ISSN 2308-6645
e-ISSN 2523-496X

ВІСНИК
НАЦІОНАЛЬНОГО ТРАНСПОРТНОГО УНІВЕРСИТЕТУ

Том 29 | № 2 | 2025

Видавець:
Національний транспортний університет
Рік заснування: 1997

*Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного транспортного університету
(протокол № 12 від 27 листопада 2025 р.)*

**Рішення Національної ради України
з питань телебачення і радіомовлення № 2217 від 23.10.2025, протокол № 23.**

Журнал входить до категорії «Б» Переліку наукових фахових видань України у галузях
051 – Економіка (28.12.2019); 073 – Менеджмент; 113 – Прикладна математика;
131 – Прикладна механіка; 133 – Галузеве машинобудування; 274 – Автомобільний транспорт;
275 – Транспортні технології (за видами); 192 – Будівництво та цивільна інженерія;
142 – Енергетичне машинобудування; 122 – Комп’ютерні науки; 124 – Системний аналіз;
151 – Автоматизація та комп’ютерно-інтегровані технології
(наказ Міністерства освіти і науки України від 26.11.2020 №747)

**Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах**:
Національна бібліотека України імені В. І. Вернадського, Litmaps

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https://ntu-bulletin.com/uk

ISSN 2308-6645
e-ISSN 2523-496X

BULLETIN

THE NATIONAL TRANSPORT UNIVERSITY

VOL. 29 | No. 2 | 2025

Publisher:
National Transport University
Year of foundation: 1997

Recommended for printing and distribution via the Internet by the Academic Council of National Transport University. (Minutes No. 12 of November 27, 2025)

Decision of the National Council of Television and Radio Broadcasting of Ukraine No. 2217 dated 23.10.2025, Minutes No. 23.

Journal is included in the Category "B" of the List of Scientific Professional Publications of Ukraine in the following fields: 051 – Economics (28.12.2019); 073 – Management; 113 – Applied Mathematics; 131 – Applied Mechanics; 133 – Industrial Engineering; 274 – Automotive Transport; 275 – Transport Technologies (by type); 192 – Civil Engineering and Construction; 142 – Power Engineering; 122 – Computer Science; 124 – Systems Analysis; 151 – Automation and Computer-Integrated Technologies (Order of the Ministry of Education and Science of Ukraine No.747, dated 26.11.2020)

Journal is presented international scientometric databases, repositories and scientific systems:
Vernadsky National Library of Ukraine, Litmaps

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BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 28.05.2025. Revised: 19.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 330.341.1 DOI: 10.33744/2308-6645-2025-2-29-08-17

Ecological and economic assessment of enterprise sustainable development management

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Abstract. The article examined the ecological and economic management of the sustainable development of an enterprise. It considered the theoretical foundations of sustainable development as well as the practical aspects of its implementation at the enterprise level, with particular attention paid to achieving a balance between economic efficiency and environmental responsibility. The purpose of the study was to determine effective mechanisms for managing the sustainable development of enterprises through an assessment of the interrelated ecological and economic factors influencing their activities. The object of the study was the municipal transport enterprise Kyivpastrans, and the research was aimed at identifying effective mechanisms for managing its sustainable development. The relationships between the ecological and economic indicators of the enterprise's performance were analysed, key factors affecting its environmental and financial stability were identified, and the enterprise's resilience to external ecological and economic challenges was assessed. The research employed statistical and graphical methods, as well as mathematical modelling, which made it possible to quantitatively evaluate the relationships between ecological and economic characteristics and to develop proposals for their optimisation. Quantitative assessment methods were used to determine the dynamics of sustainable development indicators and to substantiate approaches to their further optimisation. The results obtained generalised the methodological foundations for improving sustainable development management in urban public transport enterprises. The interdependence between environmental and economic performance indicators was identified, enabling an assessment of enterprises' resistance to external environmental changes and their adaptability to contemporary

Suggested Citation: Bakulich, O., Samoylenko, Ye., Holodenko, V., & Hrebelnyk, M. (2025). Ecological and economic assessment of enterprise sustainable development management. *Bulletin of the National Transport University*, 29(2), 8-17. doi: 10.33744/2308-6645-2025-2-29-08-17.

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challenges. The practical significance of the study lay in the development of recommendations aimed at enhancing enterprise efficiency in accordance with the principles of sustainable development. The findings could be used as a decision-making tool in environmental and economic planning

Keywords: sustainability indicators; ecological performance; economic efficiency; urban transport enterprise; Kyivpastrans; management tools; adaptive development

Introduction

Modern urban transport enterprises operate under conditions of increasing ecological pressures, economic instability, and growing demands for service quality, which necessitates the transition to sustainable development principles. Ensuring balanced ecological and economic performance is becoming a key prerequisite for strengthening the resilience and competitiveness of transport companies in the face of contemporary challenges. In this context, the development of effective management mechanisms requires a comprehensive assessment of environmental impacts, resource efficiency, and the economic outcomes of operational activities. The municipal transport company Kyivpastrans serves as a representative example of an enterprise functioning within a complex urban environment, where sustainable development indicators directly influence both operational stability and the quality of public transportation services. The need to integrate environmental considerations into economic decision-making highlights the importance of establishing reliable diagnostic tools that reflect the interconnection between ecological and economic factors. As noted by O.O. Bakulich & I.R. Kis (2021), modern transport enterprises face escalating ecological pressures, rising operational costs, and increasing expectations for safe and efficient mobility services. These challenges are particularly acute for urban public transport systems, which must simultaneously ensure environmental responsibility, economic stability, and high service quality. As a result, the need for effective sustainable development management has become especially relevant for transport companies, where the balance between ecological impact and economic performance directly influences the reliability and resilience of urban mobility. Sustainable development of enterprises in the long term is primarily conditioned by the introduction of the experience of innovative activities of highly developed countries, and the development of advanced achievements of domestic engineering, science and technology. V. Vlasova & O. Shynkaruk (2025) investigated the theoretical and methodological foundations and contemporary tools for assessing the sustainable development of transport enterprises, analysing the advantages and disadvantages of these tools for the formulation of effective innovative strategies, taking into account environmental, social, and economic aspects. A.S. Karapysh *et al.* (2025) found that the key element of the sustainable development concept is the principle of balance between economic, social, and environmental components; however, its excessive ideologisation and insufficient systematisation complicate the practical implementation of sustainable development goals, thereby necessitating the introduction of specific applied instruments, primarily at the enterprise level. E. Širá *et al.* (2021) argued that an important condition for sustainable development is the flexibility of the management system – the ability to respond to changes by adjusting the set of managerial influences and directing the system to an equilibrium state. According to the authors, sustainable development had been implemented through the “20-20-20” approach, which included the reduction of greenhouse gas emissions, the improvement of energy efficiency, and an increase in the share of renewable energy sources in the overall energy balance. The study by F.V. Bekun *et al.* (2019) demonstrated that non-renewable energy consumption and economic growth had increased CO_2 emissions, whereas the development of renewable energy had contributed to their reduction, and an excessive reliance on natural resource rents without proper management had undermined environmental sustainability.

In the context of contemporary challenges, D. Gavrykov (2025) emphasised that digital transformation, including intelligent transport systems, big data, the Internet of Things and other advanced technologies, had constituted a critical pathway towards achieving sustainability in transport enterprises. The integration of digitalisation had expanded the scope of sustainability assessment beyond traditional economic and environmental indicators by recognising operational efficiency, resource optimisation and transparency as integral components of sustainable development. The review by D. Burchart & I. Przytuła (2024) of the transport sector’s life-cycle sustainability assessment (LCSA) methods highlighted that comprehensive evaluation must integrate long-term environmental impacts, resource consumption, emissions, infrastructure lifecycle, and social outcomes – not only operational performance. This is significant because many conventional assessment methods, including enterprise-level indices, had tended to omit life-cycle impacts, thereby underestimating the actual ecological costs and the long-term risks to sustainability. A. Rossolov & S. Lyfenko (2021) assessed sustainability performance of the transport sector across European countries provides a broader context: it identifies structural challenges in reducing dependence on fossil fuels and meeting emissions targets, while recognising the need for harmonised sustainability indicators across nations for policy benchmarking. For a municipal operator like Kyivpastrans, such macro-level insights underline the importance of aligning enterprise-level sustainability efforts with wider sectoral and regulatory trends. A mixed-method investigation by M. Soufiemami (2022) examined social inclusivity and accessibility in public transport systems, especially for disadvantaged groups (elderly, disabled, children). The research showed that sustainable transport must be socially equitable, safe, and accessible, adding an important dimension often underrepresented in enterprise-level indices. Integrating such social equity metrics may improve the social component of sustainability assessment for public transport enterprises. For municipal transport operators such as Kyivpastrans, sustainable development had constituted both a strategic objective and a practical necessity due to intensive energy use, emissions, infrastructure wear, and the obligation to provide socially essential services. Integrating ecological considerations into managerial decision-making had been essential for enhancing operational efficiency, mitigating environmental risks, and meeting contemporary standards of sustainable urban transport. Despite existing theoretical models, practical implementation at transport enterprises had often lacked systematic approaches capable of capturing the complex interactions between environmental and economic factors. The aim of the study was to investigate the processes of managing the sustainable development of an enterprise and the prospects for its activities on the basis of sustainable development, using the municipal transport company Kyivpastrans as the case study.

Materials and Methods

The methodological framework of the study had been grounded in a combination of traditional general scientific and specialised methods. Statistical methods had been employed to analyse and identify patterns in the enterprise's performance indicators, while the index method had been used to determine aggregated indicators and assess the enterprise's sustainable development. A systems approach had facilitated a comprehensive examination of the management process of sustainable development in a transport-sector enterprise as an integrated technical and socio-economic system, allowing for the identification of interrelationships among its elements. Inductive and deductive reasoning had been applied to form theoretical generalisations based on empirical data, and systematisation and classification had been used to structure the key factors and indicators of the enterprise's sustainable development. In addition, modern computer-based methods had been utilised for processing and visualising economic information. The information base of the study had comprised scientific publications by domestic and foreign scholars in the field of sustainable enterprise development management, legislative and regulatory documents governing enterprise activities, as well as statistical and financial reporting from the transport sector.

The assessment of an enterprise's sustainable development had been conducted using indicators – metrics derived from primary data – that enabled the evaluation of both the current state and the dynamics of sustainable development parameters. Two approaches had been applied in constructing the system of eco-economic indicators. The first involved the development of an integrated, aggregated indicator to assess the level of social and economic resilience, typically based on three groups of indicators: economic, environmental, and socio-economic. The second approach entailed the creation of a system of individual indicators, each reflecting specific aspects of sustainable development. These indicators had been designed to encompass economic, social, and environmental dimensions, recognising that sustainable development in an enterprise should promote economic growth while maintaining a balance with societal needs for improved quality of life and preventing environmental degradation. The use of such indicators had allowed for the quantitative measurement, monitoring, evaluation, and analysis of the pace and effectiveness of sustainable development (Table 1).

Table 1. Indicators for assessing the sustainable development of an enterprise

Indicator category	Indicators
Economic indicators	Industrial production volumes, capital investment volumes, profitability level, depreciation of fixed assets
Environmental indicators	Emissions of harmful substances into the air, discharges into water bodies, use of energy-saving technologies, expenditures on environmental protection measures
Social indicators	Number of jobs created, wage level, employee qualifications, level of workplace accidents
Risk indicators	Ability to withstand extreme external and internal pressures, quality and reliability of the enterprise's components

Source: developed by the authors based on L.M. Filipishyna (2017), O.V. Aref'yeva *et al.* (2023)

A quantitative assessment of enterprise sustainable development management was carried out based on an integrated sustainable development index, which included partial economic, environmental, and social indices and was expressed as:

$$I_{sd} = \frac{1}{m+n+k}\left(\sum_{j=1}^{m} I_j^{econ} + \sum_{j=1}^{n} I_j^{ecol} + \sum_{j=1}^{k} I_j^{soc}\right), \quad (1)$$

where I_j^{econ}, I_j^{ecol}, I_j^{soc} – indicators that respectively characterise the economic, environmental, and social components of an enterprise's sustainable development; m, n, k – the number of indicators used to determine the partial indices.

The economic components of an enterprise's sustainable development refer to the state of its economic system, determined by indicators such as industrial production volumes, capital investment volumes, profitability levels, and depreciation rates of fixed assets. The environmental component of sustainable development represents the enterprise's impact on the environment. Key indicators include emissions of harmful substances into the air, discharges into water bodies, the use of energy-saving technologies, and expenditures on environmental protection measures. The social prerequisites for sustainable enterprise development encompass the state, indicators, and patterns of social sphere development. This group includes indicators such as the number of jobs created, wage levels, employee qualification levels, and workplace injury rates. Considering that all indicators and parameters forming the indices are part of the model, are measured using different physical units, have varying interpretations, fluctuate within different ranges, and exhibit different directional influences, it is necessary to standardise them using the following formulas. If indicator X_j has a direct correlation with the corresponding index (i.e., when the indicator increases, the corresponding index also increases), its standardised value is calculated as:

$$I_j = \frac{x_j - x_{min}}{x_{max} - x_{min}}, \tag{2}$$

where X_{max} and X_{min} – the maximum and minimum values of the corresponding indicator.

