic core (all types of magnetic losses) at rated voltage and frequency; ψ_1 – flux linkage under voltage U_{1ph} and frequency f_1:

$$\psi_1 = \frac{U_{1ph}}{4.44 f_1}, \quad (15)$$

ψ_{1nom} – nominal flux linkage:

$$\psi_{1nom} = \frac{U_{1phnom}}{4.44 f_{1nom}}, \quad (16)$$

U_{1phnom} – rated phase voltage, f_{1nom} – nominal frequency.

Mechanical losses:

$$P_{mech} = P_{mechnom} \frac{n_2}{n_{2nom}}, \quad (17)$$

where $P_{mechnom}$ – mechanical losses at rated speed .

Rotor speed:

$$n_2 = \frac{60 f_1}{p}(1 - s), \quad (18)$$

where p – number of pole pairs of an electric motor.

Additional losses (excluding losses from higher voltage harmonics):

$$P_{add} = 0.005 P_{1nom} \left(\frac{I_{1ph}}{I_{1phnom}}\right)^2. \quad (19)$$

Losses in an electric motor:

$$\Delta P = P_{e1} + P_{e2} + P_{st1} + P_{mech} + P_{add}. \quad (20)$$

Efficiency of the electric motor:

$$\eta = 1 - \frac{\Delta P}{P_1}. \quad (21)$$

Shaft power:

$$P_2 = P_1 - \Delta P. \quad (22)$$

Moment on the shaft:

$$M_2 = \frac{30}{\pi} \frac{P_2}{n_2}. \quad (23)$$

Traction power of the locomotive:

$$F_k = N_M \frac{2M_2}{D_k} \mu_{gb} \eta_{gb}, \quad (24)$$

where μ_{gb} – gear ratio of the drive reduction gear; η_{gb} – gearbox efficiency, equal to 0.98.

Locomotive speed (in km/h):

$$V = \frac{3.6 \pi D_k}{\mu_{gb}} n_2. \quad (25)$$

Power at the wheel rim (tractive power):

$$P_k = \frac{F_k V}{3.6}. \quad (26)$$

Thus, model (1)-(26) allowed for calculations of the characteristics of a locomotive equipped with a traction induction electric drive. To perform the calculations, a script has been developed in the Matlab environment for calculating the characteristics. I. Riabov *et al.* (2025) shown that it is advisable to regulate the voltage of the electric motor depending on its power. This leads to an increase in the efficiency of the electric motor and the power factor, which affects the efficiency of the traction converter. The smallest voltage value is chosen from the condition of ensuring the stability of the induction machine at the highest speed in the rated power mode. Based on this, based on the Kostenko law for frequency-controlled electric motors, the following expression was obtained, which determines the linear voltage depending on the power:

$$U_1 = U\sqrt{\frac{P_2}{P_{2nom}}}_{1max}, \quad (27)$$

where U_{1max} – the highest value of line voltage at rated power; P_2 – specified motor power; P_{2nom} – rated power of the electric motor.

Calculations were made for the speed range corresponding to operation on the hyperbolic part of the traction characteristic. The minimum speed is determined by the starting traction force at the given position of the driver's controller according to Table 2. It was worth noting that in models (1)-(11) and (12)-(26) the losses in the traction converter and the losses in the induction electric motors from higher harmonics of current and voltage were not taken into account, since for their determination it is necessary to know the algorithms of voltage modulation. Considering that such losses constitute several percent of the total power of the electric drive, they are not taken into account in this study.

Results and Discussion

Below are the results of calculations of the characteristics of the electric motor and the locomotive. The calculations were carried out for the variants of the traction induction electric drive with six and four electric motors for 1-6 driver controller positions and six electric motors for 7 and 8 driver controller positions. Tractive power was chosen as the criterion:

$$P_l = P_s \eta, \quad (28)$$

where P_s – power supplied to the traction electric drive at a given position of the driver's controller; η – traction motor efficiency.

Table 3-10 show the results of the calculations.

Table 3. Design characteristics for 1 driver controller positions (DCP) (supplied power 28 kW)

Number of electric motors	Parameters	Value				
4	Tractive power, kW	20	23	24	24	26
	Efficiency, %	67.2	79.4	83.2	85.6	81.6
	Speed, km/h	1.2	5.0	10.0	20.0	30.0
	Traction force, kN	90	25.2	12.6	6.3	4.2
6	Tractive power, kW	18	21	22.8	22.2	21
	Efficiency, %	60.0	72.7	83.2	80.8	75.5
	Speed, km/h	0.7	5.0	10.0	20.0	30.0
	Traction force, kN	90	25.2	8.5	4.2	2.9

Source: developed by the authors

Table 4. Design characteristics for 2DCP (supplied power 98 kW)

Number of electric motors	Parameters	Value								
4	Tractive power, kW	62	84	90	88	88	88	86	84	82
	Efficiency, %	64.4	87.5	92.4	92.5	92.1	90.8	89.3	87.5	85.5
	Speed, km/h	1.2	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	180	59.3	29.6	20.7	15.5	10.3	7.7	6.1	4.9
6	Tractive power, kW	63	84	87	87	87	87	84	81	78
	Efficiency, %	67.3	87.0	91.8	91.8	91.0	89.1	86.8	83.7	81.0
	Speed, km/h	1.3	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	180	59.1	29.6	19.8	14.8	9.9	7.4	5.3	4.3

Source: developed by the authors

Table 5. Design characteristics for 3DCP (supplied power 220 kW)

Number of electric motors	Parameters	Value								
4	Tractive power, kW	168	192	204	208	208	208	204	204	200
	Efficiency, %	75.9	87.2	93.1	93.9	94.0	93.6	93.0	92.2	91.3
	Speed, km/h	2.4	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	246.0	135.6	71.5	48.9	36.7	24.4	18.0	14.4	11.7

Table 5. Continued

Number of electric motors	Parameters	Value								
6	Tractive power, kW	174	192	204	210	210	204	204	204	198
	Efficiency, %	79.0	86.0	92.9	93.5	93.4	92.7	91.7	90.6	89.2
	Speed, km/h	2.5	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	246.0	134.5	71.5	49.3	36.7	23.9	18.0	14.4	11.6

Source: developed by the authors

Table 6. Design characteristics for 4DCP (supplied power 310 kW)

Number of electric motors	Parameters	Value								
4	Tractive power, kW	232	272	288	292	292	292	290	288	288
	Efficiency, %	74.9	87.3	93.0	94.1	94.3	94.1	93.7	93.2	92.5
	Speed, km/h	2.6	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	310	190	100	68.5	51.5	34.0	25.7	20.3	16.9
6	Tractive power, kW	246	270	291	294	294	291	288	288	282
	Efficiency, %	80.0	87.1	93.1	93.8	93.9	93.5	92.8	92.0	91.0
	Speed, km/h	2.8	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	310	190	100	69.1	51.9	34.5	25.4	20.3	16.6

Source: developed by the authors

Table 7. Design characteristics for 5DCP (supplied power 410 kW)

Number of electric motors	Parameters	Value								
4	Tractive power, kW	312	354	378	386	388	388	386	384	382
	Efficiency, %	76.1	86.4	92.3	94.2	94.5	94.4	94.2	93.8	93.3
	Speed, km/h	3.0	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	249	131.8	91.2	67.7	45.5	34.2	27.1	22.9
6	Tractive power, kW	330	357	381	384	384	384	381	378	375
	Efficiency, %	80.5	87.4	93.1	93.7	93.8	94.0	93.5	92.9	92.2
	Speed, km/h	3.2	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	250	133	90.5	67.7	45.0	33.8	26.6	21.8

Source: developed by the authors

Table 8. Design characteristics for 6DCP (supplied power 530 kW)

Number of electric motors	Parameters	Value								
4	Tractive power, kW	436	452	492	500	500	506	504	504	500
	Efficiency, %	82.3	84.3	92.5	93.6	93.8	94.8	94.6	94.4	94.0
	Speed, km/h	4.3	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	319	173.5	117.4	88.2	59.5	44.3	34.7	29.4
6	Tractive power, kW	441	459	489	498	498	498	498	498	498
	Efficiency, %	84.7	87.0	92.6	94.0	94.5	94.4	94.0	93.6	93.0
	Speed, km/h	4.3	5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	320	172.4	116.9	87.5	58.4	43.9	34.7	28.9

Source: developed by the authors

Table 9. Design characteristics for 7DCP (supplied power 720 kW)

Number of electric motors	Parameters	Value							
6	Tractive power, kW	642	666	678	681	678	678	678	672
	Efficiency, %	88.6	92.5	94.3	94.7	94.7	94.5	94.2	93.8
	Speed, km/h	6.2	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	234.2	159.2	119.0	79.5	59.7	47.4	39.1

Source: developed by the authors

Table 10. Design characteristics for 8DCP (supplied power 880 kW)

Number of electric motors	Parameters	Value							
6	Tractive power, kW	738	810	831	834	834	834	831	810
	Efficiency, %	89.7	91.9	94.3	94.6	94.7	94.5	94.2	93.9
	Speed, km/h	7.3	10.0	15.0	20.0	30.0	40.0	50.0	60.0
	Traction force, kN	360	289.3	197.5	147.7	98.6	74.1	58.7	48.7

Source: developed by the authors

Analysis of the data in Table 3-8 shows that at speeds above 10 km/h, the efficiency of the traction electric drive with six and four traction induction electric motors does not differ significantly. At higher speeds, the four-motor electric drive has higher efficiency. This is explained by lower magnetic losses in the electric motors. However, when working with high traction forces, the six-motor electric drive has higher efficiency. This is explained by the fact that the electric motors operate with lower current, which causes lower electrical losses. It is worth noting that the proposed wheelset unit and traction induction motor provide traction properties of the serial diesel locomotive ChME3 when using a traction electric drive with four electric motors. However, to achieve high starting traction force, it is necessary to increase the axial load. In the case of using a six-motor traction electric drive, the locomotive can achieve a traction force of 450...540 kN, depending on the axial load.

A common way to increase the traction and energy performance of shunting locomotives is to use unit modules: separate sections of locomotives equipped with a traction electric drive and, as a rule, a power plan. A. Falendysh & V. Gatchenko (2013) investigate the use of shunting locomotives as a system comprising multiple traction units. This allows for increased traction and reduced fuel consumption. Similar traction units are used for heavy shunting work, on complex profiles, and hilly work. Serial locomotives are used for medium and light shunting work. This approach involves increasing the locomotive fleet, which requires significant capital expenditures. However, as demonstrated by C. Bulucea *et al.* (2016), such traction units exhibit low electric drive efficiency under partial load conditions. To eliminate this, it is proposed and justified the feasibility of disconnecting traction electric motors when operating in partial load modes. However, it is worth noting that the use of traction commutator electric motors limits the possibilities for improving traction and energy indicators. Commutator electric motors have insufficiently high specific torque indicators, and the presence of a commutator-brush apparatus reduces reliability. In addition, for high-quality control of traction electric motors, it is necessary to use semiconductor converters, as a result of which capital costs for modernisation increase. Therefore, to ensure high traction performance and energy efficiency, it is necessary to use an electric drive system based on AC motors. This conclusion is supported by studies S. de Pancorbo *et al.* (2015), C. Bulucea *et al.* (2016), Y. Cho *et al.* (2021). Studies by A. Abouzeid *et al.* (2020) and S. Semenov *et al.* (2025) show that the use of AC electric motors enables effective control, achieving maximum torque under specified conditions of wheel-rail adhesion.

A. Abouzeid *et al.* (2020) and W. Jibin *et al.* (2022) note that, the most common type of traction motor used in modern rolling stock, particularly in new shunting locomotives, is the induction motor This is due to their high specific indicators, which allows to achieve a traction force of one axle of 70…80 kN. Also important is the reduction of maintenance and high reliability of traction induction electric motors. In addition, traction induction electric motors have higher energy efficiency indicators compared to collector electric motors. N. Zhao & N. Schofield (2016) demonstrated that optimal performance of the wheel-motor unit can be achieved through the co-design of its main components – the traction gearbox and the traction induction motor. Ensuring high energy performance of the traction electric drive is achieved not only by its optimal design, but also by using rational control algorithms. S. Wang *et al.* (2019) proved that the use of vector control algorithms in an induction motor increases its energy efficiency and improves its dynamic performance, which is important when applying traction forces at the slip threshold. Despite the large number of rolling stock units equipped with induction traction motors, specific studies are required to assess the feasibility of their use under the specific operating conditions of a locomotive. This explains the relevance of this study.

In order to compare the energy efficiency of the proposed induction traction electric drive with that of the standard electric drive of the ChME3 diesel locomotive, calculations were carried out for the standard electric drive of the ChME3 diesel locomotive. Both six-motor and four-motor electric drives were considered. The results of studies obtained in V. Shayda *et al.* (2024), Y. Lysenko & Y. Riabov (2025) were used to calculate the data for the standard electric drive. As a criterion for comparison, the tangential power at a fixed power supplied to the traction electric drive was chosen. Figures 2-9 show the dependence of the tractive power on the speed of movement for all positions of the driver's controller for both variants of the electric drive. The data on the traction induction electric drive correspond to Tables 4-10.

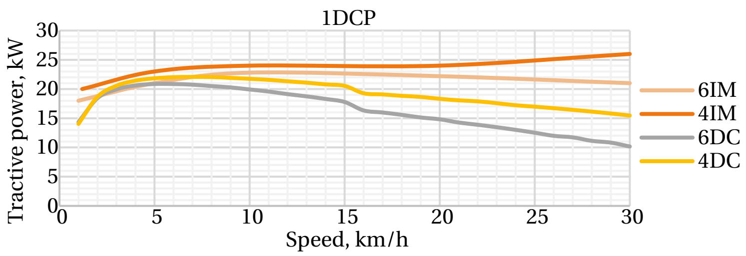

Figure 2. Dependence of tractive power on speed at 1DCP

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

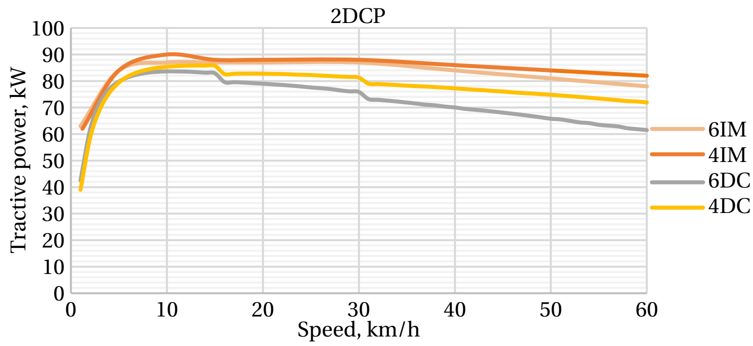

Figure 3. Dependence of tractive power on speed at the second position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

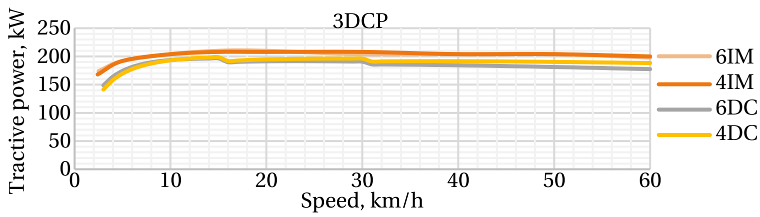

Figure 4. Dependence of tractive power on speed at the third position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

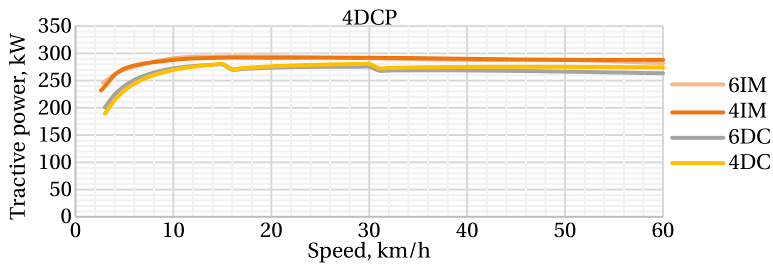

Figure 5. Dependence of tractive power on speed at the fourth position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

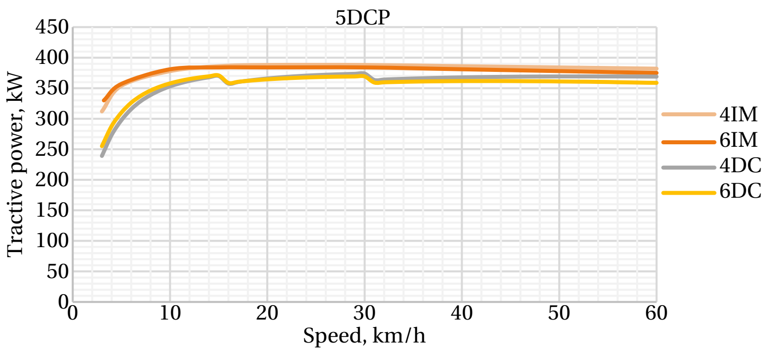

Figure 6. Dependence of tractive power on speed at the fifth position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

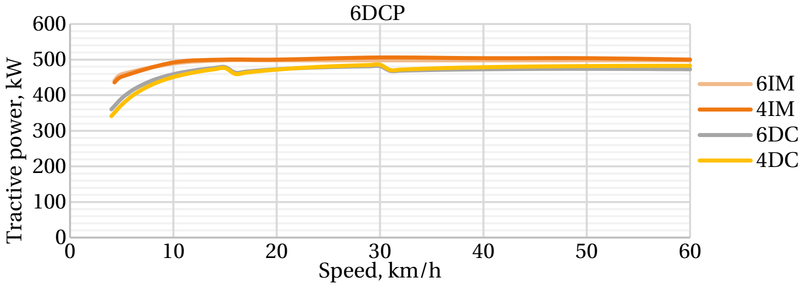

Figure 7. Dependence of tractive power on speed at the sixth position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

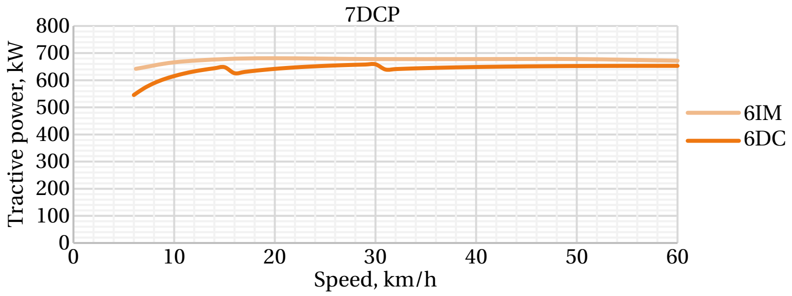

Figure 8. Dependence of tractive power on speed at the seventh position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

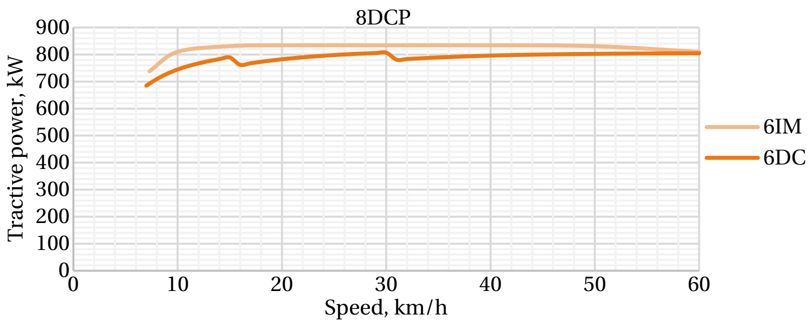

Figure 9. Dependence of tractive power on speed at the eighth position of the driver's controller

Note: 6IM – traction electric drive with six induction electric motors; 4IM – traction electric drive with four induction electric motors; 6DC – serial electric drive with six direct current electric motors TE006; 4DC – traction electric drive with four direct current electric motors TE006

Source: developed by the authors

Analysis of the dependencies shown in Figures 2-9 shows that the traction induction drive provides higher values of tractive traction force at all positions of the driver's controller. A certain exception is the first position, where the six-motor induction electric drive at low speeds has slightly lower performance than the serial traction collector electric drive. At higher positions of the driver's controller, consistently higher values of tangential power are observed in the case of using induction electric motors. In the zone of high traction forces, the increase in tractive force reaches 25% at higher positions of the driver's controller. With increasing speed, the magnitude of tractive force when using induction electric motors is higher by 5-10%. In summary, the results obtained indicate that the use of induction electric traction drives in shunting and transport locomotives will improve their traction and energy efficiency characteristics. According to studies S. Buryakovskiy *et al.* (2019), S. Buryakovskiy *et al.* (2020), S. Goolak *et al.* (2024) this has a positive impact on the parameters and indicators characterising the operation of shunting locomotives, increases the intensity of auxiliary operations at railway stations, and contributes to the stability of the railway transport system as a whole.

Conclusions

Updating the rolling stock used for shunting operations is a pressing task that involves choosing technical solutions to ensure high traction and energy characteristics and performance of locomotives. The article considers the use of a traction induction electric drive based on induction electric motors. The use of a three-phase eight-pole induction electric motor with a squirrel-cage winding with a capacity of 140 kW and a wheel-motor unit using this electric motor are proposed. A mathematical model has been developed and calculations of the characteristics of the traction electric drive with the proposed electric motor have been carried out. Variants of a six- and four-motor electric drive have been considered. According to the results of the calculations, it has been determined that the energy indicators of both variants of the electric drive are practically the same. It has been determined that a four-motor induction electric drive provides the traction characteristics of a serial six-axle shunting locomotive. A six-motor traction induction electric drive is recommended for a significant increase in traction performance.

A comparison of the traction and energy indicators of the induction electric drive and the serial electric drive of the ChME3 diesel locomotive equipped with collector electric motors was made. It was determined that in the zone of high traction efforts, the tangential traction force of the induction electric drive is higher by 25% and more percent than the traction force of the collector at the same supplied power. With increasing speed, the magnitude of the tractive traction force when using induction electric motors is higher by 5-10% than the traction force of the collector at the same supplied power. The obtained results confirm that the use of a traction induction electric drive substantially improves the traction and energy characteristics of shunting locomotives. This advancement positively impacts the performance of shunting and removal operations. At the same time, the study highlights important directions for future research, including full-scale experimental verification, development of advanced vector control systems, and detailed evaluation of the economic efficiency and reliability of induction-based modernisation projects.

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Conflict of Interest

None.

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Дослідження енергетичної ефективності тягового асинхронного електропривода маневрового локомотива

Євген Рябов
Доцент
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0000-0003-0753-514X

Євген Лисенко
Аспірант
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0009-0007-1263-7446

Багіш Єріцян
Доцент
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0000-0003-0579-3882

Ірина Білоконь
Директор
Кременчуцький фаховий коледж транспортної інфраструктури та технологій
39600, вул. Юрія Руфа,14, м. Кременчук, Україна
https://orcid.org/0000-0002-4675-3994

Антон Жуков
Незалежний дослідник
ТОВ «Харківський електро-машинобудівний завод»
61037, пр. Героїв Харкова, 199, м. Харків, Україна
https://orcid.org/0009-0001-5229-1685

Анотація. Модернізація парку локомотивів, які використовуються на залізницях України для виконання маневрової роботи, є вкрай важливою для підвищення надійності залізничного транспорту, зниження паливно-енергетичних витрат і мінімізації негативного впливу на навколишнє середовище. Метою цієї роботи було дослідження енергетичної ефективності асинхронного тягового привода маневрового локомотива, яка впливає на його тягові та енергетичні показники. Об'єктом дослідження було обрано маневровий тепловоз ЧМЕ3, для якого за допомогою математичного моделювання визначено показники енергетичної ефективності тягового привода з асинхронними електродвигунами потужністю 140 кВт. Результати розрахунків показали, що на тепловозі ЧМЕ3 може бути застосований асинхронний тяговий привод із чотирма або шістьма електродвигунами. Для обох варіантів виконано розрахунки дотичної потужності на різних позиціях контролера машиніста та встановлено, що обидва варіанти демонструють високі енергетичні показники. Водночас шестимоторний тяговий асинхронний електропривод забезпечив збільшення дотичної сили тяги порівняно з тяговим електроприводом із колекторними двигунами. Проведено порівняння коефіцієнта корисної дії (ККД) тягового асинхронного електропривода та стандартного електропривода з колекторними двигунами. Визначено, що ККД тягового асинхронного привода є вищим у всьому діапазоні навантажень, що підтверджує доцільність використання тягового асинхронного електропривода на маневрових локомотивах. Результати цього дослідження можуть бути використані при розробці нових маневрових локомотивів та модернізації існуючих на вітчизняних і зарубіжних підприємствах

Ключові слова: енергетична ефективність; енерго- та ресурсозбереження; асинхронний електродвигун; потужність; рухомий склад

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Predictive maintenance of railway point machines using digital twin and deep learning

Ihor Katkalo*
Postgraduate Student
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0008-2672-1005

Halyna Holub
PhD in Technical Sciences, Associate Professor
National Transport University
01010, 1 M. Omelyanovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0002-4028-1025

Abstract. Point machine drives are critical components of railway signalling infrastructure, with their failures accounting for 15-20% of all signal system malfunctions across European networks, causing significant operational and economic losses. This study aimed to develop a predictive maintenance approach for 1,520 mm-gauge point machine drives using a digital twin, enabling early fault detection from power electrical signatures recorded during each switch cycle. The methodology combined a four-layer digital twin architecture (physical layer, data layer, analytics layer, and decision-making layer) with a comparison of three deep learning architectures: one-dimensional convolutional neural network (1D-CNN), long short-term memory network (LSTM), and a hybrid CNN-LSTM model. These were benchmarked against logistic regression, support vector machines (SVM), and Random Forest on a synthetic, physics-based dataset comprising 5,000 power curves for SP-6M and VSP-220 point machines. Models were evaluated on five-class state classification and 50-cycle degradation forecasting. The hybrid CNN-LSTM achieved the highest classification performance (macro F1 = 0.938), while LSTM yielded the best degradation forecast ($R^2 = 0.937$); both substantially outperformed the strongest baseline model (Random Forest: F1 = 0.871, $R^2 = 0.845$). Cross-generator validation and artefact ablation experiments confirmed that deep learning advantages arise from capturing transferable signal shape features rather than memorising simulation artefacts. A recommended deployment configuration includes 1D-CNN at the edge for real-time classification, LSTM at the server level for degradation forecasting, and Random Forest as an intermediate solution for operators with limited labelled data. The practical significance of these results lies in providing evidence-based guidelines for implementing the digital twin analytics layer on 1,520 mm railway networks, supporting a transition from scheduled to condition-based maintenance and reducing unplanned downtime

Keywords: control; diagnostics; power signature analysis; monitoring; architecture; modelling

Introduction

Railway signalling infrastructure depends on point machines to direct rolling stock through track switches, and the operational consequences of their failures are disproportionate to the size of the equipment. Across European networks, signalling-related disruptions account for a substantial fraction of unplanned service interruptions, and within that fraction point machines remain a leading contributor. The cost is measured in delay-minutes, missed connections, freight throughput lost during single-line working, and on the worst occasions in compromised safety margins. Three maintenance regimes dominate the field. Reactive maintenance addresses failures as they occur, accepting the disruption cost in exchange for procedural simplicity. Preventive maintenance services equipment on a fixed schedule, replacing components by calendar time or switching-cycle count regardless of actual condition. Predictive maintenance, by contrast, infers the condition of each device from sensor data and intervenes only when degradation evidence warrants it. The recent systematic review by I. Hector & R. Panjanathan (2024) mapped 124 publications on predictive maintenance under the Industry 4.0 umbrella and showed that, across sectors, the technology has matured from research demonstrations into deployment-ready engineering, with machine learning the most common analytics layer. The digital twin paradigm offers an architectural framework

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*Corresponding author (*ihor.katkalo@icloud.com*)

for integrating predictive maintenance with data acquisition, condition monitoring, fault diagnosis and decision support. F. Tao *et al.* (2022) formalised the components of digital twin systems – physical asset, data acquisition, analytics, and decision support – and argued that the analytics layer is where the largest engineering choices accumulate. Operating on this framing, R. van Dinter *et al.* (2022) reviewed 42 papers combining digital twins with predictive maintenance and identified the analytics layer as both the most variable and the most consequential component, since model choice determines whether the digital twin produces actionable insight or merely mirrors the physical world. In the railway sector specifically, E.A. Thompson *et al.* (2025) surveyed 91 papers on digital twin applications and reported predictive maintenance as the dominant use case, with deep learning the most common analytics-layer choice. S. Kaewunruen *et al.* (2023) and J. Sresakoolchai & S. Kaewunruen (2023) demonstrated the approach for railway bridge maintenance under climate change conditions, showing that digital twins can integrate heterogeneous sensor streams and forecast component-level degradation at fleet scale. The Ukrainian context for this work has its own constraints. The 1,520 mm gauge networks operated by Joint Stock Company (JSC) "Ukrzaliznytsia" use electromechanical point machines, predominantly the SP-6M and VG-32 families, with supply standards and operational practices that differ from Western European 1,435 mm networks in voltage configuration, switching cycles, and ambient operating ranges. K.L. Kostenko *et al.* (2023) reviewed the prospects for robotisation of diagnostic procedures in Ukrainian railway automation systems and concluded that the technical foundations for predictive maintenance exist, but field deployments are constrained by data accumulation and the absence of validated reference models tailored to 1520 mm gauge equipment. H. Holub *et al.* (2025) addressed the deployment layer of any digital twin intended for network-scale operation, focusing on the integration of machine-learning workloads with cloud resource optimisation for transport big data.

A clear gap emerges from this literature. Digital twin frameworks and predictive maintenance models are individually mature, and both have been demonstrated on railway components. However, no published work has carried out a systematic, multi-task comparison of deep learning architectures specifically for railway point machines on 1,520 mm gauge infrastructure, embedded within a digital twin architecture, with the experimental controls needed to separate genuine learning from simulation-specific artefacts. Closing this gap is the contribution of the present study. The purpose of this study was to design and assess a digital twin framework for forecasting maintenance needs in railway point machines by evaluating the performance of deep learning models on electrical power signal patterns captured during switching operations. The objectives were: (1) to develop a conceptual digital twin architecture for a railway turnout with an integrated predictive diagnostics module that formalises point machine condition assessment as two complementary tasks: multi-class fault classification and degradation trend prediction; (2) to design, implement, and comparatively evaluate three deep learning architectures (1D-CNN, LSTM, hybrid CNN-LSTM) against three classical baselines across both tasks, using a multi-criteria framework covering accuracy, computational efficiency, and robustness to limited training data; (3) to formulate evidence-based recommendations for digital twin deployment on 1520 mm gauge networks. The scientific contribution of this study lies in a systematic evaluation of three deep learning architectures – a one-dimensional convolutional neural network (1D-CNN), a long short-term memory network (LSTM), and a hybrid convolutional neural network-long short-term memory model (CNN-LSTM) – in comparison with three classical baseline models for multi-class fault classification and degradation trend prediction. The robustness of the comparison was strengthened through cross-generator validation and artefact-ablation experiments. The practical contribution is a set of deployment recommendations calibrated to the operational and data-availability constraints typical of 1,520 mm gauge railway networks.

Materials and Methods

The proposed digital twin is organised as a four-layer structure (Fig. 1). The Physical Layer is the actual turnout installation with its sensors. The primary data source is the point machine power monitoring system, which records electrical current, voltage and computed power consumption during every switching cycle. Supplementary sensors include displacement transducers, accelerometers on the crossing nose and stock rails, and ambient temperature sensors. This configuration is roughly what is deployed on monitored turnouts in modern signalling systems, including those used on Ukrainian railways (Siroklyn & Kladko, 2018). In the present study, all signals analysed in subsequent sections come from a physics-informed simulation of this sensor configuration rather than from a deployed field installation. The Data Layer handles acquisition, transmission, preprocessing and storage. Raw signals are sampled at 1,000 Hz during each switching event, producing 3-7 second records depending on point machine type and switching direction. This layer runs initial quality checks, timestamps each record, and attaches metadata (turnout ID, switching direction, ambient temperature, cumulative switching count since last maintenance) before storing into a time-series database. The Analytics Layer hosts the predictive models that are the focus of this study. Two tasks run here: fault classification (current condition category) and degradation trend prediction (forecast over future switching cycles). A model management component handles periodic retraining and versioning. The output of this layer feeds into a decision-making structure that follows established system models for transport infrastructure management, where multi-level decomposition narrows control objects at each level. The Decision Layer translates the analytical output into maintenance recommendations: alerts on threshold approach, remaining useful life estimates, and schedules that respect operational constraints like traffic windows and crew availability. The first research task focused on fault classification. Given a discrete time series P = {p_1,...,p_n} representing a switching power curve, assign it to one of K = 5 condition categories defined in Table 1, were chosen to cover the dominant failure modes reported in operational maintenance records for electromechanical point machines, with each class corresponding to a physically distinct mechanism that leaves a characteristic imprint on the power signature.

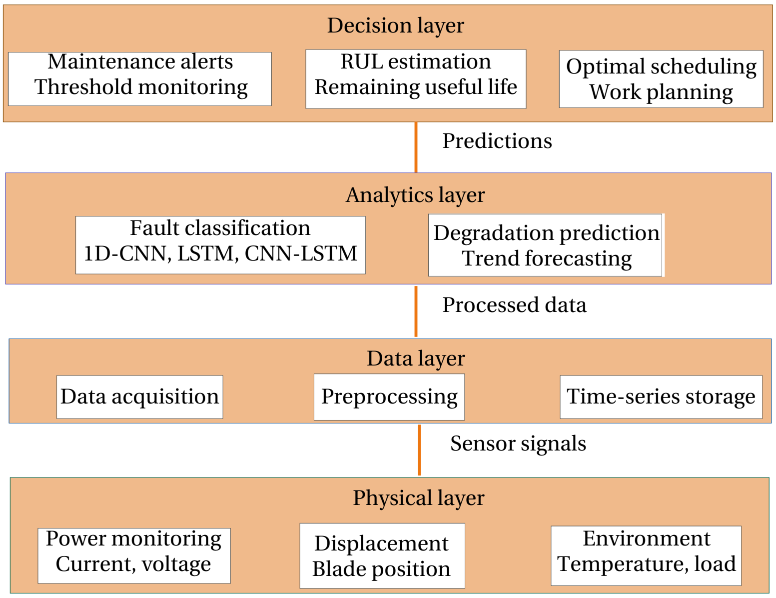

Figure 1. Conceptual architecture of the digital twin for a railway turnout

Source: developed by the authors

Table 1. Point machine condition categories

Class	Label	Physical description
C_1	Normal	Switching characteristics within normal limits
C_2	Increased friction	Elevated resistance from contamination, insufficient lubrication, or wear
C_3	Obstruction	Partial blockage of blade movement by foreign objects or geometry deformation
C_4	Electrical degradation	Brush, commutator or contact deterioration altering current characteristics
C_5	Misadjustment	Incorrect setting of switching stroke, detection rod, or locking mechanism

Source: developed by the authors

C_1 is the fault-free reference; C_2 (mechanical friction) and C_3 (mechanical obstruction) capture degradation in the rod-and-rail interface; C_4 (electrical degradation) covers motor and contactor wear; C_5 (misadjustment) covers geometric drift in the lock-and-detection mechanism. Five is a practical compromise: coarser taxonomies lose the distinctions that drive different maintenance interventions, while finer ones produce classes too rare to learn reliably from the data volumes typical of point machine fleets. The categories were treated as mutually exclusive in the simulation: each cycle was generated under exactly one active failure mode. This is a deliberate simplification of operational reality, where two or more degradation processes can coexist – friction often accompanies misadjustment, and electrical degradation can mask mechanical wear – so the single-label formulation is an approximation appropriate to early-stage diagnosis. Multi-label and hierarchical taxonomies are noted in the Prospects for further research as a natural extension once field data become available. The classification task is the mapping function:

$$f_{class}: P \to \{C_1, C_2, C_3, C_4, C_5\}. \tag{1}$$

Minimising the cross-entropy loss:

$$L_{CE} = -\left(\frac{1}{M}\right) \sum_{i=1}^{M} \sum_{k=1}^{K} y_{ik} * log(\hat{y}_{ik}), \tag{2}$$

where M is the number of training samples, y_{ik} the binary class indicator, and $\hat{y}_{ik}$ the predicted class probability.

The second task involved degradation trend prediction. For each cycle j, a feature vector x_j is computed from the corresponding power curve. Given a sliding window $X = \{x\_(j - v + 1),...,x\}$, predict the value of a degradation indicator at horizon H:

$$f_{degr}: X = \{x_{j-v+1}, \ldots, x_j\} \to \hat{y}_{j+h}. \tag{3}$$

The degradation indicator is the normalised peak power during initial blade movement, which is monotonically correlated with mechanical wear. The regression loss is mean squared error:

$$L_{MSE} = (\frac{1}{M}) \sum_{i=1}^{M} (y_i - \hat{y}_i)^2. \quad (4)$$

The dataset has 5,000 power curves (1,000 Hz sampling, 3-7 s duration) covering five condition classes. Class distribution is intentionally imbalanced to reflect operational reality: C_1: 2,000, C_2: 900, C_3: 500, C_4: 800, C_5: 800. Two point machine types are represented (SP-6M and VG-32) and both switching directions. A separate subset of 200 degradation sequences (500-1,000 cycles each) is used for second task, with parameters calibrated to documented by M. Hamadache *et al.* (2019) wear rates of electromechanical point machines. Generation runs in two stages: deterministic baseline curves from an electromechanical model, then stochastic injection of operational artefacts. Electromechanical model. Curves are computed as $P(t) = U(t) * I(t)$ from coupled electrical and mechanical equations. The electrical subsystem is modelled as a DC series-wound motor (the dominant type in SP-6M and VG-32):

$$U(t) = I(t) * (R_a + Rf) + L_a + \frac{di}{dt} + K_e * \omega(t), \quad (5)$$

where R_a = 2.8 Ω at 20°C (temperature coefficient +0.00393/°C, copper resistivity), Rf = 1.4 Ω, L_a = 15 mH, K_e = 0.42 V·s/rad, supply voltage 160 V DC (Siroklyn & Kladko, 2018).

The mechanical subsystem couples motor torque to the switching mechanism through a gear-worm reducer (n = 35, η = 0.45):

$$J * \frac{d\omega}{dt} = K_t * I(t) - T_{load}(t)/n - T_{friction}(\omega), \quad (6)$$

where J = 0.008 kg·m², K_t = 0.42 N·m/A, and Stribeck friction:

$$T_{friction}(\omega) = T_c * sign(\omega) + (T_s + T_c) *$$
$$* \exp(\left|-\frac{\omega}{\omega_s}\right|^2) * sign(\omega) * \beta * \omega, \quad (7)$$

where T_c = 0.15 N·m, T_s = 0.28 N·m, ω_s = 0.5 rad/s, β = 0.005 N·m·s/rad. These were calibrated against the SP-6M technical specifications.