If the indicator X_j has an inverse relationship with the corresponding index (i.e., when the indicator increases, the corresponding index decreases), its standardised value is determined as:

$$I_j = 1 - \frac{x_j - x_{min}}{x_{max} - x_{min}}, \tag{3}$$

Such normalisation ensures the unidirectionality of the partial indices, with their values ranging from 0 to 1. The poorest indicator values in terms of sustainable development correspond to numerical values close to 0, whereas the best approach 1. The assessment of an enterprise's sustainable development involves calculating an integrated index based on the partial indicators of sustainable development. This process includes selecting and systematising the enterprise's statistical performance indicators, followed by the calculation and normalisation of the relative indicators (Širá *et al.*, 2021). An index is a set of aggregated or weighted indicators or factors, while an indicator is a measurable or observable characteristic. Based on the normalised values of partial indicators grouped into categories – social development, economic, and environmental – partial indices are then calculated.

Results and Discussion

The process of managing the sustainable development of an enterprise is based on a management system that allows a comprehensive, holistic approach to the interaction of various subsystems involved in management processes. The enterprise management system is considered as a set of management areas (marketing, finance, human resources management, etc.) or management functions (planning, organisation, motivation and control) (Filipishyna, 2017; Bakulich *et al.*, 2021). The enterprise sustainable development management mechanism involves the sequential execution of defined actions. When establishing the foundation for managing sustainable development, it is necessary to formulate the enterprise's goals, strategies, and management principles. The implementation of the enterprise strategy is a process of reproducing its strategic potential based on the study and consideration of internal and external factors, as well as dynamic cause-and-effect relationships between the enterprise and the external environment. The core idea of sustainable enterprise development is to find an optimal balance between socio-economic growth and resource utilisation that ensures environmental safety, does not threaten the resource availability of future generations, and guarantees the necessary quality of life and well-being of the population. Additionally, the sustainable development strategy aims to ensure the financial stability, operation, and growth of the enterprise, satisfy the interests of all stakeholders, meet employees' needs for decent working and living conditions, and establish the company's image as an environmentally and socially responsible economic entity whose activities contribute to societal development and minimise negative environmental impact. Sustainable enterprise development should be considered as its ability to conduct economic activities over a certain period under conditions of uncertainty caused by external environmental influences that disrupt normal functioning and growth. The achievement of sustainable development goals is facilitated by both external and internal environmental factors and their effective utilisation (Table 2).

Table 2. Key factors of sustainable enterprise development

External factors	Internal factors
Economic: population income growth, tax burden, labor potential, inflation reduction, unemployment reduction	Management: effective development strategy, resource management system, personnel management system, information systems and technologies
Market: market capacity and dynamics, demand level, competition level	Operational: cost structure, level of technical and technological development, asset utilisation, marketing activities
Other factors: accessibility to external markets, demographic indicators, political stability	Financial: effective investment management, liquid asset structure, reduction of financial risks

Source: developed by the authors based on L.M. Filipishyna (2017), S.M. Pylypenko (2020)

Table 2 presented the key external and internal factors that influence the sustainable development of an enterprise. External factors reflect the macro-environment in which the enterprise operates and can either enable or constrain sustainable development. For instance, economic factors such as population income growth, tax burden, inflation, and unemployment levels directly affect consumer demand and purchasing power, which in turn impacts revenue generation and investment capacity. Market factors, including market capacity, dynamics, demand, and competition, determine the potential for enterprise growth and innovation, while other factors such as accessibility to external markets, demographic trends, and political stability shape the broader operational environment and affect strategic decision-making. A favourable external environment enhances the enterprise's opportunities to implement sustainability initiatives, whereas adverse conditions may require adaptive management strategies to maintain balanced development. Internal factors constitute the enterprise's inherent potential for sustainable development. Effective management, achieved through a coherent development strategy, resource allocation, personnel administration, and advanced information systems, allows the enterprise to coordinate economic, operational, and social activities efficiently. Operational factors, including cost structure, technological advancement, asset utilisation, and marketing activities, influence the efficiency with which inputs are converted into sustainable outputs. Financial factors, encompassing investment management, liquidity, and risk mitigation, provide the financial stability necessary to support long-term development projects and strategic initiatives. The interplay between external and internal factors is crucial: while external conditions set the boundaries and create opportunities or threats, internal capabilities define the enterprise's capacity to respond, adapt, and exploit these opportunities. For Kyivpastrans, external factors such as market demand for transport services, regulatory conditions, and population mobility trends directly affect the scope and efficiency of sustainability measures. Simultaneously, internal factors, particularly the effectiveness of management systems, technological readiness, and financial stability, determine the enterprise's ability to implement environmentally friendly technologies, improve service quality, and ensure social equity in urban transport provision. Overall, the Table 2 highlighted that sustainable development results from the dynamic interaction between external influences and the enterprise's internal potential. Enterprises are required to monitor external changes continuously while simultaneously enhancing internal capabilities to achieve balanced and long-term sustainability outcomes.

The primary responsibility of Kyivpastrans is to provide public transportation services to the residents and visitors of Kyiv. Despite the current state of martial law and the challenging circumstances facing the country, the municipal enterprise continues to ensure the stable operation of the city's transport infrastructure. In 2023, compared to the previous year, transport work volumes (thousands of vehicle-kilometers) in regular service increased by 43.5%, including 31.1% for trams, 76.9% for trolleybuses, and 33.0% for buses (Fig. 1). This increase resulted from the opening of new routes and the expansion of rolling stock on existing routes. Throughout 2023, the total number of passengers transported by the company amounted to 224.5 million, which is 79.8 million more than in 2022. In regular service, 224.1 million passengers were transported, representing a 55.3% increase compared to 2022. The number of fare-paying passengers reached 101.1 million, an increase of 96.3% from 2022. The dynamics of passenger transportation indicators are presented in Figure 2.

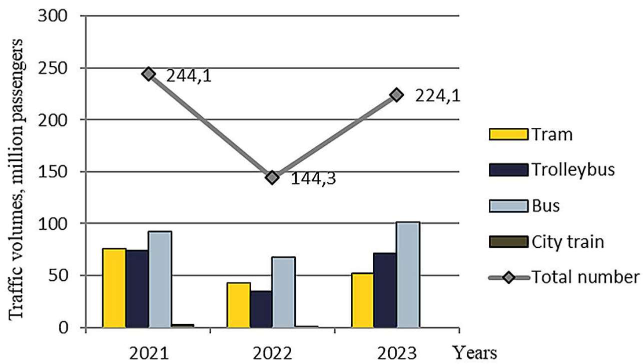

Figure 1. Dynamics of the enterprise's transport performance indicators during the period 2021-2023

Source: Kyivpastrans (2023; 2024)

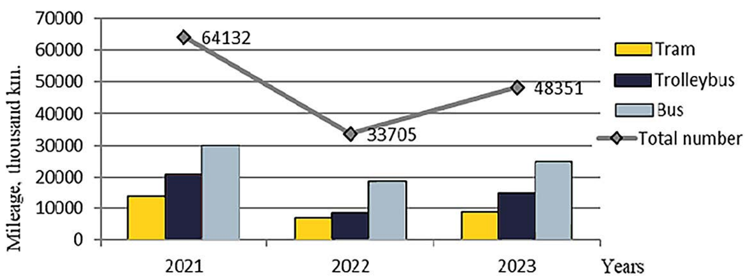

Figure 2. Dynamics of transportation volume indicators during the period 2021-2023

Source: Kyivpastrans (2023; 2024)

The analysis of passenger transportation volumes and structure at Kyivpastrans showed that buses account for the largest share – 45% of total passenger transport. When considering paid passenger transport, buses make up approximately 48%. In 2023, the company's own revenue amounted to 1,811.4 million UAH, representing an increase of 432.1 million UAH compared to the previous year. Local budget allocations in 2023 totalled 3,652.3 million UAH, an increase of 816.6 million UAH relative to 2022. Kyivpastrans's total expenditures in 2023 reached 4,686.2 million UAH, which is 900.5 million UAH higher than in 2022. The largest expenditure categories include material costs, depreciation charges, and payroll expenses. The environmental policy of Kyivpastrans is based on the principle of sustainable development, which involves economic growth while ensuring the most efficient use of natural resources, maintaining ecological stability, and preserving the environment for future generations. To support this approach, the company has planned the renewal of its fleet by replacing older buses with newer models that comply with European environmental standards and increasing the number of trolleybuses and trams, which are considered environmentally friendly transport options. The actual expenditures for implementing key environmental protection measures at Kyivpastrans are presented in Table 3.

Table 3. Enterprise expenses for environmental protection measures

No.	Environmental protection service costs	2022 (thousand UAH)	2023 (thousand UAH)
1	Water resource protection	375.3	1,754.9
2	Waste management	1,207.6	4,911.2
3	Environmental taxes	17.0	26.6

Source: Kyivpastrans (2023; 2024)

In 2023, expenses for implementing annual measures related to water resource protection, waste management, and environmental taxes significantly increased compared to 2022. At Kyivpastrans, environmental management systems are continuously updated and improved. Planned activities include the repair of gas-cleaning units for stationary sources of air emissions, efforts to reduce the generation of solid waste, and initiatives related to the disposal of hazardous waste. As of December 31, 2023, the total number of employees at Kyivpastrans is 4,448. Among them, 1,554 are women, with 141 holding managerial positions. The structural dynamics of the company's workforce in recent years are illustrated in Figure 3.

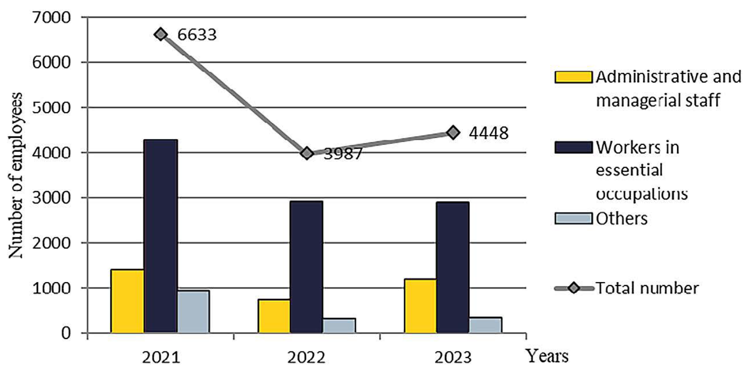

Figure 3. Structural dynamics of the enterprise's employees during the period 2021-2023
Source: Kyivpastrans (2023; 2024)

The assessment of the enterprise's sustainable development involves determining the integrated index based on the calculation of partial indices of sustainable development. This includes the selection and systematisation of the enterprise's statistical indicators, the calculation of their relative indicators, normalisation, and the determination of partial sustainable development indices for Kyivpastrans. The sustainable development assessment of the enterprise is carried out using an index formed based on the following components: economic activity development, environmental situation, and social sector development. Partial indices are calculated based on the normalised values of indicators for the identified groups. The partial index of the enterprise's economic condition is proposed to be determined using four indicators: enterprise revenue, balance profit, passenger transportation volumes, and transport work. These indicators reflect the production, economic, operational activities, and the financial situation of the enterprise. The partial index of the enterprise's environmental situation is proposed to be determined using three indicators: expenses for water resource protection, waste management expenses, and environmental taxes. Together, these provide an overview of the ecological status and the scale of environmental protection efforts. The partial index of social sector development is proposed to be calculated based on indicators such as the total number and structure of employees, and average salary. This set of measures captures the workforce structure, income distribution, and general living conditions. Figure 4 presented the model of sustainable development management implemented at Kyivpastrans.

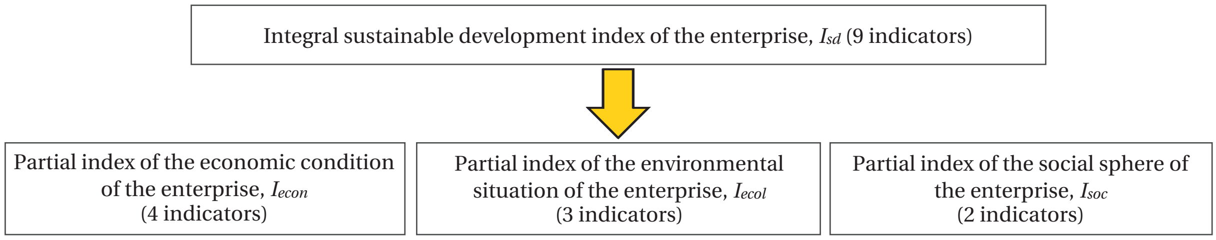

Figure 4. Sustainable development management model of the Kyivpastrans enterprise
Source: developed by the authors

Thus, the sustainable development index of the enterprise is determined as the weighted average of the three partial indices of sustainable development:

$$I_{sd} = \frac{1}{9}\left(\sum_{j=1}^{4} I_j^{econ} + \sum_{j=1}^{3} I_j^{ecol} + \sum_{j=1}^{2} I_j^{soc}\right). \qquad (4)$$

Normalisation of the studied indicators is carried out using formulas (2) and (3). The worst values of the normalised indicators, in terms of sustainable development for the enterprise, will correspond to numerical values close to 0, while the best values will approach 1. Thus, the integration of economic, social, and environmental indicators into a single sustainable development index allows for a comprehensive and balanced assessment of the enterprise's overall performance. By aggregating these three dimensions into one weighted metric, managers can identify areas of strength and weakness, track progress over time, and prioritise interventions that will have the greatest impact on sustainable growth. In practice, this approach enables enterprise leadership to make informed decisions regarding resource allocation, investment planning, and strategic initiatives, ensuring that economic efficiency, social responsibility, and environmental stewardship are considered simultaneously. The normalisation of indicators, as carried out using formulas (4), ensures comparability across diverse metrics: values closer to 1 indicate favourable conditions, whereas values near 0 highlight critical areas requiring attention. Consequently, the sustainable development index serves as both a diagnostic and strategic tool, guiding management in achieving long-term resilience and balanced enterprise development. Figure 5 illustrated the structural dynamics of the integrated sustainable development index for Kyivpastrans.