Equations (5)-(7) are integrated with fourth-order Runge-Kutta at 0.1 ms (10 kHz internal rate) and downsampled to 1,000 Hz. Validation against the published reference signatures in M. Hamadache *et al.* (2019) resulted in a Mean Absolute Percentage Error (MAPE) of 3.2% for peak power, 4.1% for steady-state power, and 2.8% for switching duration, confirming the adequacy of the electromechanical calibration. Class-distinguishing load profiles. The load torque $T_{load}(t)$ is what differs between classes (Table 2). Peak power for C_1 falls in 480-560 W, for C_2 in 620-740 W, for C_3 in 750-900 W, consistent with the references.

Table 2. Load profile parameters per class

Class	Modification of nominal model
C_1 Normal	Phase I unlock 18-22 N·m; Phase II peak 25-32 N·m; Phase III steady 12-16 N·m; Phase IV lock 15-20 N·m
C_2 Increased friction	Load profile × U[1.3, 1.6] across all phases; β × [1.5, 2.5]
C_3 Obstruction	Localised torque spike 40-65 N·m, duration 0.1-0.4 s, random position in Phase II/III; stall threshold 70 N·m
C_4 Electrical degradation	R_a + 15-40%; stochastic contact resistance Rc_0 = 0.3-0.8 Ω + $Rc_1 \cdot n(t)$, Rc_1 = 0.1-0.3 Ω, $n(t)$ band-limited 50-200 Hz
C_5 Misadjustment	Stroke ±5-12% from nominal 154 mm; Phase IV torque +30-60%; rising trend in Phase III

Source: developed by the authors based on M. Hamadache *et al.* (2019)

Table 2 specifies how each fault class from Table 1 is reproduced in the physics-informed simulation through targeted modifications of parameters in the electromechanical model (Eqs. 5-7), with the mapping driven by the physical mechanism rather than by arbitrary perturbation. Mechanical friction (C_2) is reproduced by increasing the damping and static-torque terms, raising the steady-state power level and lengthening the switching phase. Obstruction (C_3) is introduced as a transient torque spike at a randomised position within the cycle, mimicking the encounter with a foreign object or a binding point in the slide chairs. Electrical degradation (C_4) modifies the supply-side parameters – the effective armature resistance is increased and the supply voltage reduced – which together depress the peak power and slow the rise time. Misadjustment (C_5) shifts the lock-engagement point in time, producing the asymmetric end-of-stroke signature characteristic of detection-bar drift. Severity for each class was sampled uniformly across a physically plausible range, and independent stochastic noise was added per cycle so that no two curves within a class are identical. The parameter-to-class mapping is one-to-one by construction, but the resulting power signatures overlap in several diagnostic regions, which is precisely why end-to-end learning from the raw curve outperforms hand-crafted feature pipelines. Operational artefacts. Six categories of real-world interference are layered onto the baseline curves so the models train under realistic conditions rather than on idealised signatures (Table 3). Each category can be independently enabled or disabled.

Table 3. Operational artefacts injected into the simulation

Artefact	Model	Coverage
EMI from traction current (catenary 25 kV, 50 Hz)	Sum of sinusoids at 50/100/150 Hz with amplitudes 2-8%	All electrified-line records
Voltage sag during train passage	0.3-1.5 s dip, magnitude 5-12% below nominal, randomised timing	All records, randomised

Table 3. Continued

Artefact	Model	Coverage
Temperature-dependent variation	Temperature-dependent electrical resistance and lubricant viscosity variations; ±3-7% baseline shift for temperatures below −10°C and above +35°C	All records, sampled from temperature distribution
Mechanical vibration from passing trains	Band-limited noise 20-80 Hz, amplitude proportional to train speed/load	~15% of records
Power supply fluctuation	Slow drift ±3-5% over cycle; spikes 2-5 ms up to 15% above nominal	Remote-station records
Sensor noise and quantisation	12-bit ADC quantisation; Gaussian SNR uniform in [35, 45] dB, simulating typical experimental data noise; 0.5% probability of single-sample outlier	All records

Source: developed by the authors based on M. Hamadache *et al.* (2019)

Mitigation of simulation-induced overfitting. A common concern with simulated datasets is that a deep network might learn to invert the generator rather than the diagnostic problem itself. Three measures address this. First, structural perturbation: each record draws independent perturbations on R_a (±12%), η (±8%), T_c and T_s (±15%), and load anchor points (±10%), so no two curves share identical model parameters even within the same class. Second, boundary blurring: about 8% of training records are sampled from overlap zones between adjacent classes (e.g., friction multiplier 1.25 paired with misadjustment 4%), preventing single-parameter threshold shortcuts. Third, randomised phase timing: phase boundaries vary stochastically by ±8-15% per record. The effectiveness of these measures is evaluated experimentally in the following sections. Preprocessing operates on signals carrying the full set of operational artefacts, without explicit removal. This is deliberate: the deep learning models are forced to learn diagnostic features in the presence of realistic interference rather than rely on pre-cleaned signals that would not be available in an operational digital twin deployment anyway. Curves are resampled to N=4,000 samples (linear interpolation) and normalised to [0, 1] per record:

$$\hat{p}_i = (p_i - p_{min}) / (p_{max} - p_{min}). \quad (8)$$

Phases are segmented automatically by threshold detection and gradient analysis: Phase I (Unlocking), II (Blade movement initiation, peak power), III (Steady-state running), IV (Locking and detection). Figure 2 shows representative curves for each class with phase boundaries.

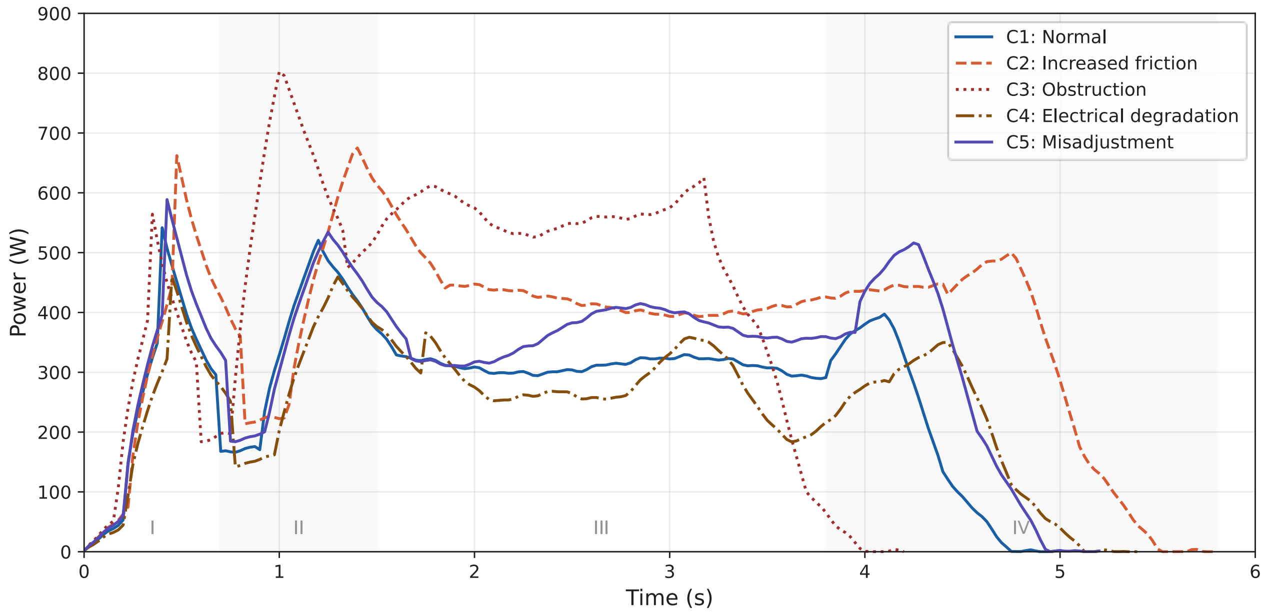

Figure 2. Switching power curves for five-point machine condition categories

Source: developed by the authors

The visible patterns match what the literature suggests. C_1 peaks near 520 W and runs at ~300 W steady-state for 5.0 s. C_2 shows elevated power across all phases (peak ~680 W, steady-state +30-40%, duration 5.8 s). C_3 has a sharp peak of ~820 W in Phase II with high Phase III variability. C_4 has a reduced peak (~460 W) but high-frequency fluctuations throughout. C_5 has a normal-looking peak but a rising Phase III trend and elevated Phase IV power (~520 W). For second task, twelve features per curve are extracted (Table 4). These were chosen to span the patterns visible in Figure 2 P_{peak} separates $C_1/C_2/C_3$ at the amplitude level; P_{std} catches the noisy character of C_4; P_{lock} flags the misadjustment locking signature; phase durations and energies cover the temporal aspects.

Table 4. Features extracted from switching power curves

No.	Feature	Description	Phase
1	P_{peak}	Maximum power	II
2	P_{mean}	Mean power during steady-state running	III
3	P_{std}	Standard deviation of power	I-IV
4	T_{total}	Total switching duration	I-IV
5	T_{unlock}	Unlocking phase duration	I
6	T_{run}	Steady-state phase duration	III
7	E_{total}	Total energy (integral of power)	I-IV
8	E_{phase2}	Energy during blade movement initiation	II
9	Skew	Skewness of power distribution	I-IV
10	Kurt	Kurtosis of power distribution	I-IV
11	$Slope_{rise}$	Gradient at Phase I-II transition	I-II
12	P_{lock}	Power level during locking	IV

Source: developed by the authors

Table 4 lists the twelve hand-crafted features supplied to the three classical baselines, organised along four dimensions: amplitude (P_{peak}, P_{mean}, P_{std}, P_{lock}), duration (T_{total}, T_{unlock}, T_{run}), energy (E_{total}, E_{phase2}), and shape (Skew, Kurt, $\text{Slope}_{\text{rise}}$), with at least one feature anchored to each phase of the switching cycle. The mapping back to Table 1 follows physically grounded patterns: friction (C_2) raises P_{mean} and T_{run}; obstruction (C_3) shows up in P_{peak} and the shape statistics through the transient torque spike; electrical degradation (C_4) depresses P_{peak} and $Slope_{rise}$ while extending T_{total}; misadjustment (C_5) shifts P_{lock} and the T_{unlock}/T_{total} ratio. Although physically interpretable, these twelve numbers compress a curve of order 10^3 time samples, and the ~7 F1 percentage points between Random Forest and CNN-LSTM measure how much diagnostic information is lost in that compression. The deep learning models for first time receive the full normalised curve as input (end-to-end learning). Split is time-aware to prevent leakage. For first task: 70/15/15 with chronological ordering, so all test records postdate all training records. For second task: split at the sequence level (140/30/30), no overlapping windows. SMOTE is applied only to the training subset for class balancing; validation and test subsets keep the original class distribution. Three classical baselines work on the 12-feature vectors of Table 4; three deep learning models work on the raw curve for classification (and on the sliding-window feature matrix for degradation).

Logistic Regression (multinomial, L2, C = 1.0) and Ridge Regression (cross-validated regularisation) serve as linear lower bounds. SVM/SVR with RBF kernel covers nonlinear kernel methods; hyperparameters were grid-searched over $C \in \{0.1, 1, 10, 100\}$, $\gamma \in \{0.001, 0.01, 0.1, 1\}$. Random Forest (300 trees, grid-searched depth, leaf size, and feature count) is the strong tabular baseline; it has been used in prior railway diagnostic work. All baselines run in scikit-learn 1.3 with feature standardisation (zero mean, unit variance). The deep learning architectures included a 1D-CNN consisting of three convolutional blocks (Conv1D + BatchNorm + ReLU + MaxPool, filters 32 → 64 → 128), global average pooling, and two fully connected layers (128, 64) with dropout 0.3. The output is softmax (5) for classification, linear for regression. The LSTM has two stacked layers (64 and 32 hidden units), dropout 0.3, and two fully connected layers (Sherstinsky, 2020). For classification, the input curve is split into 100 subsequences of 40 samples each; for degradation, the input is a sequence of feature vectors. The hybrid CNN-LSTM applies a shared 1D-CNN feature extractor (two Conv1D blocks, 32 and 64 filters) to non-overlapping segments of the curve, then feeds the resulting per-segment feature sequence into a single LSTM layer (64 units). The motivation for this hybrid is that switching curves carry both local diagnostic patterns (sharp friction spikes within Phase II), which are best captured by convolution, and global sequential structure (the relationship between Phase I and Phase III), which benefits from recurrence (Sherstinsky, 2020).

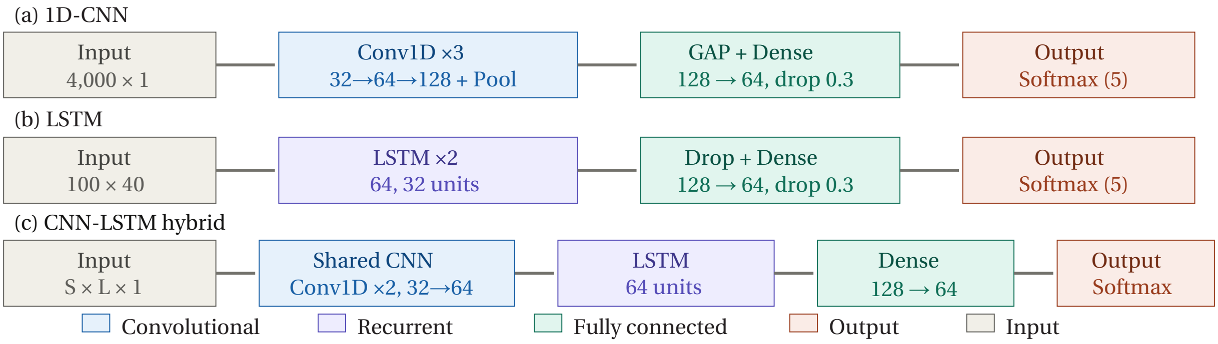

Figure 3. Schematic diagrams of the three deep learning architectures

Source: developed by the authors

All deep models train in PyTorch 2.0 on an NVIDIA RTX 5070 (12 GB), with Adam ($\beta_1 = 0.9$, $\beta_2 = 0.999$), initial learning rate 10^{-3}, batch size 64, max 150 epochs, early stopping (patience 15) on validation loss, He initialisation for convolutional layers and Xavier for dense layers. Hyperparameters are grid-searched per architecture; reported numbers are means over three runs with different random seeds. Classification metrics are accuracy, precision, recall, F1 per class, and macro F1 (the primary metric, given class imbalance): Computational metrics: training time, inference time per record, model size. Practical criteria: interpretability, robustness to reduced data (50% and 25% subsets), real-time suitability (target inference <50 ms).

Results and Discussion

Table 5 presents the test-set classification performance of all six models, covering three classical baselines and three deep learning architectures, with evaluation based on accuracy, macro F1-score and class-wise F1-scores for the five fault classes.

Table 5. Classification performance (test set)

Metric	LogReg	SVM	RF	1D-CNN	LSTM	CNN-LSTM
Accuracy	0.821	0.873	0.889	0.934	0.912	0.951
Macro F1	0.793	0.854	0.871	0.918	0.894	0.938
F1 (C_1)	0.891	0.924	0.932	0.962	0.948	0.971
F1 (C_2)	0.802	0.861	0.882	0.931	0.908	0.947
F1 (C_3)	0.694	0.772	0.801	0.878	0.852	0.912
F1 (C_4)	0.771	0.836	0.858	0.905	0.881	0.924
F1 (C_5)	0.807	0.878	0.880	0.916	0.882	0.935

Source: developed by the authors

Random Forest is the strongest classical baseline at macro F1 = 0.871. Each deep model exceeds it: 1D-CNN by 5.4 percentage points (F1 = 0.918), CNN-LSTM by 7.7 (F1 = 0.938). Logistic Regression at F1 = 0.793 is far behind, since linear decision boundaries simply do not fit this signal-feature relationship. SVM with RBF (F1 = 0.854) sits in between, beating LogReg but not RF. The widest gap is in C_3 (obstruction): 0.801 for RF against 0.912 for CNN-LSTM, a 13.9-point difference. The cause is straightforward. The obstruction-induced power spike has variable timing, irregular shape, and short duration; none of that survives reduction to twelve summary statistics. The deep models look at the raw curve and recover what the features lose. It should be noted that the full operational artefacts (EMI, voltage sags, temperature, vibration, sensor noise) were active during both training and evaluation. The models were not given a sanitised signal; the numbers above hold under realistic interference. The 1D-CNN's competitiveness despite its simpler architecture is partly explained by what convolutional filters do well: they suppress high-frequency components like EMI and vibration while preserving diagnostic content. C_1 is the easiest class for every deep model (largest sample count); C_3 is the hardest, both because the sample size is small and because obstruction signatures are highly variable. The most consistent error mode in the confusion matrices (Fig. 4) is $C_2 \leftrightarrow C_5$ confusion. That makes physical sense: both increased friction and misadjustment elevate mechanical resistance and produce overlapping signatures.

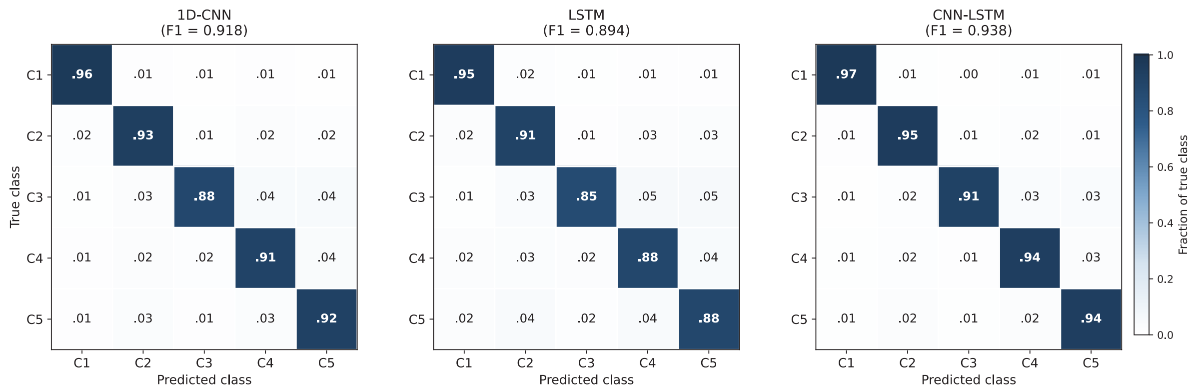

Figure 4. Confusion matrices for the three deep learning architectures

Source: developed by the authors

Figure 4 shows per-class confusion matrices for the three deep learning models. Two patterns are common to all of them: C_1 (Normal) is the easiest class (0.95-0.97 on the diagonal), C_3 (Obstruction) the hardest (0.85-0.91), with the dominant misclassification directing C_3 toward C_4 (electrical degradation) at 0.03-0.05. This is physically interpretable, since both perturb power in the same phases and only the sharpness of the obstruction spike distinguishes them. The differences between architectures concentrate on these harder classes. CNN-LSTM lifts diagonal accuracy on C_3 from 0.85 (LSTM) to 0.91 and on C_4 from 0.88 to 0.93, while 1D-CNN sits between the two and is two to three points above LSTM on C_2, C_4 and C_5. The pattern matches the underlying inductive biases: convolutional layers localise the short-duration spikes and slope changes that pure recurrence misses, and the hybrid gains by combining local detection with sequence-level context, which is why its advantage concentrates exactly on the failure modes that matter most for predictive maintenance.

Table 6. Degradation prediction performance (test set, H = 50 cycles)

Metric	Ridge	SVR	RF	1D-CNN	LSTM	CNN-LSTM
MAE	0.071	0.058	0.052	0.042	0.031	0.033
RMSE	0.094	0.078	0.069	0.058	0.044	0.046
R^2	0.713	0.802	0.845	0.891	0.937	0.931

Source: developed by the authors

The architecture ranking inverts. LSTM, which placed second on classification, gives the best degradation prediction at $R^2 = 0.937$. CNN-LSTM follows closely ($R^2 = 0.931$); 1D-CNN sits a step below at 0.891. Random Forest reaches 0.845, which is 4.6 R^2 points behind 1D-CNN. Ridge Regression collapses to 0.713. The wear trajectory is too nonlinear for straight-line extrapolation. The narrower gap between baselines and deep models on this task is informative. The twelve features in Table 4 were chosen specifically as wear indicators, guided by multiphase curve analysis principles standard in the field, so Random Forest can work with input that already encodes most of what matters. Multi-class fault classification, on the other hand, asks for distinctions that summary statistics do not capture, and the deep models recover that information from the raw curve. Why does LSTM beat CNN-LSTM here while losing to it on classification? Classification is a per-curve decision: spatial patterns within a single signal carry the answer, and convolutional filters are the natural tool. Degradation is a per-sequence decision: features evolve slowly across hundreds of cycles, and the recurrent cell state is what tracks that evolution (Sherstinsky, 2020). CNN-LSTM has the recurrent component, but the convolutional preprocessing it applies to each segment adds capacity that helps less here, and probably hurts slightly, because it gives the model more parameters to fit on the same data.

Figure 5 shows a typical LSTM prediction trajectory on a held-out 800-cycle sequence. The model tracks both the slow degradation regime in the first ~470 cycles and the transition to accelerated wear that follows, with the 95% confidence band remaining narrow throughout; visible widening occurs at the regime transition rather than at long prediction horizons, indicating that residual uncertainty is dominated by the change-of-dynamics moment rather than by error accumulation. The pointwise error at the early-life sample shown in the inset is 0.012 in absolute terms (cycle 4: actual 0.328, predicted 0.340), or 3.7% relative; the trajectory tracking remains comparably tight throughout both regimes, with no systematic bias visible at the transition or near the maintenance threshold. The prediction horizon for this trajectory is H = 50 cycles. The actual degradation indicator crosses the maintenance threshold (0.74) at cycle ~750, while the model's H = 50 prediction reaches that same threshold at cycle ~700, giving a 50-cycle lead time to schedule intervention before the device crosses the action boundary. At a typical mainline turnout throughput of 10-30 switching operations per day, this corresponds to roughly two to five days of warning, which is the practically useful margin of the predictive maintenance approach.

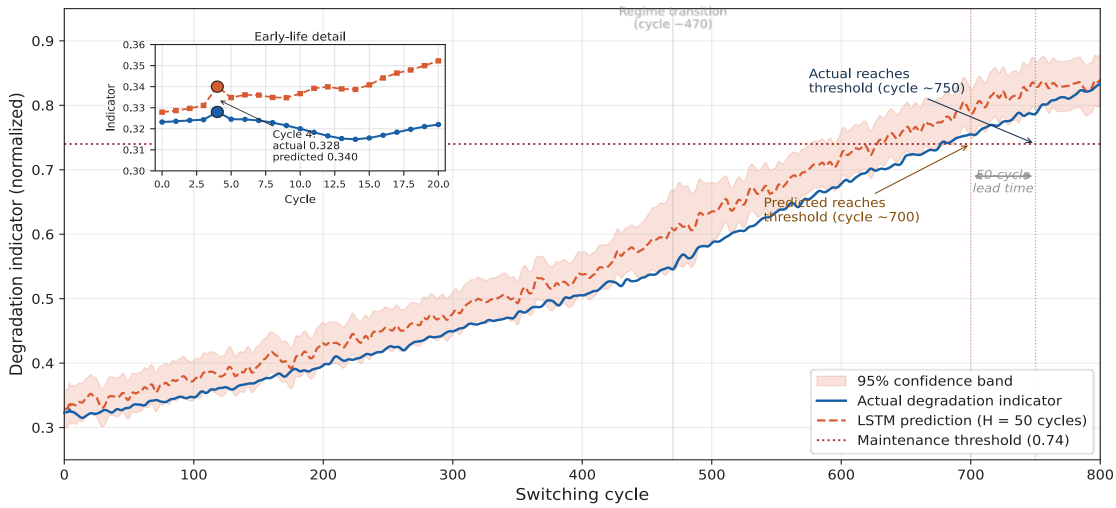

Figure 5. Predicted vs actual degradation trajectory, LSTM model

Source: developed by the authors

Table 7. Computational efficiency

Parameter	LogReg/Ridge	SVM	RF	1D-CNN	LSTM	CNN-LSTM
Training time	0.3 s	12 s	8 s	~18 min	~42 min	~55 min
Inference (ms/rec)	0.02	0.8	0.4	1.8	5.4	6.1
Model size (MB)	<0.01	0.15	38	0.72	0.48	0.84
GPU required	No	No	No	Recommended	Recommended	Recommended

Source: developed by the authors

Baselines are orders of magnitude faster in both training and inference. All six models, however, finish inference well below the 50 ms real-time threshold, so deployment inside the digital twin pipeline is feasible for any of them. The 1D-CNN at 1.8 ms is roughly 4× slower than RF but still leaves substantial margin for edge deployment on modest hardware. Baselines lose 3.7-4.7% under data reduction; deep models lose 6.1-11.4%. This is not unexpected. Tree ensembles and SVMs working on 12 features need fewer samples to fit a decent decision boundary than a deep network learning representations from 4,000 raw samples. LSTM is hit hardest at -11.4%, consistent with the well-known fact that recurrent networks are data-hungry. 1D-CNN is the most stable deep model at -6.1%, which can be attributed to the convolutional inductive bias (locality, translation invariance) acting as an implicit regulariser. A practical question follows: at what training-set size does Random Forest become competitive with the best deep model? At 25% training data, 1D-CNN reaches F1 = 0.862, and Random Forest at full data reaches 0.871. They sit within 0.009 of each other, RF marginally ahead. An operator with about a fifth of the data used here would do roughly as well with Random Forest on hand-crafted features as with a deep model. Below that threshold, RF is the safer bet; above it, deep learning pulls ahead. This has a clean deployment implication. Operators accumulating their first labelled dataset should not skip directly to deep learning. Random Forest delivers comparable accuracy faster and at lower compute cost. Migration to 1D-CNN or CNN-LSTM becomes worthwhile once the dataset reaches roughly five times the crossover threshold (full scale here).

Table 8. Macro F1-score under reduced training data

Training data	LogReg	SVM	RF	1D-CNN	LSTM	CNN-LSTM
100%	0.793	0.854	0.871	0.918	0.894	0.938
50%	0.781	0.838	0.855	0.896	0.851	0.908
25%	0.764	0.814	0.836	0.862	0.792	0.867
Drop 100 → 25%	-3.7%	-4.7%	-4.0%	-6.1%	-11.4%	-/–7.6%

Source: developed by the authors

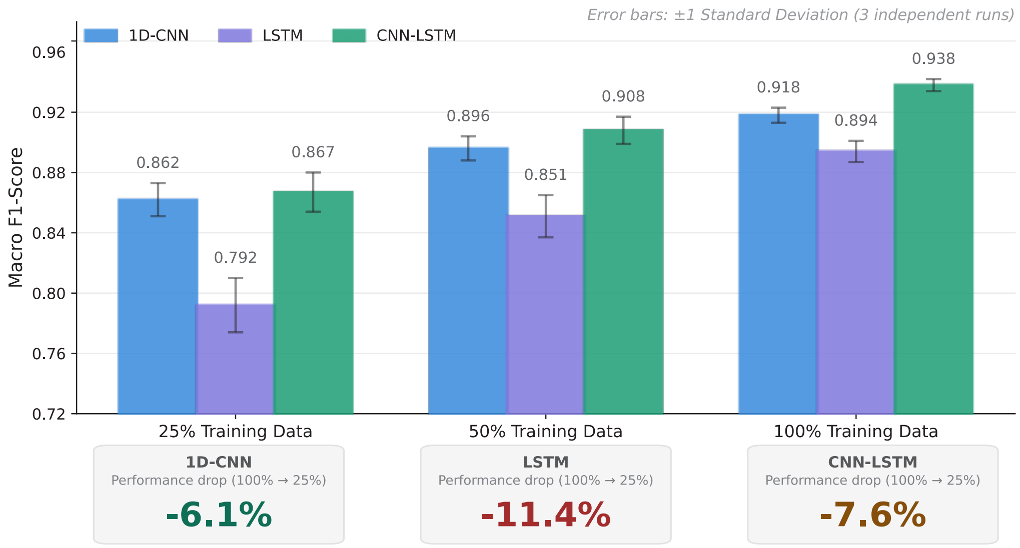

Figure 6. Classification F1 vs training data volume

Source: developed by the authors

Table 9. Multi-criteria comparison

Criterion	LogReg	SVM	RF	1D-CNN	LSTM	CNN-LSTM
Classification F1	-	-	-	++	+	+++
Degradation R^2	- -	-	-	+	+++	++

Table 9. Continued

Criterion	LogReg	SVM	RF	1D-CNN	LSTM	CNN-LSTM
Training speed	+++	+++	+++	++	+	+
Inference speed	+++	+++	+++	++	++	++
Robustness (limited data)	++	++	++	++	–	+
Feature engineering	Yes	Yes	Yes	No	No	No
Interpretability	+++	+	++	+	-	-

Note: legend: +++ excellent; ++ good; + acceptable; - weak; - - poor

Source: developed by the authors

Classical baselines train in seconds, infer in fractions of a millisecond, run on a CPU, and are easy to interpret. They also lose accuracy on both tasks, and they require manual feature engineering. That last point matters: feature engineering assumes domain expertise, may not generalise to other point machine types, and discards most of what the raw curve contains. Among the deep models, no single architecture wins everywhere. CNN-LSTM is the right pick when classification accuracy is the priority and resources allow. LSTM is preferred for degradation prediction. 1D-CNN is the practical choice for edge deployment and data-scarce scenarios; at 25% training data it still reaches F1 = 0.862, which is close to what RF achieves on full data (0.871). The numbers in Tables 5 and 6 are what justify deep learning here. The weakest deep model (LSTM, F1 = 0.894) beats the strongest baseline (RF, F1 = 0.871) on classification by 2.6 points, and the gap reaches 7.7 for CNN-LSTM. On degradation prediction, LSTM beats RF by 10.9 R^2 points. Whether those margins justify the extra training time depends on operational priorities, which connects to the cross-generator validation – the question of whether the gap is real or simply a simulation artefact. The recommended deployment uses two deep models. A 1D-CNN at the edge handles real-time classification on each switching event; an LSTM at the server level handles periodic degradation forecasting on aggregated features. Operators without the data or compute for this configuration should start with Random Forest. At full-data F1 = 0.871 it serves as a competent bootstrap, and migration to deep learning becomes worthwhile at around five times the crossover threshold. At the network level, where dozens or hundreds of turnouts feed the analytics layer simultaneously, distributed training and cost-aware resource scheduling become the binding constraints for cloud-deployed transport analytics at scale.

A reasonable concern about simulation-based studies is whether the models actually learned the diagnostic problem or just memorised the generating function. Two experiments test this directly. Cross-generator validation was performed using a second parameterisation of the electromechanical model (Generator B) was created by altering motor constants ($R_a = 3.2\ \Omega$, $K_e = 0.38$ V·s/rad), gearbox parameters ($n = 40$, $\eta = 0.42$), and load anchors (shifted ±15% from Generator A). Generator B produces curves with visibly different absolute amplitudes, durations, and phase proportions, but the five fault classes remain physically the same. All six models, trained only on Generator A, were evaluated on 750 records from Generator B without retraining or fine-tuning.

Table 10. Cross-generator validation, trained on A, tested on B

Metric	LogReg	SVM	RF	1D-CNN	LSTM	CNN-LSTM
F1 (same-gen)	0.793	0.854	0.871	0.918	0.894	0.938
F1 (cross-gen)	0.602	0.681	0.871	0.831	0.798	0.862
Drop	-24.1%	-20.3%	-18.0%	-9.5%	-10.7%	-8.1%

Source: developed by the authors

Every model loses something on the cross-generator data, which means the simulation parameters do influence what was learned; the models have not converged on a perfectly general diagnostic rule. The size of the loss separates the two groups sharply, though. Baselines lose 18-24%. Deep models lose 8-11%. CNN-LSTM keeps 91.9% of its accuracy across the shift; Random Forest keeps only 82.0%. The likely cause lies in what each kind of model is sensitive to. Random Forest, SVM, and LogReg work on absolute feature values: peak power in watts, duration in seconds. When Generator B shifts those numbers by 10-15%, the decision boundaries learned on A no longer hit them in the right places. The deep models work on the raw curve and end up learning relative shape information: the proportion of Phase II peak to Phase III steady state, the slope of power rise, the symmetry of locking. Those proportions are largely preserved across the parameter shift, which is why the deep models survive it. One comparison is particularly telling: CNN-LSTM's cross-generator F1 of 0.862 is essentially the same as Random Forest's same-generator F1 of 0.871. Under a domain shift Random Forest itself cannot survive without an 18% drop, CNN-LSTM almost matches Random Forest on home turf. This alone is arguably the strongest single piece of evidence that the deep model gain is not a simulation artefact. Artefact ablation served as a reverse test: if the deep models had memorised generator-specific artefacts, then removing the noise that obscured those artefacts should have improved their performance. The underlying pattern would be easier to read. If instead the models learned features that hold up under noise, performance should stay roughly where it was when artefacts are removed.

Table 11. Artefact ablation, classification with artefacts removed at test time

Artefact removed	1D-CNN ΔF1	LSTM ΔF1	CNN-LSTM ΔF1
None (baseline)	0.918	0.894	0.938
EMI	+0.003	+0.005	+0.002
Voltage sags	+0.008	+0.011	+0.006
Vibration	+0.002	+0.004	+0.001
Temperature	-0.004	-0.002	-0.003
All artefacts	+0.012	+0.019	+0.008
F1 without artefacts	0.930	0.913	0.946

Source: developed by the authors

Removing all artefacts at once moves F1 by only +0.008 to +0.019, small enough to confirm that none of the deep models depends on the noise structure for classification. Voltage sags account for most of the visible improvement (+0.6 to +1.1 percentage points), which fits the physics; sags directly modulate amplitude and shrink the gap between classes whose signatures already differ mainly in amplitude. The pattern across models is also instructive. LSTM, the most sequence-dependent architecture, shows the largest aggregate gain when artefacts are removed (ΔF1 = +0.019); 1D-CNN and CNN-LSTM, with their convolutional feature extractors, gain only +0.012 and +0.008 respectively. This is consistent with convolution acting as an implicit denoising operation. The filters suppress high-frequency artefacts during the forward pass, so removing those artefacts at test time produces a smaller change than for a purely sequential model. None of the three deep models gains more than two percentage points from a fully clean test set, and the individual artefact effects (≤1.1 percentage points) fall within the magnitude range typical of per-seed F1 fluctuations in deep-learning training at this data scale. The conclusion is qualitative but robust: none of the models relies on any specific artefact class as a discriminative cue – the precise property artefact ablation is designed to detect. Temperature artefacts behave the opposite way. Removing them costs the models 0.2-0.4 percentage points. A plausible explanation is that the models learned to use winding-resistance variation as a supplementary cue. Cold conditions raise resistance and also increase mechanical friction, so the two effects co-vary in the training data. Remove the temperature signal and a weak but real cue is gone. A cleaner deep-vs-classical comparison emerges in this artefact-free regime. CNN-LSTM on clean signals reaches F1 = 0.946. Random Forest, evaluated separately on clean feature vectors, reaches 0.904. The 4.2-point gap that survives in the absence of any noise rules out the explanation that the deep models' advantage came from exploiting noise patterns. What is left is the difference in input itself: twelve summary statistics on one side, four thousand raw samples on the other.

The numerical results in Tables 5-11 invite comparison with the broader literature on point machine fault diagnosis. Seven works covering different methodological strands frame this comparison. D. Ou *et al.* (2019) used hand-crafted features from switching force curves with classical classifiers and reported accuracies above 90% on multi-class problems. The Random Forest baseline reported here at F1 = 0.871 sits close to that range – the gap maps to the difference between accuracy and macro F1 on imbalanced data, and the additional 7.7 percentage points achieved by CNN-LSTM quantify how much diagnostic information the raw curve carries beyond hand-crafted features. Z. Shi *et al.* (2023) applied an improved deep CNN combined with Support Vector Data Description (SVDD) classification to ZDJ7 point machine current curves and reported 96.59% accuracy with robust performance across varying signal-to-noise ratios; this places between the same-generator CNN-LSTM result (93.8%) and the cleaner artefact-free regime (94.6%), consistent with their explicit focus on noise immunity through adaptive batch normalisation. C. Zhang *et al.* (2019) and S. Givnan *et al.* (2022) applied a locally connected autoencoder to point machine current curves, anomaly-flagging via reconstruction error. Their architecture is unsupervised in spirit, while the present approach is supervised end-to-end, complementary rather than competing: autoencoders work where labelled fault examples are scarce, supervised models pull ahead once labels accumulate. M. Sysyn *et al.* (2019) worked on instrumented 1,520 mm gauge turnouts using vehicle-based inertial sensors with classical ML, reporting accuracies in the 0.85-0.90 range, close to the Random Forest baseline reported here. The cross-modality coincidence suggests that the classical-features ceiling for this infrastructure sits independently around F1 = 0.87, a ceiling the deep models of the present study exceed by 5-8 points.

Z. Hu *et al.* (2022) surveyed data-driven fault diagnosis for point machines and observed that hybrid CNN+RNN architectures outperform single-paradigm models at the cost of higher data requirements. The reduced-data experiment gives that observation a measurable form: CNN-LSTM at 25% training data drops to F1 = 0.867, statistically indistinguishable from Random Forest at full data. Z. Hu's *et al.* (2022) crossover threshold thus has a quantifiable location for this application. Y. Sun *et al.* (2020) used SVM on acoustic signals and reported accuracy in a range similar to electrical-signature classical methods. The convergence across orthogonal sensor modalities indicates that the ~0.87-0.89 ceiling reflects the information content of any single channel rather than the feature extractor – a direct argument for multi-modal fusion as a future direction. S. Reetz *et al.* (2024) developed a Bayesian network combining expert knowledge with limited data. Their motivation overlaps with the present study, but the methodological direction inverts: knowledge-based versus data-driven. In low-data regimes the Bayesian route may close the gap exposed by the 25%-data experiment, and a hybrid deep-learning + Bayesian architecture is a natural target for integrating symptom classification with root-cause inference within the digital twin. Beyond the point-machine-specific literature, T. Zonta *et al.* (2020) surveyed predictive maintenance implementations across Industry 4.0 sectors and reported that deep learning consistently outperforms classical methods at the cost of higher training data and computational requirements, a cross-industry finding the reduced-data experiment (Table 8) and computational efficiency analysis (Table 7) confirm specifically for railway point machine diagnosis. The results indicate that advanced data-driven models can consistently outperform classical approaches, revealing additional diagnostic information and highlighting the value of combining methodologies for improved fault detection.

Conclusions

A four-layer digital twin architecture (Physical, Data, Analytics, Decision) for predictive maintenance of railway point machines on 1,520 mm gauge networks was developed and validated through systematic comparison of deep learning and classical machine learning architectures on a physics-informed simulated dataset of 5,000 switching power curves. The hybrid CNN-LSTM achieved the highest fault classification accuracy (macro F1 = 0.938), exceeding the strongest classical baseline (Random Forest, F1 = 0.871) by 7.7 percentage points. For degradation trend prediction over a 50-cycle horizon, LSTM reached $R^2 = 0.937$ against 0.845 for Random Forest. Cross-generator validation showed deep models losing 8-11% accuracy under parameter shift versus 18-24% for classical baselines, and artefact ablation moved F1 by only 0.8-1.9 percentage points – confirming that the deep learning advantage stems from learning relative shape information rather than memorising simulation artefacts or noise patterns. The recommended deployment combines 1D-CNN inference at the edge (1.8 ms per switching event) for real-time fault classification with LSTM-based degradation forecasting at the server level. Random Forest serves as an interim solution for operators with limited labelled data, becoming competitive with deep models at approximately 25% of the training data volume used here. The most consequential next step is validation on field operational data from Ukrainian railways in collaboration with JSC "Ukrzaliznytsia". Transfer learning would help adapt models across point machine types; online learning would enable continuous adaptation as new switching data accumulates; lightweight architectures may close the data-efficiency gap with classical baselines. The digital twin scope can extend to crossing-nose wear, rail fastenings, and ballast condition, transforming the framework into full turnout health management. Integration of deep reinforcement learning for track geometry maintenance, would shift the framework from passive diagnosis to closed-loop maintenance policy optimisation.

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Conflict of Interest

None.

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Прогнозне технічне обслуговування залізничних стрілочних приводів із використанням цифрового двійника та глибокого навчання

Ігор Каткало
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0008-2672-1005

Галина Голуб
Кандидат технічних наук, доцент
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0002-4028-1025

Анотація. Стрілочні електроприводи є критично важливими компонентами інфраструктури залізничної сигналізації, а їх відмови становлять 15-20 % усіх збоїв у роботі сигнальних систем європейських мереж, спричиняючи значні експлуатаційні та економічні втрати. Метою дослідження була розробка підходу до предиктивного обслуговування стрілочних електроприводів мереж колії 1520 мм на основі цифрового двійника, що забезпечує раннє виявлення несправностей за електричними сигнатурами потужності, зареєстрованими під час кожного циклу переведення. Методологія дослідження поєднала чотиришарову архітектуру цифрового двійника (фізичний шар, шар даних, аналітичний шар і шар прийняття рішень) із порівнянням трьох архітектур глибокого навчання: одновимірної згорткової нейронної мережі (1D-CNN), мережі довгої короткочасної пам'яті (LSTM) та гібридної CNN-LSTM-моделі. Їх зіставляли з логістичною регресією, методом опорних векторів (SVM) і випадковим лісом на синтетичному фізично обґрунтованому наборі з 5000 кривих потужності для стрілочних електроприводів СП-6М та ВСП-220. Моделі оцінювали за багатокласовою класифікацією п'яти категорій стану та прогнозуванням деградації на горизонті 50 циклів. Гібридна CNN-LSTM досягла найвищої точності класифікації (macro F1 = 0,938), а LSTM – найкращого результату для прогнозу деградації (R^2 = 0,937); обидві істотно перевершили найкращу baseline-модель (Random Forest: F1 = 0,871, R^2 = 0,845). Експерименти cross-generator validation та artefact ablation підтвердили, що перевага глибокого навчання походить з виявлення переносних ознак форми сигналу, а не з запам'ятовування симуляції. Рекомендовано конфігурацію розгортання: 1D-CNN на edge для класифікації у реальному часі, LSTM на серверному рівні для прогнозу деградації, Random Forest як проміжне рішення для операторів з обмеженими розміченими даними. Практична цінність отриманих результатів полягає у формуванні науково обґрунтованих рекомендацій з розгортання аналітичного шару цифрового двійника на мережах колії 1520 мм, що сприяє переходу від планового до обслуговування за фактичним станом та зменшенню непланових простоїв

Ключові слова: керування; діагностика; аналіз енергетичних сигнатур; моніторинг; архітектура; моделювання

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Infrastructural solutions for 1,435/1,520 mm railway interoperability in Ukraine

Halyna Vasilova*
PhD in Technical Sciences, Associate Professor
National Transport University
02000, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0002-4168-1434

Oksana Yurchenko
PhD in Technical Sciences, Associate Professor
National Transport University
02000, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0001-6834-692X

Roman Liashuk
Assistant Lecturer
National Transport University
02000, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0005-2267-9055

Oleksii Goretskyi
PhD in Historical Sciences, Associate Professor
National Transport University
02000, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0000-0002-2656-6120

Abstract. Under martial law and in the context of European integration, improving the interoperability between the 1,435 mm and 1,520 mm railway gauge networks through the development of multimodal transport and logistics hubs has become critically important for ensuring the functioning of Ukraine's export and import supply chains. The aim of this study was to investigate and substantiate infrastructure solutions for enhancing the interaction between the 1,435 mm and 1,520 mm railway systems through the development of a network of dry ports as key elements of Ukraine's multimodal logistics system. To achieve this objective, a systematic approach, structural-functional analysis, as well as infrastructure, logistics, and statistical analyses of freight flows were employed. Current trends in the development of multimodal transport and the operation of dry ports in the European Union and Ukraine were examined. It was found that the development of inland multimodal terminals can reduce pressure on border and port infrastructure, shorten cargo handling times, and improve the efficiency of logistics chains. Based on a synthesis of international experience in the development of multimodal logistics centres, promising directions for integrating Ukraine's transport system into the Trans-European Transport (TEN-T) network and the Solidarity Lanes initiative were identified. The technical and operational parameters of railway terminal functioning were analysed, including requirements for track layout configuration, the length of arrival and departure tracks, shunting operations, and capacity provision for handling full-length container trains. In addition, patterns of container flow imbalance and empty rolling stock accumulation within international transport corridors were identified. The study also examined the issue of container flow imbalance and the role of dry ports in ensuring efficient management of empty containers. The practical value of the research lies in the possibility of applying its findings by public authorities, logistics operators, transport companies, and design organisations in planning the development of multimodal infrastructure, border terminals, and a network of dry ports in Ukraine

Keywords: railway infrastructure; dry ports; multimodality; containerisation; logistics hubs; international freight transport; supply chains

Introduction

The transport sector plays a crucial role in strengthening Ukraine's economic resilience and supporting its integration into the European economic area. Since the beginning of the full-scale Russian invasion, ensuring the continuity of logistics operations, developing alternative export routes, and improving the efficiency of multimodal transportation have become critical priorities. The destruction of transport infrastructure, restricted access to seaports, and the reorientation of foreign trade flows have created an urgent need for new logistics solutions capable of maintaining resilient supply chains. One of the most promising approaches involves the development

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*Corresponding author (*h.vasilova@ntu.edu.ua*)

of multimodal transport and logistics hubs, particularly dry ports, which optimise interaction between different modes of transport, increase transport system capacity, and facilitate Ukraine's integration into the European transport network. Dry ports also support the technological synchronisation of railway systems with different track gauges – the European standard gauge (1,435 mm) and the Ukrainian broad gauge (1,520 mm) – thereby helping to overcome existing infrastructural barriers.

Recent studies have examined various aspects of multimodal transportation and dry port development under conditions of geopolitical instability and global logistics transformation. Kh. Prytula *et al.* (2022) analysed changes in freight movements across the Ukraine-European Union border following the outbreak of the war and emphasised the importance of container transportation and intermodal terminal networks for increasing the throughput capacity of Ukraine's logistics infrastructure. O. Nelipovych (2023) investigated the functional role of inland terminals in Ukraine and highlighted the need to redirect freight flows toward the western borders due to the limited operation of seaports during wartime. Several studies have focused on the infrastructural, operational, and environmental dimensions of dry port systems. O. Kyryllova & V. Romakh (2025) proposed a conceptual model of an integrated dry port combining production, customs, and logistics functions. C. Caballini *et al.* (2025) developed a process-oriented approach to evaluating dry port systems and demonstrated that operational efficiency and process synchronisation are more important for competitiveness than physical distance alone. T. Rožić *et al.* (2025) examined the role of inland terminals in strengthening port-hinterland connectivity and improving regional logistics efficiency. G. İnegöl & Y. Arslanoğlu (2024) showed that prioritising railway transport within multimodal logistics systems can significantly reduce greenhouse gas emissions and air pollution. Z. Lu & W. Qiu (2025) analysed the resilience of logistics networks and demonstrated that dry ports can function as dynamic buffers that protect maritime hubs from operational overloads. R. Saha & K. Khalil (2025) investigated policy measures aimed at expanding intermodal infrastructure to improve the productivity and competitiveness of trade corridors.

Recent research has also emphasised the strategic role of dry ports in integrating maritime and inland logistics systems. V. Roso *et al.* (2026) examined the growing congestion of maritime terminals and argued that dry ports can partially assume customs, storage, and cargo consolidation functions traditionally performed by seaports. Their findings indicate that transferring part of freight flows to rail and inland transport corridors can reduce congestion in coastal areas and improve supply chain sustainability. E. Kurtuluş (2023) proposed a multi-criteria optimisation model for inland container logistics and dry port location planning that incorporates environmental considerations, empty container redistribution, railway pricing mechanisms, and cargo consolidation opportunities. Despite the growing body of research on dry ports and multimodal transportation, limited attention has been paid to infrastructural solutions for interoperability between the 1,435 mm and 1,520 mm railway systems under wartime conditions in Ukraine. In particular, insufficient research addresses the technical and operational requirements of inland terminals capable of supporting large-scale multimodal integration within the European transport network.

The scientific novelty of the study lies in substantiating the role of dry ports as strategic multimodal infrastructure elements capable of supporting logistics resilience, technological synchronisation between railway systems with different gauges, and the long-term integration of Ukraine into the European transport area. The study aimed to identify ways to improve international container transport, overcome technical barriers at the border and ensure the integration of Ukraine's transport system into the European TEN-T network under current geopolitical challenges. To achieve this objective, the following tasks had been identified: to investigate the functioning of dry ports as key nodes of multimodal infrastructure to optimise the interaction of railway systems with different track gauge standards; to determine the technical and operational parameters and throughput capacity of terminal infrastructure (track layout configuration, effective length, handling capacity) required for the efficient handling of full-length container trains; justify infrastructure solutions for overcoming the 1,520/1,435 mm "track gauge barrier" through the creation of points for technological synchronisation and cargo transhipment within internal logistics systems.

Materials and Methods

This study was based on a review of academic publications, regulatory documents, reports by international organisations, and statistical data related to the development of multimodal transport infrastructure, the operation of dry ports, and the interaction between the 1,435 mm and 1,520 mm railway systems. In this study, a dry port was defined as an inland logistics facility that acts as a buffer between railway networks with different track gauges. The theoretical framework draws on concepts of multimodal transport, intermodal logistics, TEN-T corridor development, and resilient logistics systems under wartime and crisis conditions. The methodological approach combined systems, structural, functional, and logistics analysis to examine dry ports as integrated elements of the transport network that facilitate interoperability between different railway gauge systems. The study employed the following methods: systems analysis to assess the role of dry ports within multimodal transport systems; comparative analysis to evaluate international experience in the development of inland logistics terminals and its applicability to Ukraine; logistics and infrastructural analysis to determine the technical and operational parameters of terminal infrastructure; generalisation to formulate conclusions regarding Ukraine's integration into the European TEN-T network; statistical analysis to evaluate trends in freight and container traffic.

The literature review primarily focused on publications issued between 2020 and 2026 in order to capture recent transformations in logistics systems related to the war in Ukraine, the development of the Solidarity Lanes initiative, and ongoing European integration processes. This period was selected because it reflects the reorientation of Ukraine's logistics routes under wartime conditions, including recurring disruptions affecting maritime transport corridors. Sources were selected based on their scientific relevance, topicality, analytical value, and relevance to multimodal transport and dry port development. The study used materials published in international and Ukrainian academic journals, European Commission reports, analytical studies on the Solidarity Lanes initiative, and statistical data on maritime and rail transport in EU countries. The literature search used the following keywords: "dry port", "multimodal transport", "intermodal logistics", "railway infrastructure", "TEN-T", "container transportation", "1,520/1,435 mm gauge interoperability", "Solidarity Lanes", and "logistics centres". Searches were conducted using the Scopus, Web of Science, Google Scholar, and ResearchGate databases, as well as open-access analytical sources.

The study followed a progression from a general analysis of global logistics trends and freight imbalances to the examination of technical constraints related to the 1,520/1,435 mm gauge barrier and, finally, to the development of applied infrastructure solutions for Ukraine. The analysis compared the theoretical advantages of the dry port concept with the technical and operational constraints of Ukrainian border and inland railway terminals. This approach made it possible to formulate recommendations for the development of a network of railway terminals capable of strengthening Ukraine's role as a logistics hub in Eastern Europe. The proposed methodology ensured a consistent research framework and supported the formulation of conclusions regarding the development of dry ports as a tool for integrating Ukraine into the European logistics system.

Results and Discussion

Transport constitutes a fundamental component of the economy by ensuring the mobility of people and goods, facilitating access to employment and services, and supporting trade and economic growth. Since 2014, the gradual reorientation of Ukraine's trade flows has significantly reshaped transport patterns. Whereas trade with Russia and transit through Ukrainian territory previously played a major role, the growing share of trade with European Union member states has increased the strategic importance of westbound transport corridors (Ukraine Facility, n.d.). Since the beginning of the full-scale Russian invasion, ensuring the security and resilience of supply chains has become a critical priority, with transport playing a central role in maintaining the stability of the national economy. The rapid restoration of damaged infrastructure and the implementation of the Solidarity Lanes initiative between the European Union and Ukraine enabled the export of nearly 214 million tonnes of goods from May 2022 onward, including approximately 91 million tonnes of grain, oilseeds, and related products.

The Solidarity Lanes have also facilitated the import of nearly 100 million tonnes of essential goods, including military and humanitarian aid, fuel, and other critical commodities. The total trade value supported through the initiative is estimated at approximately EUR 270 billion, including around EUR 198 billion in imports to Ukraine (European Commission, n.d.). Following Russia's withdrawal from the Black Sea Grain Initiative on 17 July 2023 and the subsequent attacks on Ukrainian port infrastructure, the role of the Solidarity Lanes became even more significant for sustaining the Ukrainian economy. In addition to addressing immediate wartime logistics challenges, the initiative creates a foundation for Ukraine's future integration into the EU Single Market and the broader European transport system. Strengthening transport connectivity between Ukraine and the EU is therefore of strategic importance for ensuring secure and reliable trade routes.

Improving export routes, restoring and expanding the capacity of key transport connections, and diversifying logistics systems are essential for maintaining the competitiveness of Ukrainian products in international markets. The wider implementation of multimodal transport solutions and intelligent transport systems can improve the efficiency of transport operations and promote deeper integration into global supply chains, thereby supporting economic recovery and long-term development. Investment in transport connectivity is particularly important in the context of Ukraine's gradual integration into the EU Single Market. Such investments should comply with the principles of sustainable development and decarbonisation in line with the objectives of the European Green Deal. In this regard, Ukraine may also benefit from participation in the EU-supported Transport Community framework. According to the RDNA3 assessment, as of 31 December 2023, the total cost of Ukraine's reconstruction and recovery over the next decade is estimated at approximately USD 486 billion, compared with USD 411 billion estimated a year earlier (World Bank, 2024). Reforms and investments should complement one another and contribute to expanding export logistics capacity. Ukraine's EU candidate status should serve both as an instrument and as a driving force for the development of a modern and efficient transport system aligned with EU standards. In the short term, priority should therefore be given to reforms capable of stimulating economic growth while creating the foundation for further modernisation of transport infrastructure.

One of the priority tasks is the restoration and development of Ukraine's export logistics potential, particularly within the TEN-T framework. Reforms should focus on improving market conditions in ways that encourage private investment in transport infrastructure, especially in ports and logistics centres, while also facilitating the gradual integration of Ukrainian operators into the EU Single Market under fair and competitive conditions. In this context, the development of a new generation of inland logistics hubs – dry ports – is becoming increasingly important. These facilities ensure efficient interaction between different transport modes, optimise cargo transshipment processes, and reduce pressure on border crossings and port infrastructure (Euroterminal, n.d.). A dry port can be defined as an inland multimodal logistics centre equipped with advanced infrastructure and cargo-handling facilities that provide services traditionally associated with seaports while operating inland. Under conditions of restricted access to Black Sea ports and continuing attacks on port infrastructure, dry ports are also acquiring strategic importance as secure rear logistics hubs. They enable customs and logistics operations to be relocated away from active combat zones, thereby improving the continuity and reliability of supply chains.

The revision and modernisation of Ukraine's comprehensive transport strategy are therefore essential both for defining priorities during post-war reconstruction and for ensuring the long-term development of the transport sector in accordance with EU standards and objectives. This is particularly important in the context of current geopolitical challenges, which require deeper integration of Ukraine into the European transport area. The strategy should be long-term, financially sustainable, environmentally responsible, and based on the principle of equal territorial accessibility. The transformation of logistics systems with a focus on integration into the European transport network represents one of the key strategic tasks for the coming years. Prior to 2022, seaports accounted for up to 90% of Ukraine's food exports; therefore, current priorities must include the development and modernisation of integrated transport and logistics infrastructure (Table 1).

Particular attention should be given to the development of logistics centres in Western and Southern Ukraine, as well as to increasing transshipment capacity at border crossing points. In this regard, dry ports should be considered key components of the emerging logistics infrastructure. Functioning as inland multimodal terminals, they facilitate the consolidation, handling, and redistribution of cargo flows while also performing customs clearance and transshipment operations between different transport modes. Their development contributes to reducing congestion at seaports and border terminals, shortening cargo handling times, and improving the overall efficiency and resilience of logistics chains.

Table 1. Directions for the development of multimodal transport and logistics infrastructure

Area of development	Key measures	Expected impact
Border infrastructure	Modernisation of border crossing points with the EU and Moldova; simplification of customs and border procedures	Faster border crossing and increased throughput capacity
Port clusters	Development and protection of ports on the Danube, in Greater Odesa, and in eastern regions of the country	Improved security of maritime trade routes and support for export operations
Multimodal solutions	Expansion of container transportation and development of the dry port network	Optimisation of logistics processes through reduced pressure on border crossings and seaports; relocation of logistics operations inland

Source: compiled by the authors

The future transport system should be developed around the TEN-T network, which connects major cities, border crossings, and ports. Modernisation of railway, road, and terminal infrastructure in accordance with EU standards will strengthen regional connectivity and improve the efficiency of freight transportation. In particular, expanding the capacity of logistics centres and dry ports in Western and Southern Ukraine is essential for ensuring efficient cargo transshipment and supporting the reorientation of trade flows. In modern logistics systems, a dry port is an inland rail-road terminal located away from the seacoast but capable of performing many functions traditionally associated with a seaport. Such terminals serve as hubs for container handling and provide customs clearance, cargo consolidation, storage, and onward distribution inland. Cargo arriving at seaports is transferred to rail or road transport and delivered to inland terminals, where the main logistics and cargo-handling operations are carried out. In this sense, dry ports represent an integrated logistics network infrastructure that extends seaport functions inland without requiring direct maritime access. They support the full cycle of container and cargo handling, from customs processing and storage to dispatch to final destinations.

Dry ports have become widely used worldwide, and demand for their services continues to grow. In many countries, regular container shuttle trains connect seaports with inland logistics terminals according to fixed schedules. The presence of a developed network of inland terminals is therefore considered an indicator of the efficient functioning of major seaports and national logistics systems. A single dry port can provide cargo owners with a comprehensive range of logistics and cargo-handling services, including the following: cargo handling and storage; handling and storage of bulk cargo; customs clearance, inspection, packing, and labelling; repair and maintenance of container equipment; freight forwarding services; banking, insurance, and financial services; transport booking and brokerage services; cargo transshipment to other transport modes and delivery to final destinations (Horachek & Horova, 2021). Dry ports located near major cargo-generating areas or trade centres, while remaining distant from seaports, can significantly optimise transport costs. This is achieved through the use of light and medium-duty trucks for local cargo distribution between production or consumption points and inland terminals, while rail or inland waterway transport is used for long-distance container transportation where applicable. Such transport schemes contribute to lower logistics costs and may stimulate further growth in trade volumes.

One of the key priorities for improving Ukraine's transport and logistics infrastructure is the development of a network of dry ports capable of serving import and export cargo flows for the regions in which they are located. These terminals should facilitate cargo consolidation and the formation of freight trains for subsequent delivery to end consumers and regional distribution centres. The effectiveness of a dry port largely depends on its location. On the one hand, it should maintain strong transport connectivity with seaports; on the other hand, it must provide efficient access to warehousing and distribution infrastructure. Therefore, dry ports should be situated at the intersection of major logistics corridors. At the same time, they must be integrated into transport connections with other inland terminals, border crossing points, customs control facilities, seaports, inland waterway terminals, and airports. Equally important is their operational versatility, meaning the ability to handle different categories of cargo and provide a broad range of logistics services (Fig. 1).

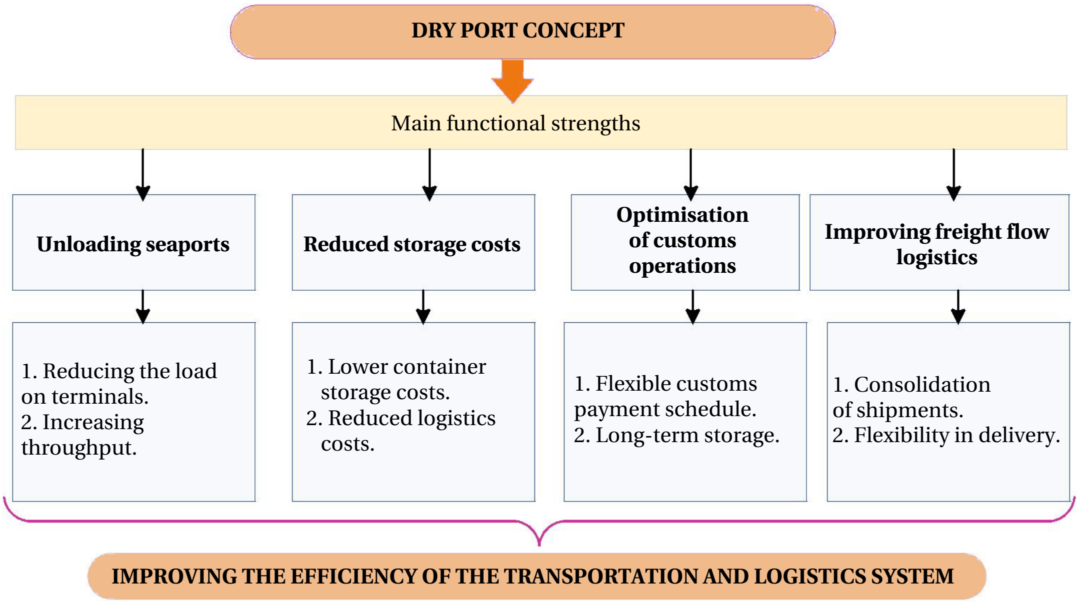

Figure 1. Scheme of the location and functioning of the dry port

Source: compiled by the authors

Such dry ports offer significant advantages for all participants in the transport and logistics sector. First, they help reduce congestion at maritime terminals. Second, the storage of containers and other cargo at inland terminals is generally less expensive than at seaports. Third, customs payments can often be deferred until cargo is released from the dry port, allowing goods to remain in storage for extended periods when necessary. Finally, dry ports improve cargo logistics by enabling the consolidation and redistribution of shipments. International experience demonstrates the growing importance of inland logistics infrastructure. In Western Europe, transport infrastructure is highly developed not only in coastal regions but also deep inland. A particularly high concentration of dry ports can be observed along the Rhine corridor and in Bavaria in southern Germany. Major logistics hubs have also emerged around key economic centres such as Paris, Milan, and Madrid, as well as within the Liverpool-Manchester-Leeds corridor. Another extensive network extends from Austria toward industrial regions in Hungary, the Czech Republic, and southern Poland.

Because many major European industrial regions and the Baltic countries are located far from primary maritime routes, seaports frequently function as intermediate gateways connecting inland markets with global trade networks. Connections between inland terminals and major European seaports – including Rotterdam, Antwerp, Hamburg, Bremerhaven, Le Havre, Barcelona, and Marseille – are supported by medium-distance transport corridors using combined transport technologies, including rail transport, road haulage, and inland waterway shipping. As noted by M. Raimondi (2023), a rail-oriented dry port is planned in Salaspils. The logistics park is expected to integrate both 1,520 mm and 1,435 mm railway systems, together with motorway connections and large-scale warehouse infrastructure. Dry ports are exerting an increasingly important influence on the development of transport infrastructure and supply chain systems by reducing cargo transit times and lowering delivery costs. Four major dimensions of this impact can be identified.

1. Location and surrounding infrastructure. Like any major transport facility, a dry port requires a strategically advantageous location with efficient access to rail transport and, where possible, to other transport modes such as inland waterways. Another important factor is the availability of land reserves for future expansion.

Proximity to economically developed and densely populated regions is particularly significant, since such areas generate stable cargo flows and become integrated into logistics corridors passing through inland terminals. As a result, demand for terminal capacity and adjacent warehouse infrastructure increases. Logistics operators, distributors, and foreign trade participants are often willing to pay higher rents for warehouse facilities in strategically located logistics zones because of the resulting reductions in transport and delivery costs. The development of logistics centres and intermodal terminals also creates a mutually reinforcing effect. Intermodal terminals require logistics centres to consolidate cargo flows and generate sufficient freight volumes, while logistics centres benefit from inland terminals by gaining improved access to multimodal transport networks.

2. Empty container repositioning. As a substantial share of international and domestic freight transportation is containerised, imbalances between export and import flow frequently arise. Under such conditions, dry ports must possess both the physical infrastructure and logistical capacity necessary for the efficient redistribution of empty containers to regions experiencing container shortages. This can be achieved through the organisation of dedicated empty-container repositioning flows and through coordination agreements with shipping companies and freight forwarders regarding available transport capacity. According to the L. Nguyen (2025), approximately 41% of global container transport activity, measured in TEU-miles, is currently associated with empty containers. This represents a significant increase compared with 31% in 2019, prior to the disruptions caused by the COVID-19 pandemic. In practical terms, this means that for every ten miles travelled by a loaded container, empty containers must now be repositioned for an additional 4.1 miles, compared with 3.1 miles in 2019. Over the past five years, this indicator has shown a generally upward trend, with only a slight temporary decline observed in 2022. According to L. Nguyen (2025), these imbalances are primarily driven by uneven trade patterns between regions. Asian ports frequently experience shortages of empty containers due to high export volumes, whereas many ports in North America and Europe accumulate surpluses of empty containers because imports exceed exports. As a result, significant inefficiencies and additional costs emerge throughout the container logistics chain.

For shipping lines and logistics operators, the growth in the share of empty-container movements increases operating costs, lowers equipment utilisation rates, and creates additional challenges for repositioning operations. The management of empty-container flows has therefore become a strategic issue not only for major global carriers but also for regional and feeder shipping operators. In addition, ports that accumulate large volumes of empty containers increasingly face storage and handling constraints. In congested logistics markets, this may affect terminal charges, storage fees, and route-planning strategies. Consequently, balancing empty-container flows is becoming an increasingly important component of logistics system management. According to data published by Eurostat (2025), cargo imports through EU ports reached approximately 2.1 billion tonnes in 2024, whereas exports amounted to only 1.3 billion tonnes (Fig. 2). This imbalance contributes to the accumulation of empty containers within European logistics systems and increases the importance of dry ports as inland hubs for container redistribution.

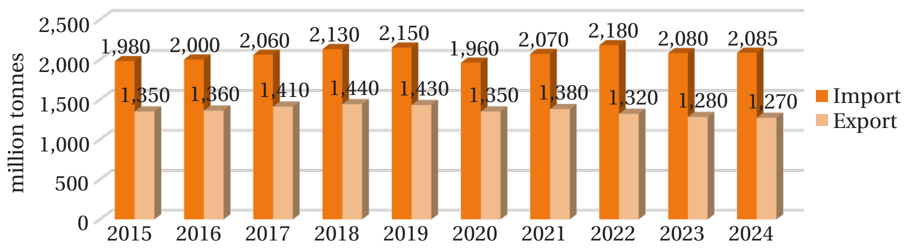

Figure 2. Volumes of maritime freight transport in the EU

Source: developed by the authors based on Eurostat (2025)

The total volume of cargo handled by EU ports in 2024 was estimated at approximately 3.4 billion tonnes, remaining relatively stable compared with 2023 (-0.2%) (Fig. 2). The decline in cargo volumes observed in 2023-2024 relative to 2022 can largely be attributed to restrictions on trade with Russia following the invasion of Ukraine. Although freight volumes partially recovered after the sharp decline recorded in 2020, which was mainly associated with the COVID-19 pandemic and related restrictions, cargo turnover in 2024 still remained somewhat below the levels observed in 2018-2019.

3. Cargo turnover. Despite imbalances in global container flows, dry ports play an important role in improving the coordination of import and export operations. In practice, containers used for imports are often subsequently reused for export shipments after unloading and reloading procedures have been completed. For container owners – including shipping lines, leasing companies, and terminal operators – rapid container turnover represents one of the key indicators of operational efficiency, as it ensures the continuous utilisation of container assets. Effective strategies for managing container circulation and cargo turnover therefore contribute to improving the operational performance of both container owners and dry port operators.

4. Trade facilitation. Dry ports also serve as important instruments for supporting regional import and export

activity. By reducing transport and logistics costs, they expand economic opportunities for inland regions and improve access to international markets. This is especially important for small and medium-sized enterprises, which often cannot independently achieve the economies of scale required for efficient participation in global supply chains. At the same time, the effective performance of dry port functions largely depends on the quality and capacity of inland transport infrastructure, particularly the railway component. Rail transport ensures high cargo throughput, service reliability, and economically efficient connections between seaports and inland terminals. Consequently, the design and organisation of railway infrastructure within dry ports are of particular importance, as such infrastructure must comply with the requirements of modern intermodal transport systems and ensure uninterrupted logistics operations.

Dry ports served by rail transport should be connected to the nearest main railway line through a short access track, which is typically designed and managed by the relevant railway infrastructure authorities. Rail-served inland terminals must also possess infrastructure capable of handling full-length freight trains. The railway infrastructure of dry ports should allow the reception and handling of full-length container trains operating directly between origin and destination terminals without the need for train splitting or regrouping outside the terminal area (Fig. 3).

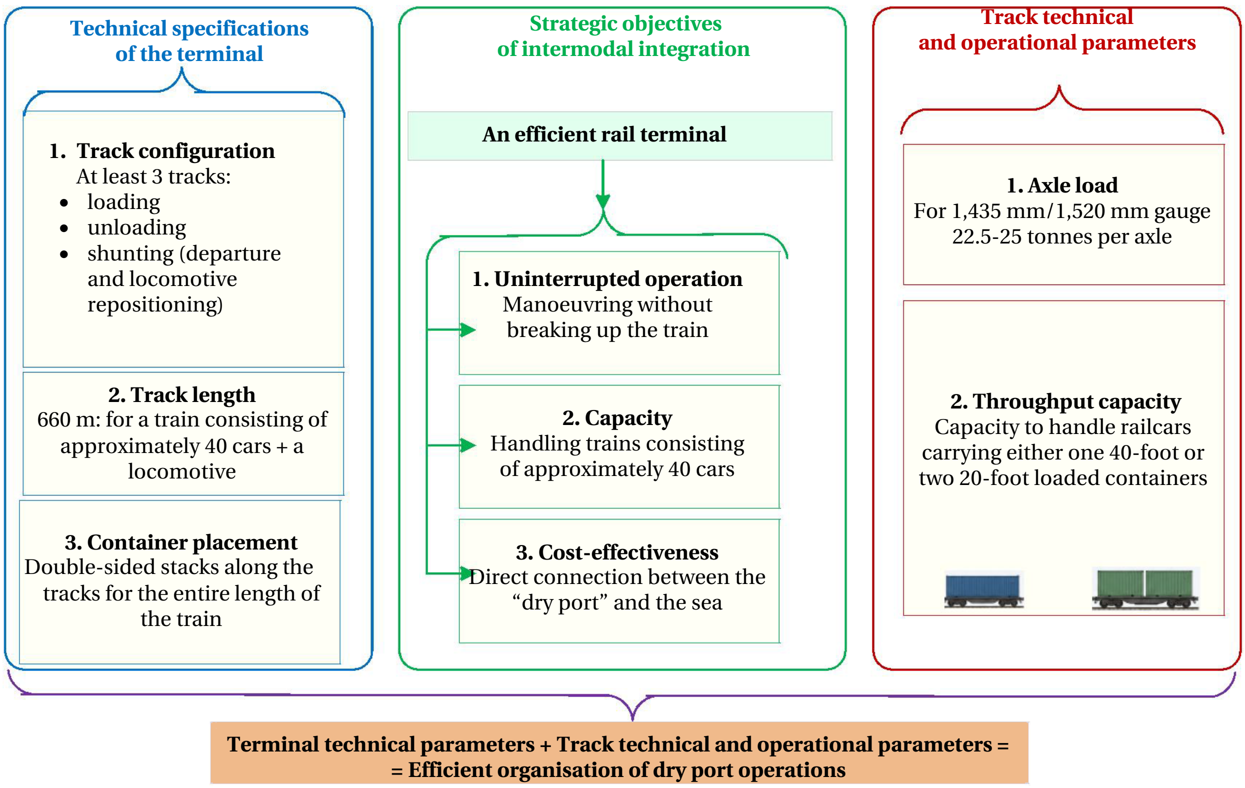

Figure 3. Scheme of organisation of the work of a railway terminal in the dry port system

Source: compiled by the authors

Loading and unloading operations should be performed on centrally located terminal tracks consisting of at least three railway tracks: one loading track, one unloading track, and one track intended for locomotive movements and shunting operations. The required number of loading and unloading tracks depends on traffic intensity and terminal throughput. Container stacks within the paved terminal yard should be arranged along both sides of the railway tracks throughout their full length in order to ensure continuous operation of handling equipment along the entire train formation. The required length of loading and unloading tracks is determined by the number and length of wagons within the train formation. For example, a train consisting of 40 wagons and one locomotive may require track lengths of approximately 660 m between switch points. The design axle load of terminal sidings should correspond to the axle load standards of the adjacent main railway lines. For 1,435 mm and 1,520 mm gauge systems, this typically ranges from 22.5 to 25 tonnes per axle. Even on less intensively used sections, the infrastructure must be capable of accommodating heavy locomotives and wagons carrying either two fully loaded 20-foot containers or one fully loaded 40-foot container.

When designing the layout and infrastructure of dry ports, particular attention should therefore be paid to ensuring uninterrupted railway connectivity between inland terminals, seaports, and other dry ports. Rail infrastructure must support reliable and continuous freight operations within multimodal transport corridors. The concept of the dry port as an inland logistics hub is highly relevant for Ukraine under conditions of war and European integration. Such terminals perform many functions traditionally associated with seaports, including cargo handling, storage, customs clearance, and the formation of container trains, while simultaneously strengthening the resilience and flexibility of national logistics systems. These facilities are becoming particularly important in the context of the development of the Solidarity Corridors. Given restricted access to deep-water Black Sea ports and continuing attacks on port infrastructure, dry ports are increasingly functioning as secure inland logistics hubs (Fig. 4).

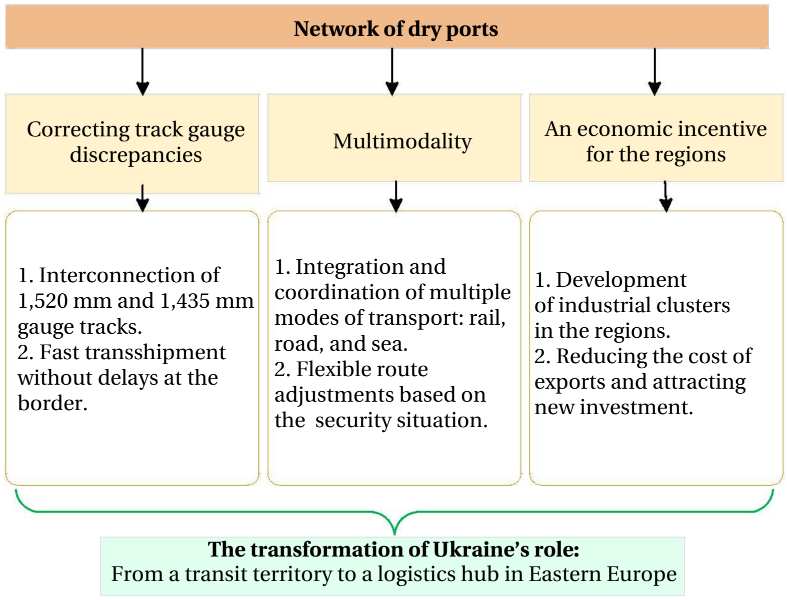

Figure 4. Model of the impact of the development of the dry ports network on Ukraine's integration into TEN-T
Source: compiled by the authors

The implementation of such a strategy makes it possible to overcome the incompatibility between Ukrainian and European railway gauge systems through the rapid integration of 1,520 mm and 1,435 mm railway infrastructure, thereby accelerating cargo transshipment processes. Through multimodal integration, these logistics hubs combine different modes of transport and provide greater route flexibility under unstable security conditions. At the same time, the development of dry ports stimulates the emergence of regional industrial and logistics clusters, reduces export-related costs, and attracts new investment. Ultimately, this contributes to Ukraine's integration into the European TEN-T network and strengthens its position as a major logistics hub in Eastern Europe.

Recent studies demonstrate growing academic and practical interest in the development of dry ports as key elements of multimodal transport systems, particularly in the context of increasing containerisation, logistics disruptions, and the need to improve supply chain resilience. I. Lovrić *et al.* (2020) examined the operations of the Port of Rijeka, the largest seaport in Croatia and an important component of the EU TEN-T Mediterranean Corridor. Due to the steady growth of container traffic over the last two decades, the authors analysed the potential role of dry ports in expanding terminal capacity and improving logistics efficiency. In this study, a dry port is defined as an inland intermodal terminal directly connected to a seaport by rail or road infrastructure and capable of performing logistics and cargo handling functions for inland destinations. Simulation results demonstrated that transferring part of logistics operations inland can significantly reduce container dwell time and improve the efficiency of freight transportation. The study also confirmed the strategic importance of rail transport as a core element of sustainable freight mobility within the European transport system.