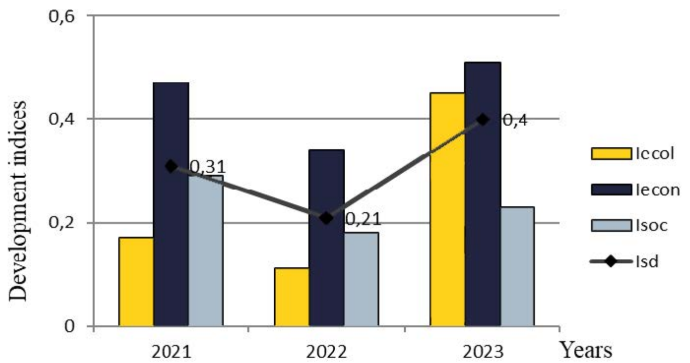

Figure 5. Dynamics of the integrated index of sustainable development of the enterprise during the period 2021-2023
Source: Kyivpastrans (2023; 2024)

It is worth noting that as of 2023, all partial indices increased compared to 2022. Notably, the environmental situation index saw a nearly fourfold increase, indicating positive dynamics in the enterprise's sustainable development. In 2022, the integrated sustainable development index of the enterprise decreased compared to 2021, but in 2023, it increased by almost twice. Thus, improving the effectiveness of activities and ensuring sustainable development at Kyivpastrans is a crucial task to provide convenient, fast, accessible, and safe public transportation. The results of the study are consistent with the findings of other authors regarding sustainable development in transport enterprises and systems. V.M. Kudriavtsev & O.V. Kudriavtseva (2023) proposed a flexible, multi-stage method tailored to transport enterprises' starting conditions. Authors differentiate between qualitative and quantitative indicators and combine them into an overall integrated index, similar to our approach. However, this framework allows enterprises to adjust the indicator set and weights depending on strategic priorities, providing flexibility that our fixed-set, expert-weighted index does not offer. For Kyivpastrans, adopting a configurable framework could enhance the adaptability of sustainability assessment, especially under changing operational conditions. A. Kwilinski *et al.* (2023) emphasised the role of digitalisation in improving environmental sustainability in the transport sector, including emissions monitoring, operational efficiency, and transparency. Compared to conducted study, which does not explicitly include digital or technological indicators, this research highlighted a future direction: integrating technological metrics into the ecological and economic assessment of Kyivpastrans could provide a more accurate picture of sustainability performance and identify digital transformation benefits. V.M. Kudriavtsev (2025) found that the sustainable development of a transport enterprise is determined by a system of interrelated economic, social, and environmental criteria, with effective income and cost management playing a key role in ensuring its stability, while the developed set of economic indicators enables a comprehensive assessment of the level of sustainable development and the identification of problematic aspects of enterprise activity.

V. Soti *et al.* (2023) developed a structural equation modelling (SEM) framework to analyse sustainability indicators for freight transportation in emerging economies. The authors grouped 16 indicators into economic, environmental, social, and risk categories, allowing the identification of latent factors and interactions. Compared to proposed in this study integral index method, SEM provided deeper insights into causal relationships between dimensions. Applying SEM to Kyivpastrans could help determine which sustainability components (economic, environmental, or social) most influence overall performance and guide targeted interventions. G.B. Suprayoga *et al.* (2020) analysed sustainability assessment indicators for road infrastructure projects, highlighting methodological challenges, such as indicator selection, weighting, and comparability. And the safest approach is to combine methods or adopt the integrated set developed to ensure exhaustive criteria inclusion. G. Boeing *et al.* (2022) developed a spatial indicator framework using open data to assess urban design and transport features for sustainable cities. Their approach situates enterprise-level operations within broader urban sustainability, considering factors such as network connectivity and accessibility. For Kyivpastrans, integrating such spatial indicators could enhance strategic planning by linking enterprise-level sustainability to city-level mobility goals. Proposed in this study integrated index aligns with the widely accepted three-dimensional framework of sustainability (economic, environmental, social), confirming its applicability for practical enterprise-level assessment. However, the aforementioned studies highlighted opportunities to refine and expand the methodology:

1) incorporating digitalisation and technological indicators;

2) applying advanced statistical models (e.g., SEM) to analyse interactions between sustainability components;

3) including life-cycle and long-term environmental impacts;

4) expanding social metrics to reflect accessibility, equity, and safety;

5) linking enterprise indicators to urban-scale spatial and transport features for strategic planning.

Thus, while proposed integral index provided a clear and practical tool for Kyivpastrans, adopting these enhancements would increase the depth, validity, and strategic value of sustainability assessments for urban transport enterprises. The development of an integrated index for Kyivpastrans was conducted in accordance with current best practices: it was context-specific rather than generic, balanced economic, environmental, and social dimensions, and remained open to future expansion (e.g., through the inclusion of digital-technological and spatial/urban indicators). At the same time, the literature indicated that no universal model existed, and that each assessment framework had to be adapted to the enterprise's operational context, data availability, strategic objectives, and external environment.

Conclusions

The study examined the principal methodological approaches to managing the sustainable development of a transport enterprise, with particular emphasis on the integrated evaluation of ecological, economic, and social performance. Using a comprehensive analytical framework, it provided a detailed assessment of the enterprise's sustainability status and identified the key factors influencing its long-term development. An in-depth analysis of the financial and economic indicators of Kyivpastrans has revealed structural imbalances in revenue generation, cost allocation, and resource efficiency, which collectively constrain the enterprise's capacity for sustainable growth. At the environmental level, the evaluation has highlighted persistent issues associated with the aging vehicle fleet, high emissions, and insufficient implementation of modern ecological practices. The social dimension of the assessment underscored both the strengths of the enterprise – such as its critical role in ensuring mobility for the urban population – and the challenges related to service quality, workforce conditions, and passenger satisfaction. To consolidate these multidimensional findings, an integral sustainability index was constructed. This index integrates three core components: the development of economic activity, the environmental situation, and the social sphere. The results demonstrated that while Kyivpastrans exhibits moderate progress in certain sustainability components, its overall sustainable development level remains constrained by environmental and financial limitations. The assessment provided a clear foundation for identifying priority areas requiring strategic intervention, including fleet modernisation, energy-efficient technologies, optimisation of financial resources, and enhanced social responsibility initiatives. The findings of this study underscored the necessity of adopting a holistic and system-based approach to sustainable development management within urban transport enterprises. Furthermore, the research highlights the importance of integrating sustainability considerations into operational decision-making to increase resilience, efficiency, and service quality. Future research should focus on developing predictive models for evaluating the long-term effects of sustainability-oriented measures at transport enterprises, expanding the methodological toolkit for assessing ecological and economic risks, and exploring digitalisation tools that support real-time monitoring of sustainability indicators. Additionally, comparative studies involving multiple transport operators could further refine the understanding of best practices and enhance the generalisability of sustainability management approaches in the urban transport sector.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Aref'yeva, O.V., Safonik, N.P., & Dudik, A.O. (2023). Strategic analysis of the development of transport enterprises under innovative trends. *Problems of Contemporary Transformations. Series: Economics and Management*, 7. doi: 10.54929/2786-5738-2023-7-04-16.

[2] Bakulich, O., Holodenko, V., & Zaiats, O. (2021). Environmental-oriented model of integrated management. *International Journal of Innovative Technologies in Economy*, 1(33). doi: 10.31435/rsglobal_ijite/30032021/7471.

[3] Bakulich, O.O., & Kis, I.R. (2021). Situational method of environmental risk management of transport industry enterprises projects in a circular economy. *Management of Development of Complex Systems*, 46, 6-11. doi: 10.32347/2412-9933.2021.46.6-11.

[4] Bekun, F.V., Alola, A.A., & Sarkodie, S.A. (2019). Toward a sustainable environment: Nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Science of The Total Environment*, 657, 1023-1029. doi: 10.1016/j.scitotenv.2018.12.104.

[5] Boeing, G., *et al.* (2022). Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. *The Lancet Global Health*, 10(6), 907-918. doi: 10.1016/S2214-109X(22)00072-9.

[6] Burchart, D., & Przytuła, I. (2024). Sustainability assessment methods for the transport sector considering the life cycle concept – a review. *Sustainability*, 16(18), article number 8148. doi: 10.3390/su16188148.

[7] Filipishyna, L.M. (2017). Integrated assessment of industrial enterprises' development stability. *Economics and Enterprise Management*, 19, 280-285.

[8] Gavrykov, D. (2025). Innovative and digital transformations as a path to sustainable development of transport complex enterprises. *International Science Journal of Management, Economics & Finance*, 4(4), 96-103. doi: 10.46299/j.isjmef.20250404.10.

[9] Gruetzmacher, S.B., Vaz, C.B., & Ferreira, Â. (2022). Sustainability performance assessment of the transport sector in European countries. *Faculty of Engineering Journal*, 104, 42-52. doi: 10.17533/udea.redin.20210742.

[10] Karapysh, A.S., Kharchenko, O.I., & Barkalova, N.O. (2025). Analysis of socio-economic provisions of sustainable development of transport enterprises. *Transport Systems and Transportation Technologies*, 29, 95-102. doi: 10.15802/tstt2025/325489.

[11] Kudriavtsev, V.M. (2025). Sustainable development of the transport enterprise: Integration of economic, social and environmental criteria. *Economics of the Transport Complex*, 45, 239-250. doi: 10.30977/ETK.2225-2304.2025.45.239.

[12] Kudriavtsev, V.M., & Kudriavtseva, O.V. (2023). Methodology for assessing the level of sustainable development of a transport enterprise. *Economics of the Transport Complex*, 42, 168-181. doi: 10.30977/ETK.2225-2304.2023.42.168.

[13] Kwilinski, A., Lyulyov, O., & Pimonenko, T. (2023). Environmental sustainability within attaining sustainable development goals: The role of digitalization and the transport sector. *Sustainability*, 15, article number 11282. doi: 10.3390/su151911282.

[14] Kyivpastrans. (2023). *Cash flow statement (direct method) for 2022*. Retrieved from https://surl.li/xsyoun.

[15] Kyivpastrans. (2024). *Cash flow statement (direct method) for 2023*. Retrieved from https://surl.lt/wligip.

[16] Pylypenko, S.M. (2020). Strategic enterprise management based on the concept of sustainable development. *Economics and Society*, 21, 79-85. doi: 10.32782/2524-0072/2019-20-47.

[17] Rossolov, A., & Lyfenko, S. (2021). Assessment of sustainable development scenarios of city transport systems under car-oriented mobility. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 4(35), 221-231. doi: 10.32515/2664-262X.2021.4(35).221-231.

[18] Šírá, E., Kotulič, R., Kravčáková Vozárová, I., & Daňová, M. (2021). Sustainable development in EU countries in the framework of the Europe 2020 strategy. *Processes*, 9(3), article number 443. doi: 10.3390/pr9030443.

[19] Soti, V., Pratap, S., Dwivedi, A., & Lakshay. (2023). A structural equation modeling framework for studying sustainable freight transportation indicators in emerging economies. *Decision Analytics Journal*, 9, article number 100337. doi: 10.1016/j.dajour.2023.100337.

[20] Soufiemami, M. (2022). *Ameliorating transport system focusing on sustainability and inclusiveness through a mixed-method research (a case study in Tehran, Iran).* Tehran: Shahid Beheshti University. doi: 10.48550/arXiv.2301.07504.

[21] Suprayoga, G.B., Bakker, M., Witte, P., & Spit, T. (2020). A systematic review of indicators to assess the sustainability of road infrastructure projects. *European Transport Research Review*, 12, article number 19. doi: 10.1186/s12544-020-0400-6.

[22] Vlasova, V., & Shynkaruk, O. (2025). Preconditions for the formation of an innovative strategy for sustainable development of transport enterprises. *Economics and Society*, 75. doi: 10.32782/2524-0072/2025-75-47.

Екологічно-економічна оцінка управління сталим розвитком підприємства

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Анотація. У статті досліджено екологічне та економічне управління сталим розвитком підприємства. Розглянуто теоретичні засади сталого розвитку, а також практичні аспекти його впровадження на рівні підприємства, з особливою увагою до досягнення балансу між економічною ефективністю та екологічною відповідальністю. Метою дослідження було визначення ефективних механізмів управління сталим розвитком підприємств через оцінку взаємопов'язаних екологічних та економічних факторів, що впливають на їхню діяльність. Об'єктом дослідження було муніципальне транспортне підприємство «Київпастранс», а мета дослідження полягала у виявленні ефективних механізмів управління його сталим розвитком. Було проаналізовано взаємозв'язки між екологічними та економічними показниками діяльності підприємства, визначено ключові фактори, що впливають на його екологічну та фінансову стабільність, а також оцінено стійкість підприємства до зовнішніх екологічних та економічних викликів. У дослідженні застосовувалися статистичні та графічні методи, а також математичне моделювання, що дозволило кількісно оцінити взаємозв'язки між екологічними та економічними характеристиками та розробити пропозиції щодо їх оптимізації. Методи кількісної оцінки використовувалися для визначення динаміки показників сталого розвитку та обґрунтування підходів до їх подальшої оптимізації. Отримані результати узагальнили методологічні засади покращення управління сталим розвитком у міських підприємствах громадського транспорту. Виявлено взаємозалежність між показниками екологічної та економічної діяльності, що дозволяє оцінити стійкість підприємств до зовнішніх змін навколишнього середовища та їхню адаптивність до сучасних викликів. Практичне значення дослідження полягає у розробці рекомендацій, спрямованих на підвищення ефективності підприємства відповідно до принципів сталого розвитку. Результати можуть використовуватися як інструмент прийняття рішень у сфері екологічного та економічного планування

Ключові слова: показники сталості; екологічна ефективність; економічна ефективність; міське транспортне підприємство; Київпастранс; інструменти управління; адаптивний розвиток

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 15.06.2025. Revised: 26.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 629.017:629.083:681.518 DOI: 10.33744/2308-6645-2025-2-29-18-29

Analysis and synthesis of functional capabilities of monitoring systems of vehicle operation processes

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Abstract. Vehicle monitoring and operational management systems constitute a key component of modern transport infrastructure. The aim of this study was to analyse and systematise the functional capabilities of vehicle operational monitoring systems. The functional features of existing vehicle monitoring systems were examined, analysed, and synthesised. The systematisation of hardware configurations within these systems was conducted using morphological analysis. The analysis and synthesis of functional capabilities were performed through the systematisation of hardware configurations in existing monitoring systems. A generalised morphological formula for an integrated vehicle monitoring system was developed, comprising five core functional elements: operator monitoring tools; vehicle condition monitoring tools; vehicle monitoring tools; infrastructure interaction monitoring tools; and information analysis and utilisation tools for end users. This formula captured twenty morphological characteristics of these functional elements, as implemented in current monitoring systems. The synthesis of permissible morphological variants enables the construction of actual system configurations and facilitates the identification of the structure and functional potential of existing monitoring systems. Existing vehicle monitoring systems were identified, and their capabilities for monitoring vehicle operation were determined. Based on an analysis of the advantages and limitations of the systems under study, appropriate conditions for their application were established, along with the level of implementation of core monitoring functions, and the potential for developing both basic and diverse system components. The practical value of this research lies in providing guidelines for optimising the design and deployment of vehicle monitoring systems to enhance operational efficiency and safety

Keywords: control; registration of parameters; technical condition; hardware; morphological formula; systematisation

Introduction

Monitoring systems for vehicles and their operation processes are an integral part of modern transport infrastructure. They allow for constant monitoring of the technical condition of the vehicle, traffic parameters and resource consumption. This increases the level of traffic safety, reduces operating costs and increases the efficiency of fleet management. The main areas of application of monitoring are the technical condition of vehicles, traffic safety, economic efficiency, environmental aspects, fleet management. The main advantages of using monitoring are:

Suggested Citation: Dobrovolskyi , O., & Navrotskyi , A. (2025). Analysis and synthesis of functional capabilities of monitoring systems of vehicle operation processes. *Bulletin of the National Transport University*, 29(2), 18-29. doi: 10.33744/2308-6645-2025-2-29-18-29.

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reducing operating costs due to route optimisation and fuel economy; increasing repair intervals due to timely detection of defects; reducing the number of accidents; the ability to predict failures and plan maintenance; increasing transparency and controllability of transport enterprises. The main limitations for their intensive further development are: the need for significant initial investments in sensors, telematics and software; the need to protect data from unauthorised access; requirements for personnel qualifications; technical complexity of integration with existing transport systems, etc. The effectiveness of vehicle monitoring systems has been demonstrated across a wide range of sectors, from urban transport to international logistics. The implementation of such systems enables the simultaneous achievement of economic, technical, and social benefits (Cordoș *et al.*, 2025). As noted by V. Mateichyk & A. Navrotskyi (2024) further development of technologies (digital twins, big data, artificial intelligence) will further increase their effectiveness and ensure the transition to the concept of "intelligent transport". Therefore, the combination of tools and technologies in the appropriate hardware support for vehicle operation monitoring systems guarantees the most reliable information and ensures their effective operation in real conditions. V. Mateichyk & A. Navrotskyi have systematised the hardware support schemes of vehicle operation monitoring systems using the morphological analysis method. The morphological analysis method consists of decomposing the system into functional elements, determining the main morphological features on which the degree of achievement of the system's functioning goals depends, and identifying the options for their implementation. According to I.V. Khudiakov (2021) the combination of individual options for all morphological features of functional elements forms a new system with its own properties and ensures the search for the most rational system scheme. Functional elements, morphological features, and options for their implementation are conventionally depicted in the form of a morphological matrix, which allows to search for all possible alternatives to solve the problem and choose the most optimal solution. It is precisely because of this that it is possible to create different options for monitoring system configurations, evaluate their advantages and disadvantages, and choose the optimal solution for specific transport operating conditions.

In the work I.V. Khudiakov *et al.* (2021) monitoring systems for vehicles and operators are considered. Modern prospects are shown for their application. However, the issues of systematisation of schemes and justification of configurations of monitoring means in the conditions of vehicle operation require further development. S. Burlaka *et al.* (2024) examined diagnostic models of vehicles that establish causal relationships between the technical condition of components and measurable diagnostic signals, in particular through structural-causal and simulation-based models, which enable the assessment of complex systems without disassembly. The authors concluded that, for effective non-intrusive vehicle diagnostics, the most appropriate approach is the application of structural-causal and simulation models employing sensitive, unambiguous, and stable diagnostic parameters. Simultaneously the study of V. Migal *et al.* (2022) demonstrated that the effectiveness of vehicle diagnostics largely depends on the intellectual capabilities of the diagnostic operator, as well as their knowledge and experience. It outlines the stages of intelligent diagnostics, discusses the advantages and limitations of organoleptic methods, and provides recommendations for training and professional development aimed at the rapid and accurate identification of 70-90% of faults. L. Görne *et al.* (2022) investigated methods of efficient data pre-processing for remote vehicle diagnostics aimed at substantially reducing the volume of transmitted data without loss of essential information. They propose a pre-processing algorithm for CAN FD (Controller Area Network Flexible Data-rate) bus data prior to the application of standard compression algorithms (e.g., LZMA2), which enables improved compression performance and, consequently, enhances the efficiency of data transmission and subsequent analysis of large-scale diagnostic datasets in cloud or backend systems for further use in analytics and machine learning. E.T. Michailidis *et al.* (2025) reviewed the integration of OBD-II (On-Board Diagnostics) with machine learning, emphasising its application in predictive maintenance, emissions monitoring, driver behaviour analysis, anomaly detection, and vehicle cybersecurity. While OBD-II provides standardised access to diagnostic and performance data under EU regulatory frameworks, machine learning extends traditional reactive approaches by enabling failure prediction, real-time anomaly detection, and fuel efficiency optimisation. The work A. Sipos (2024) is devoted to the application of monitoring information complexes in transport. However, the issues of combining means and technologies into appropriate schemes of hardware support for vehicle operation monitoring systems require development. This is what guarantees the receipt of the most reliable information and ensures their effective operation in real conditions. According to the results of the analysis of recent publications, it can be stated that the issue of developing a method for systematising schemes of hardware support for existing systems for monitoring vehicle operation processes, taking into account their functional capabilities, remains relevant. Given the results of recent research in this area, it is necessary to take into account the most significant of them for the further development of this area. Further research involves combining tools and technologies into appropriate hardware schemes for vehicle operation monitoring systems, which guarantees the receipt of the most reliable information and ensures their effective operation in real conditions. Additionally, performing an analysis and synthesis of the functional capabilities of existing vehicle operation monitoring systems will allow determining the appropriate conditions for the use and development of such systems. The goal of the study was to analyse and synthesise the functional capabilities of existing systems for monitoring vehicle operation processes. To achieve the goal, the following tasks were solved in the article:

1) to form a generalised morphological formula for a complex system for monitoring vehicle operation processes;

2) to identify existing vehicle monitoring systems with the determination of their functional capabilities;

3) based on an analysis of the advantages and disadvantages of the studied systems, to determine the appropriate conditions for their practical use and development within the scope of the generalised morphological formula for a complex vehicle monitoring system.

Materials and Methods

The study used a set of materials and methods that ensured the construction of a generalised morphological model of vehicle technical condition monitoring systems and the determination of their functional capabilities. The basis for the formation of the methodological base was the actual data obtained from the hardware of real monitoring systems, in particular from ELM327 scanners, Launch diagnostic devices, Ruptela trackers, tachographs and remote diagnostics and technical condition prediction systems. In addition, technical documentation, descriptions of the functionality of sensor channels and information models used in the practice of operating motor vehicles were used. The key method of the study was morphological analysis, which allowed the decomposition of the monitoring system into five main functional components: means of controlling the operator's actions, means of controlling the technical condition of the vehicle, means of monitoring the cargo or object of transportation, means of interaction with the infrastructure and means of processing information to support user decision-making. For each component, a set of morphological features was determined – a total of twenty characteristics that reflect possible implementation options for system elements. Based on these features, a morphological matrix was constructed, which provided a systematisation of possible configurations of monitoring systems and justification of their application in various conditions. The morphological formula of the system was formed by step-by-step coding of functional elements with the assignment of designations of the type x_{11}, x_{41}, x_{51}, x_{61} in accordance with the type of data received, the method of their collection, transmission channels and analytical processing methods. The formula was constructed according to an algorithm that provided for the selection of basic functional elements, the establishment of options for their technical implementation, verification of the logical compatibility of the combined features and further analytical interpretation of the resulting configuration. Thus, it was possible to obtain a generalised description of the monitoring system, which allows comparing different hardware solutions by the level of their functional coverage.

To assess the functional capabilities of monitoring systems, methods of comparative analysis, evaluation and criterion comparison were used. The systems were analysed for completeness of coverage of morphological features, ability to provide accurate and relevant data on the technical condition of the vehicle, integration capabilities and suitability for use in real-world conditions. In particular, it was found that ELM327 provides the minimum permissible level of functionality, while Launch diagnostic complexes are characterised by much broader capabilities for collecting and analysing information. Verification of the constructed morphological model was carried out by analysing real operational data of vehicles. For this purpose, time series of parameters recorded during engine operation, data on operator actions, arrays of diagnostic codes of the OBD system, as well as information obtained through additional and infrastructure sensors were used. Comparison of real data with the results of morphological modeling confirmed the correctness of the formed structure and its compliance with the practical capabilities of various types of monitoring systems. The logic of the study involved the sequential execution of several stages: collection and classification of source data, isolation of morphological features, construction of a generalised system formula, evaluation of functional properties of various technical solutions and verification of the model on real operational data. The use of such a methodological approach allowed to obtain a comprehensive characteristic of monitoring systems, to identify promising directions of their modernisation and to form scientifically based recommendations on the choice of the optimal configuration of hardware for various operating conditions.

Results and Discussion

Formation of a generalised morphological formula for a complex system to monitor vehicle operation processes. For an effective combination of means and technologies in the corresponding schemes of hardware support of vehicle operation monitoring systems, it is necessary to guarantee the receipt of the most reliable information and ensure the effective operation of vehicles in real conditions. To ensure the flexibility of the process of forming certain monitoring systems and systematic research of vehicle operation processes, an approach to systematising the hardware support of such systems has been developed, presented in V. Mateichyk & A. Navrotskyi (2024). Five main functional elements have been identified in the complex monitoring system:

1) means of monitoring operators;

2) means of monitoring the technical condition of vehicles;

3) means of monitoring transportation facilities;

4) means of monitoring interaction with the infrastructure;

5) means of analysing and using information by the consumer.