R. Saha & K. Khalil (2025) investigated policy strategies for expanding dry port infrastructure in Bangladesh to improve the competitiveness and efficiency of maritime trade hubs. Against the background of rapidly growing cargo volumes at the Port of Chittagong, the authors highlighted the insufficient development of intermodal transport infrastructure. Their findings indicate strong expert support for the establishment of new inland terminals, particularly outside major port cities, in order to reduce congestion, improve regional connectivity, and lower logistics costs and emissions. The integration of advanced digital technologies into dry port systems has also attracted growing research attention. S. Rekabi & Z. Sazvar (2026) proposed a multi-stage stochastic model of a flexible logistics network based on Industry 5.0 principles and machine learning tools to optimise interaction between maritime and inland terminals. Their study emphasises the increasing importance of digitalisation and intelligent logistics management in multimodal transport systems. Several studies have focused on the infrastructural and economic dimensions of multimodal transportation development in Ukraine. V. Sytnik & O. Pikulina (2025) emphasised the need to modernise Ukraine's border and terminal infrastructure in accordance with EU standards and identified priority directions for the development of logistics centres within the TEN-T network. A. Dalivand & S. Torabi (2024) demonstrated that integrating dry ports into transport and logistics systems can reduce congestion at seaports, optimise container transportation, and mitigate the environmental impact of freight operations.

The resilience of transport and logistics systems under crisis conditions has become another important research direction. K. Węcel *et al.* (2024) analysed the impact of the COVID-19 pandemic and the war in Ukraine on maritime freight flows and concluded that diversified logistics routes and inland multimodal hubs are essential for maintaining the stability of international transportation. S. Karakas *et al.* (2024) further highlighted the importance of alternative transport corridors and inland terminals for minimising supply chain disruption risks in Ukrainian agricultural exports. Environmental sustainability and supply chain resilience are increasingly considered key criteria in dry port planning. G. İnegöl & Y. Arslanoğlu (2026) developed a hybrid FR-SWARA model for evaluating dry port location criteria and demonstrated the growing importance of spatial and infrastructural factors compared with purely financial considerations. Their findings redefine dry ports as strategic infrastructure buffers capable of absorbing systemic shocks within logistics networks.

Recent Ukrainian studies have also examined the transformation of port logistics systems under wartime conditions. I. Smyrnova *et al.* (2026) analysed changes in the operation of seaports, dry ports, and multimodal transport systems during martial law. The authors identified several major transformation trends, including the spatial decentralisation of port functions, the diversification of logistics routes, the adaptation of operational procedures to heightened security requirements, and the increasing importance of resilient supply chains. Their study highlights the strategic role of inland logistics terminals in maintaining continuity of freight transportation under conditions of infrastructure disruption and geopolitical instability. These findings are consistent with the conclusions of A. Nechyporuk *et al.* (2023), who emphasised that maintaining export operations under martial law required the rapid reorganisation of logistics chains, the expansion of alternative transport corridors, and the increased use of multimodal transport solutions.

N. Shayan & N. Mohabbati-Kalejahi (2026) analysed the contribution of inland ports to sustainable development through a structured review of academic literature. Their study demonstrated that inland ports play a significant role in advancing sustainable logistics, regional development, and the achievement of the United Nations Sustainable Development Goals, particularly SDGs 9 and 11. Despite the extensive body of research on dry ports, multimodal transportation, and logistics resilience, insufficient attention has been devoted to infrastructural solutions for interoperability between the 1,435 mm and 1,520 mm railway gauge systems in Ukraine. In particular, limited research addresses the technical and operational requirements of inland multimodal terminals capable of supporting efficient cargo transshipment, full-length container train operations, and technological synchronisation between railway systems with different gauge standards under wartime and European integration conditions.

In Ukraine, dry ports are gradually becoming a key component of the modern transport and logistics system, operating as inland multimodal terminals that partially assume functions traditionally performed by seaports. They provide cargo transshipment, storage, customs clearance, and cargo consolidation services, thereby reducing pressure on port infrastructure and improving the efficiency of freight handling operations. The primary driver behind the development of dry ports has been the need to optimise logistics processes under conditions of growing containerisation and limited seaport capacity. International and domestic experience demonstrates that transferring part of logistics operations to inland terminals helps reduce cargo dwell times in ports and lowers handling costs. In the Ukrainian context, dry ports primarily function as multimodal logistics centres located near major transport junctions and railway stations. They integrate transport, warehousing, and customs infrastructure while providing a comprehensive range of cargo-handling services. A particularly important feature is the availability of railway connections, which enable the formation of container trains and ensure regular freight operations (Port Clearance, 2020).

April 2026 became an important milestone for Ukrainian logistics development. Following a prolonged period of border congestion and instability of transport routes, the launch of new multimodal terminals and dry ports began to systematically transform the structure of export flows. According to the Zakarpattia Regional State Administration, the Chornotysiv Terminal became one of the most significant additions to this emerging network (Kurta, 2024). Located in the Berehove district, the project involved investments of approximately UAH 282 million and demonstrated the advantages of geographical proximity to Hungary and Romania. The terminal supports the transshipment of both agricultural products and energy resources, thereby providing Ukrainian businesses with more direct access to international markets. Alongside the western border regions, inland logistics hubs in central Ukraine are also gaining strategic importance. According to O. Yavorskyi (2024), construction of a railway terminal in Vinnytsia region has been completed, establishing transport connections between the region, the ports of Greater Odesa, and the European Union. Total investment in the project exceeded USD 15 million. The first development phase of the Vinnytsia dry port includes modern railway infrastructure and a container terminal with an annual capacity of 30,000 TEU. Through its connection with the Mostyska terminal, exporters obtained a more predictable transport route toward the Polish border. This development is particularly important given that, according to the Ukrainian government, the maritime corridor has already facilitated cargo turnover exceeding 60 million tonnes, while inland terminal development further strengthens the resilience of national logistics systems (Yavorskyi, 2024). These developments reflect not only infrastructure expansion but also the emergence of a fundamentally new approach to freight transportation. Whereas border crossing congestion previously represented one of the main logistical bottlenecks, businesses are now able to plan deliveries with significantly greater predictability. Such operational stability is critically important for fulfilling contracts with European partners, where compliance with delivery schedules directly affects financial performance and business reputation.

Ukrainian logistics systems has gradually begun transitioning from emergency adaptation toward more strategic optimisation, with dry ports becoming one of the foundations for integration into global supply chains. One of the key functions of inland terminals is the relocation of customs procedures away from border crossings and seaports, which contributes to reducing congestion and accelerating container turnover. This approach corresponds to international logistics practices and improves the transparency and manageability of supply chains (Delo.net.ua, 2026).

At the same time, the technical level of Ukrainian dry ports remains uneven. Alongside modern logistics complexes equipped with advanced technologies, some facilities still possess limited operational and technological capabilities. This creates a need for further infrastructure modernisation, the introduction of advanced cargo-handling technologies, and the implementation of digital solutions for transport and logistics flow management (Port Clearance, 2020). Under current geopolitical and economic conditions, particularly the transformation of logistics routes and the reorientation of export flows, dry ports are acquiring strategic importance for Ukraine's economy. They increase the resilience of the transport system, facilitate integration into European transport corridors, and create the foundation for the further development of multimodal transportation (Delo.net.ua, 2026).

Consequently, the formation of an interconnected network of dry ports transforms these facilities from isolated infrastructure elements into integrated coordinators of Ukraine's foreign trade logistics system. The combined development of western border terminals and inland multimodal hubs enables the country to reduce geopolitical risks, optimise empty-container management, and improve the stability of cargo flows. In the long term, the systematic modernisation of inland terminals will not only help overcome the technical constraints associated with dual-gauge railway operations but will also serve as one of the key drivers of Ukraine's full integration into the European TEN-T transport network.

Conclusions

The findings of this study demonstrate that the development of a network of dry ports represents one of the most promising directions for the modernisation of Ukraine's transport and logistics system under wartime conditions, changing international trade patterns, and the country's ongoing integration into the European transport area. The research confirms that inland multimodal terminals can significantly improve interoperability between the 1,435 mm European standard gauge and the 1,520 mm broad-gauge railway systems by reducing the negative effects of infrastructural incompatibilities and facilitating more efficient international container transportation. The analysis of international experience in the operation of dry ports showed that inland logistics hubs contribute to the optimisation of freight flows, reduce congestion at seaports and border crossing points, shorten cargo handling times, and increase the resilience of supply chains. For Ukraine, the formation of a network of inland terminals in the western and central regions is particularly important because such facilities support the functioning of the Solidarity Lanes initiative and strengthen integration into the TEN-T transport network. Under conditions of restricted access to Black Sea ports and continuing geopolitical instability, dry ports increasingly perform the role of secure inland logistics centres capable of maintaining the continuity of export and import operations. The study of the technical and operational parameters of railway terminal infrastructure demonstrated that the efficient functioning of dry ports depends on appropriate track layout configurations, sufficient receiving and departure track lengths, the capability to handle full-length container trains, and the uninterrupted execution of shunting operations. The development of such infrastructure creates the conditions necessary for increasing the throughput capacity of multimodal transport corridors and improving the predictability and reliability of international logistics routes.

Particular attention was devoted to the imbalance of container flows and the management of empty containers. The research established that dry ports can function as logistics buffers that facilitate cargo consolidation, container redistribution, and the optimisation of transport costs. These functions contribute to improving the operational efficiency of logistics systems and increasing the competitiveness of Ukrainian exporters in international markets. Overall, the establishment of an interconnected dry port network should be considered a strategic component of Ukraine's long-term transport policy. The implementation of multimodal infrastructure projects in this field will support export-oriented economic development, attract investment, strengthen transport security, and accelerate Ukraine's integration into the unified European transport system. Future research should focus on the development of economic and mathematical models for the optimal location of dry ports, the assessment of their influence on transport network capacity and supply chain resilience, and the application of digital technologies, intelligent transport systems, and advanced container flow management tools within the framework of Ukraine's integration into the European logistics space.

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Conflict of Interest

None.

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Інфраструктурні рішення взаємодії залізничних систем колії 1435/1520 мм в Україні

Галина Васілова
Кандидат технічних наук, доцент
Національний транспортний університет
02000, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0002-4168-1434

Оксана Юрченко
Кандидат технічних наук, доцент
Національний транспортний університет
02000, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0001-6834-692X

Роман Ляшук
Асистент
Національний транспортний університет
02000, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0005-2267-9055

Олексій Горецький
Кандидат історичних наук, доцент
Національний транспортний університет
02000, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0000-0002-2656-6120

Анотація. В умовах воєнного стану та євроінтеграції удосконалення взаємодії залізничних мереж колій 1435 мм та 1520 мм через розбудову мультимодальних транспортно-логістичних вузлів набуває критично важливого значення для забезпечення функціонування експортно-імпортних ланцюгів постачання України. Метою роботи було дослідження та обґрунтування інфраструктурних рішень щодо забезпечення взаємодії залізничних систем колії 1435 мм та 1520 мм через розвиток мережі «сухих портів» як ключових елементів мультимодальної логістичної системи України. Для досягнення поставленої мети було використано системний підхід, структурно-функціональний аналіз, а також інфраструктурний, логістичний та статистичний аналіз транспортних потоків. Проаналізовано сучасні тенденції розвитку мультимодальних перевезень та функціонування «сухих портів» у країнах Європейського Союзу й Україні. Встановлено, що розвиток внутрішніх мультимодальних терміналів дозволяє зменшити навантаження на прикордонну та портову інфраструктуру, скоротити час обробки вантажів та підвищити ефективність логістичних ланцюгів. На основі узагальненого міжнародного досвід розвитку мультимодальних логістичних центрів визначено перспективні напрями інтеграції транспортної системи України до мережі TEN-T та «Шляхів солідарності». Досліджено техніко-технологічні параметри функціонування залізничних терміналів, зокрема вимоги до конфігурації колійного розвитку, довжини приймально-відправних колій, організації маневрової роботи та забезпечення пропускної спроможності для обслуговування повносоставних контейнерних поїздів. Також виявлено закономірності накопичення дисбалансу контейнерних потоків і порожнього рухомого складу в межах міжнародних транспортних коридорів. Проаналізовано проблему дисбалансу контейнерних потоків та роль «сухих портів» у забезпеченні ефективного управління порожніми контейнерами. Практична цінність роботи полягає у можливості використання отриманих результатів органами державного управління, логістичними операторами, транспортними компаніями та проєктними організаціями при плануванні розвитку мультимодальної інфраструктури, прикордонних терміналів і мережі «сухих портів» в Україні

Ключові слова: залізнична інфраструктура; «сухий порт»; мультимодальність; контейнеризація; логістичний хаб; експортний потенціал; ланцюги постачання

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Identifying priority directions for carbon emission reduction in railway transport using multi-criteria analysis

Oleksandr Rohovyi*
Postgraduate Student
National Transport University
03115, 29/18 M. Kotelnykov Str., Kyiv, Ukraine
https://orcid.org/0009-0001-4867-6793

Valerii Samsonkin
Doctor of Sciences, Professor
National Transport University
03115, 29/18 M. Kotelnykov Str., Kyiv, Ukraine
https://orcid.org/0000-0002-1521-2263

Abstract. In the short and medium term, the decarbonisation of diesel traction cannot rely solely on full electrification and the rapid replacement of rolling stock, which creates a need for renewable diesel fuels. The aim of the study was to develop a multi-criteria procedure for ranking renewable diesel fuels for railway diesel traction and to identify the priority option for reducing carbon emissions. The article considered four renewable diesel fuel alternatives, namely fully hydrotreated vegetable oil (HVO) fuel, pure biodiesel fuel, a blend containing 20% biodiesel and 80% fossil diesel fuel, and synthetic paraffinic diesel fuel, proposes a formalised selection procedure based on a combination of the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods, and established a matrix of seven criteria: environmental performance, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory alignment. The weights of the criteria were determined using the AHP, consistency was verified, and the alternatives were ranked using the TOPSIS. The results indicated the superiority of the paraffinic fuels fully HVO fuel and synthetic paraffinic diesel fuel, which are suitable for use without retrofitting existing rolling stock. These fuels demonstrated the best combination of low total greenhouse gas emissions throughout the fuel life cycle and high technical compatibility. Pure biodiesel fuel and the blend containing 20% biodiesel were ranked lower due to their lower technical and operational suitability, higher sensitivity to storage and fuel-handling conditions, and a weaker overall emission-reduction effect in the case of the blend containing 20% biodiesel. The proposed approach can be used by railway operators, infrastructure managers, transport authorities, and researchers as a decision-support tool for the phased transition from fossil diesel fuel to renewable liquid fuels in the railway sector

Keywords: decarbonisation; transport technologies; renewable diesel fuels; diesel traction; biodiesel fuel; fuel compatibility; operational suitability

Introduction

Decarbonisation of rail transport is a key priority of modern transport policy. Under the climate agenda, the rail sector is regarded as a fundamental component of a low-carbon transport system. Achieving decarbonisation targets requires reducing dependence on fossil diesel fuel on non-electrified lines. Despite the high energy efficiency of rail transport compared with other modes of transport, diesel traction remains critically important for both train operations and shunting. This is particularly relevant where electrification is absent, or where its further expansion is economically or technologically constrained. In the short term, decarbonisation cannot rely solely on large-scale traction replacement, the deployment of hydrogen or battery-powered trains, or the complete restructuring of infrastructure. Therefore, the use of renewable liquid fuels appears to be a reasonable transitional option, because it can reduce the carbon footprint without radical intervention in the existing rolling stock fleet.

Recent studies confirm that railway decarbonisation depends on infrastructure constraints, operational profile, investment needs, as well as full life-cycle emissions. M. Kapetanović *et al.* (2024) evaluated traction alternatives for regional railways and showed that well-to-wheel greenhouse gas emissions must be considered when

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*Corresponding author (*oleksroho@gmail.com*)

comparing non-electrified railway options. A. Aredah *et al.* (2024) compared alternative powertrain technologies for freight trains in their work and demonstrated that technical feasibility should be assessed together with operational and environmental consequences. A. Hernandez *et al.* (2024a) proposed a framework for evaluating railway decarbonisation alternatives, including alternative fuels and the deployment of battery-electric systems. A. Hernandez *et al.* (2024b) conducted an analysis of freight railway decarbonisation using the logic of emission reduction costs. As a result, the researchers show that the decarbonisation of diesel traction cannot be reduced to a single technological pathway.

At present, the most realistic fuel alternatives for diesel traction in the rail sector are paraffinic fuels such as HVO100, a renewable diesel fuel produced by hydrotreatment of oils and fats, and XTL, a synthetic liquid fuel, as well as biodiesel fuels, including B100 and B20. W. Szeto & D. Leung (2022) reviewed the production, properties, engine performance, and emissions of hydrotreated vegetable oil and emphasised its potential as a substitute for fossil diesel. C. McCaffery *et al.* (2022) examined HVO and HVO/biodiesel blends in an off-road heavy-duty diesel engine and provided evidence on the emissions and physicochemical characteristics of such fuels. H. Xu *et al.* (2022) showed that biodiesel and renewable diesel pathways may differ substantially in life-cycle greenhouse gas emissions depending on feedstock and production route. Y. Pradana *et al.* (2024) reviewed cold-flow limitations and improvement methods for biodiesel application. These findings are important for railway operation, because fuel quality deterioration may directly affect rolling stock reliability, filtration, maintenance frequency, and the stability of the transport process.

However, the technical feasibility of these alternatives does not in itself determine their implementation priority. The existing literature covers individual aspects of the problem, including general decarbonisation pathways, engine and environmental characteristics of renewable diesel fuels, and operational risks connected with storage and fuel handling. At the same time, most studies do not provide a unified procedure for comparing HVO100, B100, B20, and XTL within one decision-making model for railway diesel traction. This creates the need to identify the most appropriate option among alternative fuels that differ in terms of life-cycle greenhouse gas emissions, technical compatibility, operational suitability, fuel supply infrastructure requirements, economic feasibility, feedstock availability, and regulatory alignment. Multi-criteria decision-making methods are suitable for this type of task. Multi-criteria methods make it possible to compare alternatives according to many criteria, for example: technical, environmental, economic, and regulatory ones. A. Abdulvahitoglu & M. Kilic (2022) applied an integrated AHP-TOPSIS approach to biodiesel fuel selection. W. Kriswardhana *et al.* (2025) reviewed the use of the AHP in transportation decision-making. Similar studies confirm the suitability of combining criteria weighting with ranking procedures in fuel comparison tasks.

The purpose of this study was to develop a procedure for ranking renewable diesel fuels for use in railway diesel traction in order to reduce carbon emissions. The tasks of the study were as follows: to analyse the existing renewable diesel fuel alternatives and to define the set of criteria for their evaluation; to develop a multi-criteria evaluation procedure for HVO100, B100, B20, and XTL based on the sequential application of the AHP and TOPSIS methods; to determine the criterion weights using the AHP method and to rank the renewable diesel fuel alternatives using the TOPSIS method.

Materials and Methods

Materials used in this study: scientific publications on railway decarbonisation and alternative traction technologies (Aredah *et al.*, 2024; Hernandez *et al.*, 2024a; Kapetanović *et al.*, 2024). Limitations on railway decarbonisation and traction were reviewed in F. Zenith *et al.* (2020), F. Barbosa (2023) and A. Hernandez *et al.* (2024b). Studies on HVO and renewable diesel fuels were represented by C. McCaffery *et al.* (2022), W. Szeto & D. Leung (2022), and J. Hunicz *et al.* (2025). The properties of biodiesel fuel and storage risks were considered in the works of E. Christensen & R. McCormick (2023), W. Ai *et al.* (2024), and Y. Pradana *et al.* (2024). Regarding multi-criteria decision-making and fuel selection, the publications by M. Behzadian *et al.* (2012), G. Yannis *et al.* (2020), and W. Kriswardhana *et al.* (2025) were considered. Regarding the application of transport fuel selection, G. Chaitanya *et al.* (2020), A. Abdulvahitoglu & M. Kilic (2022) and M. Kügemann & H. Polatidis (2024) were additionally considered. The application of alternative fuels for transport was also considered more broadly in the work of N. Aboushaqrah *et al.* (2022). The materials also include industry analytical reports and materials from operators (AERRL, 2022; European Union Agency for Railways, 2024; CER, 2025). Regarding the implementation of HVO, materials presented by Neste (2023), DB Cargo (n.d.) and LTG Group (n.d.) were reviewed. The description of the LTG Group (n.d.) project was used to verify the pilot context of HVO100. Data on railway biofuels were supplemented from sources of the International Union of Railways (2007), CONCAWE (2009), and the Federal Railroad Administration (2014). European policy documents were reviewed from the European Commission (2019; 2021). Regulatory and technical documents included standards of the BSI (2021; 2023a; 2023b) for paraffinic diesel fuel and diesel fuel. Additional standards for information on diesel fuel and EU regulation on renewable energy were also used (Directive of the European Parliament and of the Council No. 2001, 2018; Regulation of the European Parliament and of the Council No. 1119, 2021; BSI, 2024).

The study was based on data on the properties of renewable diesel fuels, including their technical compatibility with diesel engines, storage conditions, fuel handling requirements, regulatory constraints, and total greenhouse gas emissions across the entire fuel life cycle. The analysis also took into account the provisions of EU fuel standards, the findings of recent scientific studies, publicly available materials from railway operators, as well as materials obtained within the framework of the PhDs EU-Rail project. The study was conducted during 2025-2026. It covered the analysis of scientific publications, regulatory documents, technical standards, materials from railway operators, and project materials. The analysis of sources was conducted and structured into four thematic groups, namely: railway decarbonisation and alternative traction technologies; properties of HVO, XTL, and renewable diesel fuel; biodiesel storage and contamination risks; and multi-criteria decision-making methods. Generalisation and analysis of the sources were used to identify the main approaches to the decarbonisation of diesel traction and to the selection of alternative renewable diesel fuels. At the first stage, alternatives suitable for further comparison were selected, namely: HVO100, B100, B20, and XTL. At the second stage, the evaluation criteria were determined. As a result, the set of criteria included environmental indicators, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory compliance.

The weighting and scoring stages were carried out by the authors. A documentary and analytical approach was used in combination. The judgments were also formed on the basis of the research aim and the synthesis of scientific literature, including fuel standards, railway operator materials, and the technical applicability framework. The weights of the criteria were formed through pairwise comparisons using the Saaty scale. In each of the pairwise comparisons, the relative importance of one criterion over another was determined according to its contribution to the decarbonisation objective, as well as the practical feasibility of introducing the fuel into existing railway diesel traction. Environmental performance was considered the leading criterion. The scores for criteria C2-C7 were determined after comparing each fuel alternative with the criterion content. The scoring procedure was carried out according to a five-point rule, namely: 5 indicated full or near-full suitability, clear compliance with the relevant standard, and no need for substantial changes; 4 indicated high suitability with minor transition or control measures; 3 indicated medium suitability requiring additional monitoring or agreed application rules; 2 indicated low suitability with substantial technical, operational, economic, or infrastructure limitations; and 1 indicated very low suitability and practical unsuitability under the assumed railway operating conditions. For all criteria C2-C7, a higher score corresponded to a more favourable solution. To determine the weights of the evaluation criteria, the AHP and the Saaty scale were applied (Saaty, 1980). The pairwise comparison matrix was formed for seven criteria. The weights were calculated as the normalised principal eigenvector of the pairwise comparison matrix. The consistency index was calculated:

$$CI = (\lambda\_max-n)/(n-1), \qquad (1)$$

where λ_{max} – the maximum eigenvalue of the pairwise comparison matrix; n – the number of criteria in the pairwise comparison matrix.

The consistency ratio was calculated:

$$CR = CI/RI, \qquad (2)$$

where CI is the consistency index calculated using formula (1); is the average random consistency index for pairwise comparison matrices of the corresponding size, the values of which are given in the AHP method tables.

For n = 7 the adopted value is RI = 1.32. For the given matrix: $\lambda_{max} \approx 7.0505$; CI ≈ 0.00842; CR ≈ 0.00638. Since CR < 0.10, the pairwise judgments can be considered consistent and may therefore be accepted as valid for further analysis. The next stage is the application of the TOPSIS method. The following notation is used: x_{ij} – denotes the value of alternative *i* under criterion *j*. TOPSIS normalisation is calculated using the formula (3):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \qquad (3)$$

where r_{ij} – the normalised value of the *j*-th criterion for the *i*-th alternative; *m* – the number of alternatives; x_{ij} – the initial value of the *i*-th alternative under the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion; Σ – the summation sign over all alternatives; √ – the square-root operation.

The weighted normalised values are calculated using the formula (4):

$$v_{ij} = w_j \cdot r_{ij}, \qquad (4)$$

where w_j – the weight of the *j*-th criterion determined using the AHP method; r_{ij} – the normalised value of the *i*-th alternative under the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion.

The ideal and anti-ideal points for the cost criterion C1 (*WTW* – total greenhouse gas emissions over the entire fuel chain) are defined as follows):

$$v_j^+ = min_i^{vij}, v_j^- = max_i^{vij}, \qquad (5)$$

where v_j^+ – the ideal value of the criterion; v_j^- – the anti-ideal value of the criterion; v_{ij} – the weighted normalised value of the *i*-th alternative under the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion; min_i – the minimum value among all alternatives; max_i – the maximum value among all alternatives.

For the benefit criteria C2-C7, the ideal and anti-ideal points are defined as follows:

$$v_j^+ = max_i^{vij}, v_j^- = min_i^{vij}, \qquad (6)$$

where v_j^+ – the ideal value of the *j*-th criterion; v_j^- – the anti-ideal value of the *j*-th criterion; v_{ij} – the weighted normalised value of the *i*-th alternative under the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion; max_i – the maximum value among all alternatives; min_i – the minimum value among all alternatives.

The distance to the ideal point is calculated using the formula (7):

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2}, \qquad (7)$$

where D_i^+ – the distance of the *i*-th alternative to the ideal point; v_{ij} – the weighted normalised value of the *i*-th alternative under the *j*-th criterion; v_j^+ – the ideal value of the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion; *n* – the number of criteria; Σ – the summation sign over all criteria; √ – the square-root operation.

And the distance to the anti-ideal point is calculated using the formula (8):

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2}, \qquad (8)$$

where D_i^- – the distance of the *i*-th alternative to the anti-ideal point; v_{ij} – the weighted normalised value of the *i*-th alternative under the *j*-th criterion; v_j^- – the anti-ideal value of the *j*-th criterion; *i* – the index of the alternative; *j* – the index of the criterion; *n* – the number of criteria; Σ – the summation sign over all criteria; √ – the square-root operation.

The closeness-to-ideal index is calculated using the formula (9):

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}, \qquad (9)$$

where S_i – the closeness-to-ideal index of the *i*-th alternative; D_i^+ – the distance of the *i*-th alternative to the ideal point; D_i^- – the distance of the *i*-th alternative to the anti-ideal point; *i* – the index of the alternative.

The values of are taken from formulas (7), (8). The higher the value of the higher the rank of the alternative. The AHP–TOPSIS sequence makes it possible first to establish the relative importance of the criteria and then to obtain an integrated ranking of alternatives on the basis of a single evaluation matrix. For the final TOPSIS matrix, the following *WTW* values, representing total greenhouse gas emissions over the entire fuel chain, were used: HVO100 from waste oils – 16.0; B100 from rapeseed – 50.1; and XTL from waste wood – 15.6. Fossil diesel fuel was taken as the reference value at 94. For B20, the value of 85.2 was obtained by calculation as a first approximation based on the biodiesel content in the blend. The model uses one quantitative criterion, WTW, and six criteria evaluated on a scale from 1 to 5. The scores for criteria C2-C7 were formed on the basis of the analysed scientific publications, fuel standards, technical documents, railway operator materials, and the technical applicability framework.

The *WTW* value for B20 was determined using the formula (10):

$$WTW(B20) = 0.20 \cdot WTW\_B100 + 0.80 \cdot WTW\_Diesel, \qquad (10)$$

where *WTW(B20)* – the total greenhouse gas emissions of the B20 fuel blend over the entire fuel chain; *WTW_B100* – the total greenhouse gas emissions of pure biodiesel fuel over the entire fuel chain; *WTW_Diesel* – the total greenhouse gas emissions of fossil diesel fuel over the entire fuel chain; 0.20 – the share of biodiesel fuel in the B20 blend; 0.80 – is the share of fossil diesel fuel in the B20 blend; *WTW* – denotes the well-to-wheel assessment boundary and refers to total greenhouse gas emissions over the full fuel chain, from fuel production to final use.

And the relative reduction compared with fossil diesel fuel was determined as follows:

$$\eta = (1 - WTW_{alt} \,/\, WTW\_Diesel) \cdot 100\%, \qquad (11)$$

where η – the relative reduction in greenhouse gas emissions compared with fossil diesel fuel; *WTW_alt* – the total greenhouse gas emissions of the selected fuel alternative over the entire fuel chain; *WTW_Diesel* – is the reference value for fossil diesel fuel; 100% – the multiplier used to express the result as a percentage.

Thus, the methodological basis of the study was built on the sequential application of the AHP and TOPSIS methods, which made it possible first to substantiate the relative importance of the evaluation criteria and then to obtain an overall ranking of alternative fuels for railway diesel traction.

Results and Discussion

The study considers four renewable diesel fuel alternatives for use in railway diesel traction:

1) Alt 1 – HVO100 (paraffinic diesel fuel produced in accordance with EN 15940);

2) Alt 2 – B100 (biodiesel based on fatty acid methyl esters, produced from vegetable oils and fats in accordance with EN 14214);

3) Alt 3 – B20 (a diesel fuel blend containing 20% biodiesel);

4) Alt 4 – XTL (synthetic paraffinic diesel fuel produced in accordance with EN 15940).

The selection of alternatives was based on fuel standards and data on renewable diesel fuel and railway decarbonisation pathways. W. Szeto & D. Leung (2022) and C. McCaffery *et al.* (2022) support the technical relevance of HVO and HVO/biodiesel blends, while M. Kapetanović *et al.* (2024) used full fuel-chain assessment in railway traction comparison. These alternatives were selected because they have either practical relevance to the railway sector or have already been considered in pilot applications, and because they are covered by clearly defined fuel standards. Typical values of life-cycle greenhouse gas emissions were used in the assessment. This means that the evaluation considered not only the fuel itself, but the entire production pathway from feedstock to final use.

At the stage of preliminary selection, both the fuel type and the conditions under which it can realistically be used in diesel traction were examined. In particular, consideration was given to whether the fuel could be used without modification of the rolling stock, how sensitive it is to the characteristics of the fuel system, what risks may arise during the transition from one fuel to another, and what storage conditions are required. Such preliminary selection makes it possible to identify the options that are generally suitable for further consideration, but it does not determine which fuel should be implemented. The final decision should be made on a rational basis using the results of a multi-criteria assessment that takes into account both environmental impact and operational reliability under railway operating conditions (Table 1).

Table 1. Renewable diesel fuel alternatives and their technical applicability framework

Alternative	Standard and class	Technical applicability in diesel traction	Typical compatibility risks	Typical storage risks
Alt 1	EN 15940; paraffinic diesel fuel	Can be used without retrofitting; suitable both in neat form and in blends	Insufficient lubricity if not controlled, need for batch quality verification, possible issues with seals and elastomers in older rolling stock	Tank flushing and cleaning are required during the transition; filter clogging may occur at the initial stage
Alt 2	EN 14214; biodiesel based on fatty acid methyl esters	Use without retrofitting is limited; suitability depends on fuel quality and operating conditions; additional monitoring is required	Risks of incompatibility with certain materials, deposit formation, and filter clogging during the transition	Sensitivity to oxidation, water accumulation, microbiological contamination and deterioration of properties at low temperatures
Alt 3	EN 590 base fuel; high-FAME diesel considered within EN 16709	Intermediate option; requires a specifically defined blend composition and agreed application rules	Dependence on the quality of the biodiesel component; risks for filtration and seals are lower than for B100, but remain present	Sediment formation may occur at low temperatures; water content, microbiological condition and sampling procedures must be controlled
Alt 4	EN 15940; synthetic paraffinic diesel fuel	Can be used without retrofitting; the main limitations are related to availability, price and certification	Similar to HVO100: lubricity, batch quality control and risks for older fuel-system materials	Similar to HVO100: cleaning and control are required during the transition; the main difficulties are related more to supply than to fuel properties

Source: compiled by the authors based on International Union of Railways (2007), CONCAWE (2009), Federal Railroad Administration (2014), L. Komariah *et al.* (2022), BSI (2021; 2023a; 2023b; 2024), W. Ai *et al.* (2024), Y. Pradana *et al.* (2024)

The alternatives and technical frameworks presented in Table 1 serve as a suitability filter. However, they do not determine the priority of implementation. To address this, a multi-criteria AHP-TOPSIS procedure was developed, taking into account not only life-cycle greenhouse gas emissions, but also technical compatibility, operational suitability, economic factors, feedstock availability, infrastructure compatibility, and regulatory aspects. A set of seven criteria was established for evaluating the alternatives: C1 – environmental performance; C2 – technical compatibility; C3 – operational suitability; C4 – economic feasibility; C5 – feedstock availability; C6 – infrastructure compatibility; and C7 – regulatory alignment. The characteristics of these criteria are presented in Table 2. The environmental criterion, C1, was assessed on the basis of life-cycle greenhouse gas emissions across the entire fuel chain, from fuel production to final use. This indicator is expressed numerically as grams of carbon dioxide equivalent per unit of fuel energy. For criteria C2-C7, a rating scale from 1 to 5 was applied, following the principle that a higher score indicates a better result.

Table 2. Criteria and evaluation rules

Criterion	Designation	Evaluation format	Optimality rule	Criterion content
Environmental performance	C1	Total greenhouse gas emissions across the entire fuel chain, gCO_2e/MJ	Lower is better	Total greenhouse gas emissions from fuel production to end use
Technical compatibility	C2	1-5 scale	Higher is better	Compliance with the relevant standard, possibility of use without retrofitting, compatibility with the fuel system
Operational suitability	C3	1-5 scale	Higher is better	Performance at low temperatures, storage behaviour, filterability, risk of additional maintenance
Economic feasibility	C4	1-5 scale	Higher is better	Fuel cost, price volatility, transition costs
Feedstock availability	C5	1-5 scale	Higher is better	Origin of feedstock, its availability, and potential for wide-scale use
Infrastructure compatibility	C6	1-5 scale	Higher is better	Suitability of tanks and fuel-handling infrastructure; need for flushing, cleaning and quality control
Regulatory alignment	C7	1-5 scale	Higher is better	Compliance with standards and certification requirements, possibility of official accounting and practical application

Source: developed by the authors based on BSI (2021; 2023a; 2023b; 2024), W. Szeto & D. Leung (2022), C. McCaffery *et al.* (2022), H. Xu *et al.* (2022), M. Kapetanović *et al.* (2024), A. Aredah *et al.* (2024), A. Hernandez *et al.* (2024a)

A wide range of technical, environmental, and economic indicators was taken into account when developing the evaluation criteria. It was decided not to include these indicators separately in the final model; instead, they formed the basis for scoring criteria C2-C7. This approach made it possible to preserve the substantive value of the assessment while ensuring comparability of the alternatives under conditions of limited publicly available data. The criteria are described below. The environmental component of the model is based on total greenhouse gas emissions across the entire fuel chain, from feedstock to final fuel use. This indicator was selected as the main measure of decarbonisation, since exhaust emissions alone do not reflect the full climate impact of a fuel. The indicator is expressed in gCO_2e/MJ and characterises the total greenhouse gas emissions, in CO_2-equivalent, attributed to a unit of fuel energy over the entire fuel life cycle.

Parameters such as nitrogen oxides (NOx) emissions were also considered important for assessing local pollution and operating conditions, particularly during shunting operations and in areas sensitive to air quality. However, they were not treated as separate criteria because no single set of comparable data for railway equipment under identical test conditions was available. Lubricity, density, viscosity, and compatibility with fuel-system materials were considered as components of technical compatibility (Knothe, 2005; Lapuerta *et al.*, 2011; ISO 12156-1:2018, 2018). Low-temperature properties, filter replacement frequency, failures of fuel equipment, and performance under cold-weather conditions were considered as components of operational suitability (Christensen & McCormick, 2023; Ai *et al.*, 2024; Pradana *et al.*, 2024).

Criterion C2 reflects the extent to which a given type of fuel complies with current standards and can be used in existing diesel engines without modification. The criterion also takes into account the risks posed to the fuel system during the transition to a new fuel. The highest scores are assigned to the paraffinic fuels HVO100 and XTL. To better understand fuel lubricity and fuel-system materials, reference materials from G. Knothe (2005), ISO 12156-1:2018 (2018), and DieselNet (n.d.) were analysed. Their use is associated with fewer technical limitations (Szeto & Leung, 2022; MTU, 2023; Hunicz *et al.*, 2025). By contrast, B20 and especially B100 receive lower scores because of their higher biodiesel content, greater sensitivity of sealing materials, a higher risk of deposit formation, and stricter fuel handling and storage requirements. International Union of Railways (2007), Federal Railroad Administration (2014), and W. Ai *et al.* (2024) provide an understanding that fuels containing biodiesel require additional attention to fuel quality, filtration, and storage. L. Komariah *et al.* (2022) also confirm the relevance of microbiological contamination risks for diesel-biodiesel blends.

Criterion C3 reflects operational suitability, including fuel performance in different seasons, behaviour at low temperatures, suitability for long-term storage, filterability, and the impact on maintenance requirements. This criterion takes into account low-temperature properties, storage stability, and the risk of contamination. For a better understanding of how biodiesel is stored and what storage risks exist, the studies by E. Christensen & R. McCormick (2023), W. Ai *et al.* (2024), as well as Y. Pradana *et al.* (2024), were used. Regarding fuel quality deterioration and risks characteristic of railways, data from DieselNet (n.d.), International Union of Railways (2007), and Federal Railroad Administration (2014), were used. The study by E. Christensen & R. McCormick (2014) was used as an additional source of information on the long-term storage stability of biodiesel and biodiesel blends. According to these characteristics, HVO100 and XTL have an advantage, whereas B100 receives a lower rating because of its greater sensitivity to operating and storage conditions. B20 occupies an intermediate position (Münzer, 2023; BSI, 2024; Pradana *et al.*, 2024).