Reflecting individual implementation options for 20 different morphological features of these functional elements, it is possible to form a large number of valid combinations of system configurations. This method ensures that the solution will always be unique, while each configuration has its own advantages and disadvantages to meet specific needs under given operating conditions. The generalised morphological formula for a complex monitoring system is:

$$\begin{bmatrix} \left(x_{14}(x_{11}, x_{12}, x_{13}); x_{23}(x_{21}, x_{22}); x_{32}(x_{31}, x_{33})\right) \\ + \begin{pmatrix} x_{41}(x_{42}, x_{43}, x_{44}); x_{51}(x_{52}, x_{53}, x_{54}); x_{61}(x_{62}, x_{63}); \\ x_{72}(x_{71}, x_{73}, x_{74}); x_{82}(x_{81}, x_{83}) \end{pmatrix} + \\ + \begin{pmatrix} x_{91}(x_{92}, x_{93}, x_{95}); x_{10\;1}(x_{102}, x_{103}, x_{104}); \\ x_{111}(x_{112}, x_{113}, x_{114}); x_{121}(x_{122}, x_{123}, x_{124}) \end{pmatrix} \\ + \left(x_{134}; x_{143}; x_{154}((x_{152})); x_{163}(x_{161}, x_{164})\right) \\ + \left(x_{171}(x_{173}); x_{182}(x_{181}); x_{193}(x_{191}); x_{202}(x_{203})\right) \end{bmatrix}. \quad (1)$$

The variable part of the first functional element of the operator monitoring tools (driver, etc.) (x_{14}) is statistical information (x_{11}), information about the person (x_{12}) and information of a reference nature (x_{13}). This information is obtained using special equipment in the external infrastructure environment (x_{23}) and is transmitted to the consumer (operator) in the form of information variants about external networks (x_{32}), which can be applied. This is the first component of the formula (1) solution of the problem. For the second functional element (1) of the considered variant N. Penna *et al.* (2001): information is obtained and has the form of working statistical information (x_{41}), with the variable part in the components: information about the vehicle (x_{42}), information of a reference nature (x_{43}), special information statistical information (x_{11}), information about the person (x_{12}) and information of a reference nature (x_{44}). According to the method of obtaining information is obtained as for a variety of formed/received information about the technical condition of the vehicle, obtained from standard sensors and systems (x_{51}), with a variable part in the components: additional vehicle sensors (x_{52}) – installed directly on the vehicle, engine and units, a combined version (x_{53}) – when combining standard and additional sensors into one information system, special equipment in the external infrastructure environment (x_{54}). The transmitted information has the form of statistical information (x_{61}), with a variable part in the components: information about the vehicle (x_{62}), information of a reference nature (x_{63}), special information (x_{64}). All information transmitted, according to the formula solution, is processed on a carrier outside the vehicle in the infrastructure environment (x_{72}) and transmitted using external information communication networks (x_{82}). For the implementation of the third functional element of the solution (1), the approaches described by S. Storm van Leeuwen *et al.* (2004), E. Krueger *et al.* (2005), and A. Holovan *et al.* (2019) are adopted. This element corresponds to a category of information that does not include data on the condition of objects transported by the vehicle (x_{91}). This may be a type of information about the state of objects transported by the vehicle, which is not transmitted (x_{101}) to the consumer. In addition, according to the method of obtaining information – it is not received from outside the vehicle (x_{111}) by the consumer. Also, according to the method of transmitting information, it is not transmitted outside the vehicle (x_{121}) into the surrounding environment. The fourth functional element of the formula solution (1) of the problem is implemented by considering the option Y. Bai (2016): for the type of information – for which information about the parameters of the infrastructure environment is obtained on the basis of information about the parameters of the infrastructure environment (x_{132}), with a variable part in the components: statistical information (x_{131}), reference information (x_{133}), special information (x_{134}). In terms of the means of obtaining and transmitting information about the parameters of the infrastructure environment, it is transmitted from the infrastructure (x_{143}), with a variable part in the components: by means of radio, video communications (x_{141}), from the vehicle itself (x_{142}), a combined option based on a combination of all the previously mentioned options (x_{144}). Also, according to the means of obtaining and transmitting information about the parameters of the infrastructure environment, it is transmitted using special equipment in the infrastructure environment (x_{154}), with a variable part in the components: standard sensors and systems (x_{151}), additional vehicle sensors (x_{152}), a combined option (x_{153}). In addition, according to the same feature, information is transmitted in the following way – using external communication networks (x_{163}), with a variable part in the components: cable connection (x_{161}), the use of gadgets (x_{162}) and (or) special equipment in the infrastructure environment (x_{164}). The fifth functional element of the formula solution (1) of the problem is implemented by considering an option for using means of analysis and the use of information by the consumer M. Kelller (2004) and S. Eggleston *et al.* (2006): which is stored in the following way – on an external medium in an external infrastructure environment (x_{172}), for a sufficiently long observation time (x_{182}). Moreover, the level of processing of the received information for the formation of the corresponding monitoring base – has the form of structured and unstructured information. Also, the means of analysis and use of information by the consumer in terms of the level of information processing – are adapted for use by computer systems (x_{193}) of the observer (consumer, technical supervision bodies, etc.). And in terms of the level of use – they are used for control in general and/or for individual parameters of the vehicle (x_{202}), with a variable part in the components: for diagnosing the condition (x_{203}), for determining indicators of the operational efficiency of the vehicle and/or individual units (x_{205}), for predicting the condition parameters (x_{206}), for forming combined (integrated) indicators of operation (x_{207}).

Identification of existing vehicle monitoring systems. Here are some individual structural options for the hardware of existing monitoring systems for studying vehicle operation processes. ELM 327 scanner-adapter. The morphological formula of the monitoring system based on ELM 327 has the form:

$$\begin{bmatrix} (x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{54});x_{61}(x_{62},x_{63});x_{72}(x_{71});x_{82}(x_{81},x_{83})) + \\ +(x_{143};x_{154}((x_{151}));x_{163}) + (x_{172}(x_{171});x_{182}(x_{181});x_{193};x_{202}(x_{203},x_{205},x_{207})) \end{bmatrix}. \quad (2)$$

The ELM327 scanner-adapter is designed for self-diagnosis (by the operator, driver, etc.) of a vehicle by connecting to the OBD-II diagnostic connector, reading and clearing error codes, as well as real-time monitoring of various engine parameters and other systems. It works in conjunction with a smartphone or computer via Bluetooth or Wi-Fi, displaying data through special applications such as Torque, allowing car owners to independently detect and eliminate malfunctions without contacting a car service. The system provides comprehensive troubleshooting capabilities, enabling the reading of error codes from electronic control units and their subsequent clearance. It supports real-time monitoring through the display of key engine operating parameters, including engine speed, vehicle speed, fuel consumption, coolant temperature, sensor readings, and other data, depending on the specific vehicle configuration and installed software. In addition, the device may function as an on-board computer, allowing trip-related data to be tracked and stored. Certain models offer configurable settings, permitting adjustments to selected parameters, such as smoothing engine temperature indicators for steady driving conditions or activating service-related functions. Furthermore, vehicle identification is supported through the reading of the vehicle identification number (VIN) and the assessment of system readiness for diagnostic procedures. This vehicle diagnostic adapter is characterised by a relatively low cost and offers several advantages, including affordability, versatility, ease of use, broad compatibility with various vehicle models and user devices, and support for self-diagnostic functions. However, a number of limitations should also be noted. These include comparatively low build quality and durability, potential connectivity issues with certain vehicle models, limited or absent iOS support in earlier versions, the risk of overheating during operation, and possible vulnerabilities related to data security. The device is advisable to use for self-diagnosis of the car by connecting to the OBD-II connector and reading data from electronic systems using smartphone applications such as Torque or OBD Car Doctor. The adapter is compatible with most cars manufactured after 1996 (USA) and 2001 (Europe), allows to detect errors, monitor parameters in real time (fuel consumption, engine temperature), build graphs and even delete errors, which makes it a convenient and economical tool for car owners. Of the studied and analysed tools, this option is not complete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. This option is one of the least developed: the first and third functional elements are not covered, the implementation options for the second, fourth and fifth functional elements are limited.

Launch diagnostic device. The morphological formula of the Launch-based monitoring system has the form:

$$\begin{bmatrix} (x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{54});x_{61}(x_{62},x_{63});x_{72}(x_{71});x_{82}(x_{81},x_{83})) + \\ +(x_{143};x_{154}((x_{151}));x_{163}) \\ +(x_{172}(x_{171});x_{182}(x_{181});x_{193};x_{202}(x_{201},x_{203},x_{204},x_{205},x_{206},x_{207})) \end{bmatrix}. \quad (3)$$

Launch diagnostic devices are multibrand scanners and tools for computer diagnostics of cars, performing a wide range of functions, including reading and erasing error codes, viewing parameters in real time, performing service functions (coding, adaptation, actuator tests), as well as diagnosing all electronic systems of the car. These devices exhibit considerable variation in functionality, ranging from compact standalone units to advanced Android-based tablets that support modern communication protocols such as DoIP (Diagnostics over Internet Protocol) and CAN FD. Their functional scope typically includes comprehensive diagnostics of vehicle systems, encompassing the engine, transmission, ABS, airbags, immobiliser, and other electronic control units. They enable the reading and clearing of diagnostic trouble codes (DTCs) and support real-time data visualisation by displaying system parameters in both numerical and graphical formats. In addition, many devices provide access to specialised service functions, including control unit adaptation and coding, service interval resetting, and actuator testing. A further characteristic is broad multi-brand compatibility, with support for approximately 150-200 vehicle manufacturers across European, American, and Asian markets. Selected models also incorporate intelligent diagnostic features, such as automated VIN reading and system readiness assessment. Launch diagnostic devices are characterised by a high level of functionality and broad vehicle coverage, combined with an intuitive user interface and access to online support services. At the same time, certain limitations should be noted, including relatively high acquisition costs and the need for regular software updates to maintain full operational capability. The use of Launch diagnostic devices is considered most appropriate in professional automotive workshops, where comprehensive diagnostic, coding, programming, and adaptation procedures for electronic vehicle systems are required. These systems include, but are not limited to, the engine, transmission, ABS, and airbag control units. The devices enable the reading and clearing of error codes, real-time monitoring of system parameters, testing of actuators, and the execution of service-specific functions, such as key coding, diesel particulate filter (DPF) regeneration, and electronic parking brake (EPB) maintenance. This option is incomplete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first, third and fourth functional elements should be attributed to the uncovered functional elements. The second and fifth functional elements can be attributed to the insufficiently developed in this option. Although the fifth functional element has the greatest prospects in the development of diagnostics and forecasting of the technical condition of the vehicle.

Ruptela tracker (Ruptela FM-Tco4 HCV/HCV 3G). The morphological formula of the monitoring system based on the Ruptela tracker has the form:

$$\begin{bmatrix} (x_{14}(x_{11},x_{12},x_{13});x_{23}(x_{21},x_{22});x_{32}) \\ +\begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{134};x_{143};x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{173});x_{182}(x_{181});x_{193}(x_{191});x_{202}(x_{203})) \end{bmatrix}. \tag{4}$$

The Ruptela tracker is a satellite-based vehicle monitoring device that determines the location of the vehicle and transmits data to the monitoring system in real time. Ruptela devices are characterised by a reliable design, can have internal and external antennas, and are also equipped with backup batteries and functions for driver control and vehicle safety. Ruptela tracking devices provide a comprehensive set of functional capabilities for vehicle monitoring applications. The devices determine precise vehicle coordinates using GPS technology and transmit this information to a remote server for processing within the monitoring system. Data transmission is performed via cellular communication networks, while an integrated backup battery ensures continued operation for several hours in the event of a primary power supply failure. The devices support a wide range of interfaces, including 1-Wire and RS232, as well as digital and analogue inputs and outputs. Selected models additionally incorporate driving style analysis, driver identification, and fleet management functionalities. Continuous monitoring of GSM signal quality is supported, and certain configurations allow remote ignition immobilisation to enhance vehicle security. The advantages of Ruptela trackers are primarily associated with their reliability and advanced fleet management capabilities. The hardware is designed to operate under harsh conditions, with enclosures resistant to moisture, mechanical shock, and extreme temperatures. The systems enable real-time fleet monitoring, contributing to improved operational efficiency through detailed supervision of vehicle movement and status. Fuel consumption control is supported through the monitoring of fuel levels and usage patterns, which facilitates the prevention of fuel theft and the optimisation of consumption. Driving behaviour analytics, including the detection of harsh braking, rapid acceleration, and speeding events, support improvements in road safety and reductions in vehicle wear. In addition, monitoring of equipment operation allows the tracking of operating time, work cycles, and other performance indicators, which is particularly relevant for specialised vehicles and machinery. The systems also enhance theft protection by providing accurate location data to support rapid response in the event of vehicle or cargo theft. Furthermore, Ruptela offers specialised solutions tailored to the requirements of various sectors, including logistics, construction, and agriculture. Despite these advantages, several limitations should be considered. Ruptela solutions are positioned in the premium segment, resulting in relatively high equipment and service costs compared with less sophisticated alternatives. The configuration and integration of complex system architectures require the involvement of qualified personnel with appropriate technical expertise. In addition, system performance is dependent on the availability of stable mobile network coverage, which may be limited in certain regions. Ongoing software maintenance and regular updates are also required to ensure reliable operation, increasing the overall demands on system administration. The appropriate conditions for using the Ruptela tracker include installation on commercial vehicles (trucks, special equipment) for accurate location tracking, fuel consumption control, vehicle condition monitoring and cargo safety, which allows to optimise logistics and prevent abuse. Of the studied and analysed means, this option is relatively complete from the point of view of covering the functionality in the generalised morphological formula (1) of the monitoring system. However, not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first and fifth functional elements have the possibility of further development of the basic components without sufficient development of the varied components.

Tachograph. The morphological formula of the monitoring system based on the tachograph has the form:

$$\begin{bmatrix} \left(x_{14}(x_{11},x_{12},x_{13});x_{23};x_{32}(x_{31},x_{33})\right) \\ +\begin{pmatrix} x_{41}(x_{42},x_{44});x_{51};x_{61}(x_{62},x_{63},x_{64}); \\ x_{72}(x_{71});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +(x_{91};x_{10\ 1};x_{11\ 1};x_{121}) \\ +(x_{134};x_{143}(x_{142});x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{172},x_{173});x_{182}(x_{181});x_{193}(x_{191},x_{192},x_{194});x_{202}(x_{203},x_{207})) \end{bmatrix}. \quad (5)$$

A tachograph is an on-board monitoring device that records and stores data on the movement of a vehicle, as well as the driver's work and rest schedule, including the vehicle's speed, distance traveled, and working hours. Its main task is to ensure road safety by preventing driver fatigue and monitoring compliance with the rules, as well as increasing overall transportation safety. The primary purpose of a tachograph is to support the monitoring of vehicle operators through the recording of drivers' working and rest periods, thereby contributing to the prevention of fatigue, which is recognised as a significant factor in road accidents. In addition, tachographs facilitate compliance with traffic regulations by enabling the monitoring of vehicle speed and other driving parameters, helping to prevent speeding violations and associated penalties. Their use also contributes to enhanced road safety, particularly in the context of commercial freight and passenger transportation. From an organisational perspective, tachographs enable companies to monitor driver activity and operational performance, supporting the optimisation of transport processes. Functionally, tachographs provide continuous data recording by capturing and storing information on vehicle speed, distance travelled, working day start and end times, rest periods, and other traffic-related parameters. Driver identification is ensured through the use of dedicated driver cards, which allow personal data to be securely recorded. The devices support encrypted data storage within internal memory and, in the case of modern tachographs, data transmission to remote servers via integrated GPRS communication modules. Information is made accessible through built-in displays for on-screen visualisation, while thermal printing mechanisms enable the generation of hardcopy records when required. The use of tachographs offers several advantages, including improved road safety, enhanced control over driver activity and fuel usage, route optimisation, and the provision of legally valid evidence for dispute resolution and regulatory compliance. However, certain limitations must also be acknowledged. These include additional costs associated with device installation and maintenance, as well as the need to adhere to strict operational regulations, which may impose constraints on drivers' working schedules. Expedient conditions of use: it is advisable to use the tachograph on trucks with a gross weight of more than 3.5 tons and buses carrying more than 8 passengers for commercial transportation. It is also needed for regular paid transportation outside the settlement, even if the weight of the vehicle is less than 3.5 tons. This option is incomplete from the point of view of the coverage of the functionality in the generalised morphological formula (1) of the monitoring system. Not all functional elements of formula (1) in the presented system have sufficient development in the basic and varied components. The first, third and fifth functional elements can be attributed to the insufficiently developed in this option. They can mostly be implemented partially in the basic components and varied components.

System of remote monitoring and forecasting of the technical condition of the vehicle KhNADU TESA. Morphological formula of the monitoring system based on the system of remote monitoring and forecasting of the technical condition of the vehicle KhNADU TESA:

$$\begin{bmatrix} \begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63},x_{64}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{94},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{132}(x_{131},x_{133},x_{134});x_{143}(x_{141},x_{142},x_{144}); \\ x_{154}((x_{151},x_{152},x_{153}));x_{163}(x_{161},x_{162},x_{164})) \\ +(x_{172}(x_{171},x_{173},x_{174});x_{182}(x_{181},x_{183}); \\ x_{193}(x_{191},x_{192},x_{194});x_{202}(x_{201},x_{203},x_{204},x_{205},x_{206},x_{207})) \end{bmatrix}. \quad (6)$$

KhNADU TESA is a satellite monitoring system for rolling stock, which is a specialised software and hardware complex for managing commercial operation and technical operation at small motor transport enterprises. The system is founded on the concept of integrating into a unified complex, first, the full range of tasks currently faced by transport systems from both infrastructural and vehicle-related perspectives, and second, the coordinated actions required to address these tasks. It is intended to support the operational needs of small motor transport enterprises by optimising fleet performance and represents a comprehensive solution for diagnostics, control, monitoring, and life-cycle management at the vehicle operation stage. Structurally, the KhNADU TESA system comprises a telematics server with dedicated software, BN-Complex™ telematics server software, a GIS-based telematics server, and core application modules, including the "Virtual Mechanic" and "Service Fuel Eco NTU-HADI-12" software packages. In addition, the system incorporates subscriber terminals that enable data acquisition, transmission, and interaction with the central infrastructure. The functional capabilities of the KhNADU TESA system are organised into three principal groups: monitoring functions, management (control) functions, and functions related to information storage and integration with external communication networks. The monitoring functions of the KhNADU TESA system provide continuous automated determination of vehicle navigation parameters and assessment of vehicle status based on data received from telematics receivers and control sensors. These functions include monitoring the activation of sound and light signalling systems, the position of a dump truck body, the operation of attached and auxiliary equipment, temperature conditions, instances of exceeding permissible driving speeds, and fluid levels in vehicle tanks. Navigation and operational data are automatically transmitted to the enterprise at predefined time intervals, while emergency messages are generated and transmitted in response to changes in vehicle status parameters detected by sensors or control devices. In the event of external communication channel failure, navigation and status data are automatically recorded in non-volatile memory and subsequently transmitted once communication is restored. The system also supports automated monitoring of vehicle routes and schedules, generating emergency notifications in cases of deviation. Real-time tracking of selected vehicle units is enabled, accompanied by graphical visualisation of vehicle locations and parameters on vector-based electronic maps, tabular representation of location and status data, and the display of emergency alerts at the enterprise in the form of alarm windows with warning signals. The management functions of the KhNADU TESA system include the formation of control zones on electronic maps to supervise vehicle movement, as well as the control and analysis of actual vehicle mileage over specified time intervals. The system enables the transmission of dispatcher commands to vehicle actuators and supports voice communication between enterprise dispatchers, the server, and vehicle operators. All actions performed by operators are automatically logged in an event register, ensuring traceability and accountability of operational activities. Functions related to information storage and integration with external networks are implemented through the centralised storage of data in a unified database. The system provides conversion of information into formats compatible with user networks, supports data exchange with external information systems, and enables the creation of databases structured in accordance with user-defined archival formats.

The KhNADU TESA system demonstrates a number of significant advantages. It provides continuous automated monitoring of vehicle movement processes, including the assessment of operating conditions, route duration, and compliance with work schedules, as well as real-time visualisation of vehicle locations and routes on electronic maps. The system also ensures continuous automated control of technical condition parameters and preventive and corrective maintenance modes, enabling the evaluation of vehicle reliability and fuel and energy efficiency. Additional advantages include high message delivery efficiency, full confidentiality of processed and transmitted data, compatibility with cartographic information systems, and the capability to integrate customised software modules developed to address specific user requirements. Furthermore, the system is characterised by relatively low equipment costs and minimal operational expenses. At the same time, certain limitations must be acknowledged. These primarily relate to additional costs associated with the installation and maintenance of system components, as well as the requirement to comply with strict operational and maintenance regulations for life-support and monitoring subsystems responsible for supervising operator activities. With regard to conditions of use, client workstations may be deployed both within the enterprise's local network and externally via Internet-based connections. In cases where only periodic monitoring of vehicle activity is required, simplified dispatcher centre configurations can be connected to the telematics server using web technologies. In addition, the KhNADU TESA transport and telematics system is capable of integration into the architecture of intelligent transport systems. Based on the analysis of the examined solutions, this system provides a comprehensive level of functional coverage with respect to the generalised morphological formula (1) of the monitoring system. All functional elements defined by formula (1) are implemented through basic and variable components, with the exception of the first functional element related to operator monitoring. This element can be partially realised through basic components, without the development of corresponding variable components.

System of remote control and forecasting of the technical condition of the vehicle and the condition of the operators CMV. Morphological formula of the monitoring system based on the system of remote monitoring and forecasting of the technical condition of the vehicle and the condition of the operators CMV:

$$\begin{bmatrix} (x_{14}(x_{11},x_{12},x_{13});x_{23}(x_{21},x_{22});x_{32}) \\ +\begin{pmatrix} x_{41}(x_{42},x_{43},x_{44});x_{51}(x_{52},x_{53},x_{54});x_{61}(x_{62},x_{63}); \\ x_{72}(x_{71},x_{73},x_{74});x_{82}(x_{81},x_{83}) \end{pmatrix}+ \\ +\begin{pmatrix} x_{91}(x_{92},x_{93},x_{95});x_{10\ 1}(x_{10\ 2},x_{10\ 3},x_{10\ 4}); \\ x_{11\ 1}(x_{11\ 2},x_{11\ 3},x_{11\ 4});x_{121}(x_{122},x_{123},x_{124}) \end{pmatrix} \\ +(x_{134};x_{143};x_{154}((x_{152}));x_{163}(x_{161},x_{164})) \\ +(x_{171}(x_{173});x_{182}(x_{181});x_{193}(x_{191});x_{202}(x_{203})) \end{bmatrix}. \quad (7)$$

CMV works similarly to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Advantages and disadvantages: similar to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Expedient conditions of use: similar to the KhNADU TESA system, only with the possibility of deep monitoring of the operators' condition. Of the studied and analysed means, this option is the most complete from the position of covering the functionality in the generalised morphological formula (1) of the monitoring system. All functional elements of formula (1) in the presented system have development in basic and varied components. A summary of the study of the functional capabilities of existing systems for monitoring vehicle operation processes is shown in Table 1.

Table 1. Generalisation of the functional capabilities of studied vehicle operation monitoring systems

No.	Studied vehicle operation monitoring systems	Functional capabilities of studied vehicle operation monitoring systems				
		Receiving and transmitting information about operators	Receiving and transmitting information about vehicle technical condition	Receiving and transmitting information about the status of transportation objects	Receiving and transmitting information about the parameters of the infrastructure environment	Analysis and use of information by the consumer
1	ELM 327	–	– +	–	– +	– +
2	Launch	–	– +	–	–	– +
3	Ruptela FM-Tco4 HCV/HCV 3G	– +	+	+	+	– +
4	Tachograph	– +	+	– +	+	– +
5	KhNADU TESA	– +	+	+	+	+
6	CMV	+	+	+	+	+

Note: "–" – does not correspond; "+" – corresponds; "– +" – partially corresponds

Source: calculated per data from the Official website of the State Statistics Service of Ukraine (n.d.)

Table 1 demonstrated significant variation in the functional coverage of the analysed vehicle operation monitoring systems. Basic diagnostic solutions, such as ELM 327 and Launch, provide only partial support for selected functional elements, whereas integrated telematics platforms, including Ruptela FM-Tco4, tachographs, and KhNADU TESA, ensure broader functional implementation. The most comprehensive coverage is observed for the CMV system, which fully satisfies all functional elements of the generalised morphological model, while KhNADU TESA demonstrates near-complete coverage with a partial limitation in operator monitoring functionality. Figure 1 showed the working graphs of changes in vehicle parameters during diagnostics in a separate mode.

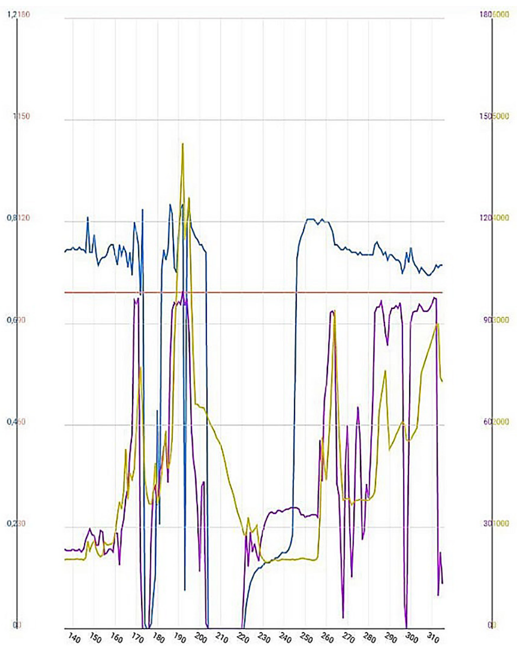

Figure 1. Working graphs of changes in vehicle parameters during the diagnosis process

Note: 1 – lambda probe 2, voltage 0.715V; 2 – lambda probe 2, short-term mixture adaptation; 3 – normalised load value; 4 – engine speed (max. engine speed 2428 min-1)

Source: developed by the authors

Figure 1 illustrated the dynamic behaviour of key engine parameters during the diagnostic process. Fluctuations in lambda probe voltage and short-term fuel mixture adaptation indicate active regulation of the air-fuel mixture in response to changing engine load and operating conditions. The observed variations in normalised load and engine speed, reaching a maximum of 2428 min^{-1}, reflect transient operating modes, confirming the responsiveness of the engine management system during diagnostics. Overall, the application of the morphological approach enabled the development of an optimised intelligent vehicle diagnostic system configuration by identifying key functional parameters and integrating heterogeneous diagnostic and telematics tools into a unified decision support framework, thereby enhancing monitoring efficiency, diagnostic depth, long-term observation capabilities, and early fault detection in accordance with existing research findings. Previous research, notably by I.V. Khudiakov *et al.* (2021), primarily addressed the structural and informational aspects of developing vehicle monitoring systems, yet it did not fully explore the integration of various classes of diagnostic equipment into a unified model. In contrast, the work by Y. Yao *et al.* (2015) focused on organising data flows and constructing information and analytical systems, but it did not employ morphological analysis as a formalised method for selecting model parameters. Particular attention should be given to the comparison of the results of this study with the findings presented by M. Kacmarik & D. Fojtik (2023), which highlight the importance of integrating telematics systems with traditional diagnostic methods. However, in contrast to these approaches, the proposed model facilitates the integration of multiple tools for different purposes within a single decision support system, thereby enhancing its functional capabilities. In the work by K.-P. Schwarz (2000), modern vehicle monitoring systems are discussed; however, the selection and systematisation of their application schemes are not addressed. D.A. Roozemond (1999) investigated the applicability of autonomous intelligent agents in urban traffic control, proposing an agent-based model in which distributed intelligent agents adaptively respond to real-time traffic conditions to optimise signal control at intersections. The study demonstrated how such agent-based urban traffic control systems can improve responsiveness and intersection capacity compared with conventional traffic management approaches. T. Schüler (2001) investigated the use of GPS technologies for scientific purposes, particularly in climatology and meteorology. The study focuses on the precise measurement of tropospheric delays, which are critical for estimating atmospheric water vapour content and, consequently, for improving climate models and weather forecasting. In addition, the work examines the integration of GPS-derived data with numerical weather prediction models in order to enhance estimation accuracy and support advances in both fields. M.M. Atia *et al.* (2015) presented an autonomous indoor navigation system for ground vehicles that integrates inertial sensors, LiDAR, WLAN RSS, odometry, and floor maps to address position initialisation and self-alignment in GNSS-denied environments. By combining extended Kalman filtering with LiDAR-based positioning and heading estimation algorithms, the system achieves sub-metre positioning accuracy, as demonstrated through experiments conducted in a real indoor environment, confirming the effectiveness of multi-sensor data fusion for enhanced navigation performance. Thus, the results of the study confirm the effectiveness of using morphological analysis as a methodological basis for building the supporting structure of the diagnostic system, and also demonstrate the prospects of the developed model for use in intelligent transport systems. Comparison with previous scientific developments shows that the proposed approach has a higher level of structural flexibility, the ability to scale and integrate additional analysis modules, which ensures its competitiveness and scientific novelty.