Criterion C4 reflects economic feasibility, including fuel price fluctuations, transition costs, fuel-system cleaning, filter replacement, and quality control costs (AERRL, 2022; Hernandez *et al.*, 2024b). Criterion C5 characterises feedstock availability, including the origin of the fuel, dependence on food-based feedstocks, and the potential for large-scale use of such fuel in a particular region (Directive of the European Parliament and of the Council No. 2001, 2018; AERRL, 2022; Xu *et al.*, 2022). Criterion C6 reflects infrastructure compatibility (International Union of Railways, 2007; CONCAWE, 2009). Criterion C7 reflects the availability of the relevant standard, certification, the possibility of officially accounting for the decarbonisation effect, and the practical suitability of the fuel for application in the railway sector. These elements were assessed using fuel standards for fatty acid methyl esters, which are the main components of conventional biodiesel, as well as for paraffinic diesel fuel and conventional diesel fuel (BSI, 2021; 2023a; 2023b). The standard for diesel fuel with a high content of fatty acid methyl esters and EU regulation on renewable energy were also considered (Directive of the European Parliament and of the Council No. 2001, 2018; BSI, 2024).

After identifying the alternatives and criteria, the evaluation rules for constructing the comparison matrix were established (Table 3). In the TOPSIS matrix, one quantitative criterion was used, namely total greenhouse gas emissions across the entire fuel chain, expressed as WTW (well-to-wheel), gCO_2e/MJ. The remaining six criteria were evaluated on a scale from 1 to 5 according to pre-established rules. The article developed a multi-criteria "AHP→TOPSIS procedure". At the first stage, the weights of the criteria were determined using the AHP method. A pairwise comparison matrix based on the Saaty scale was used. In the problem formulation, the environmental criterion receives the greatest weight; however, technical compatibility and operational suitability cannot be treated as secondary either, since they determine the actual feasibility of using the fuel under the conditions of the existing fleet. Economic feasibility and feedstock availability also have a significant influence due to supply conditions and market uncertainty. The infrastructural and regulatory components are important derivatives of the fuel class, supply practices, and the possibility of formal implementation.

Table 3. AHP pairwise comparison matrix on the Saaty scale

-	C1	C2	C3	C4	C5	C6	C7
C1 Environmental performance	1	2	2	2	3	4	6
C2 Technical compatibility	1/2	1	1	1	2	3	4
C3 Operational suitability	1/2	1	1	1	2	2	3
C4 Economic feasibility	1/2	1	1	1	2	2	3
C5 Feedstock availability	1/3	1/2	1/2	1/2	1	1	2
C6 Infrastructure compatibility	1/4	1/3	1/2	1/2	1	1	1
C7 Regulatory alignment	1/6	1/4	1/3	1/3	1/2	1	1

Source: authors' pairwise comparison based on the criterion system in Table 2 and the AHP scale proposed by T. Saaty (1980)

The weights were calculated as the normalised principal eigenvector of the AHP pairwise comparison matrix (Table 4, Fig. 1). The consistency ratio was below 0.10; therefore, the pairwise judgments were accepted for further TOPSIS analysis. For the adopted matrix, the largest weight belongs to C1, environmental performance. Technical compatibility, operational suitability and economic feasibility also remain significant, which reflects the practical constraints of introducing renewable fuels in existing diesel traction.

Table 4. AHP criterion weights

Criterion	Weight
C1 Environmental performance	0.302
C2 Technical compatibility	0.175
C3 Operational suitability	0.157
C4 Economic feasibility	0.157
C5 Feedstock availability	0.086
C6 Infrastructure compatibility	0.071
C7 Regulatory alignment	0.052

Source: calculations based on the AHP pairwise comparison matrix in Table 3

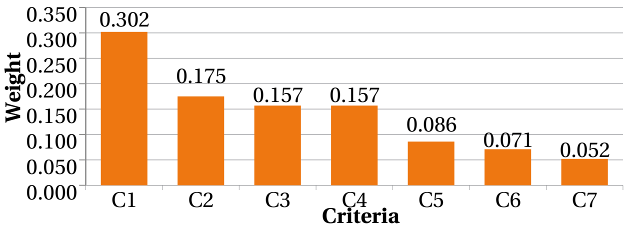

Figure 1. Criteria weights determined using the AHP method

Source: visualisation based on the AHP criterion weights in Table 4

The next stage is the application of the TOPSIS method (Table 5). Since the calculation procedure was described in the Materials and Methods section, this subsection presents the input matrix, the scores of alternatives, and the final ranking results. For the final TOPSIS matrix, the following *WTW* values, representing total greenhouse gas emissions over the entire fuel chain, were used: HVO100 from waste oils – 16.0; B100 from rapeseed – 50.1; and XTL from waste wood – 15.6. Fossil diesel fuel was taken as the reference value at 94. For B20, the value of 85.2 was obtained by calculation as a first approximation based on the biodiesel content in the blend. The model uses one quantitative criterion, WTW, and six criteria evaluated on a scale from 1 to 5.

Table 5. Evaluation matrix for TOPSIS

Alternative	*WTW* GHG emissions gCO_2e/MJ↓	*WTW* savings relative to 94 gCO_2e/MJ, %↑
Alt 1	16.0	≈83.0
Alt 2	50.1	≈46.7
Alt 3	85.2	≈9.3
Alt 4	15.6	≈83.4

Note: ↓ – the lower the value, the better; ↑ – the higher the value, the better

Source: compilation and calculation based on Directive of the European Parliament and of the Council No. 2001 (2018), with the B20 value calculated using formula (10)

The values of total greenhouse gas emissions across the entire fuel chain are as follows: 16.0 for HVO produced from used cooking oil, 50.1 for rapeseed-based biodiesel, and 15.6 for synthetic diesel fuel produced from wood waste. The reference value for fossil diesel fuel was taken as 94. The five-point assessment scale for criteria C2-C7 was based on systematically organised information, including compliance with standards, the possibility of use without modification, fuel behaviour at low temperatures, suitability for long-term storage, the risk of additional maintenance, transition costs, feedstock availability, compatibility with fuel infrastructure, and compliance with certification requirements (Table 6).

Table 6. Scores of alternatives under criteria C2-C7

Alternative	C2 (1-5) ↑	C3 (1-5) ↑	C4 (1-5) ↑	C5 (1-5) ↑	C6 (1-5) ↑	C7 (1-5) ↑
Alt 1	5	4	3	4	4	5
Alt 2	2	2	2	2	2	3
Alt 3	3	3	3	2	3	3
Alt 4	5	4	2	4	4	4

Source: scoring based on the applicability framework in Table 1 and the fuel-standard framework for EN 15940, EN 14214, EN 590 and EN 16709, International Union of Railways (2007), CONCAWE (2009), Federal Railroad Administration (2014), W. Szeto & D. Leung (2022), C. McCaffery *et al.* (2022), L. Komariah *et al.* (2022), W. Ai *et al.* (2024), Y. Pradana *et al.* (2024), J. Hunicz *et al.* (2025)

The high scores of Alt 1 – HVO100 in terms of technical compatibility, operational suitability, and infrastructure compatibility are explained by the fact that it is a paraffinic fuel of the EN 15940 class. This fuel can be used in existing equipment without modification, blended with diesel fuel, and introduced with relatively moderate transition-related risks (Szeto & Leung, 2022; Hunicz *et al.*, 2025; Neste, n.d.). Alt 2 – B100 received lower scores because of its higher biodiesel content, greater sensitivity to storage conditions, the risk of microbiological contamination, filter-related problems, and stricter requirements for fuel handling. Alt 3 – B20 occupies an intermediate position. At the same time, its effect on reducing total greenhouse gas emissions across the entire fuel chain is more limited, which prevents it from competing with paraffinic alternatives. Alt 4 – XTL is close to HVO100 in terms of its technical and operational properties. However, it is inferior to HVO100 in terms of economic feasibility. After normalising the values, applying the criterion weights, and calculating the distances to the conditional ideal and anti-ideal solutions, the following results were obtained (Table 7, Fig. 2).

Table 7. TOPSIS results

Alternative	D^+	D^-	S	Rank
Alt 1	0.0012	0.2268	0.9948	1
Alt 4	0.0315	0.2254	0.8773	2
Alt 2	0.1395	0.1046	0.4286	3
Alt 3	0.2158	0.0458	0.1750	4

Source: TOPSIS calculations based on Tables 4-6

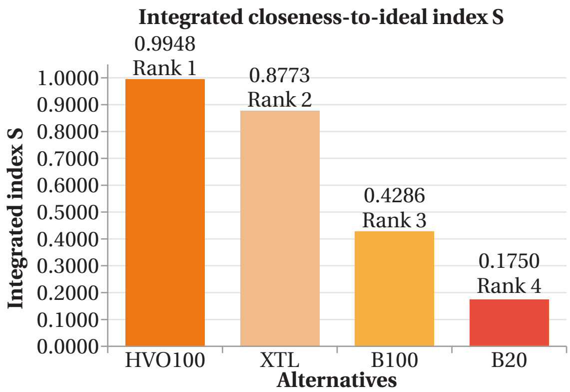

Figure 2. Integrated closeness coefficient to the ideal solution

Source: visualisation based on the TOPSIS results in Table 7

The best-performing option was HVO100. This alternative combines very low total greenhouse gas emissions across the entire fuel chain with high scores for technical compatibility, operational suitability, infrastructure compatibility, and regulatory alignment. In essence, it represents the most straightforward pathway for the initial stage of decarbonisation without significant modification of the rolling stock. XTL ranked second. In terms of technical compatibility, operational suitability, and infrastructure requirements, it is close to HVO100, but it is inferior in terms of economic feasibility. B100 ranked third because of the combination of higher total greenhouse gas emissions across the fuel chain and lower scores for technical compatibility. The lowest result was obtained for B20. Its moderate technical scores do not compensate for the limited overall decarbonisation effect under criterion C1.

The obtained ranking is consistent with the results of W. Szeto & D. Leung (2022), who showed that hydrotreated vegetable oil has properties that make it suitable as a substitute for fossil diesel fuel, as well as with C. McCaffery *et al.* (2022), who demonstrated the relevance of HVO and HVO/biodiesel blends for application in heavy-duty diesel engines. However, it should be noted that the present study differs from these and most similar works. This study focuses not only on fuel properties and engine emissions, but also compares fuel alternatives within a single decision-making model for railway diesel traction. The lower ranking of B100 and B20 is consistent with the findings of L. Komariah *et al.* (2022), W. Ai *et al.* (2024), and Y. Pradana *et al.* (2024), who considered storage stability, low-temperature behaviour, and microbiological contamination as important limitations of fuels containing biodiesel. In comparison with similar studies, the present research integrates technical compatibility, infrastructure suitability, economic feasibility, feedstock availability, and regulatory alignment into a single ranking procedure, which is an important factor. Additionally, a scenario was considered in which biodiesel derived from waste cooking oils was used instead of rapeseed feedstock for B100, with a corresponding reduction in total greenhouse gas emissions across the fuel chain for B20. Under this scenario, the integrated closeness index improved for Alt 2 and Alt 3; however, the ranking order did not change. It should be noted that the obtained ranking reflects the results under the scenario assumptions adopted in this study regarding feedstock origin and the level of emissions across the full fuel life cycle. This means that the overall result is valid within the adopted system of criteria and weights.

Conclusions

Renewable fuel alternatives for existing diesel traction engines were identified and classified, namely HVO100, XTL, B100, and the B20 blend. For each alternative, the technical scope of application, typical compatibility risks, and key storage characteristics were determined. It was found that, for paraffinic fuels, the main issues concern batch quality, supply conditions, and the transition to a new fuel type, whereas fuels with a high biodiesel content involve greater risks in terms of compatibility, operational stability, and storage. A seven-criteria evaluation model was developed, including environmental performance, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory alignment. The criterion weights were determined using the AHP method. The most important criterion was C1, environmental performance, while C2, technical compatibility, C3, operational suitability, and C4, economic feasibility, were also identified as major criteria. The TOPSIS ranking produced the following result: the paraffinic fuels HVO100 and XTL were identified as the preferred options, as they combine lower emissions across the fuel life cycle with high technical compatibility, appropriate operational suitability, and better manageability of infrastructure-related risks. The B100 and B20 alternatives proved less favourable because of a combination of factors, namely lower technical compatibility, greater sensitivity to storage conditions, stricter fuel handling requirements, and, in the case of the blended option, a weaker overall emission reduction effect. The proposed approach can be used as a decision-support tool for railways, railway operators, and researchers planning a phased transition from fossil diesel fuel to renewable liquid fuels. In further studies, it is necessary to focus on verifying the obtained ranking by taking into account real data on railway fuel consumption, maintenance, fuel quality, pilot operation, and so on. It is also necessary to assess the sensitivity of the ranking to changes in the weights of the criteria. These directions will make it possible to adapt the proposed approach to specific railway networks and operational scenarios.

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Conflict of Interest

There is no conflict of interest. The authors of the article did not take part in the peer-review process or in editorial decisions regarding their own manuscript.

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Визначення пріоритетних напрямків зменшення вуглецевих викидів в залізничних перевезеннях за допомогою багатокритеріального аналізу

Олександр Роговий
Аспірант
Національний транспортний університет
03115, вул. М. Котельникова, 29/18, м. Київ, Україна
https://orcid.org/0009-0001-4867-6793

Валерій Самсонкін
Доктор наук, професор
Національний транспортний університет
03115, вул. М. Котельникова, 29/18, м. Київ, Україна
https://orcid.org/0000-0002-1521-2263

Анотація. У короткостроковій та середньостроковій перспективі декарбонізація дизельної тяги не може ґрунтуватися виключно на повній електрифікації та швидкій заміні рухомого складу, що зумовлює потребу у використанні відновлюваних дизельних палив. Метою дослідження було розроблення багатокритеріальної процедури ранжування відновлюваних дизельних палив для залізничної дизельної тяги та визначення пріоритетного варіанта для скорочення викидів вуглецю. У статті було розглянуто чотири альтернативні види відновлюваного дизельного палива: повністю гідроочищене рослинне паливо (HVO), чисте біодизельне паливо, суміш, що містить 20 % біодизеля та 80 % викопного дизельного палива, а також синтетичне парафінове дизельне паливо. Запропоновано формалізовану процедуру вибору на основі поєднання методу аналізу ієрархій (AHP) та методу наближення до ідеального рішення (TOPSIS). Сформовано матрицю з семи критеріїв: екологічна ефективність, технічна сумісність, експлуатаційна придатність, економічна доцільність, доступність сировини, сумісність з інфраструктурою та відповідність нормативним вимогам. Вагові коефіцієнти критеріїв були визначені за допомогою методу аналізу ієрархій, перевірено узгодженість оцінок, а ранжування альтернатив здійснено методом TOPSIS. Результати дослідження засвідчили перевагу парафінових палив – повністю гідроочищеного рослинного палива та синтетичного парафінового дизельного палива, які можуть використовуватися без модернізації наявного рухомого складу. Ці види палива продемонстрували найкраще поєднання низьких сукупних викидів парникових газів протягом життєвого циклу палива та високої технічної сумісності. Чисте біодизельне паливо та суміш із вмістом 20 % біодизеля посіли нижчі позиції через меншу технічну та експлуатаційну придатність, вищу чутливість до умов зберігання й поводження з паливом, а також менш виражений ефект скорочення викидів у випадку суміші з 20 % біодизеля. Запропонований підхід може бути використаний залізничними операторами, менеджерами інфраструктури, транспортними органами та науковцями як інструмент підтримки прийняття рішень щодо поетапного переходу від викопного дизельного палива до відновлюваних рідких палив у залізничному секторі

Ключові слова: декарбонізація; транспортні технології; відновлювані дизельні палива; дизельна тяга; біодизельне паливо; сумісність з паливом; експлуатаційна придатність

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Prospective methods for enhancing the energy efficiency of multi-motor traction electric drive systems for rail vehicles

Artem Maslii*
Associate Professor
Ukrainian State University of Railway Transport
61050, 7 Oboronny Val Sq., Kharkiv, Ukraine
https://orcid.org/0000-0002-0554-8150

Iaroslav Iakubovskyi
Postgraduate Student
Ukrainian State University of Railway Transport
61050, 7 Oboronny Val Sq., Kharkiv, Ukraine
https://orcid.org/0009-0003-7833-6604

Abstract. The relevance of the study is determined by the need to improve the energy efficiency of the multi-motor traction electric drive of commuter electric trains by reducing electricity consumption and losses in traction equipment, power converters, the overhead contact system and auxiliary systems. The aim of the study was to determine the most appropriate technical solutions for improving the energy efficiency of a multi-motor traction electric drive based on a comprehensive analysis of the structure of energy losses, types of traction electric motors, control methods and approaches to optimising movement modes. The study used a multicriteria analysis method applying the Harrington desirability function. The results established that the main reserves for improving energy efficiency are concentrated in reducing losses in the traction electric drive, power converters and the mechanical part of the drive, which account for the largest share of the total energy losses of an electric train. It was determined that the asynchronous traction motor is the most appropriate option for use in a multi-motor traction electric drive, as it provides a rational combination of energy efficiency, reliability, ease of maintenance and acceptable weight and dimensional characteristics. A comparison of asynchronous electric drive control methods showed the advantage of vector control, which ensures high accuracy in regulating electromagnetic torque, stable operation under variable loads and improved energy characteristics of the drive. Among the methods for optimising the movement modes of electric trains, dynamic programming was identified as the most promising, as it enables the formation of energy-saving movement trajectories while taking into account speed limits, track profile and variable operating conditions. The obtained results confirm the feasibility of the integrated combination of an asynchronous traction motor, vector control and dynamic programming algorithms as a basis for creating energy-efficient traction electric drive systems for modern rail rolling stock

Keywords: induction traction motor; vector control; dynamic programming; electric train; energy losses; optimisation of operating modes; multicriteria analysis

Introduction

Rail transport is traditionally regarded as one of the most energy-efficient modes of mass transportation due to the low rolling resistance of steel wheels on rails, high carrying capacity, and centralised power supply for rolling stock. However, the rising cost of electrical energy, stricter environmental requirements, and the need to reduce operating costs make further improvement of traction rolling stock energy efficiency an urgent task. This issue is particularly important for suburban multiple-unit trains, which operate over short interstation distances with frequent stops and repeated acceleration-braking cycles. Under such conditions, a considerable part of the consumed electrical energy is spent not only on useful train movement, but also on covering losses in traction electric drives, power converters, catenary systems, and auxiliary equipment. Therefore, improving the efficiency of multi-motor traction electric drive systems is of significant scientific and practical importance.

A typical operating cycle of an electric train between adjacent stations consists of acceleration, cruising, coasting, and braking before stopping. The highest electricity consumption is observed during acceleration, when traction

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*Corresponding author (*a.masliy@ukr.net*)

motors operate under high-current conditions and significant electromagnetic loads. During this period, instantaneous power consumption may exceed average values, leading to increased losses in converters, electric machines, and the catenary system. Since electricity costs constitute a significant component of operating expenses, even a slight reduction in the specific energy consumption of electric trains can provide a substantial economic effect. In research, improving the energy efficiency of rail rolling stock is regarded as a multidimensional problem that includes energy-efficient train operation, reduction of losses in traction power supply systems, rational use of braking energy, and optimisation of traction drive performance. Y. Rao *et al.* (2022) considered energy-efficient train control taking into account traction system efficiency and concluded that rolling stock energy consumption should be assessed through train motion and traction equipment efficiency. I. Riabov *et al.* (2023) considered the energy efficiency of a multi-motor traction electric drive and emphasised that energy savings can be achieved through rational load distribution between traction motors and adaptation of drive operation to actual traction demand.

A separate group of studies is devoted to traction motors and traction electric drive structures. S. Paul *et al.* (2022) reviewed railway traction motors for distributed traction systems and showed that induction motors and permanent magnet synchronous motors are among the most promising solutions for modern rail vehicles. Y. Peng *et al.* (2024) compared energy-efficient train control based on permanent magnet synchronous motors and induction motors, confirming that motor type influences the attainable energy-saving effect. However, these studies mainly focus either on motor design or on particular operating conditions, while an integrated multicriteria comparison of traction motor types for suburban multi-motor rolling stock remains insufficiently developed.

The choice of the control method for induction traction drives is also widely discussed in the literature. S. Goolak *et al.* (2023) analysed traction drive control systems of electric locomotives with asynchronous traction motors and showed that vector control and direct torque control have different sensitivity to supply voltage and load disturbances. These results are important for multi-motor traction systems, where uneven load distribution, supply asymmetry, and variations in wheel-rail adhesion may reduce overall drive efficiency. Therefore, the effectiveness of a control method should be assessed by its ability to maintain stable and energy-efficient operation under variable traction loads. Another important research direction is the optimisation of train operating modes and speed trajectories. D. Kouzoupis *et al.* (2023) proposed a direct multiple shooting approach and showed that this method provides flexibility in problem formulation and sufficient computational efficiency for complex energy-efficient train control tasks. Z. Xing *et al.* (2023) developed an improved brute-force search approach and concluded that transforming the problem into the search for optimal turning points can reduce the solution space and improve computational speed.

Thus, individual aspects of rail rolling stock energy efficiency have been studied in sufficient depth, ranging from traction motor selection to train driving algorithms. However, the integrated multicriteria selection of ways to improve multi-motor traction electric drive efficiency, simultaneously taking into account motor type, control method, operating conditions, and train operating mode optimisation, remains insufficiently explored. The purpose of the study was to substantiate promising approaches to improving multi-motor traction electric drive energy efficiency through comparison of traction motor types, induction drive control methods, and electric train operating mode optimisation approaches.

Materials and Methods

The study was conducted as a comparative analytical investigation based on the systematisation of scientific publications, technical characteristics of traction equipment, and expert evaluation of alternatives. The factual material consisted of twenty peer-reviewed scientific sources devoted to traction motors, induction-drive control, energy-efficient train operation, and railway trajectory optimisation. The publications were selected because they directly addressed distributed or multi-motor traction, induction and permanent-magnet machines, vector and direct torque control, dynamic programming, model predictive control, genetic algorithms, and optimal-control methods. The main sources used for the comparison of traction-machine types were the works by S. Nategh *et al.* (2020), I. Riabov *et al.* (2023), and H.J. Kaleybar *et al.* (2023). The comparison of induction-drive control methods was based mainly on B. Liubarskyi *et al.* (2017), A. Fathy Abouzeid *et al.* (2020), and S. Goolak *et al.* (2023). The analysis of train-motion optimisation methods relied on Y. Rao *et al.* (2022), D. Kouzoupis *et al.* (2023), Z. Zhang *et al.* (2023).

The research sequence consisted of four stages. At the first stage, the structure of energy losses in a suburban electric train was generalised from the literature and from the typical energy chain of an electric train: catenary system – power converter – traction machine – gearbox – wheelset – wheel-rail contact. At the second stage, the main alternatives for the traction machine were selected: DC motor, induction motor, permanent magnet synchronous motor, and switched reluctance motor. At the third stage, three control methods for induction drives were compared: scalar control, vector control, and direct torque control. At the fourth stage, four approaches to train-motion optimisation were compared: model predictive control, Pontryagin's maximum principle, genetic algorithms, and dynamic programming.

A multicriteria evaluation was used because the alternatives differed by parameters that could not be reduced to a single physical dimension. For each group of alternatives, five criteria were selected. For traction motors, the criteria were efficiency factor, control-system complexity, reliability, weight-and-size characteristics, and operating costs. For induction-drive control, the criteria were energy efficiency, torque control accuracy, control-system response speed, implementation complexity, and operational stability. For train-motion optimisation, the criteria were optimisation accuracy, computational complexity, real-time implementation, solution stability, and versatility. For the criteria related to cost and complexity, a higher desirability value corresponded to a more favourable state, that is, lower cost or lower complexity.

The numerical values in the tables were obtained through expert scoring and subsequent normalisation. The expert group included seven specialists: four academic researchers in electric traction and electric drives and three engineers with experience in operation or maintenance of electric rolling stock. The research involving respondents was conducted on a voluntary basis. All participants were informed about the purpose of the study, the nature of their participation, and the intended use of the obtained results. Written informed consent was obtained from all respondents, including consent to publish the generalised research results. The confidentiality and anonymity of the participants were ensured, and no personal data allowing the identification of respondents were disclosed. Participation in the study did not involve any form of discrimination, coercion, pressure, or unequal treatment. The ethical principles of the study were consistent with the Code of Ethics of the American Sociological Association (2018), the ICC/ESOMAR International Code on Market, Opinion and Social Research and Data Analytics (2025).

Each expert evaluated every alternative on a 10-point scale for each criterion. The individual scores were averaged, after which the averaged values were transformed into partial desirability indices on the Harrington scale. The interpretation of the desirability index was as follows: values from 0.80 to 1.00 corresponded to a very good level, 0.63 to 0.80 to a good level, 0.37 to 0.63 to a satisfactory level, 0.20 to 0.37 to a low level, and values below 0.20 to an unacceptable level. This procedure made it possible to convert heterogeneous technical judgments into comparable dimensionless indicators. The generalised Harrington desirability function was used to obtain an integral indicator for each alternative. The partial desirability for the *i*-th criterion was defined as:

$$d_i = exp[-\exp(-y_i)], \quad (1)$$

where y_i is a normalised coded value of the corresponding criterion. When an expert-score scale was used, the coded value was formed from the averaged expert score after accounting for whether the criterion was beneficial or cost-type. The generalised desirability index was calculated as:

$$D_j = \sqrt[n]{d_{1j} \cdot d_{2j} \cdot \ldots \cdot d_{nj}}, \quad (2)$$

where n is the number of criteria. The geometric form of the aggregation was chosen because it penalised alternatives with one very weak criterion and therefore better reflected the requirements of traction systems, where high efficiency cannot compensate for insufficient reliability or excessive implementation complexity.

Results

A typical operating cycle of an electric train between two adjacent stations consists of acceleration, cruising at constant speed, coasting, and braking before stopping. The highest electricity consumption is observed during acceleration, when traction motors operate under high-current conditions and significant electromagnetic loads (Haahr *et al.*, 2017). During this period, instantaneous power consumption may considerably exceed average values, leading to increased losses in power converters, electric machines, and the catenary system (Feng *et al.*, 2013; Rao *et al.*, 2022). Electricity costs constitute one of the most significant components in the structure of operating expenses of multiple-unit rolling stock. According to estimates by railway operating services, their share may reach 25-35% of total passenger transportation costs. Under such conditions, even a slight reduction in the specific energy consumption of electric trains can provide a substantial economic effect on the scale of the entire transport system (Liu & Golovitcher, 2003; González-Gil *et al.*, 2014). Analysis of the energy performance of suburban electric train operation shows that the pattern of electricity consumption has a pronounced cyclical structure. Each operating cycle between adjacent stops includes a period of intensive acceleration, a phase of motion at limited or steady speed, and a braking stage. Within this cycle, the electrical energy supplied from the catenary system is used both to produce the useful mechanical work required for train movement and to cover losses in various elements of the energy chain. During acceleration, traction motors operate under high-current conditions, which is accompanied by increased electrical losses in their windings as well as increased switching losses in power converters. In addition, high traction currents cause extra losses in the catenary system and in the power cables of the electric train. As a result, the actual efficiency of the entire electric traction system is significantly lower than the efficiency of its individual components.

For assessing the energy efficiency of an electric train, the analysis of the structure of energy losses during traction operation is of particular importance. Energy losses in an electric train are formed in several major subsystems. A significant share of these losses arises in the traction electric drive, which includes traction motors, power converters, and elements of the electrical circuits. Another part is associated with mechanical losses in gearboxes, bearing assemblies, and the wheel-rail contact. Additional losses occur in the catenary system and current collection equipment, as well as in the auxiliary systems of the electric train. A generalised distribution of the energy losses of an electric train is shown in Figure 1. The presented values are average values for modern DC electric trains and may vary depending on the type of traction equipment, operating conditions, and track profile.

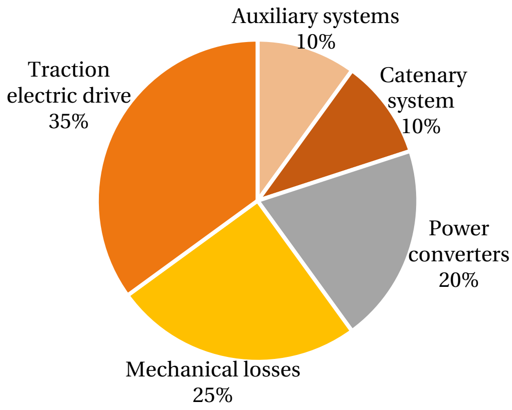

Figure 1. Approximate distribution of energy losses in an electric train

Source: developed by the authors

A conventional distribution of energy losses may be represented by the following shares. Approximately one third of the total losses is attributed to the traction electric drive, where electrical and magnetic losses occur in the motors and power converters. A significant portion of the losses is also formed in the mechanical part of the system, including losses in gearboxes, bearings, and the wheel-rail contact. Some of the energy is dissipated in the catenary system due to voltage drops and conductor heating. A separate group consists of losses in the auxiliary systems of the electric train, including ventilation units, compressors, heating systems, and lighting. The analysis of the loss structure shows that the greatest reserve for improving the energy efficiency of electric trains is associated with the enhancement of the traction electric drive and the optimisation of its operating modes. It is precisely in this subsystem that the most intensive energy processes occur, determining the level of electricity consumption during train acceleration and motion. For this reason, improving the energy efficiency of electric trains requires an integrated approach involving simultaneous enhancement of the traction electric drive design, optimisation of its control algorithms, and rational formation of train operating modes. Such an approach makes it possible to consider the electric train as a unified energy system in which electrical and mechanical processes are closely interconnected (Rao *et al.*, 2022). Structurally, an electric train consists of motor cars and trailer cars. The motor cars are equipped with traction motors, power converters, and auxiliary electrical equipment, whereas the trailer cars primarily perform a transport function. Such a configuration ensures a rational distribution of train mass and makes it possible to provide sufficient adhesion between the wheels and the rails (Paul *et al.*, 2022).

The energy process in an electric train can be represented as a sequence of conversions of electrical energy from the catenary system into the mechanical energy of wheelset rotation. In general, this sequence includes several main stages. Electrical energy is supplied through the current collector to the power converters, where it is converted into the parameters required to supply the traction motors. Then, in the motors, electromagnetic energy is converted into mechanical energy, which is transmitted through the gearbox to the wheelsets, generating the traction force required to move the train (Nategh *et al.*, 2020). An important feature of electric trains is the presence of a multi-motor traction drive structure. Each motor bogie may have one or two traction motors operating in parallel and producing the total traction torque. This arrangement makes it possible to ensure a more uniform distribution of traction effort among the train axles and improves the utilisation of adhesive weight. At the same time, the multi-motor drive structure complicates the control system and increases the requirements for synchronisation of the individual traction motors. Uneven load distribution among the motors may lead to increased energy losses and a reduction in the overall efficiency of the system. Under actual operating conditions, the power levels of individual drives may differ due to variations in axle load, wheel-rail contact conditions, and control system parameters. This leads to additional energy losses associated with the uneven distribution of traction torque (Goolak *et al.*, 2023). An increase in the efficiency of traction motors makes it possible to directly reduce electricity consumption during train operation. In modern induction traction motors, this efficiency can exceed 0.9 over a wide load range, which makes them attractive for application in multiple-unit rolling stock (Peng *et al.*, 2024). At the same time, the selection of the optimal type of traction motor cannot be based on a single parameter alone. For an objective comparison, it is necessary to take into account a whole set of criteria, among which energy efficiency, weight and dimensional characteristics, reliability, control system complexity, and operating costs are of primary importance. Given the heterogeneity of these indicators, it is advisable to use multicriteria evaluation methods that make it possible to integrate different technical characteristics into a single generalised criterion. One of the most widely used approaches for solving such problems is the Harrington desirability function method (Harrington, 1965). Since different types of traction motors are characterised by a combination of technical and operational indicators, the selection of the most appropriate option for use in the electric traction system of an electric train should be carried out using multicriteria analysis methods.

One effective approach to solving such problems is the use of the generalised Harrington desirability function, which makes it possible to transform heterogeneous technical characteristics into dimensionless indicators and combine them into a single integral criterion. The desirability function method is based on transforming each technical parameter into a partial desirability index ranging from zero to one. Values close to zero correspond to unsatisfactory characteristics, whereas values close to one indicate a high level of technical excellence of the respective parameter. For each type of traction motor, the corresponding values of the partial desirability functions are determined. After that, based on the given relationship, a generalised indicator is calculated that characterises the overall efficiency of using a particular type of motor in the electric traction system. Several main types of traction electric motors are used in modern electric traction systems. Each of these motor types has its own technical and operational characteristics, which necessitates their comprehensive comparison. The choice of these motor types and comparison criteria is consistent with the works by S. Paul *et al.* (2022), who emphasised the prospects of induction and permanent magnet synchronous motors for distributed traction systems, and S. Nategh *et al.* (2020), who identified efficiency, reliability, thermal loading, mass-dimensional parameters, and manufacturability as important factors in traction motor design. DC motors remained the principal type of traction motor for electric trains for a long time. Their widespread use was due to the relative simplicity of speed control and the ability to develop a high starting torque. At the same time, the presence of a commutator-brush assembly results in increased operating costs associated with maintenance and brush replacement. In addition, electrical losses in the commutator assembly reduce the efficiency of such machines.

Induction traction motors became widely used with the development of power semiconductor technology. They are characterised by a simple design, the absence of a commutator-brush assembly, and high operational reliability. The squirrel-cage rotor of an induction motor does not require special maintenance, which reduces operating costs. Furthermore, modern control systems make it possible to provide effective control of the speed and torque of such motors. I. Riabov *et al.* (2023) showed that the energy efficiency of a multi-motor traction electric drive depends on rational load distribution between traction motors, which confirms the importance of considering induction motors in such systems. Permanent magnet synchronous motors are distinguished by high efficiency and high specific power. The use of permanent magnets makes it possible to reduce excitation losses and improve the energy efficiency of the motor. However, such machines are characterised by a more complex design and the high cost of magnetic materials, which limits their widespread application in multiple-unit rolling stock. Switched reluctance motors attract the attention of researchers due to their simple rotor design and high reliability. The absence of rotor windings provides increased mechanical strength and overload resistance. At the same time, the complexity of the control system and the increased torque ripple are factors that limit the use of such machines in the traction drives of electric trains. H.J. Kaleybar *et al.* (2023) confirmed the relevance of multicriteria and optimisation approaches for rail vehicle systems, which supports the use of comparative evaluation when selecting traction equipment. The initial values of the desirability indices for different types of traction motors are presented in Table 1.

Table 1. Values of partial desirability indices for different types of traction motors

Criterion	DC motor	Induction motor	Permanent magnet synchronous motor	Switched reluctance motor
Efficiency factor	0.90	0.95	0.96	0.94
Control system complexity	0.80	0.63	0.63	0.37
Reliability	0.37	0.80	0.80	0.80
Weight and dimensional characteristics	0.37	0.80	0.90	0.85
Operating costs	0.37	0.80	0.70	0.80

Source: developed by the authors

These values were obtained on the basis of expert evaluation and subsequent normalisation of the criteria according to the Harrington desirability scale. The partial desirability indices were determined using formula 1, while the generalised assessment of each motor type was performed using formula 2. The data presented in Table 1 show that the permanent magnet synchronous motor has the highest values for efficiency factor and weight-and-dimensional characteristics. However, its operating costs are lower in desirability than those of the induction motor and switched reluctance motor. The induction motor demonstrates the most balanced combination of efficiency, reliability, weight-and-dimensional characteristics, and operating costs. DC motors are characterised by relatively favourable control simplicity, but their reliability, weight-and-dimensional characteristics, and operating costs have lower desirability values. Switched reluctance motors show acceptable reliability and operating costs, but their practical application is limited by the complexity of the control system. Therefore, taking into account the partial desirability indices calculated by formula 1 and their generalised aggregation according to formula 2, the induction motor can be considered the most rational option for use in a multi-motor traction electric drive of an electric train. For a more illustrative comparison of the technical characteristics of different motor types, the evaluation results should be presented in the form of a radar chart (Fig. 2), which makes it possible to graphically represent the relationship among the individual evaluation criteria. The chart presents the values of the partial desirability indices according to the following criteria: efficiency, control system complexity, reliability, weight and dimensional characteristics, and operating costs. Each motor type is represented by a separate curve, which makes it possible to visually assess the relationship among the different technical parameters. Thus, the results of the multicriteria analysis show that the most appropriate option for application in the traction electric drive system of electric trains is the induction traction motor. It is this type of electric machine that provides the optimal combination of energy efficiency, reliability, and operational suitability. Determining the feasibility of using an induction traction motor in the electric traction system of an electric train necessitates a detailed analysis of possible control methods for such a drive. The efficiency of an induction electric drive largely depends on the control algorithms that ensure the formation of the required electromagnetic torque and motor speed operating modes. Unlike DC motors, in which speed control is achieved by varying the supply voltage or field current, induction motors require more sophisticated control systems. Similarly, to the previous analysis of traction motor types, the Harrington desirability function method is used to compare control systems. This approach makes it possible to take into account several technical characteristics of control systems and combine them into a single integral indicator.

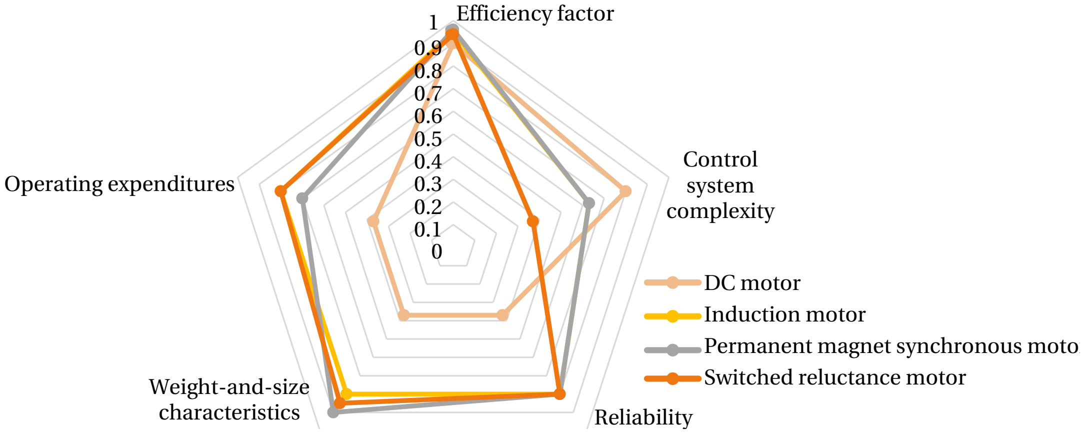

Figure 2. Radar chart of desirability indices for different types of traction motors

Source: developed by the authors

The evaluation criteria for induction drive control systems include energy efficiency, electromagnetic torque control accuracy, control system response speed, implementation complexity, and operational stability under different load conditions. The choice of these criteria is determined by their direct influence on the operational and energy performance of the electric train. Scalar control is based on maintaining a specified relationship between the supply voltage and frequency of the electric motor. This approach is relatively simple to implement and does not require complex computational algorithms. At the same time, the torque control accuracy of scalar systems is limited, which reduces their effectiveness in traction electric drives, where precise control of traction effort is of great importance. Vector control of an induction electric drive is based on the independent regulation of the stator current components responsible for generating the magnetic flux and the electromagnetic torque. This approach makes it possible to achieve control characteristics similar to those of a DC motor, thereby ensuring high torque and speed control accuracy. The direct torque control method involves the direct regulation of the electromagnetic torque and magnetic flux of the motor based on the analysis of instantaneous values of currents and voltages. This method is characterised by high dynamic response and makes it possible to react quickly to load changes. At the same time, its implementation requires the use of high-speed computing devices and sophisticated signal processing algorithms. For each of the considered control methods, the corresponding values of the partial desirability indices are determined. The normalised values of the criteria for the three main control methods are presented in Table 2.