Conclusions

During the study, an analysis and synthesis of the functional capabilities of existing vehicle operation monitoring systems were conducted using the morphological analysis method, which was employed to systematise the hardware architectures of such systems. A generalised morphological formula for a complex vehicle monitoring system was developed, consisting of five main functional elements: monitoring of operators, monitoring of vehicle technical condition, monitoring of transportation objects, monitoring of interaction with infrastructure, and the analysis and use of information by the consumer. The formula incorporates 20 morphological features of these functional elements, as implemented in existing systems. The synthesis of valid combinations of these morphological features enables the formation of feasible system configurations and identification of the structure and functional capabilities of current monitoring systems. The study identified existing vehicle monitoring systems, including the ELM 327 scanner-adapter, Launch diagnostic device, Ruptela tracker (Ruptela FM-Tco4 HCV/HCV 3G), tachograph, and the KhNADU TESA and CMV remote control and forecasting systems for vehicle and operator condition. Their functional capabilities for monitoring vehicle operation processes were evaluated. Based on the analysis of the advantages and disadvantages of these systems, the conditions for their appropriate use, the degree of implementation of basic monitoring functions, and the potential for further development of core and auxiliary components were determined. The analysis of the obtained results demonstrated that the model facilitates the integration of diverse data channels and their unification within a single decision support system. This approach enhanced the accuracy of technical condition assessments and ensures early detection of deviations, a conclusion that is corroborated by the consistency of the results with data from other studies presented in the paper. A comparison of the results with previous scientific works highlighted several common and distinct aspects. Future research will focus on developing models for the interaction of information components within vehicle operation monitoring systems, as well as decision-making algorithms within intelligent diagnostic frameworks.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Atia, M.M., Liu, S., Nematallah, H., Karamat, T.B., & Noureldin, A. (2015). Integrated indoor navigation system for ground vehicles with automatic 3-D alignment and position initialisation. *IEEE Transactions on Vehicular Technology*, 64(4), 1279-1292. doi: 10.1109/TVT.2015.2397004.

[2] Bai, Y. (2016). *Microcontroller engineering with MSP432: Fundamentals and applications* (1st ed.). Boca Raton: CRC Press. doi: 10.1201/9781315367101.

[3] Burlaka, S., Mytko, M., & Borysiuk, D. (2024). Analysis of diagnostic models for determining technical condition vehicles. *Herald of Khmelnytskyi National University. Technical Sciences*, 6(1), 39-42. doi: 10.31891/2307-5732-2024-343-6-5.

[4] Cordoș, N., Duma, I., Moldovanu, D., Todoruț, A., & Barabás, I. (2025). An overview of intelligent transportation systems in Europe. *World Electric Vehicle Journal*, *16*(7), article number 387. doi: 10.3390/wevj16070387.

[5] Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Geneva: IPCC.

[6] Görne, L., Reuss, H.-C., Krätschmer, A., & Sauerwald, R. (2022). Smart data preprocessing method for remote vehicle diagnostics to increase data compression efficiency. *Automotive and Engine Technology*, 7, 307-316. doi: 10.1007/s41104-022-00113-9.

[7] Holovan, A., Gritsuk, I., Rudenko, S., & Kovalova, V. (2019). Aspects of forming the information V2I model of the transport vessel. In *2019 IEEE international conference on modern electrical and energy systems (MEES)* (pp. 390-393). Kremenchuk: IEEE. doi: 10.1109/MEES.2019.8896595.

[8] Kacmarik, M., & Fojtik, D. (2023). Positioning performance of low-cost U-BLOX NEO-M8U module in urban environment. *MM Science Journal*, 3, 6776-6784. doi: 10.17973/MMSJ.2023_10_2023080.

[9] Kelller, M. (2004). *Handbook emission factors for road transport 2.1 quick reference*. Bern: HBEFA.

[10] Khudiakov, I.V. (2021). *Improvement of methods for operational control of a vehicle's technical condition under operating conditions*. (Doctoral dissertation, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine).

[11] Khudiakov, I.V., Hrytsuk, I.V., Chernenko, V.V., Hrytsuk, Y.V., Pohorletskyi, D.S., Makarova, T.V., & Manzhelei, V.S. (2021). Features of modeling and construction of the information system of remote monitoring of the technical condition of vehicles. *Journal of Mechanical Engineering and Transport*, 14(2), 140-148. doi: 10.31649/2413-4503-2021-14-2-140-148.

[12] Krueger, E., Schueler, T., & Arbesser-Rastburg, B. (2005). *The standard tropospheric correction model for the European satellite navigation system Galileo*. Kraków: General Assembly URSI.

[13] Mateichyk, V., & Navrotskyi, A. (2024). Systematisation of hardware schemes of vehicle operation monitoring systems. *Bulletin of the Pryazovskyi State Technical University. Series: Technical Sciences*, 48, 184-192. doi: 10.31498/2225-6733.48.2024.310711.

[14] Michailidis, E.T., Panagiotopoulou, A., & Papadakis, A.A. (2025). Review of OBD-II-based machine learning applications for sustainable, efficient, secure, and safe vehicle driving. *Sensors*, 25(13), article number 4057. doi: 10.3390/s25134057.

[15] Migal, V., Arhun, Sh., Hnatov, A., Hnatova, H., & Sokhin, P. (2022). Intelligent diagnostics of vehicles. *Vehicle and Electronics Innovative Technologies*, 22, 72-80. doi: 10.30977/VEIT.2022.22.0.5.

[16] Penna, N., Dodson, A., & Chen, W. (2001). Assessment of EGNOS tropospheric correction model. *Journal of Navigation*, 54(1), 37-55. doi: 10.1017/S0373463300001107.

[17] Roozemond, D.A. (1999). Using autonomous intelligent agents for urban traffic control systems. In *Proceedings of the 6th world congress on intelligent transport systems*. Washington, DC: ITS America and MIRO digital publishing.

[18] Schüler, T. (2001). *On ground-based GPS tropospheric delay estimation*. (Doctoral dissertation, University of the Bundeswehr Munich, Munich, Germany).

[19] Schwarz, K.-P. (Ed.). (2000). *Geodesy beyond 2000. The challenges of the first decade, IAG general assembly Birmingham, July 19-30, 1999*. Heidelberg: Springer Berlin. doi: 10.1007/978-3-642-59742-8.

[20] Sipos, A. (2024). ICAO standards and recommended practices (SARPs). In *International aviation law: Regulations in three dimensions* (pp. 203-231). Cham: Springer International Publishing. doi: 10.1007/978-3-031-39066-1_4.

[21] Storm van Leeuwen, S., van der Marel, H., Tossaint, M.M.M., & Martelluci, A. (2004). *Validation of SBAS MOPS troposphere model*. Amsterdam: National Aerospace Laboratory (NLR).

[22] Yao, Y., Xu, C.Q., Shi, J., & Cao, N. (2015). ITG: A new global GNSS tropospheric correction model. *Scientific Reports*, 5, article number 10273. doi: 10.1038/srep10273.

Аналіз та синтез функціональних можливостей систем моніторингу процесів експлуатації транспортних засобів

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Анотація. Системи моніторингу та управління експлуатацією транспортних засобів є ключовим компонентом сучасної транспортної інфраструктури. Метою цього дослідження було проаналізувати та систематизувати функціональні можливості систем моніторингу експлуатації транспортних засобів. Було досліджено, проаналізовано та синтезовано функціональні характеристики існуючих систем моніторингу транспортних засобів. Систематизація апаратних конфігурацій у цих системах була проведена за допомогою морфологічного аналізу. Аналіз і синтез функціональних можливостей здійснено через систематизацію апаратних конфігурацій у наявних системах моніторингу. Була розроблена узагальнена морфологічна формула для інтегрованої системи моніторингу транспортних засобів, яка складається з п'яти основних функціональних елементів: засоби моніторингу операторів; засоби моніторингу технічного стану транспортних засобів; засоби моніторингу транспортних засобів; засоби моніторингу взаємодії з інфраструктурою; та засоби аналізу та використання інформації кінцевими користувачами. Формула охопила двадцять морфологічних характеристик цих функціональних елементів, що реалізовані в існуючих системах моніторингу. Синтез допустимих морфологічних варіантів дозволяє побудувати фактичні конфігурації систем і сприяє визначенню структури та функціонального потенціалу існуючих систем моніторингу. Було ідентифіковано існуючі системи моніторингу транспортних засобів, та визначені їхні можливості для моніторингу процесів експлуатації транспортних засобів. На основі аналізу переваг і обмежень досліджених систем були визначені відповідні умови їх застосування, рівень реалізації основних функцій моніторингу, а також потенціал для розвитку як основних, так і різноманітних компонентів систем. Практична цінність цього дослідження полягає у наданні рекомендацій для оптимізації проектування та впровадження систем моніторингу транспортних засобів з метою підвищення ефективності та безпеки експлуатації

Ключові слова: управління; реєстрація параметрів; технічний стан; апаратне забезпечення; морфологічна формула; систематизація

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 09.07.2025. Revised: 30.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 336.717 DOI: 10.33744/2308-6645-2025-2-29-30-38

Theoretical basis of cash analysis in an enterprise

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Abstract. The purpose of the study was to identify methodological approaches to cash flow analysis and to assess their impact on the financial stability of an enterprise. The use of inductive and deductive methods enabled the generalisation of key characteristics of cash flows and ensured a coherent transition from theoretical foundations to the analysis of specific financial indicators of LLC "Lvivske ATP-14631", which served as an illustrative case within the road transportation sector. The study established that enterprises should adopt an individualised analytical approach that reflects the specific nature of their operations, scale of activity, managerial requirements, and the influence of internal and external factors on particular financial processes. Ensuring an adequate volume of cash resources, together with the ability to employ them effectively, was found to have a significant impact on the overall efficiency of the enterprise and its structural units. The analysis highlighted that cash flow assessment constituted a key component of cash flow management, providing high-quality informational support for managerial decision-making, forecasting, and financial planning. The evaluation of methodological approaches demonstrated that the scholarly literature offered a wide range of techniques, each supported by its own rationale. However, the selection of analytical stages, methods, and combinations of indicators depended on the enterprise's objectives and the specific analytical tasks. Consequently, the study concluded that an individualised approach was advisable, taking into account business specifics, operational scale, management needs, and factor-driven variations in financial processes. The study revealed key trends in the formation and use of cash flows, in particular, insufficient liquidity, irregular inflows and increased dependence on external sources of financing. The results can be applied by enterprises to optimise cash flow management and enhance financial stability through the implementation of individualised analytical approaches

Keywords: financial sustainability; solvency; liquidity management; factor analysis; regression analysis; SWOT-assessment

Introduction

Cash is the most liquid asset and constitutes both the starting and concluding point of the accounting cycle, which includes the acquisition, production, sale of goods and services, and the receipt of income. Except for pre-existing obligations requiring cash payments, it represents the phase of the cycle in which management exercises the greatest discretion over the allocation and utilisation of resources. Given its continuous inflow from operations and outflow to cover expenditures, regular analysis of cash flow is essential for effective financial management and the maintenance of enterprise stability. H. Koshelok & R. Hrinchenko (2020) and M. Iorgachova &

Suggested Citation: Hutsaliuk, O., & Samar, O. (2025). Theoretical basis of cash analysis in an enterprise. *Bulletin of the National Transport University*, 29(2), 30-38. doi: 10.33744/2308-6645-2025-2-29-30-38.