Table 2. Values of partial desirability indices for different control systems of an induction electric drive

Criterion	Scalar control	Vector control	Direct torque control
Energy efficiency	0.63	0.90	0.85
Torque control accuracy	0.50	0.90	0.85
Control system response speed	0.50	0.85	0.90
Implementation complexity	0.90	0.63	0.63
Operational stability	0.63	0.90	0.85

Source: developed by the authors

The values were obtained by averaging expert scores and converting them into partial desirability indices using formula 1. The overall comparison of the considered control methods was carried out using the generalised Harrington desirability function according to formula 2. The results presented in Table 2 indicate that vector control provides the most favourable combination of energy efficiency, torque control accuracy, control system response speed, and operational stability. Direct torque control is characterised by a high response speed and good energy performance, but its implementation complexity reduces its overall desirability. Scalar control has the highest desirability value for implementation complexity because of its relative simplicity, but it is inferior to vector control and direct torque control in terms of energy efficiency, torque control accuracy, and dynamic response. Thus, based on the partial desirability indices calculated by formula 1 and their generalised evaluation according to formula 2, vector control is the most appropriate method for induction traction drives operating under variable load conditions typical of suburban electric trains. Figure 3 shows the values of the partial desirability indices for each control method, which makes it possible to visually assess their advantages and disadvantages. The analysis of the graphical representation confirms that vector control provides the most optimal combination of energy efficiency, control accuracy, and operational stability.

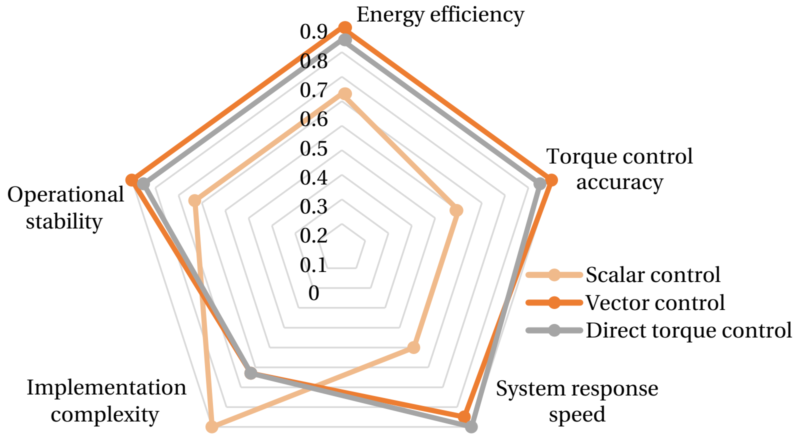

Figure 3. Radar chart of desirability indices for induction electric drive control systems

Source: developed by the authors

Various mathematical approaches may be used to optimize the operating modes of electric trains. Each of them has its own advantages and limitations, which become apparent depending on the operating conditions, the required calculation accuracy, and the feasibility of implementation in real-time control systems. Therefore, it is advisable to carry out a comprehensive evaluation of different train motion optimisation methods using a multicriteria approach. To perform such an analysis, the Harrington desirability function is used, making it possible to integrate heterogeneous characteristics of optimisation methods into a single generalised indicator. As in the previous cases, each evaluation criterion is transformed into a partial desirability index ranging from zero to one. The higher the value of the index, the more desirable the corresponding characteristic of the method. The following train motion optimisation methods are considered in the evaluation process: dynamic programming, Pontryagin's maximum principle, genetic algorithms, and model predictive control. The normalised values of the criteria for train motion optimisation methods are presented in Table 3.

Table 3. Values of partial desirability indices for train motion optimisation methods

Criterion	Model predictive control	Pontryagin's maximum principle	Genetic algorithms	Dynamic programming
Optimisation accuracy	0.90	0.85	0.80	0.90
Computational complexity	0.37	0.63	0.63	0.63
Real-time implementation	0.37	0.50	0.63	0.75
Solution stability	0.80	0.80	0.63	0.90
Versatility	0.63	0.63	0.90	0.85

Source: developed by the authors

These values were formed on the basis of expert evaluation of the methods according to optimisation accuracy, computational complexity, real-time implementation, solution stability, and versatility. The averaged expert scores were transformed into partial desirability indices using formula 1, and the integral comparison of the optimisation methods was performed using the generalised desirability index calculated by formula 2. The data in Table 3 show that model predictive control has a high value for optimisation accuracy, but its practical use is limited by high computational complexity and difficulties in real-time implementation. Pontryagin's maximum principle demonstrates satisfactory values for most criteria, but its versatility and real-time implementation are lower than those of heuristic and dynamic programming approaches. For a more illustrative comparison of the different optimisation methods, the evaluation results should be presented in the form of a radar chart (Fig. 4).

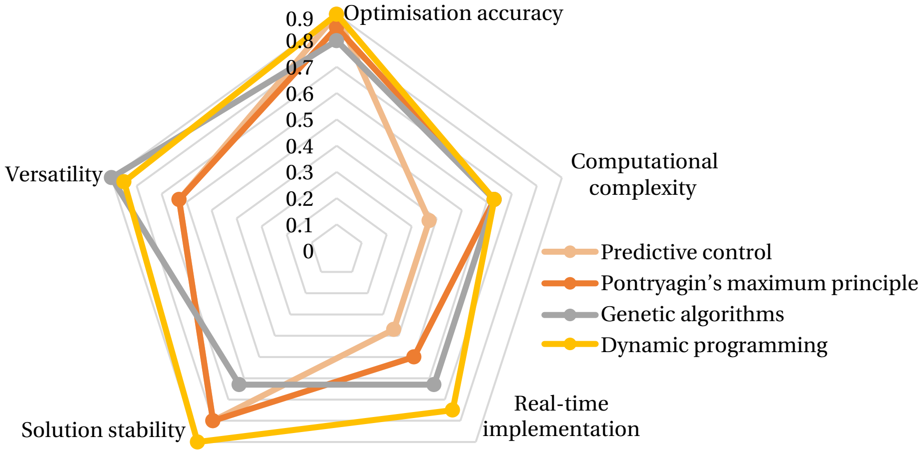

Figure 4. Radar chart of desirability indices for electric train motion optimisation methods
Source: developed by the authors

The chart shows the values of the partial desirability indices for each optimisation method, which makes it possible to graphically assess their advantages and limitations. Thus, the conducted analysis indicates the expediency of using dynamic programming methods for the formation of energy-efficient operating modes of electric trains. The application of this approach makes it possible to take into account changes in operating conditions in real time and to generate optimal control actions for the traction electric drive. The results of the performed analysis of the traction electric drive of an electric train, control methods for induction motors, and optimisation algorithms for train operating modes make it possible to formulate general principles for constructing a control system that ensures improved energy efficiency of rolling stock. Such a system should combine the functions of traction electric drive control, optimisation of train operating modes, and interaction with the railway power supply system. The general operating principle of the control system may be described as a sequence of interactions among several functional modules. First, the motion parameters and electrical quantities are measured. The obtained information is then transmitted to a data processing unit, where the current state of the system is assessed. After that, the optimisation unit determines the optimal control actions, which are transmitted to the traction electric drive control system. The implementation of such a control system structure makes it possible to adapt the operating modes of the traction electric drive to changing train operating conditions. As a result, more efficient use of electrical energy is achieved, and losses in the electric traction system are reduced.

Discussion

In contemporary research, improving the energy efficiency of rail rolling stock is regarded as a multidimensional problem that includes energy-efficient train operation, reduction of losses in traction power supply systems, rational use of regenerative braking energy, and optimisation of traction drive performance. X. Feng *et al.* (2013) systematised the main directions of traction energy saving in rail transport and showed that energy consumption depends not only on rolling stock parameters, but also on driving strategy, timetable constraints, traction and braking modes, and infrastructure conditions. V.I. Shynkarenko *et al.* (2016) focused on the modelling of recovery energy distribution zones in DC traction systems and demonstrated the importance of assessing the conditions under which regenerated energy can be reused within the traction power network. Y. Rao *et al.* (2022) further developed this research direction by considering the efficiency of the traction system itself in energy-efficient train control. These studies confirm that the energy performance of rail rolling stock should be evaluated as the result of interaction between the vehicle, traction drive, power supply system, and operating conditions.

A separate group of studies is devoted to the design of traction motors and the structure of multi-motor traction electric drives. I. Riabov *et al.* (2023) considered the problem of increasing the energy efficiency of a multi-motor traction electric drive and emphasised that energy savings can be achieved through rational distribution of load between traction motors and adaptation of the drive operating mode to actual traction demand. S. Nategh *et al.* (2020) analysed the main aspects of traction motor design for railway applications, including efficiency, thermal loading, reliability, mass and dimensional parameters, and manufacturability. S. Paul *et al.* (2022) reviewed the state of railway traction motors for distributed traction systems and showed that induction motors and permanent magnet synchronous motors are among the most promising solutions for modern rail vehicles. Y. Peng *et al.* (2024) compared energy-efficient train control based on permanent magnet synchronous motors and induction motors, confirming that the choice of motor type has a direct influence on the attainable energy-saving effect. However, these studies mainly focus either on motor design or on particular operating conditions, while an integrated multicriteria comparison of traction motor types for suburban multi-motor rolling stock remains insufficiently developed.

The choice of the control method for induction traction drives is also widely discussed in the literature. A. Fathy Abouzeid *et al.* (2020) analysed control strategies for induction motors in railway traction applications and showed that vector control and direct torque control provide better dynamic and energy performance than scalar control, although they require more complex control algorithms and higher computational resources. B. Liubarskyi *et al.* (2017) studied optimal operating modes of induction traction drives and substantiated the need to coordinate motor operating conditions with the control algorithm of the semiconductor converter. These results are especially important for multi-motor traction systems, where uneven load distribution, supply asymmetry, and variations in wheel-rail adhesion may reduce the overall efficiency of the drive. Therefore, the effectiveness of a control method should be assessed not only by its theoretical accuracy, but also by its ability to maintain stable and energy-efficient operation under variable traction loads.

Another important research direction is the optimisation of train operating modes and speed trajectories. J.T. Haahr *et al.* (2017) proposed a dynamic programming approach for optimising train speed profiles under speed restrictions and passage point constraints, which is directly relevant to railway sections with complex operating limitations. P. Wang & R.M.P. Goverde (2019) extended this problem to multi-train trajectory optimisation for energy-efficient timetabling, showing that energy consumption should be minimised while taking into account the interaction between trains. D. He *et al.* (2021) applied an improved differential evolution algorithm and a multi-particle train model to energy-efficient trajectory optimisation, while Z. Xing *et al.* (2023) proposed an improved brute-force search approach for energy-saving train operation. These studies indicate that different optimisation methods can provide significant energy savings, but their practical applicability depends on computational complexity, stability of the obtained solution, and the possibility of real-time implementation.

Studies increasingly focus on real-time and onboard optimisation methods. D. Kouzoupis *et al.* (2023) proposed a direct multiple shooting approach aimed at improving the computational efficiency of train trajectory optimisation. A. Liebhold *et al.* (2023) considered onboard train speed optimisation using the prediction of block clearing times under real-time rescheduling conditions. A. Yildiz *et al.* (2023) analysed traction energy optimisation with regard to passenger comfort, which is particularly important for urban and suburban rail systems with frequent stops. D. Wang *et al.* (2024) investigated the use of deep reinforcement learning for energy-saving operation in urban rail transit. At the same time, H.J. Kaleybar *et al.* (2023) showed that genetic algorithms and their variants are widely used in rail vehicle optimisation problems, mainly as heuristic tools for complex multi-parameter tasks. Thus, the available studies confirm the effectiveness of modern optimisation methods, but they do not fully solve the problem of jointly selecting the traction motor type, induction drive control method, and train motion optimisation algorithm within a single multicriteria framework.

The results of the study were generally consistent with the conclusions of previous investigations, but they also extended them by integrating three decision levels into one multicriteria framework. I. Riabov *et al.* (2023) demonstrated that the energy efficiency of a multi-motor traction drive could be improved by rationally disconnecting or loading traction motors in accordance with the operating mode. The present study reached a comparable conclusion in a broader form: the highest energy effect should be expected not only from the drive topology itself, but also from the coordinated selection of machine type, control method, and trajectory optimisation algorithm. The conclusion regarding the preference for the induction machine partially coincided with the findings of S. Nategh *et al.* (2020) and S. Paul *et al.* (2022). These authors emphasised that permanent magnet synchronous machines offer very high efficiency and high specific power, whereas induction machines remain attractive because of their robustness, simpler rotor design, and lower maintenance sensitivity. In the present study, the permanent magnet synchronous machine also received the highest partial score for efficiency and compactness. However, after the inclusion of reliability and operating-cost criteria, the induction machine obtained a slightly more rational position for suburban rolling stock. This difference showed the importance of multicriteria evaluation: the most efficient component by one criterion is not necessarily the most appropriate component for a fleet with intensive operation and high maintainability requirements.

The obtained preference for vector control was supported by the results of A. Fathy Abouzeid *et al.* (2020), who showed that advanced induction-motor control strategies were required in railway traction because the drive often operated at low switching frequencies and in nonlinear inverter modes. S. Goolak *et al.* (2023) also showed that the control system of asynchronous traction motors should be assessed under disturbances and asymmetrical supply conditions. The present study agreed with these conclusions and indicated that vector control provided the best compromise between energy efficiency, torque-control accuracy, and operational stability. Direct torque control remained competitive because of its high response speed, but the multicriteria score reflected the need to limit ripple and ensure predictable operation in a multi-motor system. The results concerning train-motion optimisation corresponded with the findings of Y. Rao *et al.* (2022), who proved that traction-system efficiency had to be included in train-control models. M. Nold & F. Corman (2024) similarly demonstrated that more realistic modelling of energy losses could change the optimal control strategy. In the present study, this idea was reflected in the use of loss distribution and drive-specific criteria before selecting the optimisation method. Y. Peng *et al.* (2024) emphasised that braking characteristics and reduced-power operation should be included in the control model; this supported the conclusion that a universal energy-saving algorithm must account for actual vehicle limitations rather than only the theoretical speed profile.

The choice of dynamic programming as the most promising basic method should be interpreted with regard to alternative modern approaches. D. Kouzoupis *et al.* (2023) showed that direct multiple shooting could provide high computational efficiency for some trajectory optimisation problems. Z. Zhang *et al.* (2023) and D. Wang *et al.* (2024) demonstrated the advantages of model predictive control for online and cooperative train operation. J. Liu *et al.* (2025) showed that deep reinforcement learning could reduce dependence on an exact mathematical model. These methods are promising, but they require either higher computational resources, extensive operational data, or more complex validation procedures. Dynamic programming was therefore evaluated as the most balanced method for the considered task because it provided stable solutions, transparent interpretation, and compatibility with discretised representations of speed, position, and operating constraints.

The main limitation of the study was that the quantitative values of the desirability indices were based on expert scoring and generalised data from the literature rather than on direct experimental measurements from a specific electric-train type. Therefore, the obtained integral indicators should be regarded as a substantiated comparative assessment rather than as universal numerical constants. Thus, the obtained results summarise the approach to improving the energy efficiency of a multi-motor traction electric drive as an interconnected system of decisions, in which the choice of motor type, converter control algorithm and speed trajectory optimisation method should be made not separately, but comprehensively. For commuter electric trains, this approach is particularly important, since frequent acceleration and braking cycles require coordination between traction drive control and the optimisation of operating modes as a key condition for reducing energy consumption.

Conclusions

The conducted study confirmed that improving the energy efficiency of the multi-motor traction electric drive of rail rolling stock should be considered as a comprehensive task associated not only with the improvement of individual drive components, but also with the optimisation of the entire system of energy conversion and utilisation. It was established that a significant share of energy losses is generated precisely in the traction electric drive, especially during acceleration and operation under variable load conditions typical of suburban electric trains. This confirms that the main reserve for reducing energy consumption is associated with the rational selection of the traction motor type, an efficient control method, and an appropriate train motion optimisation approach. According to the results of the multicriteria analysis, it was found that the induction motor is the most appropriate option for use in the traction electric drive system of electric trains, as it provides the most balanced combination of energy efficiency, reliability, and operational suitability. The comparison of control methods for the induction drive showed the advantage of vector control, since it offers the best combination of high control accuracy, operational stability, and energy efficiency. The analysis of train motion optimisation methods demonstrated the expediency of applying dynamic programming as the most promising approach for forming energy-saving control actions under variable operating conditions.

Thus, a promising way to improve the energy efficiency of the multi-motor traction electric drive of rail rolling stock is the integrated combination of an induction traction motor, vector control, and dynamic programming methods, which makes it possible to reduce energy losses, improve the efficiency of traction power utilisation, and enhance the operational performance of electric trains. Further research should be aimed at developing and validating a mathematical model of the proposed integrated control system under real operating conditions, taking into account train mass, track profile, interstation distances, speed restrictions, traction power supply parameters, and the dynamic redistribution of load between traction motors.

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Conflict of Interest

None.

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Перспективні шляхи підвищення енергоефективності багатодвигункового тягового електроприводу рейкового рухомого складу

Артем Маслій
Доцент
Український державний університет залізничного транспорту
61050, майдан Оборонний Вал, 7, м. Харків, Україна
https://orcid.org/0000-0002-0554-8150

Ярослав Якубовський
Аспірант
Український державний університет залізничного транспорту
61050, майдан Оборонний Вал, 7, м. Харків, Україна
https://orcid.org/0009-0003-7833-6604

Анотація. Актуальність дослідження зумовлена необхідністю підвищення енергоефективності багатодвигункового тягового електроприводу приміських електропоїздів шляхом зниження витрат електроенергії та втрат у тяговому обладнанні, силових перетворювачах, контактній мережі й допоміжних системах. Метою роботи було визначення найбільш доцільних технічних рішень щодо підвищення енергоефективності багатодвигункового тягового електроприводу на основі комплексного аналізу структури енергетичних втрат, типів тягових електродвигунів, методів керування та способів оптимізації режимів руху. У роботі використано метод багатокритеріального аналізу із застосуванням функції бажаності Харінгтона. У результаті дослідження встановлено, що основні резерви підвищення енергоефективності зосереджені у зменшенні втрат у тяговому електроприводі, силових перетворювачах і механічній частині привода, які формують найбільшу частку загальних енергетичних втрат електропоїзда. Визначено, що найбільш доцільним для використання у складі багатодвигункового тягового електроприводу є асинхронний тяговий двигун, оскільки він забезпечує раціональне поєднання енергоефективності, надійності, простоти експлуатаційного обслуговування та прийнятних масогабаритних показників. Порівняння методів керування асинхронним електроприводом показало перевагу векторного керування, яке забезпечує високу точність регулювання електромагнітного моменту, стійкість роботи за змінних навантажень і покращення енергетичних характеристик привода. Серед методів оптимізації режимів руху електропоїздів найбільш перспективним визначено динамічне програмування, що дає змогу формувати енергоощадні траєкторії руху з урахуванням обмежень швидкості, профілю колії та змінних умов експлуатації. Отримані результати підтверджують доцільність комплексного поєднання асинхронного тягового двигуна, векторного керування та алгоритмів динамічного програмування як основи для створення енергоефективних систем тягового електроприводу сучасного рейкового рухомого складу

Ключові слова: асинхронний тяговий двигун; векторне керування; динамічне програмування; електропоїзд; енергетичні втрати; оптимізація режимів руху; багатокритеріальний аналіз

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Development of existing and new multimodal logistics schemes as steady trend for Ukraine's transport system

Artur Hurinchuk*
Postgraduate Student
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
https://orcid.org/0009-0003-1588-9818

Abstract. The current transformation of international transport corridors, the blocking of sea routes and the redirection of Ukraine's logistics flows necessitate the development of efficient multimodal transport systems and integration into the European logistics space. The aim of article was to study the current trends in the development of Ukraine's transport system, analyse the functioning of multimodal logistics schemes, and identify the prospects for their modernisation in the context of European integration and military challenges. This study involved the use of methods such as system analysis, comparative analysis, statistical evaluation, and the synthesis of scientific sources, analytical reports, and statistical data from international organisations. It has been established that after 2022, Ukraine's transport system underwent a significant transformation linked to changes in the main directions of freight flows and the formation of new multimodal routes through European Union countries. The experience of European countries in optimising the interaction of different modes of transport and stimulating the environmentally safe railway segment has been examined. The analysis revealed the growing importance of dry ports, border logistics hubs and the Danube transport cluster in maintaining the continuity of international supply chains. It has been established that the integration of multimodal schemes with digital logistics management technologies, freight flow monitoring systems and route optimisation tools helps to enhance the resilience of the transport system, reduce logistics costs and minimise risks. It has also been shown that the development of multimodal infrastructure and the harmonisation of Ukraine's transport system with TEN-T standards is a prerequisite for strengthening the country's transit potential and its integration into the European economic area. The practical significance of the results obtained stems from the possibility of applying them in the formation of state transport policy, the modernisation of logistics infrastructure and the optimisation of multimodal transport in Ukraine

Keywords: supply chains; multimodal technologies; transport services; economic partners; freight transportation

Introduction

The effective functioning of the transport system forms the basis of economic stability, the maintenance of foreign trade links and the country's international competitiveness. Due to global geopolitical changes, large-scale infrastructure damage and the forced closure of traditional sea routes, there is an urgent need for a radical restructuring of logistics chains based on multimodality, which makes it possible to minimise financial costs, reduce delivery times and optimise the use of technical resources. Investigation of the possibilities for developing such systems and establishing new land corridors is vitally important for integrating the national network into the Trans-European Transport Network (TEN-T) and enhancing the resilience of the economic system. In accordance with Ukraine's National Transport Strategy until 2030 (Resolution of the Cabinet of Ministers of Ukraine No. 1550-2024-p, 2024), one of the priority areas for the development of the transport sector is the modernisation of multimodal infrastructure and the expansion of integration into the European transport area.

The issues of organising, modelling and improving the efficiency of combined freight transportation under extreme conditions are the focus of many researchers. In particular, the specifics of optimising and restructuring transport routes were investigated by I. Taran *et al.* (2023), who, in their work, established the mathematical dependence of optimisation criteria on the total volume of freight deliveries and proposed an algorithm for synchronising the discrete stages of the multimodal process. The authors have proven that splitting large consignments into separate parts allows for flexible adjustment of carriers'

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*Corresponding author (*artur23321@gmail.com*)

variable and fixed costs. Models of integrated planning and the selection of logistics providers were examined by S. Onyshchenko *et al.* (2024). The researchers developed a comprehensive economic-mathematical model aimed at improving operational efficiency and minimising costs by coordinating the schedules of motor, railway and sea transport, taking into account specific regional constraints. I. Derpich *et al.* (2024) analysed the environmental aspects of transport systems and the potential for reducing carbon dioxide emissions. The scientists proposed a strategic approach to the centralised concentration of freight flows and mathematically demonstrated that, under conditions of high transit density, the use of a significant number of intermediate logistics hubs is economically and environmentally inefficient.

The specific features of logistics management in emergency situations and under conditions of direct infrastructure threats are examined in the study by V. Samsonkin *et al.* (2022). The authors developed a digital information and organisational system for security management at the level of large transport enterprises, demonstrating the high effectiveness of simplified route calculation methods during military operations in Ukraine. A.S. Shuaibu *et al.* (2025) examined the problems of cargo delivery within the "last mile" concept as one of the most costly elements of the supply chain. The researchers demonstrated the potential of applying artificial intelligence technologies for dynamic routing and justified the advantages of using hybrid networks that combine unmanned aerial vehicles with traditional vehicles in an urbanised environment. N. Kalicheva *et al.* (2022) examined the processes involved in the development of a network of logistics hubs at the regional and national levels. The researchers identified the key risks associated with the creation of multimodal centres and noted that infrastructure instability and the low quality of ancillary services remain the main obstacles to attracting investment in Ukraine. D.V. Lomotko & H.O. Prymachenko (2023) analysed the importance of the railway sector and its interaction with other modes of transport in the context of the transformation of the geopolitical landscape. The author emphasised the insufficient level of research on economic security issues in the transport sector and argued that it is multimodal technologies which allow the strengths of each means of transport to be maximised at specific stages of the logistics chain. N. Trushkina (2022) examined the challenges of international partnerships and the diversification of freight logistics routes during military conflicts. The author justified the importance of strengthening cross-border cooperation with European Union countries, expanding the use of Danube port facilities, and establishing joint logistics enterprises to ensure the uninterrupted export of agricultural products.

However, despite the existence of a significant body of studies, the mechanisms for adapting Ukraine's logistics infrastructure to rapid changes in transit conditions and integration with specific hubs in Central and Western Europe require further analysis. The purpose of this article was to examine current transformational trends in Ukraine's transport system, to assess the effectiveness of existing multimodal schemes, and to identify strategic priorities for their modernisation.

Literature Review

The organisation, management, and improvement of multimodal freight transport services using effective logistics tools are the subject of intensive scientific research. Current approaches for organising multimodal freight delivery based on the agile approach were proposed in the work by V. Berestenko & S. Onyshchenko (2024). The authors study digital mechanisms for coordinating multimodal transport and the issue of reconciling the interests of participants in the logistics process. The main scientific contribution of the work is the introduction and justification of the concept of the "compromise zone." The authors prove that this "compromise zone" should become a central tool in agile planning cycles. It clearly demonstrates how a change in one customer requirement (e.g., a shorter lead time) affects other parameters (cost, reliability), offering the operator and the customer a set of new alternatives for balancing interests.

The issue of developing Ukraine's transport and logistics infrastructure in the context of European integration and global challenges is highlighted in N. Tyukhtenko (2024). The author systematises the main components of transport and logistics infrastructure and emphasises the need to adapt it to European standards and the principles of sustainable development. The author examines the theoretical foundations of the concept in detail, systematising it into four key components: technical, infrastructural, institutional, and organisational-economic. The article discusses the critical importance of a functioning integrated transport and logistics system and its structural elements – transport and logistics centres. On the basis of global experience of developed countries, the effectiveness of such centres is demonstrated, and their essence, main development goals, and prerequisites for successful implementation in Ukraine are explored. Taking into account Ukraine's unprecedented infrastructure losses due to full-scale Russian aggression, the article outlines priority areas for the reconstruction and modernisation of the branch. These areas are based on the adaptation of advanced European and global experience.

The study by O.V. Svychynska & A.V. Reznyk (2025) analysed the transformation of Ukraine's logistics system amid a full-scale invasion. The authors note a sharp decline in freight volumes in 2022, followed by a gradual recovery during 2023-2024 due to the optimisation of rail transport, the implementation of multimodal logistics schemes, the revitalisation of the Danube transport corridor, and the resumption of international container traffic. At the same time, the study substantiates the feasibility of digitisation the industry (implementing modern management systems). Special attention is given to the socio-environmental challenges of wartime. In particular, the author highlights ways to address labour shortages through retraining programmes for women and the integration of artificial intelligence to automate heavy physical labour. The environmental dimension of the study explores the potential of "green logistics" and the decarbonisation of operations as key drivers of sustainable industrial development. According to the authors' conclusions, the implementation of these priorities will ensure the transition of the domestic logistics market from survival tactics to systematic modernisation and integration into global supply chains.

In her work, V. Puzikova (2024) examined the specific nature of the transformation and the prospects for the recovery of Ukraine's logistics system under martial law. The author emphasises the dual nature of the country's geopolitical position: its status as a logistics hub and high transit index (which, according to 2018 estimates, surpassed those of its closest European neighbours) are combined with the risks of being located in a buffer zone. It has been emphasised that the destruction of industrial and transport infrastructure as a result of Russia's full-scale aggression has necessitated a shift in traditional supply chains, where railways and seaports historically accounted for up to 75% of foreign trade. At the same time, the large-scale destruction has been seen as a determinant for the radical modernisation of the economy through the development of next-generation infrastructure. The key vectors for Ukraine's integration into the global space have been identified as the reform of the transport sector based on multimodality, the optimisation of domestic routes, and the digitalisation of customs regulation. In the paper by A. Karam *et al.* (2023), a theoretical and methodological analysis of the barriers to the development of multimodal freight transport was conducted, and strategies for overcoming them were identified. Based on a meta-synthesis of 104 scientific papers, the authors identified 31 specific barriers hindering the shift of freight flows from road transport to more environmentally friendly alternatives (railway and inland waterways). The article focuses on justifying risk mitigation tools, particularly through digitalisation, the development of synchro-modality, the optimisation of business models, and the strengthening of integration between the government and private sectors.

The research by A. Orozonova *et al.* (2022) analysed the specifics and prospects of integrating smart technologies into the organisation of multimodal freight transportation. The authors argue that traditional methods of logistics analysis are insufficient and propose a new conceptual model of market functioning based on the activities of a smart logistics operator (provider-integrator). The authors developed a unified framework for the thinking and operational context of such an integrator, as well as classified the types of smart technologies implemented by it. Particular attention was paid to the operational characteristics of niche logistics markets – the delivery of special categories of cargo within the submarkets of temperature-sensitive (refrigerated) products, fresh goods, and pharmaceuticals, which require enhanced technological control to ensure compliance with safety and reliability parameters of supply chains. S. Okyere *et al.* (2022) investigated the issue of optimising multimodal transport and logistics systems using genetic algorithms to improve transport efficiency and ensure the sustainable development of the transport sector. The authors emphasise the need to integrate various modes of transport into a single logistics system to minimise costs, reduce delivery times, and lessen the negative environmental impact of transport activities. A model for optimising multimodal transportation is proposed, based on the application of a genetic algorithm to select the most efficient cargo delivery routes. The study takes into account economic, environmental, and time-related transportation parameters, enabling a comprehensive approach to managing logistics processes. The authors claim that the use of intelligent optimisation algorithms contributes to increasing the sustainability of the transport system, improving coordination between modes of transport, and reducing logistics costs.

In a scientific review, D. Kurniawan (2024) summarised theoretical and practical approaches to improve the efficiency and viability of integrated logistics networks through multimodal transportation. Based on an analysis of a corpus of leading publications from 2010 to 2024, the author identifies five strategic dimensions of multimodal systems: economic efficiency, resilience to crises, environmental sustainability, the level of digital integration, and network design architecture. The study demonstrates that the use of synchromodality concepts, Internet of Things technologies, and real-time analytics enables the minimisation of operational costs, the flexible adaptation of logistics chains to large-scale geopolitical or economic crises, and the reduction of the carbon footprint. At the same time, the author states that there are barriers to the large-scale implementation of such solutions, in particular, infrastructure disparities between regions of the world and the fragmentation of regulatory frameworks. The study concludes by justifying the need for institutional reforms and the implementation of adaptive logistics models based on artificial intelligence.

O. Strelko *et al.* (2022) investigated the theoretical foundations for the development of multimodal transport and logistics technologies in the context of integrating Ukraine's transport system into the TEN-T. The research focuses on the formation of modern multimodal infrastructure, the development of logistics centres, and ensuring effective coordination among different modes of transport. The authors argue that harmonising national logistics routes with European standards requires rethinking the coordination of different modes of transport and developing compatible cross-border infrastructure. Special attention was paid to the regulatory and technical compatibility (interoperability) of logistics systems, which is critically important for the seamless integration of domestic operators into European supply chains and the realisation of the country's transit potential. The authors also emphasise the importance of developing railway transport as a key element of the multimodal transport system to the European Union.

The article by K. Cherednichenko *et al.* (2023) is aimed at developing a scientific and methodological approach for assessing the operational safety of multimodal transport systems. The authors critically analyse existing risk management models and identify their key shortcomings, including the problem of local optima, the difficulties of unifying assessments for different modes of transport, and the limitations of safety management in situations where the operator is not the direct owner of the infrastructure. The scientific novelty of the work lies in the development of a mathematical model based on system reliability theory, risk concepts, and critical failures. The proposed tools allow for the consideration of both the objective conditions for the formation and development of a logistics network and the subjective factors involved in ensuring the protection of its facilities. The practical significance of the research is confirmed by the testing of the model on an existing multimodal route, which demonstrates its applicability both for monitoring the current level of security and as a baseline criterion during the design of optimal logistics chains. The authors proposed a methodological approach to security assessment using the example of multimodal transport, which takes into account the shortcomings of existing studies. The practical application of the developed model was demonstrated on an existing multimodal transport system.

The study by J. Gupta *et al.* (2024) highlights the strategic role of multimodal logistics parks in stimulating economic development and optimising a country's macro-logistics costs. Using the example of a large-scale infrastructure project in a multimodal logistics park, the authors demonstrate an approach to the planning and construction of major transportation hubs. Significant attention was paid to the methodological aspects of design, covering the calculation of infrastructure capacities, the implementation of flexible financial mechanisms (in particular, public-private partnerships), as well as compliance with strict environmental standards to ensure the region's environmental safety. The authors claim that the creation of such hubs not only increases the speed and transparency of cargo delivery but also serves as a driver for the development of intelligent transportation systems. S. Fazi & J.C. Fransoo (2025) focused on the study of freight mobility in their work. They proposed and theoretically substantiated the concept of "Freight Mobility as a Service" as a tool for scaling up synchro-modal transport. The authors argue that the concept of multimodality didn't gain widespread practical application due to the critical heterogeneity and fragmentation of transport offerings, as well as the specific nature of freight requests. Unlike most existing digital platforms, which operate on an "on-demand" basis, the FMaaS (Freight Mobility as a Service) model integrates regular schedules of linear services (rail, barge, and coastal shipping) into flexible and transparent delivery chains. Despite the commercial, legal, and psychological barriers to the implementation of FMaaS, the authors argue that this approach dramatically increases network capacity utilisation and is key to the sustainable and environmentally friendly development of global logistics.

Materials and Methods

The study on the development of multimodal logistics schemes in Ukraine was based on a comprehensive approach to the analysis of transport processes, international logistics routes, and the integration of Ukraine's transport system into the European transport area. The methodological basis of the work consisted of general scientific and specialised research methods, the application of which enabled a systematic analysis of current trends in the development of multimodal transport and the identification of prospects for modernising the transport and logistics infrastructure. The sequence of the research process comprised three interrelated stages: the collection and systematisation of source data, statistical and analytical processing of information, and the formulation of practical recommendations for the modernisation of transport corridors. The study applied a systematic analysis method, which allowed for the examination of Ukraine's transport system as a complex integrated mechanism of interaction between rail, road, maritime, and river transport. Using this method, the study identified the characteristics of the transformation of logistics flows after 2022, changes in the structure of international transport, and the role of multimodal schemes in ensuring the sustainability of the transport system.

The reference period for the statistical study, 2015-2024, was selected to ensure a representative analysis of long-term structural changes based on complete and consolidated annual financial statements. The start of the period (2015) reflects the stabilisation of the transport sector following previous economic fluctuations. The end of the period (2024) marks the cut-off point for fully consolidated annual data from official international databases (such as Eurostat). However, to ensure the integration of up-to-date data, the study additionally includes operational data, interim reports and development trends for 2025-2026 in the "Results and Discussion" section. This time range allows to carry out comparative analysis of pre- and post-crisis changes in the transport system.

A comparative analysis was used to compare the functioning of Ukraine's transport system before and after changes to major international logistics routes. The comparison was based on criteria such as dominant modes of transport, the structure of logistics schemes, cargo flow directions, the role of border infrastructure, and the level of integration into the European Union's transport network. This made it possible to identify key trends in the development of multimodal transport and to determine promising directions for the modernisation of transport infrastructure. A specific comparative cross-national analysis was used to assess the use of railway transport within the multimodal logistics infrastructure of European countries. This analysis was carried out to evaluate the strategic transition towards environmentally sustainable transport solutions and to analyse the adaptability of continental supply chains. Railway transport was chosen exclusively as the central element of this comparison, as it serves as the operational basis for the EU-Ukraine "corridors of solidarity" and acts as the primary green alternative for alleviating bottlenecks in cross-border freight transport. The evaluation criteria are based on the share of rail transport by mode of transport (%) in the total volume of domestic freight transport. Chronology is specifically focused on the years 2014, 2023 and 2024. The year 2014 serves as a structural macro-historical baseline, marking the beginning of Ukraine's intensive economic integration with the EU and the onset of early regional geopolitical disturbances. The years 2023 and 2024 represent the most critical contemporary phase, encompassing a full-scale reorientation and stabilisation of international logistics corridors amidst extraordinary military and trade challenges.

Specific descriptive and structural statistical methods were used to process the statistical data and to assess the dynamics of transport processes. In particular, a time series analysis (dynamic analysis) was applied to assess changes in freight transport volumes and to track chronological transformations from 2015 to 2024. The analysis of structural shifts (assessment of the distribution of transport modes) was used to calculate the exact percentage share of different modes of transport, such as maritime, road and railway, in global and national logistics systems. Furthermore, methods of comparative statistical grouping and normalisation were employed to assess and visualise railway transport usage indicators for individual European countries in comparison with the European Union average. An analytical synthesis of these statistical indicators enabled the systematisation of logistics trends both before and after the turn of 2022. The empirical basis of the study consisted of finalised and operational data from key international and national transport institutions. Specifically, long-term indicators on freight volumes and modal shift trends were retrieved from the verified database of the Statistical Office of the European Union (Eurostat, 2026). The metrics regarding cross-border infrastructure capacity and the performance of alternative logistics routes were sourced from the official evaluation reports on the launch and expansion of the "Solidarity Lanes" initiative (European Commission, 2022). For the analysis of the Danube River corridor and the implementation of alternative maritime cluster models, industry-specific analytical resources and governmental monitoring data were utilised (Potaieva, 2026). These core sources provided a reliable foundation for capturing transport dynamics over the monitored timeframe.

To carry out a detailed comparative analysis of the efficiency of alternative multimodal freight corridors between Ukraine and the EU, the study used the method of relative normalisation and systematic generalisation of technical and economic parameters. The combined railway-road route via the border crossings of Poland and Slovakia was taken as the base index (100%) for financial costs. The relative indices for other means of transport were calculated using the formula (1):

$$I_{cost} = \left(\frac{C_x}{C_{base}}\right) \cdot 100\%, \qquad (1)$$

where C_x – absolute cost of shipping 1 TEU on the route under study, C_{base} – the average absolute cost of delivery via the standard railway-road route. The fluctuation ranges for direct road transport (145-160%) and the Danube River cluster (70-80%) have been established based on an analysis of data from logistics operators in the "Solidarity Lanes" reports (European Commission, 2022) and analytical studies (Samoiliuk & Polushkin, 2026). Delivery times are defined as the total "door-to-door" transportation time based on monitoring data from the UNHCR (n.d.). Carbon dioxide (CO_2) emission ranges (g/t-km) are integrated based on transport environmental matrices from the work of I. Derpich *et al.* (2024) and Eurostat (2026) reports.

The study analysed recent scientific publications on the development of multimodal transport systems, the digitalisation of logistics, and the integration of transport infrastructure into the TEN-T. In particular, it examined fundamental research on route optimisation (Taran *et al.*, 2023), modelling the operational efficiency of providers (Onyshchenko *et al.*, 2024), as well as the environmentalisation and decarbonisation of transportation (Derpich *et al.*, 2024). It also analysed concepts for the implementation of intelligent digital platforms in logistics (Berestenko & Onyshchenko, 2024; Fazi & Fransoo, 2025). Additionally, analytical studies on the development of logistics hubs, dry ports, and Ukraine's integration into the TEN-T were used.

Official analytical reports and centralised statistical datasets from European and national institutions formed the empirical backbone of this research. The chronological window for data collection spanned a ten-year interval from 2015 to 2024, ensuring internal consistency across the methodological sections and providing a sufficient baseline to trace structural transformations. The primary source of numeric datasets regarding intermodal distribution was the Eurostat (2026). This was cross-referenced with the European Commission's annual monitoring reports on the EU-Ukraine Solidarity Lanes (European Commission, 2022). The institutional framework of the study was substantiated through strategic national documentation, specifically Resolution of the Cabinet of Ministers of Ukraine No. 1550-2024-p (2024), which approved the National Transport Strategy of Ukraine for the Period up to 2030.

To substantiate suggestions for diversifying routes, actual data from specialised digital platforms, statistical dashboards, and transport monitorings were analysed. The operational characteristics of Solidarity Lanes were examined based on the official tracking portal of the European Commission (2022). The development status of the Moldova Motorway (A7 corridor) was assessed using the regional infrastructure platform Firtka (Liubchyk, 2024). Indicators of bilateral trade with Germany were derived from the macroeconomic database of the Centre for Economic Strategy (Samoiliuk & Polushkin, 2026). Furthermore, parameters regarding the operational capacity of the Danube and Baltic ports were evaluated based on the data from the integrated

Government Portal of Ukraine (Government Portal, 2026), the specialised agricultural analytics platform AgroTimes (Potaieva, 2026), and the international logistics media portal IntermodalNews EU (Zasiadko, 2022).

The criteria for selecting scientific sources included the relevance of the research, publication in specialised international journals, indexing in the Scopus and Web of Science scientometric databases, as well as alignment with the subject matter of multimodal transport and transport logistics. Particular attention was paid to sources published between 2022 and 2026, ensuring the relevance and scientific reliability of the research. The criteria for selecting specific case studies (Poland, Romania, Slovakia, and Bulgaria) as subjects for the analysis of logistics corridors were: the presence of shared land or sea borders with Ukraine, the dynamics of cross-border cooperation, and the strategic role of these countries in ensuring the uninterrupted export of Ukrainian agricultural products under conditions where traditional port infrastructure is blocked.

Results and Discussion

Multimodal transport helps to organise logistics efficiently, as it enables the transportation of goods over long distances using several modes of transport. Multimodal transport involves sea, motor, railway and air transport. Large consignments of commercial cargo are typically delivered by sea from distant countries – the USA, Canada, China and others. Goods are often shipped by sea from Europe. Air transport plays a key role in multimodal transport for the urgent delivery of cargo over long distances, ensuring maximum speed in the supply chain and increasing the flexibility of the logistics system. Although this mode of transport cannot be described as cheap, it is the optimal option for perishable and urgent cargo. Railways and automobile transport can serve as either auxiliary or primary modes of transport in mixed routes (Sloboda Region, 2022). The integration of different means of transport is based on uniform standards and a single information environment, both within the country and its regions, and in international traffic. Multimodality applies to transport infrastructure, vehicles, cargo units and management systems. The core concept of multimodality is transhipment and transit. Multimodality is characterised by the presence of hubs that connect networks of different modes of transport into a single large integrated network, where cargo is transferred from one means of transport to another.

The key feature of a multimodal transport system, as with any system, is its integrity and unity, which is achieved through specific interconnections and interactions between its constituent elements. The constituent elements of a multimodal transport system are: logistics flows; transport infrastructure; parties involved; and the regulatory framework. Multimodal transportations, carried out by logistics companies on behalf of businesses, are cost-effective and efficient in terms of increasing speed, ensuring safety and reducing transport costs. Logistics companies with considerable experience in this field develop optimal routes and choose the most efficient and suitable combinations of transport modes, loading and unloading points, and the necessary equipment for handling the specific product. This refers to all types of delivery, including containerised multimodal transport. The timely and correct preparation of the necessary documents significantly reduces the time lost due to delays caused by errors or the absence of required documents. Routes planning taking into account road and traffic conditions, knowledge of the particularities of sea and air ports, and other logistical factors, enables to respond promptly to potential obstacles and quickly redirect cargo. This flexibility in transportations allows to guarantee compliance with delivery deadlines and other terms of the agreement with the customer.

Different means of transport have different technical and operational characteristics and capabilities (Table 1). Multimodal systems allow each means of transport to develop its capabilities to meet the demand for specific transport services, which, as part of the overall demand for transport by all modes within the system, can be met by integrating one type of transport with another and through competition between interacting modes of transport (transport companies). Multimodality also involves digital logistics, which can be built on the basis of uniform rules and algorithms for the management, planning and operation of different transport modes. Multimodality also envisages digital logistics, which can be built on the basis of uniform rules and algorithms for the management, planning and operation of different modes of transport. In this context, the transition to "Freight Mobility as a Service" platforms acts as a critical catalyst for integrating regular rail and maritime schedules into open, transparent and synchronised multimodal chains (Fazi & Fransoo, 2025). The deployment of such digital systems creates a unified information environment, enabling operators and shippers to establish flexible "trade-off zones" that dynamically balance cost, speed and reliability of delivery during crisis-driven reorientations (Berestenko & Onyshchenko, 2024).

Table 1. The functional role of transport modes in multimodal transportations

Transport mode	Role in the logistics chain	Cargo characteristics	Advantages
Maritime	Main line (intercontinental)	Large shipments, commercial goods	Low cost per cargo unit
Air	Express delivery	Perishable, urgent, and costly freight	Maximum speed and flexibility
Railways	Main or auxiliary	Bulky freight, containers	Stability, weather independence
Motor transport	Auxiliary ("last mile") or main	A wide range (small and medium-sized batches)	Delivery "from door to door"

Source: compiled and systematised by the author based on O. Strelko *et al.* (2022), Sloboda Region (2022)

The European Union has an extensive network of multimodal logistics centres, which play a fundamental role in ensuring the efficiency and competitiveness of the region's transport system. The synchronisation of the operational activities of such centres depends to a large extent on advanced modelling algorithms for carrier selection and tactical route planning, as illustrated in the integrated framework proposed by S. Onyshchenko *et al.* (2024). Furthermore, the overall efficiency of combining road and railway transport segments in these networks depends on the dynamic allocation of freight transport to balance carriers' fixed and variable costs (Taran *et al.*, 2023). An analysis of the structure of freight transportation by means of transport within the global logistics system for the period 2015-2024 indicates the consistent dominance of maritime transport, which share fluctuates between 67% and 69%, confirming its key role in securing global trade flows (Table 2). Motor transport is showing gradual growth (from 22.5% to 25.7%), reflecting its increasing importance in regional and intra-continental transport. The share of railway transport remains relatively stable at 5.3-6.0%, indicating its steady but supporting role in the global transport system. At the same time, air transport retains a negligible share (around 0.2%), which is explained by the high cost of transport, but its importance remains significant for urgent and high-value cargo. Inland waterways account for a small share (1.6-2.1%), characterising them as a local element of multimodal logistics schemes.

Table 2. Percentage of transport modes for the period 2015-2024, %

Transport mode	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Air	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Railways	5.7	6.0	5.8	5.7	5.5	5.3	5.5	5.6	5.5	5.4
Motor transport	22.5	23.1	23.3	22.9	23.1	24.0	24.4	24.9	25.3	25.7
Maritime	69.5	68.7	68.8	69.4	69.4	68.8	68.1	67.7	67.4	67.0
Inland waterways	2.1	2.1	2.0	1.7	1.8	1.8	1.8	1.6	1.6	1.7

Source: developed by the author based on Eurostat (2026)

Building upon the general transport mode dynamics presented in Table 2, Figure 1 offers a deeper comparative insight into how specific countries perform in relation to the baseline EU average (100%).

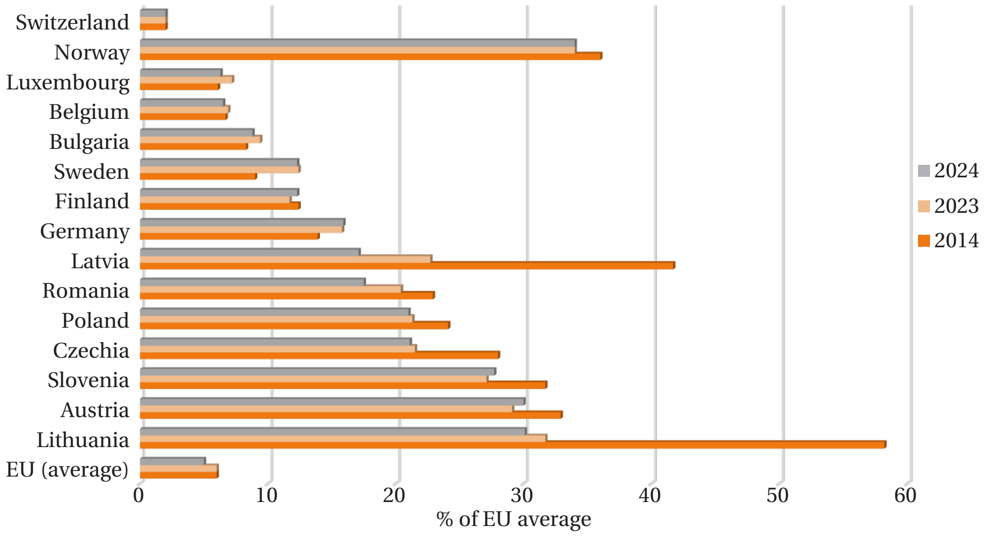

Figure 1. A comparative analysis of the use of railway transport in multimodal systems across European countries
Source: developed by the author based on Eurostat (2026)

The analysis was carried out to assess the transit resilience and environmental sustainability of European logistics chains, using the share of railway transport in the multimodal transport system as the main criterion. An analysis of the statistical data presented in Figure 1 allows to identify key trends in the development of multimodal transport systems in European countries. The horizontal axis (0-60) reflects the exact percentage (%) of railway transport in the total volume of freight transport for each country. A comparison of 2024 with the 2014 baseline shows that the share of railway transport in total freight transport has decreased in 17 of the 25 EU countries with railways. The choice of 2014 as a historical benchmark, compared with the recent period of 2023-2024, clearly highlights how long-term geopolitical realignments and immediate security crises are forcing structural shifts in logistics. Although the average share of railway transport in the EU remains low but relatively stable at 5.0-6.0% (confirming the continued dominance of road transport), the development trajectories of individual countries differ significantly. For example, the experience of Switzerland, where the share of railways remains stable at

34-36%, demonstrates an effective state strategy for shifting freight flows from motorways to railways. By contrast, the sharp decline in Lithuania (from 58.2% in 2014 to 30.1% in 2024) and Latvia (from 41.7% to 17.1%) highlights how the collapse of traditional post-Soviet transit corridors has led to a radical, crisis-driven restructuring of multimodal schemes towards Western European markets.

The most significant changes have been observed in Lithuania and Latvia. In particular, in Lithuania, the share of railway transport has almost fallen by half: from 58.2% in 2014 to 30.1% in 2024. A similar decline is also characteristic of Latvia (a drop from 41.7% to 17.1%). This is explained by the reorientation of transport corridors and changes in the geopolitical situation, which are forcing these countries to restructure their multimodal schemes toward Western European markets. Counties like Austria (30.0%), Slovenia (27.7%) and Czechia (21.1%) demonstrate a high and stable level of integration of the railway segment into logistics chains. This is due to both their geographical location (transit hubs) and the well-developed infrastructure of intermodal terminals.

The modest growth in the rail share in Germany (from 13.9% to 15.9%) and Sweden (from 9.0% to 12.3%) indicates the gradual implementation of the "Greening Transport" policy. For Ukraine, the experience of these countries is important in the context of developing its own algorithms for optimising multimodal transport, which will improve the efficiency of the logistics system and reduce the load on the highway network. The obtained results confirm that the modern global transport system is distinctly multimodal in nature, with the integration of maritime and motor transport with other modes of transport playing a leading role in ensuring the efficiency of logistics chains of essential goods, and support for Ukrainian exports via European ports (Sarahman, 2025).

To conduct a detailed assessment of the effectiveness of Ukraine's logistics system transformation after 2022, a comparative analysis has been carried out of key land and river multimodal routes to European Union countries. The assessment has been based on three key criteria: financial costs (cost of delivering 1 TEU), time (door-to-door transit time), and environmental impact (CO_2 emissions). The results of the analysis and comparison of logistics parameters for the "Central Ukraine – Central European Hub (Germany)" route are summarised in Table 3.

Table 3. Comparative analysis of the efficiency of logistics routes from Ukraine to the EU

Multimodal route (corridor)	Financial costs (per TEU)	Delivery time (days)	Emissions (CO_2) (g/t-km)	Major infrastructure constraint
Railway and road (via Poland/Slovakia)	100% (base level)	3-5	12-18	Congestion at border crossings, track gauge change (1,520/1,435 mm)
Direct road transport (via border crossings)	145-160%	2-4	62-80	Shortage of permits, long queues at the borders, high fuel costs
River-sea (Danube cluster) (via Romania/Bulgaria)	70-80%	8-12	5-10	Dependence on the dimensions of the navigation channel; limited capacity of the docks

Source: calculated and compiled by the author based on the normalisation methodology described in the "Materials and Methods" section (formula 1), using input data from I. Derpich *et al.* (2024), O. Potaieva (2026)

Based on an assessment of the effectiveness of existing transport schemes, it has been determined that road transport, despite its high speed and mobility, shows the lowest economic and environmental efficiency. It increases logistics costs by an average of 50% compared to combined railway schemes. At the same time, the Danube River Cluster ensures the greatest reduction in financial costs (20-30% cheaper than rail) and has the smallest carbon footprint, but it significantly loses out in delivery speed due to lengthy cargo transshipment operations at the ports of Izmail and Reni. Based on the comparison of the parameters of individual corridors, a comprehensive assessment of global changes across the entire transport system becomes possible. The general macro-logistics indicators of these transformations are presented in Table 4. To summarise the systemic changes in the operational paradigm of national logistics, a comparative matrix of macrostructural changes has been developed (Table 4). Although the quantitative statistical baseline of this study remains tied to the period 2015-2024 due to the availability of consolidated annual datasets, the qualitative assessment of transformations after 2022 is projected to extend to the period 2025-2026. This enables the study to contextually cover the final integration benchmarks, the medium-term outcomes of the evolutionary phases of the "Solidarity Corridors", and the current institutional reorientation towards the TEN-T framework. The synthesis is based on the regulatory frameworks of the Resolution of the Cabinet of Ministers of Ukraine No. 1550-2024-p (2024), the European Commission's strategic assessment documents (2022) and recent transport capacity models proposed by sectoral researchers (Berestenko & Onyshchenko, 2024; Derpich *et al.*, 2024).

Table 4. Transformation of Ukraine's transport system (before and after 2022)

Indicator	Before 2022 (2014-2021)	After 2022 (2022-2026)	The trend
Main export route	Seaports of the Black Sea	Overland and Danube routes	Relocation to the EU
The predominant mode of transport	Maritime + railway	Automobile + railway + multimodal	Multimodality
Logistics structure	Linear	Networking	Decentralisation

Table 4. Continued

Indicator	Before 2022 (2014-2021)	After 2022 (2022-2026)	The trend
The role of the EU	Restricted	Key (Solidarity Lanes)	Integration
Risks	Low	High (war)	The growth of risk management

Source: compiled and structured by the author based on European Commission (2022), Resolution of the Cabinet of Ministers of Ukraine No. 1550-2024-p (2024), V. Berestenko & S. Onyshchenko (2024)

During the period up to 2022, the system was primarily focused towards maritime transport via Black Sea ports and was characterised by relative stability and a centralised logistics structure. After 2022, there was a shift towards motorway, railway and multimodal transport, with a focus on land corridors to EU countries. Following Russia's invasion of Ukraine and its blockade of Ukrainian ports, Ukrainian grain and other agricultural goods could no longer reach their destinations. The situation threatened global food security, and there was an urgent need to establish alternative logistics routes utilising all relevant modes of transport. It would not be an exaggeration to say that a key step in supporting the export of Ukrainian agricultural produce and the import of critical goods amid the blockade of seaports was the launch on 12 May 2022 of the EU's "Solidarity Lanes" initiative, designed to enable Ukraine to export grain and import essential goods, ranging from humanitarian aid to animal food and fertilisers (Table 5). The specified logistics routes include rail, road, and river routes through neighbouring EU countries – Poland, Romania, Slovakia, and Hungary – and have become critically important for the Ukrainian economy (European Commission, 2022). The structural integration and survival of Ukraine's foreign trade under wartime restrictions were largely supported by coordinated institutional actions at the transnational level. To monitor the operational vectors and strategic outcomes of these measures, Table 5 presents an overview of the main logistics corridors and emergency programmes deployed by international partners. The operational objectives, timelines and logistical impact of these initiatives were structured based on a systematic assessment of the European Commission's Communication on Solidarity Lanes (European Commission, 2022), assessments of global supply chain adaptation by M. Samoiliuk & H. Polushkin (2026), and sectoral monitoring reports on western border dry ports and maritime clusters (Zasiadko, 2022).

Table 5. Key EU logistics initiatives for Ukraine during the war

Initiative	Launch period	Objective	Means of transport	Significance
"EU Solidarity Lanes"	12.05.2022	Alternative export/import routes in the context of port blockades	Railway, motorway, river	Crucial channel for grain exports and imports of goods
Transit expansion through the EU	2022 – present	Providing access to EU ports	Railway, motorway	Supports for agricultural exports
The use of EU ports	2022 – present	Transhipment of Ukrainian goods	Maritime + multimodal	Expansion into global markets

Source: compiled and structured by the author based on European Commission (2022), M. Zasiadko (2022), M. Samoiliuk & H. Polushkin (2026)

The construction of the Moldova Motorway is underway in Romania. The new transport corridor will link southern Romania (Ploiești) with the north-eastern part of the country, partly following Pan-European Corridor IX. It will pass through Buzău, Focșani, Bacău, Roman, Pașcani and Suceava, connecting with the Ukrainian M19 motorway near the Siret River and the Chernivtsi region. Thanks to this route, Ukraine could gain a new European transport corridor. In the future, this motorway could provide Ukraine with access to Romanian ports. Furthermore, it will create an alternative route to EU countries, allowing traffic to bypass Poland, Hungary and Slovakia. The route via Siret and through Romania has become one of the largest transit routes for transporting grain from Ukraine by land following the full-scale Russian invasion. Currently, around 3,000 workers are working on the motorway 24/7. To avoid losing European funding, work on the A7 motorway must be completed by 2027 (Liubchyk, 2024).

Germany is a significant partner on Ukraine's course to EU membership. The Federal Republic of Germany is helping to ensure that the economy of a country, which is subjected to attacks by Russian drones almost every night, remains in relatively good shape. Although Ukraine is not yet an EU member, both countries are already cooperating in all four areas of the single market: trade, services, people and capital. Bilateral trade in goods alone reached a record high in 2025, whilst relations in the areas of services, labour and investment continued to deepen. According to preliminary data, trade volume in 2025 amounted to €12.4 billion, which is 52% higher than the trade volume between Russia and Germany. This relationship is not one-sided: Ukraine is of great importance to Germany's supply chains and labour market, just as Germany remains one of Ukraine's most important economic partners. Germany has a trade surplus with Ukraine. Before the war, German exports to Ukraine consisted mainly of cars and lorries, medicines and agricultural machinery. Since 2022, the structure of exports has changed significantly: Germany now exports primarily defence and military products. Ukraine has become an important market for these highly technological goods, which often have dual-use applications (Samoiliuk & Polushkin, 2026).

Ukraine's airspace remains closed for civil aviation due to ongoing military threats, which means that cross-border freight transport between Germany and Ukraine relies exclusively on land and multimodal land corridors (Safe Airspace, n.d.). Road transport serves as the primary operational option at this stage. Shipments from Germany via this route account for the majority of transport, providing crucial logistical flexibility. Remarkably, Germany is one of the leading suppliers of high-quality equipment for energy infrastructure, including industrial generators, heavy transformers and energy storage systems – components that remain vital for stabilising the resilience of Ukraine's power grid against the backdrop of systematic attacks on its civilian energy infrastructure (Samoiliuk & Polushkin, 2026). At the same time, the Port of Hamburg (Germany) plays a crucial role in these supply chains, ranking among Europe's leading container hubs with an annual throughput that has historically fluctuated around 8-9 million TEU (Port of Hamburg, 2026). Hamburg's distinctiveness lies in its extensive and highly integrated network of port railways (Hafenbahn), which facilitates rapid inland intermodal connections throughout Central and Eastern Europe. Modern container terminals within the hub are equipped with automated cargo handling and synchronous tracking systems, providing a strategic blueprint for the sustainable diversification of corridors (Zasiadko, 2022).

Ukrainian-Slovak cross-border cooperation began with Slovakia's accession to the EU. The main participants in cross-border cooperation between Ukraine and Slovakia are the Zakarpattia region (Ukraine) and Prešov and Košice (Slovakia). As part of this cross-border cooperation, the Ukrainian-Slovak Business Council was established to monitor, provide recommendations and make decisions aimed at improving cooperation between the parties. The creation of this Council enables the swift resolution of various issues, as well as the development of a further action plan to achieve the medium-term goals of deepening cross-border cooperation. In recent years, particular attention in bilateral scientific and technical projects between Ukraine and Slovakia has been focused on the development of devices and technologies for the safe and environmentally friendly use of natural resources, as well as energy-efficient management. On the whole, despite the positive dynamics of bilateral political and trade-economic relations, problematic issues remain between Ukraine and Slovakia. These include asymmetry in political interaction (however, with the start of Russia's full-scale invasion of Ukraine, Ukrainian diplomacy has become more active, particularly in terms of cooperation with Bratislava); the uneven investment activity of both Ukraine and Slovakia; the presence of unresolved issues regarding the Slovak diaspora in Ukraine, and so on. Nevertheless, the positive aspects of Ukrainian-Slovak cooperation still prevail. In particular, this is due to the intensification of cooperation in the fields of science, education and innovations. With the support of the EU and various European programmes and initiatives, cross-border cooperation between the two countries has been further strengthened, and this is likely to become even more robust following Ukraine's victory in the war currently raging across Europe (Balanchuk & Sokolovska, 2024).

Within the framework of modern border logistics, the transport corridor between Slovakia and Ukraine serves as a key channel for the import and export of goods to the EU, supported by a highly integrated road and railway infrastructure. The main land gateway for these operations is the "Uzhhorod – Vyshne Nemetske" border crossing point, where standard delivery times for freight typically range from 1 to 3 days in accordance with coordinated customs procedures (UNHCR, n.d.). At the same time, freight transport between Ukraine and Poland remains a cornerstone of regional supply chain management, developing rapidly thanks to geographical proximity, deep economic integration and well-established bilateral trade channels. For many operational supply chains, particularly those handling often small batches and industrial parcels, rapid cross-border delivery is vital for business continuity. However, the operational environment at the Ukrainian-Polish border has faced periods of extreme strain, characterised by serious truck blockages and technical bottlenecks at major road checkpoints (Samoiliuk & Polushkin, 2026). Despite these logistical crises and temporary restrictions, Poland has consistently maintained its position as one of Ukraine's key strategic and economic partners within the EU, contributing to the long-term stabilisation of land-based trade flows (Zasiadko, 2022).

It is worth mentioning that cooperation with Poland in the field of transport and logistics has become particularly relevant at present, during Russia's armed aggression against Ukraine, when significant problems have arisen in organising foreign trade logistics due to the blockade of seaports. The Polish route is becoming essential for Ukrainian exports from a logistics perspective due to the blockade of Black Sea ports. In other words, new opportunities and prospects have emerged for cooperation with Poland as a strategic partner. For example, the Polish seaport of Kolobrzeg, located on the Baltic Sea coast between Świnoujście and Gdynia, is offering to handle the transhipment of Ukrainian agricultural exports at its facilities. Several pilot projects have already been launched. In addition, Ukraine and Poland have signed a memorandum on strengthening bilateral cooperation in the field of rail transport, under which the establishment of a joint logistics enterprise is planned. This, in turn, will enable a significant increase in the volume of railway transport of Ukrainian exports to the EU and to global markets via Europe. The Polish Ministry of Economic Development and Technology and the Ukrainian Ministry of Economy have signed a Memorandum regarding the development of trade facilitation tools. The aim of the agreement is to strengthen bilateral economic cooperation by simplifying trade, with a focus on ensuring insurance coverage for the supply of goods and services (Trushkina, 2022).

Economic cooperation between Ukraine and Bulgaria focuses on integration into the European area, the development of alternative logistics routes and the strengthening of security in the Black Sea. A key area of logistics here is the launch of direct passenger rail routes (via Romania), which will help to strengthen Ukraine's integration with the European transport space, develop the Danube cluster and coordinate road transport (Fig. 2). The governments of Ukraine and Bulgaria have reached an agreement on establishing the transport of agricultural products from Ukraine via Bulgarian ports on the Black Sea coast. Bulgaria plays an important role for Ukrainian exporters, particularly in new supply chains and the export of fuel and agricultural raw materials, and is one of the largest suppliers of diesel fuel to Ukraine, providing a significant proportion of the country's needs, notably through oil refinement at a local plant. In order to strengthen the region's energy security, Ukraine and Bulgaria are also developing the "Vertical Gas Corridor". The country also serves as a hub for infrastructure restoration and the development of transport corridors, particularly railway connections, which strengthens Ukraine's integration into the European transport area. The port of Varna is regarded as a key logistics hub (Government Portal, 2026).

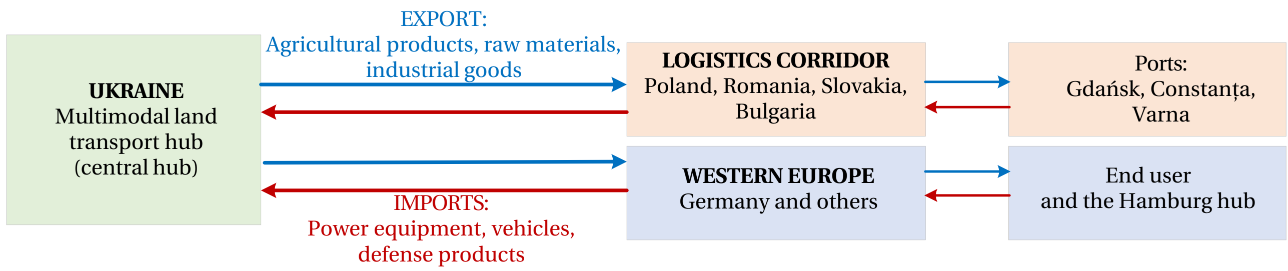

Figure 2. Integrated model of trade and logistics flows

Source: compiled and structured by the author based on N. Trushkina (2022), European Commission (2022), M. Zasiadko (2022), I. Balanchuk & N. Sokolovska (2024), Government Portal (2026)

Figure 2 demonstrates the current structure of international freight flows, shaped by the transformation of Ukraine's transport system following 2022 and the shift towards European logistics routes. Economic cooperation between Ukraine and Bulgaria is focused on integration into the European space and the development of alternative logistics routes in the Black Sea region. A key direction is the development of the Danube cluster and the launch of direct passenger and freight railway routes through the territory of Romania (Government Portal, 2026). Bulgaria plays a significant role in ensuring Ukraine's energy security, being one of the largest suppliers of diesel fuel (Cabinet of Ministers of Ukraine, 2024). In addition, agreements have been reached on the use of Bulgarian Black Sea ports (in particular, the Port of Varna, which is a key logistics hub) for the export of Ukrainian agricultural raw materials (Zasiadko, 2022). The countries are also actively developing the "Vertical Gas Corridor" project, which strengthens Ukraine's integration into the European transport and energy network (Reuters, 2024). The core of the model identifies Ukraine as a key transit and logistics hub facilitating interaction between domestic producers and European Union countries. This emphasises the changing functional role of the national transport system – shifting from a focus on maritime exports to the development of a multimodal land-based transit hub. Export flows are directed towards EU countries (Poland, Romania, Slovakia, Bulgaria), which serve as a border logistics belt and ensure the further transportation of goods to major European hubs, notably Germany and the ports of Hamburg, Gdańsk, Constanța and Varna. Imports are mainly agricultural products, raw materials and industrial goods.

The import flows run in the opposite direction and originate mainly from leading EU countries, primarily Germany and Poland. They include supplies of energy equipment, vehicles, defence and high-tech products, which ensure the functioning of Ukraine's critical infrastructure. An important element of the scheme is the logistics infrastructure, which includes border crossings, the network of EU logistics hubs and integration into the TEN-T. This is evidence of the steady harmonisation of Ukraine's transport system with European standards and the strengthening of intermodal transport. The development of a network of dry ports along Ukraine's western borders is becoming a strategic priority, as it enables the transformation of the border "belt" from a logistical bottleneck into powerful multimodal hubs for transshipping cargo from the Ukrainian gauge (1,520 mm) to the European gauge (1,435 mm) (Derpich *et al.*, 2024). This, in turn, ensures the continuity of supply chains within the "Solidarity Lanes" initiative and strengthens the national economy's resilience to external challenges (European Commission, 2022). This approach allows for a significant increase in the capacity of border infrastructure, reduces cargo processing time, and mitigates logistics risks arising at border crossing points. The formation of a dry port network also facilitates the redistribution of cargo flows from congested road routes to more efficient railway and intermodal corridors. One of the priority areas for enhancing the resilience of Ukraine's export and import routes is the implementation of a pilot project to develop the Danube Transport and Logistics Cluster. Initiated by the Ministry of Community and Territorial Development of Ukraine, this project aims to create competitive conditions for the stevedoring business and integrate river infrastructure into the EU's single logistics space (Potaieva, 2026).

The integration of Ukraine's river and railway infrastructure into the TEN-T network enhances the interoperability of transport systems and contributes to the creation of a single European logistics area, which is a key factor in the long-term competitiveness of the Ukrainian economy (Table 6). The structural components of this modernisation system, including targeted tariff adjustments and the centralisation of port assets, have been systematised on the basis of strategic development plans issued by the Ministry of Community and Territorial Development of Ukraine. This matrix also includes institutional roadmaps for the synchronisation of the Danube cluster, as assessed in regional logistics studies (Potaieva, 2026), and reports on operational infrastructure from specialised transport platforms (Zasiadko, 2022).

Table 6. Key instruments for modernising the Danube corridor

Modernisation area	Content of the measure	Expected effect
Financial incentives	Reinvestment of state enterprise profits and targeted allocation of port fees	Modernisation of port infrastructure and fleet renewal
Tariff policy optimisation	Compensation mechanisms for rail transport to the ports of Izmail and Reni	Reduction of logistics costs and increased route competitiveness
Institutional centralisation	Establishment of a unified Danube branch of the SE "USPA"	Optimisation of asset management and resource centralisation
Industrial hub formation	Establishment of industrial parks based on ports and PJSC "UDP"	Capital attraction, employment growth, and stable cargo flow

Source: compiled and structured by the author based on M. Zasiadko (2022), O. Potaieva (2026), UNHCR (n.d.)

According to forecasts, the implementation of these measures will ensure a guaranteed cargo flow of up to 2.5 million tons per year and preserve over 5,500 jobs in the maritime complex and Joint Stock Company "Ukrzaliznytsia" (Potaieva, 2026). From the viewpoint of international logistics, the development of the Danube cluster is of paramount importance for deepening Ukraine's integration into the TEN-T. These efforts provide the basis for establishing sustainable intermodal supply chains linking Ukrainian manufacturers with countries in the Danube basin and strategic European markets. Therefore, Ukraine serves as a transit hub, the countries of Central and Eastern Europe act as a cross-border transport corridor, and Western Europe functions as the final distribution and consumer market.

The contemporary structural transformation of Ukraine's freight transport system post-2022 and the accelerated roll-out of multimodal corridors require in-depth academic analysis through comparison with existing scientific discourse. The results obtained in this study regarding route optimisation, digitalisation tools, and the adaptation of regional infrastructure demonstrate both strategic alignment and significant differences from previously established models. In their study, I. Taran *et al.* (2023) established a mathematical relationship between optimisation criteria and total delivery volumes, and proposed algorithms for synchronising the discrete stages of the multimodal process. Their assertion that splitting large consignments allows for flexible adjustment of carriers' variable costs clearly correlates with the results of this study. In particular, analysis of the rail-road route through Poland and Slovakia confirms that the tactical splitting of consignments helps to mitigate infrastructure constraints associated with the change in rail gauge from 1,520 mm to 1,435 mm. Similarly, S. Onyshchenko *et al.* (2024) developed a comprehensive economic-mathematical model for coordinating road, railway and sea transport schedules with the aim of minimising costs under regional constraints. Their focus on inter-provider coordination serves as the theoretical basis for the integrated model of trade and logistics flows proposed in this work. However, whereas their model relies on stable hub capacity, presented results demonstrate that under extreme conditions the effectiveness of such coordination critically depends on unpredictable border congestion, which requires the formation of dynamic "compromise zones" rather than rigid schedule planning.

The conceptual application of such flexible zones in the context of logistical crises expands upon the academic approaches proposed by V. Berestenko & S. Onyshchenko (2024). The authors substantiated that a flexible approach and dynamic balancing of customer requirements regarding speed, cost and reliability should become the operator's primary tool. This position is fully confirmed by presented findings regarding the Danube cluster's river-sea route. Although this corridor offers a unique reduction in financial costs of 20-30% and has the lowest carbon footprint (5-10 g/t-km), it is significantly slower in terms of delivery time (8-12 days). Thus, this study empirically confirms that the Danube route is a classic "trade-off zone", where shippers consciously exchange delivery time for economic and environmental benefits.

With regard to the environmental aspect, I. Derpich *et al.* (2024) have mathematically demonstrated that an excessive concentration of intermediate logistics hubs in conditions of high transit density is economically and environmentally inefficient. This statement differs somewhat from the current situation observed on Ukraine's western border. The study shows that the high density of border "dry ports" is not a source of inefficiency, but a strategic necessity for transforming logistical bottlenecks into powerful multimodal hubs. The pressing operational need to adapt to the blockage of traditional routes justifies the decentralised logistics structure. Moreover, N. Tyukhtenko (2024) systematised the technical, infrastructural and organisational components of logistics, emphasising the priority of adapting the national network to European TEN-T standards. Presented structural analysis of the tools for modernising the Danube Corridor strongly supports this view. The transition to institutional centralisation and the optimisation of tariff policy directly implements the integration priorities outlined by N. Tyukhtenko, demonstrating that infrastructure harmonisation is a prerequisite for the post-war resilience of the economy. The socio-economic developments highlighted in this study also reflect the findings of O.V. Svychynska & A.V. Reznyk (2025), who examined the dynamics of market recovery through railway optimisation and the resumption of container transport. However, whilst they focused primarily on internal market survival strategies and overcoming labour shortages, this study examines another aspect of the problem. This study assessed the transformation of the national system into a macro-regional transit hub linking the end markets of Western Europe (e.g., the Hamburg hub) with alternative ports on the Black and Baltic Seas.

From a global operational perspective, S. Fazi & J.C. Fransoo (2025) proposed the concept of FMaaS to scale up synchronous multimodal transport, arguing that the fragmentation of service offerings hinders practical multimodality. Whereas their theoretical model promotes open digital platforms in stable market conditions, this empirical data show that in crisis-hit regions, multimodality is achieved not only through digitalisation, but primarily through physical infrastructure diversification, such as the construction of the "Moldovan Motorwa" (A7 corridor) in Romania. Finally, V. Puzikova (2024) examined the dual nature of Ukraine's transit potential, highlighting the catastrophic disruption of traditional supply chains, where railways and seaports had historically accounted for up to 75% of foreign trade. V. Puzikova structural baseline fully confirms the historical shift recorded in this comparative matrix. This study expands on this idea, demonstrating that the transition from a linear, sea-dependent structure to a decentralised land-based network is no longer a temporary survival measure, but a sustained trend towards Ukraine's long-term integration into the European economic space.

The study has therefore identified the key trends in the development of Ukraine's transport system after 2022, which involve a shift towards multimodal and decentralised logistics models in response to European integration processes and military challenges. An analysis of how multimodal logistics systems operate has shown that their effectiveness is determined by a combination of route optimisation, digitalisation and infrastructure adaptation, taking into account crisis-related constraints and border instability. The prospects for modernising the transport system are linked to Ukraine's further integration into the European logistics space, the development of flexible intermodal corridors and the formation of a sustainable macro-regional transit hub.

Conclusions

This study revealed that Ukraine has significant potential to expand its participation in international and transit freight transport. An analysis of existing approaches to organising multimodal transport has shown that their effectiveness largely depends on the level of integration of the transport system, the coordination of interaction between modes of transport, and the degree of digitisation of logistics processes. Furthermore, an analysis of global market trends has confirmed the stable leading role of maritime transport and the steady growth of the road transport segment at the regional level, while the railway component in most European countries continues to show relatively low performance.

It has been determined that the key areas for improving the efficiency of multimodal transport are the optimisation of traffic flows, the reduction of cargo transshipment times, the reduction of logistics costs, and the improvement of delivery reliability. An important outcome of the study is the justification of the need to create an integrated transport environment focused on European Union standards, which involves harmonising the regulatory framework and developing infrastructure compatibility. It has been established that the introduction of intelligent transportation systems, electronic document management, and freight flow management platforms create the conditions for improving the transparency, manageability, and efficiency of logistics processes. It has also been demonstrated that multimodal logistics schemes help reduce the negative impact of transport on the environment through the rational selection of routes and the wider use of energy-efficient modes of transport. Prospects for further research include an in-depth analysis of the digital transformation of multimodal transport, an assessment of its economic efficiency in the context of the post-war reconstruction of Ukraine's transport system, and the development of adaptive models for managing logistics flows. Additionally, they involve mathematical modelling of risks in multimodal transport and the implementation of intelligent digital platforms based on artificial intelligence for dynamic management of cargo flows in crisis conditions.

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Розвиток існуючих та нових мультимодальних логістичних схем як усталена тенденція для транспортної системи України

Артур Гурінчук
Аспірант
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
https://orcid.org/0009-0003-1588-9818

Анотація. Сучасна трансформація міжнародних транспортних коридорів, блокування морських шляхів та переорієнтація логістичних потоків України зумовлюють необхідність розвитку ефективних мультимодальних транспортних систем та інтеграції до європейського логістичного простору. Метою статті було дослідження сучасних тенденцій розвитку транспортної системи України, аналіз функціонування мультимодальних логістичних схем та визначення перспектив їх модернізації в умовах євроінтеграції та воєнних викликів. В дослідженні були використані методи системного аналізу, порівняльного аналізу, статистичного оцінювання та узагальнення наукових джерел, аналітичних звітів і статистичних даних міжнародних організацій. Встановлено, що після 2022 року транспортна система України зазнала суттєвої трансформації, пов'язаної зі зміною основних напрямків вантажопотоків та формуванням нових мультимодальних маршрутів через країни Європейського Союзу. Досліджено досвід європейських країн щодо оптимізації взаємодії різних видів транспорту та стимулювання екологічно безпечного залізничного сегмента. Проведений аналіз показав зростання значення сухих портів, прикордонних логістичних хабів і Дунайського транспортного кластеру для підтримки безперервності міжнародних ланцюгів постачання. Встановлено, що інтеграція мультимодальних схем із цифровими технологіями управління логістикою, системами моніторингу вантажопотоків та інструментами оптимізації маршрутів сприяє підвищенню стійкості транспортної системи, скороченню логістичних витрат і мінімізації ризиків. Також доведено, що розвиток мультимодальної інфраструктури та гармонізація транспортної системи України зі стандартами TEN-T є необхідною умовою зміцнення транзитного потенціалу держави та її інтеграції до європейського економічного простору. Практичне значення отриманих результатів полягає у можливості їх використання під час формування державної транспортної політики, модернізації логістичної інфраструктури, розвитку міжнародних транспортних коридорів та оптимізації мультимодальних перевезень в Україні

Ключові слова: ланцюги постачання; мультимодальні технології; транспортні послуги; економічні партнери; вантажні перевезення

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Investigation of the application of LiDAR technology to optimise automatic traffic flow control

Yaroslav Korpan*
PhD in Technical Sciences, Associate Professor
Cherkasy State Technological University
18006, 460 T. Shevchenko Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0002-1455-5977

Eugene Fedorov
Doctor of Technical Sciences, Professor
Cherkasy State Technological University
18006, 460 T. Shevchenko Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0003-3841-7373

Tetyana Utkina
PhD in Technical Sciences, Associate Professor
Cherkasy State Technological University
18006, 460 T. Shevchenko Blvd., Cherkasy, Ukraine
https://orcid.org/0000-0002-6614-4133

Abstract. The paper examined a topical issue arising from the need to improve the efficiency of urban traffic management through the use of advanced technologies. The purpose of the study was to investigate an approach to optimising the operating modes of traffic lights at intersections based on traffic flow data obtained using Light Detection and Ranging (LiDAR) sensors to improve traffic efficiency and reduce delays. The paper described the method of using LiDAR sensors for calculating turn signals at intersections and further optimising the operating modes of traffic lights based on the obtained data. The study found that, in order to function correctly, the method must include the following stages: placement of LiDAR sensors at key intersection points in order to obtain three-dimensional point clouds reflecting the dynamics of traffic flow; processing and analysis of data generated by the sensor (advanced data processing methods are used, in particular, algorithms for segmentation of point clouds and object recognition); analysis of information about the object's trajectory (in particular, for highlighting and counting return flows from primary LiDAR data); development of a mathematical model of the traffic control system; application of adaptive control strategies for the formation of optimised traffic light modes; development of recommendations for improving efficiency and optimisation on the methods of statistical analysis and machine learning to identify stable patterns and time trends in the structure of traffic; implementation of traffic light objects management. The generalised results of the study showed that the described method can provide an integrated approach and support for automatic adaptive control of traffic lights due to the use of LiDAR technology to collect detailed information about turning movements at intersections and optimise the time of traffic lights, which, as a result, will help to increase the capacity of intersections and reduce congestion in urban transport networks. The results of the study can be used by traffic management bodies and transport infrastructure engineers when designing and optimising traffic light regulation at urban intersections

Keywords: Light Detection and Ranging sensors; object recognition; mathematical model; traffic; real-time correction; machine learning

Introduction

Against a backdrop of rapid growth and increasing complexity in urban traffic, the issue of effective intersection management has become a pressing and urgent concern, as congestion on the road network leads to longer journey times, traffic jams, an increase in the number of accidents, and a negative impact on the environment. It is well known that optimisation of traffic light operating modes involves adapting signal phase durations to fluctuating traffic conditions, thereby minimising delays at intersections and increasing traffic capacity. The implementation of effective optimisation strategies not only helps to improve transport logistics, but also enhances the safety of pedestrians (and other road users) and reduces the negative impact of transport infrastructure on the environment. An intersection is a key element of the road transport network, within which multidirectional traffic flows cross and interact. Therefore, understanding the nature of vehicle traffic at intersections, in particular

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*Corresponding author (*y.korpan@chdtu.edu.ua*)

turning manoeuvres, is a necessary condition for effective optimisation of automatic traffic light control modes. As a rule, classical approaches to controlling traffic lights are based on the use of predefined action protocols or a limited amount of data received from induction sensors or video systems. Such methods provide a basic level of functioning, but they are weak from the standpoint of adaptation to the conditions of dynamic changes in traffic flows, as noted by P. Li *et al.* (2020). In particular, induction loops described by L. Klein (2001) allow determining only the fact of passing a vehicle, but do not provide detailed information about its trajectory, behaviour, or interaction with other road users. But counting turn signals at intersections provides complete information about the nature and intensity of traffic, which allows correction systems to adapt the time parameters of traffic lights to the specific conditions of a particular intersection and increase the overall efficiency of the entire road transport system.

One of the most promising areas for collecting high-precision spatiotemporal information about vehicle movement is the use of LiDAR technologies. LiDAR technology allows obtaining high-precision spatial data in the form of three-dimensional (3D) point clouds in real time, which provide opportunities for detailed analysis of traffic flows, including the determination of traffic trajectories, speeds, time delays, and the occurrence of conflict situations described by F. Guan *et al.* (2023) and Y. Liang *et al.* (2024). The principle of operation of LiDAR sensors is based on the emission of laser pulses and measuring the time of their return after reflection from objects, which allows creating a detailed 3D spatial model of the environment. In traffic flow monitoring tasks, LiDAR sensors provide accurate detection and tracking of vehicles, pedestrians, and other road users, thus forming an informative database for analysing intersections and further optimising traffic light control modes. Unlike conventional detection tools, three-dimensional point clouds provide the ability to classify objects, determine their trajectories, and analyse return flows in real time, which was confirmed by contemporary research in this area (Saldivar-Carranza *et al.*, 2024). Recent research demonstrated the significant potential of using LiDAR to evaluate the performance of traffic lights and analyse transport processes. In particular, E. Saldivar-Carranza *et al.* (2021; 2024) showed the possibility of forming accurate vehicle trajectories based on LiDAR data, and then obtaining indicators such as delay time, queue length, and intersection throughput. This, in turn, creates prerequisites for the transition from static to adaptive and intelligent traffic management methods.

Despite the significant development of traffic light optimisation methods in recent years, most of the available approaches are based on the use of generalised transport data obtained either from a limited number of sources or in a short period of time. This often leads to inefficient adjustment of signal timing parameters, especially in difficult intersections. Therefore, there is a need to apply more accurate and adaptive methods of collecting information to develop sound strategies for optimising the operation of traffic lights, in particular, considering turning manoeuvres of vehicles. Contemporary approaches to traffic light control optimisation involve the use of mathematical modelling, statistical analysis, and machine learning methods, in particular, reinforcement learning algorithms that allow adapting alarm modes to changing traffic conditions (Wei *et al.*, 2018). In particular, P. Li *et al.* (2020) and Y. Hu *et al.* (2025) described reinforcement learning algorithms that demonstrate high efficiency in traffic light optimisation tasks, providing adaptation to changes in the traffic situation in real time. In addition, the use of neural networks, in particular LSTM, which was described by L. Yang & R. Guo (2024) allowed for short-term forecasting of traffic flows, which is an important element of proactive management. Thus, the study of the use of LiDAR technologies to optimise automatic traffic control at intersections is an urgent scientific and practical task aimed at developing intelligent transport systems and improving the quality of urban mobility.

The purpose of this study was to overcome the above limitations by using LiDAR sensors to calculate turn signals at intersections and further optimise traffic light operating modes based on the data obtained. The methodology of the study was based on a comprehensive approach to analysing ways to optimise traffic flows at intersections using LiDAR technologies. In the course of the study, methods of research analysis were applied, which were covered in scientific literature sources. The contemporary approaches to creating adaptive traffic light regulation were analysed. Methods for processing three-dimensional point clouds for segmentation and classification of traffic objects were applied. Methods of mathematical modelling of traffic flows were also used considering statistical data and elements of mathematical training.

Contemporary approaches to optimising traffic light regulation and using LiDAR in transport systems

The task of optimising the time parameters of traffic lights has been in the focus of attention of the scientific community and practitioners for several decades (Guadamuz *et al.*, 2022). The first approaches were based on the use of simple traffic light control schemes with fixed intervals, which were formed based on pre-defined traffic flow models and observation results, or forecasting algorithms (Lv *et al.*, 2015; Ma *et al.*, 2015). Further complexity and branching of the transport network contributed to the transition to more complex optimisation methods, including signal management systems with activation in the presence of vehicles, traffic-oriented regulation, and adaptive traffic light systems. These approaches provide for dynamic adjustment of the duration of signal phases in accordance with current traffic conditions, which reduced delays and increased the efficiency of the functioning of intersections, were investigated by C. Gartner *et al.* (2025). Historically, the calculation of turning manoeuvres of vehicles at intersections was carried out mainly using manual methods, in particular, visual observations, manual counting, and analysis of video recordings, and other approaches, for example, the use of "research" vehicles (Waddell *et al.*, 2020; Mahmud & Day, 2023). Despite the fact that such approaches allow getting useful information, they were characterised by a significant expenditure of time and resources, and a high probability of errors, including those related to the human factor. F. Viadero-Monasterio *et al.* (2024), J. Enayati *et al.* (2024), K. Deng *et al.* (2025) described various technological solutions that were used to automate the information collection process, in particular, induction loop detectors and radar sensors. Machine vision systems are also of great importance (Buch *et al.*, 2011). However, these tools have a number of limitations, including insufficient accuracy, dependence on weather and light conditions, and the complexity of maintenance. In this regard, there is still an urgent need to introduce more reliable and highly accurate methods for collecting data on turning movements of vehicles at intersections.

E. Saldivar-Carranza *et al.* (2024) presented a system study based on the use of data from LiDAR sensors as the main source of information. This ensures accurate tracking of the trajectory of objects, correct detection of turns, and independence from lighting. The main focus of the study was on analysing the flow that performs turning manoeuvres and dangerous manoeuvres. The paper described the sequence of operation of the system: data collection, point cloud processing, tracking, data calculation, optimisation of traffic lights. The implementation of the mathematical model and the results of adaptive control (after experimental research and statistical analysis of the results obtained) were presented. As a result, the researchers emphasised that the delay time and queue length were reduced, and the traffic flow capacity was increased. However, given that the study was performed at a limited number of intersections in specific conditions, the question arises of generalising the results. In addition, a detailed analysis of the impact of weather conditions (rain, fog, snow) on LiDAR operation was carried out. The presented system does not have a full assessment of the operation of a combination of several different systems (camera/radar/LiDAR), since LiDAR sensors are not often used without additional functional components.

The paper by A. Ansariyar (2023) presented a study of time distribution using two LiDAR sensors and simulations using OpenCV-based video analysis. The described approach is economically accessible and scalable. The presented algorithm can detect vehicles, track them, and count them (when crossing the control line). The algorithm includes: background selection, background detailing, tracking, and calculations. It uses classical methods of machine vision: Gaussian background subtraction, Canny boundary determination, feature matching. The video stream is processed frame-by-frame and can be used in monitoring systems. The algorithm presented here is designed to measure traffic intensity and provide basic traffic analytics; it is inexpensive and straightforward to implement. However, the disadvantage of this approach to organising the system is a typical weakness of the classic OpenCV approach, i.e., errors in poor lighting, shadows, overlapping objects, rain/fog. This can lead to "loss" of objects, duplication of calculations, and errors when crossing the control line. The information obtained is not sufficient to optimise the operation of traffic lights, because the system records only traffic and does not analyse the type of vehicle and its trajectory (for example, turns).

L. Yang & R. Guo (2024) presented a study of short-term traffic forecasting using a model that smooths out noise in traffic data and predicts time series (SG-LSTM). The use of Particle Swarm Optimisation (PSO) described by them should minimise time delays, reduce queues, and increase throughput. The PSO algorithm is easy to implement and allows quickly finding optimal solutions. Compared to other studies, L. Yang & R. Guo presented a combined approach (forecasting together with optimisation), which significantly improves the efficiency of the system. This approach ensures that the system adapts to changes in traffic during peak hours and when traffic intensity increases/decreases. However, the operation of this algorithm depends on the quality of the current data, and in cases where the data is incomplete or "noisy", the forecast may deteriorate and optimisation becomes less effective. In addition, LSTM requires a large amount of data and does not work well in emergency situations. Computing large amounts of data and then optimising it usually requires large resources, such as using a neural network. PSO does not guarantee overall optimisation, as it can get "stuck" in local solutions, and the results depend on the algorithm parameters. The algorithm does not take into consideration pedestrians and emergencies.

The study by A. Çıldır *et al.* (2023) was devoted to the development of an algorithm for optimal control of traffic lights to minimise traffic delays at intersections. The researchers proposed an algorithm that: analyses the traffic flow; determines the optimal parameters of the traffic light; changes the phase duration, green time, and signal cycle. Mathematical optimisation of the delay considers the traffic intensity, the distribution of flows in directions, the structure of traffic light phases, and the capacity of lanes. The mathematical approach allows using formalised models and the possibility of analytical calculation. The algorithm requires only a basic set of traffic data and can be implemented in existing traffic light systems without using complex sensors. However, the algorithm shows that it is partially adaptive and has a weak response to traffic changes and accidents. In other words, the presented model is simplified and does not consider complex driver behaviour and randomness. The effectiveness of the algorithm results depends on the accuracy of the input data. W. Zeng *et al.* (2022) presented a study on optimising traffic light timing using traffic flow modelling. According to the presented algorithm: a mathematical model of traffic at an intersection is constructed (based on collecting or setting traffic parameters, forming an intersection model); the cycle duration, green time distribution, and signal phasing are optimised; the result is checked through simulation modelling. The described mathematical modelling allows testing various scenarios of traffic intensity and operating modes. This algorithm is well suited for engineering tasks. However, it is known that real traffic is more complex than a model in which some events or behaviours may not be considered. The algorithm also lacks real-time adaptability, meaning that if optimisation is performed, it is offline and does not respond instantly to changes. In addition, the model does not consider all types of road users (pedestrians, cyclists). The modelling accuracy depends on the input data, and as the volume of this data increases, the complexity of modelling also increases. Therefore, it is difficult to apply the presented algorithm to a large number of intersections and coordinate between them.

Available scientific research on traffic light regulation optimisation at intersections covers a wide range of methods and algorithms, in particular, mathematical optimisation methods, simulation modelling, and machine learning algorithms (Zeng *et al.*, 2022; Yang & Guo, 2024). The main goal of these studies is to improve the intervals of traffic lights in order to increase the capacity of intersections, reduce traffic delays, and improve overall traffic efficiency. Most of the proposed methods are based on simplified traffic flow models or the use of aggregated data, which does not always adequately reflect the complex dynamics of real traffic. This raises the question of obtaining detailed data on the functioning of intersections, in particular, information on return flows obtained using LiDAR sensors, in order to improve the accuracy of traffic light optimisation algorithms and improve the operational performance of intersections. V. Bandaru *et al.* (2021) described the TScan system, a conditionally stationary LiDAR platform for monitoring traffic flows and analysing road safety. This paper proposed methods for automatic detection, classification, and tracking of vehicles based on 3D point cloud data. It was shown that conditionally stationary LiDAR platforms provide high-precision formulation of vehicle trajectories and facilitate effective analysis of conflict situations and traffic flow parameters in real time.

Despite the existing achievements in the field of automation of traffic light regulation and intersection management, the analysis of open scientific literature indicates the presence of a number of unresolved issues and limitations. In particular, the main problems include: an insufficient number of studies devoted to the direct use of LiDAR sensors for calculating return traffic flows and optimising traffic light control modes; the lack of holistic and unified methodologies for integrating data obtained using LiDAR in the traffic light optimisation model; the complexity of practical implementation of adaptive strategies for controlling traffic lights in real time using LiDAR data; the need for thorough validation and evaluation of the proposed approaches based on real experiments and comparative analysis with conventional methods. Overcoming these gaps and limitations will contribute to the further development of methods for optimising traffic light regulation at intersections and the development of more effective and efficient urban traffic management strategies.

Application of LiDAR technologies for monitoring traffic flows

The expansion of LiDAR technology is conditioned by the ability to form detailed three-dimensional point clouds that reflect the spatial characteristics of the environment. A number of academic papers have examined the use of LiDAR sensors to address various transport-related problems, including the detection and classification of vehicles, the estimation of their speed, and the analysis of the structure and intensity of traffic flows. Thus, T. Raj *et al.* (2020) reviewed the main scanning mechanisms of LiDAR systems used in intelligent transport systems and autonomous transport. The researchers compared mechanical MEMS-based flash memory and optical phased array LiDAR architectures based on scanning speed, spatial resolution, field of view, and reliability criteria. It was shown that the development of advanced LiDAR systems is aimed at moving to solid-state technologies that can provide high-precision 3D perception of the road environment in real time. The main advantages of LiDAR sensors are the contactless and unobtrusive nature of data collection, high measurement accuracy and versatility in use, which makes them suitable for monitoring intersections and obtaining detailed traffic information. The number of studies devoted to the direct use of LiDAR for calculating turning manoeuvres and optimising traffic light control modes remains limited. O. Kilani *et al.* (2021) presented one of the options for using mobile LiDAR data to assess visibility at urban intersections. The researchers proposed a method for spatial analysis of the coverage space based on 3D point clouds, which helps to automatically identify areas of limited visibility and potentially dangerous sections of road infrastructure.

Research shows that to ensure the adaptability of the system, it is advisable to use stationary LiDAR sensors that are installed at key points to provide comprehensive coverage of both the intersection and the area of approaches to the intersection. The location of sensors is determined considering the geometry of the intersection, the number of traffic lanes, the presence of pedestrian crossings, and potential traffic jams. Thus, A. Emtenan & C. Day (2020) and E. Saldivar-Carranza *et al.* (2024) argued that the effectiveness of vehicle tracking systems significantly depends not only on the type and characteristics of LiDAR sensors, but also on their spatial location. They offer a method for optimal sensor placement, which should ensure maximum coverage of the road zone (minimise “blind spots”) and stable detection of vehicles. They considered the LiDAR sensor not as an autonomous local sensor, but as part of an intelligent road infrastructure, Vehicle-to-Infrastructure, and a cooperative intelligent transportation system. The researchers proposed a mathematical and geometric model for determining the optimal height of the LiDAR sensor installation, the optimal viewing angle, and the area of intersection monitoring coverage. Each sensor is calibrated to match the coordinate system with the global crosshair reference system. This is a prerequisite for minimising blind spots. A single time system is used to synchronise timestamps, which allows correctly combining data from multiple sensors.

Figure 1 shows the algorithm of the method of using LiDAR sensors and data from them to adjust and optimise the timing of traffic light objects at an intersection (or group of intersections). LiDAR sensors are used to detect and track individual vehicles approaching, entering, and exiting intersections, and pedestrian traffic near and at crosswalks. Figure 1 shows that the obtained LiDAR data in the form of a three-dimensional point cloud goes through several processing stages – noise filtering, sensor offset correction, and point cloud alignment, which ensures accurate reflection of the spatial configuration of intersections, removal of static objects (buildings, pillars, road signs), segmentation of moving objects, and point clustering to form individual vehicles. To ensure the integrity and accuracy of the collected data, quality control procedures are applied, including checking sensor calibration, evaluating the completeness of data sets, and comparing them with available real-world observations or reference data (if available). Space-time smoothing algorithms are used to reduce the impact of weather conditions and random errors.

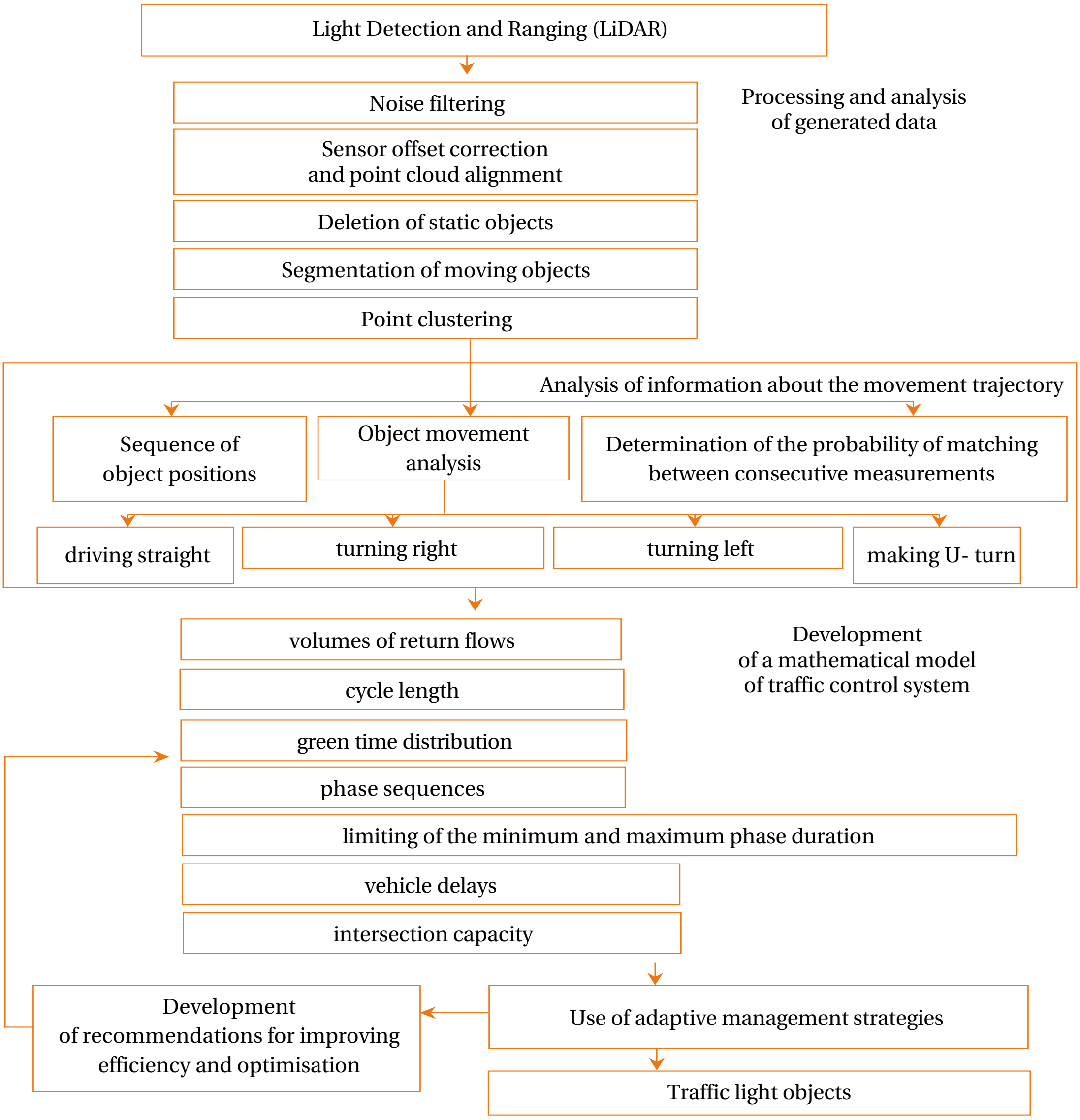

Figure 1. Algorithm for applying LiDAR technologies to optimise automated traffic management at intersections
Source: compiled by the authors

Segmented point cloud clusters are classified as vehicles or pedestrians based on geometric characteristics (dimensions, height, shape) and kinematic parameters (speed, direction of travel). In the study by X. Xu *et al.* (2022), segmentation of LiDAR point clouds was considered as a key stage in the operation of SLAM systems with combining data from multiple sensors. The researchers noted that LiDAR spatial points are grouped into clusters to highlight geometric features of the environment, in particular, planes, contours, and individual objects. For this purpose, both classical clustering methods and deep learning methods for semantic segmentation were used. Dedicated clusters were used for localisation, mapping, object tracking, and road scene analysis tasks. Thus, for example, H. Zhou *et al.* (2020) proposed a method for semantic segmentation of a point cloud based on a cylindrical representation of space. The researchers performed spatial clustering of points by cylindrical voxelisation, which enabled more efficient grouping of LiDAR points in road scenes. Based on the generated voxel clusters, the neural network performs semantic segmentation of vehicles, pedestrians, and other road objects.

Another approach was presented by J. Zhang *et al.* (2026), who divided the algorithm of work into: collection of LiDAR data (fixing point clouds, determining spatial coordinates, collecting information about intensity), scene processing (segmentation, object detection, clustering, tracking), situation interpretation (analysis of traffic flows; definition of conflict situations, behavioural analysis, anomaly detection). To track trajectories, as a rule, a multi-step tracking algorithm was used, which considered the sequence of changes in the position of an object, predicting its further movement, and the probability of correspondence between consecutive measurements. This allows accurately reconstructing the mathematical model of the trajectory of vehicles passing through intersections, and the direction of movement of pedestrians. This approach was described by X. Weng *et al.* (2020), who presented an approach to 3D tracking of multiple objects based on LiDAR data, in which vehicle tracking was performed by combining traffic forecasting and establishing correspondence between consecutive observations. The researchers used the Kalman filter to estimate the future position of objects and the Hungarian algorithm to link 3D bounding rectangles between frames. The effectiveness of multi-step tracking for formulating stable vehicle trajectories in a dynamic road environment was shown.

After determining the trajectories, each vehicle is classified according to the type of manoeuvre, such as driving straight ahead, turning right or left, or making a U-turn (where applicable). Classification is based on the analysis of changes in the angle of the trajectory and its spatial position relative to the intersection geometry. Rotational movements are counted within the specified time limits. The length of queues is determined based on the spatial distribution of vehicles within a given LiDAR scanning area. J. Zhao *et al.* (2019) presented the concept of queue estimation, which is implemented through point cloud segmentation, vehicle clustering, trajectory tracking; spatial fill analysis. In other words, the queue length is determined based on the spatial position and accumulation of vehicles in the stationary LiDAR observation area. The study by S. Cao *et al.* (2021) proposed the concept of an intelligent multimodal traffic monitoring system. Such a concept is presented as a system that must simultaneously perceive different types of objects, analyse their interaction, and form a high-precision digital representation of the road scene. When analysing multimodal interactions, particular attention is paid to the dynamics between cars, pedestrians, and cyclists. The system considers “conflict zones”, road crossing behaviour, and dangerous interactions.

Optimisation of traffic light regulation based on LiDAR data

The obtained values of traffic intensity and cornering distribution are used as input parameters to describe a mathematical model for optimising traffic light regulation. In modern traffic light control systems, various mathematical optimisation models are used, which are aimed at minimising delays. The classic Webster method is based on the analytical determination of the optimal duration of the traffic light control cycle and phase distribution, considering the intensity of traffic flows (Zhang *et al.*, 2021; Liang *et al.*, 2024). The TRANSYT model is designed to optimise the operation of a group of interconnected traffic light objects by minimising delays and the number of vehicle stops in the network (Qadri *et al.*, 2020; Kim *et al.*, 2023). The MAXBAND method provides coordination of traffic light regulation by maximising the “green wave” and creating the largest possible lane of continuous traffic flows in two directions (Dai *et al.*, 2016; Lan *et al.*, 2026). Simultaneously, contemporary adaptive intelligent transport systems use methods of dynamic programming, optimisation with a moving horizon, maximum load regulation, and reinforcement learning. Most optimisation models consider the spatial and temporal distribution of traffic flows, queue parameters, and real-time traffic state forecasting. Such integration involves the creation of mathematical optimisation models that consider: the volume of return flows; cycle length; distribution of green time; phase sequences; limiting the minimum and maximum duration of phases; vehicle delays; intersection throughput. In addition, machine learning techniques can be used to identify permanent patterns based on historical data and dynamically adjust the signal timing in response to changes in traffic conditions. For example, J. Ugirumurera *et al.* (2023) proposed a method for predicting traffic light regulation parameters based on the analysis of mobile vehicle data using machine learning algorithms. The researchers showed that vehicle trajectory data can be used to estimate cycle duration, red zone time, and other signal synchronisation parameters without direct access to traffic light controllers. The paper uses XGBoost and neural networks to analyse transport trajectories and identify patterns of traffic light phases.

An interesting approach using machine learning was presented in the paper by S. Eteifa *et al.* (2021), who proposed a method for predicting phase change moments coordinated by adaptive traffic lights using a neural network. It was shown that deep recurrent neural networks can effectively model time dependencies in traffic light intersections and predict future signal changes based on historical transport data. The methodology was focused on the use of connected mobile vehicle systems and intelligent transport systems. Existing interval parameters of signals at the intersection are estimated based on models created as a result of real observations of traffic and the volume of return flows. The analysis showed inefficiencies in signal phasing and time distribution between phases, which leads to a decrease in the “performance” of intersections and an increase in vehicle delays. Potential optimisation areas were identified, in particular, adjusting the duration of signal cycles, green light time, and phase sequence. This allows increasing the efficiency of the intersection and reducing traffic jams.

Statistical methods are usually used to process calculations of rotational movements and traffic flow data, in particular, regression analysis and hypothesis testing. This approach allows identifying correlations, patterns, and statistically significant effects. Data analysis shows that the LiDAR-based system provides high accuracy in determining vehicle trajectories and classifying turning manoeuvres. Thus, for example, in comparison with conventional methods of data collection (manual calculations, inductive loops, video surveillance, etc.), the LiDAR-based method demonstrates: higher stability of data acquisition; reduced error in object classification; better identification of complex manoeuvres (in particular, left turns in a dense flow); accuracy and reliability of the received information. The system is capable of operating in conditions of varying traffic intensity, including peak periods. It was determined that an integrated approach to data collection and analysis using LiDAR contributes to understanding the dynamics of object movement at intersections, optimising the duration of signals, and improving the overall efficiency of traffic flow in the urban environment. Calculations of the number of turning manoeuvres obtained using LiDAR sensors are integrated into the optimisation algorithm to form informed decisions on traffic light synchronisation. The model incorporates observed volumes of turning movements, the distribution of directions, and the temporal variations in traffic flows. Based on the use of real-time traffic data, the algorithm can dynamically adjust the duration of signals, which allows adapting to changing traffic conditions and minimising delays at the intersection.

During traffic signal optimisation, several key parameters and constraints are considered: the geometry and configuration of the intersection, including lane layout restrictions, prohibited turning movements, and the presence of pedestrian crossings; traffic flow characteristics, reflecting traffic volumes, vehicle arrival rates, and traffic composition (e.g., passenger cars, lorries, and bicycles), which enable realistic modelling of traffic dynamics; signal timing constraints, including minimum and maximum green times, cycle lengths, and phase sequences to ensure technical feasibility and compliance with traffic regulations; and coordination with adjacent intersections, whereby signal synchronisation with neighbouring intersections is considered to optimise capacity and improve traffic flow along arterial corridors. Sensitivity analysis is performed to assess the impact of parameter variations and uncertainties on the performance of the optimisation algorithm. This analysis allows identifying critical parameters and assessing their impact on the results of synchronisation of traffic light signals. Reliability testing is necessary to determine the stability of the algorithm to changes in traffic conditions, sensor failures, or interruptions in communication systems. In the future, after applying the optimised time parameters of the signals, it is necessary to constantly monitor and collect data to evaluate the effectiveness of changes. LiDAR sensors continuously record turning movements at intersections, providing real-time feedback on traffic dynamics and intersection performance. Video cameras or other monitoring systems may be used to supplement LiDAR data, thereby providing additional information about events at the intersection and improving the accuracy of assessments of the effectiveness of the optimisation strategies implemented.

The expected efficiency of optimised signal timings is estimated by several key indicators, such as: reducing the average delay time of vehicles at the intersection; reducing the length of queues of traffic flows, especially during peak hours; increasing the number of vehicles crossing the intersection per unit of time; increasing throughput (reducing the total time of movement of vehicles through the intersection); more uniform load distribution between phases; reducing emissions of harmful substances into the environment and fuel consumption due to increased efficiency of traffic flow. Optimisation will allow using the available green time more efficiently and reducing capacity losses due to inconsistent phases.

Conclusions

The research presented in this paper was devoted to the topical issue of improving the efficiency of the functioning of transport intersections by improving approaches to optimising traffic light regulation. The analysis of scientific publications showed that most of the existing optimisation methods are based on aggregated or limited information content, which significantly reduces the efficiency of decision-making, especially in complex and dynamic situations. In the course of the study, the expediency of using LiDAR technologies as a source of three-dimensional space-time information about the movement of vehicles, pedestrians, and other road users was substantiated. It was shown that the use of three-dimensional point clouds enables high-precision detection, tracking, and classification of objects. This, in turn, creates prerequisites for the correct determination of both the usual intersection and turning manoeuvres, and the assessment of the intensity of traffic flows and the development of an expanded set of parameters necessary for optimising the control of traffic light objects.

A comprehensive approach to LiDAR data processing was proposed, which included stages of noise filtering, point cloud alignment, segmentation of moving objects, clustering, multi-step tracking, and vehicle classification by manoeuvre type. Based on the results obtained, “direct” and “return” traffic flows were calculated, the length of queues was estimated, and other characteristics of the transport process were determined. This detailed data allowed moving from simplified models to a more detailed description of the actual dynamics of traffic at intersections. It was established that the integration of the obtained parameters into mathematical models of traffic light regulation optimisation provided the possibility of adaptive adjustment of the time characteristics of signals based on current traffic conditions. In particular, consideration the volume of return flows, intersection geometry, phase constraints, and variations in traffic intensity helps to more reasonably determine the cycle duration, green time distribution, and phase sequence. This allows increasing the capacity of intersections, reducing vehicle delays, and optimising the use of existing infrastructure.

An analysis of data collection methods has shown that the revised approach is characterised by the stability and informativeness of its results. In particular, it provided identification of complex manoeuvres (including left turns in dense traffic), reduced the probability of counting errors, and improved the quality of output data for optimisation algorithms. This substantiates the feasibility of using LiDAR as a basic technology for building contemporary traffic monitoring and management systems. However, a number of limitations and areas for further research have been identified. In particular, additional study is required into the impact of weather conditions on the quality of data obtained from LiDAR sensors, ensuring the system's resilience to sensor and data transmission channel failures, and the integration of LiDAR with other data sources (video, radar systems). The investigation of these issues is necessary to improve the reliability and completeness of observations. An important task is also to scale the proposed approach to a network of interconnected intersections and validate it in real-world operation conditions. The results obtained indicate a significant potential for using LiDAR technologies in the tasks of optimising automated traffic management. The proposed approach lays the foundations for the development of a new generation of intelligent traffic management systems capable of enhancing the efficiency of the urban road network, improving road user safety, and reducing the negative impact of transport on the environment.

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Дослідження методу застосування LiDAR-технологій для оптимізації автоматичного керування транспортним потоком

Ярослав Корпань
Кандидат технічних наук, доцент
Черкаський державний технологічний університет
18006, бульв. Т. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0002-1455-5977

Євген Федоров
Доктор технічних наук, професор
Черкаський державний технологічний університет
18006, бульв. Т. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0003-3841-7373

Тетяна Уткіна
Кандидат технічних наук, доцент
Черкаський державний технологічний університет
18006, бульв. Т. Шевченка, 460, м. Черкаси, Україна
https://orcid.org/0000-0002-6614-4133

Анотація. Робота присвячена дослідженню актуального питання, яке зумовлене необхідністю підвищення ефективності керування міським дорожнім рухом шляхом використання сучасних технологій. Метою роботи було дослідження підходу до оптимізації режимів роботи світлофорів на перехрестях на основі даних про транспортні потоки, отриманих із застосуванням датчиків Light Detection and Ranging (LiDAR), для підвищення ефективності дорожнього руху та зменшення затримок. В роботі представлено опис методу використання датчиків LiDAR для підрахунку поворотних потоків на перехрестях та подальшої оптимізації режимів роботи світлофорів на основі отриманих даних. При досліджені було встановлено, що для коректної роботи метод повинен включати наступні етапи: розміщення датчиків LiDAR у ключових точках перехрестя з метою отримання тривимірних хмар точок, що відображають динаміку транспортного потоку; обробка та аналіз згенерованих датчиком даних (застосовуються сучасні методи обробки даних, зокрема алгоритми сегментації хмар точок та розпізнавання об'єктів); проведення аналізу інформації про траєкторії руху об'єкту (зокрема для виділення та підрахунку поворотних потоків із первинних LiDAR-даних); формування математичної моделі системи керування рухом; використання адаптивних стратегій керування для формування оптимізованих режимів роботи світлофорів; розробка рекомендацій щодо підвищення ефективності та оптимізації на основі методів статистичного аналізу та машинного навчання для виявлення стійких закономірностей і часових тенденцій у структурі транспортного руху; здійснення керування світлофорними об'єктами. В роботі приведено узагальнені результати дослідження, які показали, що описаний метод може забезпечувати комплексний підхід та підтримку автоматичного адаптивного керування світлофорними об'єктами завдяки використанню LiDAR-технології для збору детальної інформації про поворотні рухи на перехрестях та оптимізації часу світлофорних сигналів, що в підсумку сприятиме підвищенню пропускної здатності перехресть і зменшенню заторів у міських транспортних мережах. Результати дослідження можуть бути використані органами управління дорожнім рухом та інженерами транспортної інфраструктури під час проєктування й оптимізації світлофорного регулювання на міських перехрестях

Ключові слова: датчики Light Detection and Ranging; розпізнавання об'єктів; математична модель; рух транспорту; корегування в реальному часі; машинне навчання

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