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O. Kovalova (2023) viewed cash flow analysis as a key element of the enterprise management system, enabling the assessment of past and current operational performance, as well as the use of results for planning and forecasting cash movements. The authors emphasised that maintaining a balance between positive and negative flows is essential to avoid cash deficits or surpluses and to ensure the financial stability of the enterprise. O. Kudyrko & I. Kopchykova (2022) highlighted methodological approaches to analysing an enterprise's cash flows, defining its purpose as accelerating cash movement, increasing asset turnover, and enhancing solvency. The article systematised the information base for analysis, including the cash flow statement, balance sheet, income statement, and notes to the financial statements. O. Kudyrko & I. Kopchykova identified three main stages of analysis: the preparatory stage (selection of information sources), the main stage (assessment of the volume, structure, dynamics, and efficiency of cash utilisation), and the final stage (summarising results and formulating recommendations). N. Boiko (2021) investigated the cash flows analysis of transport enterprises in the context of financial security and the risk of losing solvency. The researcher assessed the need to combine express analysis with in-depth calculations, in particular through the use of horizontal, trend, and ratio analysis to identify imbalances between cash inflows and outflows by type of activity. Particular attention is paid to the interpretation of net cash flow as an indicator of an enterprise's ability to meet its obligations on time and to finance investment programs.

The development of a systemic vision of cash flow analysis is observed in the work of V. Pokynchereda & O. Timchenko (2024), where cash flow analysis is integrated into the enterprise's financial management system. The authors detailed the goals and objectives of the analysis, offer procedures for horizontal, vertical, trend, ratio, and factor analysis of cash flows, as well as a system of indicators characterising cash sufficiency, circulation intensity, and the balance of inflows and outflows. Special emphasis is placed on linking the results of cash flow analysis with the structure of working capital and the overall liquidity level of the enterprise. Using the case of PT Astra International Tbk, T.Y. Suciani & S. Setyawan (2022) demonstrated the application of a system of calculated ratios based on cash flows for a comprehensive assessment of financial performance. The authors proved that the analysis of cash flows from operating activities, capital expenditures, net income, and total debt allows for a more accurate evaluation of the enterprise's ability to generate cash and service debts than traditional analysis based solely on financial results. A similar approach was used in the work of A.N. Asyifa *et al.* (2025), where the analysis of the Cash Flows Statement was applied to assess the financial results of PT Akasha Wira International Tbk. The researchers show that a prolonged decrease in operating cash flow leads to a deterioration in the enterprise's ability to repay liabilities, finance investment projects, and maintain a stable level of profitability. The authors emphasised that it is the dynamics of cash flows, and not just profit indicators, which signals the accumulation of financial problems and the risk of a liquid cash deficit. Y. Wang (2025) regarded cash flow as one of the key determinants of enterprise success, emphasising the importance of pro forma (forecasted) cash flow statements for identifying potential future deficits or surpluses of funds. The study demonstrated that cash flow information was utilised by management not only for short-term financial planning but also for strategic decision-making concerning the financing structure, dividend policy, and investment priorities. A significant contribution to the theoretical substantiation of the cash flows statement role was made in the practical guide by KPMG (2024), where the Cash Flows Statement is considered a central element of financial reporting. The document formalised the purpose of this statement, providing relevant information on cash receipts and payments for the period, classified by operating, investing, and financing activities, as well as substantiating its importance for assessing the enterprise's ability to generate cash, meet obligations, and explain the differences between profit indicators and net cash flow. In this regard, in the context of the global economic crisis, it is particularly important for enterprises to develop mechanisms for operational and adaptive management of their own cash inflows and outflows. The study aimed to examine various methodological frameworks for cash flow analysis and to evaluate their role in ensuring an enterprise's financial stability.

Materials and Methods

A comprehensive set of research methods was employed to ensure the scientific rigour and reliability of the study on the theoretical foundations of cash flow analysis at the enterprise level. The object of the study was the enterprise's cash resources, while the subject encompassed theoretical and methodological approaches to their analysis, with particular emphasis placed on liquidity assessment and the balance of cash flows. The empirical basis of the research comprised the financial statements of LLC "Lvivske ATP-14631" (2024) for the period 2019-2023, as well as relevant regulatory and analytical documents issued by the National Bank of Ukraine (2022) and the Ministry of Economy of Ukraine (2022). The calculations were conducted in two stages: the pre-war period, spanning 2019 to 2021, and the period of martial law, covering 2022 to 2023. At the initial stage, the inductive method was used to generalise theoretical approaches, definitions, and conceptual categories that explain the essence of cash funds and their movement. Deduction was further employed to specify methodological recommendations for analysing the enterprise's cash flows based on general theoretical provisions. This allowed for the formulation of the research logic, identification of key directions of cash flow analysis, and determination of core indicators and calculation methods.

At subsequent stages, horizontal, vertical, and ratio analysis were applied, enabling the assessment of the dynamics of absolute and relative liquidity indicators, their comparison with normative values, and the identification of trends in the enterprise's financial condition during the pre-war and wartime periods. The comparison method was additionally used to juxtapose results across the analysed years and to evaluate the balance and stability of cash flows. To examine the factors influencing changes in cash funds, factor analysis was conducted, allowing the identification of key drivers of liquidity fluctuations. To complement quantitative findings with a qualitative assessment, Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis was applied, making it possible to evaluate the strengths and weaknesses of cash management practices in connection with the enterprise's internal capabilities and external environment. Thus, the integrated application of these methods ensured the systematic and comprehensive nature of the study, contributed to the substantiation of scientific conclusions, and provided a basis for developing recommendations aimed at improving the efficiency of the enterprise's cash flow management.

Results and Discussion

One of the key conditions for starting and successfully operating any business is to ensure the required amount of cash. In the process of production activity, capital is constantly circulating, passing through the stages of monetary, production and commodity forms, after which it again acquires a monetary form. This process is called cash flow, which is characterised by the constant movement of funds, both cash inflows and outflows. The mutual consistency of these flows in terms of volume and time largely determines the financial stability and sustainable development of the enterprise. The problem of cash shortages remains relevant for most Ukrainian enterprises. This is caused by a combination of internal factors (loss of clients, limited product range, weak financial planning, deficiencies in the structure of financial departments, insufficient cost control, etc.) and external economic factors. According to the National Bank of Ukraine (2022), in 2022 consumer inflation reached 26.6%, which significantly increased the cost of energy resources, logistics, and operating expenses for enterprises. Similar trends are confirmed by the inflation review of the Ministry of Economy of Ukraine (2022), which records a significant rise in the cost of production resources and an increased need for working capital. The sharp decline in Gross Domestic Product (GDP) in 2022 had long-term consequences, with real GDP growth slowing to 2.9% in 2024 compared to 5.5% in 2023, indicating an unstable and uneven economic recovery (Ukraine's GDP growth…, 2025). In addition, a substantial increase in electricity and natural gas tariffs in the years 2021-2022, which further intensified pressure on business solvency (Prices for natural gas and electricity…, n.d.). The combination of these factors significantly increases the risks of liquidity shortages and complicates the effective management of enterprise cash flows. Taking into account the variety of approaches to the analysis of enterprises cash funds, highlighted in the thematic literature, business entities are faced with the task of choosing the most effective approach for conducting such an analysis. This choice is due to the fact that each approach involves the use of certain methods and indicators, the effectiveness of which depends on the quality of the information support used in the analysis process. For a thorough investigation of a company's cash resources, it is recommended to employ both rapid (express) and comprehensive analytical approaches. Express analysis relies on the swift processing of financial reporting data and enables an operational assessment of the state of cash flows through key performance indicators. In contrast, comprehensive analysis entails a more in-depth examination, conducted across several sequential stages, including preliminary evaluation, horizontal and vertical analyses of indicators, as well as ratio and factor analysis. Within this framework, cash flow analysis encompasses assessing their sufficiency, determining levels of solvency and liquidity, and examining the volume and structure of inflows and outflows according to the enterprise's various activities. Moreover, considerable attention is given to evaluating the quality and balance of cash flows, analysing the efficiency of their formation and utilisation, and identifying factors influencing their dynamics. To complement quantitative findings with a qualitative assessment of internal and external conditions, SWOT analysis is frequently applied, facilitating the identification of strengths and weaknesses in the cash management system, alongside opportunities and threats affecting the enterprise's financial stability. When analysing the sufficiency of cash resources at enterprises, the assessment focuses on whether the company possesses adequate internal financial resources to fund operational and other activities, the potential for attracting external financing if required, and the frequency with which such financing may be necessary.

In parallel with the analysis of cash sufficiency, models for optimising cash balances, which are widely used in financial practice, are described in detail in the works on financial management. One such model is the model by W.J. Baumol (1952), which aims to determine the optimal cash balance by balancing the costs of replenishing cash and the costs of holding it. W.J. Baumol justified that an enterprise can minimise total transaction costs by periodically converting short-term financial investments into cash to cover operating expenses. The model by M.H. Miller & D. Orr (1966), presented in subsequent studies of cash management theory, takes into account the stochastic nature of cash inflows and outflows, proposing the establishment of three control limits: lower, target, and upper cash balances. Within this model, the enterprise responds to deviations of the actual cash balance from the target level: if cash approaches the upper limit, the excess should be invested in short-term financial instruments; if the balance falls to the lower limit, the enterprise must replenish cash resources to restore the optimal level. S. Slaviohlo (2023) analysed the possibilities of optimising the average cash balance of industrial enterprises based on these models and demonstrated the conditions under which the calculation results can be used for managerial decision-making regarding the formation of cash reserves. In the research by D.V. Demchenko (2023), the models by W.J. Baumol and M.H. Miller & D. Orr were adapted to manage the cash flows of an insurance company, which made it possible to determine the optimal level of cash reserves and assess the efficiency of their use in the Ukrainian insurance market. Furthermore, in recent studies devoted to the formation of cash inflows and outflows of enterprises, the model by M.H. Miller & D. Orr is considered to be a suitable tool for regulating cash balances in the accounts of Ukrainian enterprises, taking the irregularity of cash flows into account (Kostruba, 2022). To assess the liquidity of an economic entity, it is customary to calculate three ratios: absolute, quick, and current liquidity. The latter is also called the coverage ratio or critical solvency. The existence of different indicators is explained, among other things, by differences in the information needs of users. Suppliers of raw materials primarily pay attention to the absolute liquidity ratio, as it is important for them that the company can settle accounts with them as quickly as possible. Banks, when lending, are interested in the quick liquidity ratio, and buyers and owners of the company's securities analyse the current liquidity ratio (Table 1).

Table 1. Characteristics of key liquidity indicator

Indicator	Calculation method	Limit value
Absolute liquidity ratio	$\text{Abs Liq Ratio} = \frac{M+CFI}{CL}$, (1) where M – cash on hand and cash equivalents; CFI – current financial investments; CL – current liabilities	In the range from 0.2 to 0.35. If it is less than 0.2, then the company will not be able to repay debts at the first need. If it is more than 1, then there is inadequate cash management
Quick liquidity ratio	$\text{Quick Liq Ratio} = \frac{M+CFI+AR}{CL}$, (2) where M – cash on hand and cash equivalents; CFI – current financial investments; AR – accounts receivable; CL – current liabilities	If the quick ratio is within 0.6–1 (depending on the scope of activity), the company can settle accounts on existing obligations in a timely manner. At the same time, it is important to pay attention to the share of receivables, part of which is difficult to collect on time
Current liquidity ratio	$\text{Cur Liq Ratio} = \frac{CA}{CL}$, (3) where CA – current assets; CL – current liabilities	1 ≤ Cur Liq Ratio < 2; If the current ratio is less than 1, it indicates a lack of short-term solvency, and if it is more than 2, then it indicates inadequate management of current assets

Source: developed by the authors based on T.Yu. Chayka *et al.* (2018)

The presented in Table 1 indicators allow for the assessment of an enterprise's ability to timely meet short-term obligations, taking varying levels of asset liquidity into account. Absolute, quick, and current liquidity provide a sequential understanding of financial stability: from the strictest criteria for debt coverage to broader evaluations of working capital. Deviations from the recommended ranges indicate either a risk of insolvency or inefficient management of current assets. Vertical cash flow analysis involves calculating the ratio of cash volume to individual components of current assets. Horizontal cash flow analysis aims to identify changes in the dynamics of net cash flow, which can be both positive and negative. The analysis of the quality and balance of cash flows (i.e., the ratio of cash inflows and outflows) is carried out both with the help of absolute and relative indicators, and through the use of correlation and regression analysis methods. The use of this method allows to determine the deviation of the average absolute value of the cash flow, as well as to identify possible causes of these deviations. Regression analysis, in turn, allows the company to assess the rhythm of spending money and the frequency of delays in their inflows. Regression analysis makes it possible to convert chaotic cash flows into formalised statistical relationships, which allows not only identifying irregularities in expenses and delays in receipts, but also forecasting future financial gaps and developing effective managerial decisions. Factor analysis of cash flows belongs to analytical methods aimed at quantitatively determining the influence of individual factors on changes in the volume of cash inflows and outflows. It can be applied both to the company's overall cash flow and to its components, such as operating, investing, and financing activities, which makes it possible to detail the structure of influences and identify the sources of deviations. During factor analysis, the indicator is broken down into separate components and an assessment is made of how much each factor has changed the final result compared to the base period or planned value. By applying methods such as chain substitution, difference, or integration analysis, an analyst is able to identify the specific factors responsible for increases or decreases in cash flows, as well as to determine the direction of their positive or negative impact. In the context of operating cash flows, such factors may include variations in revenue, levels of operating expenses, the volume of accounts receivable, or the efficiency of their collection. Within investment activities, relevant factors encompass the scale of capital expenditures, the disposal of fixed assets, and dividends received. For financial activities, key determinants may involve the acquisition of loans, repayment of borrowings, or alterations in payments to owners. By comparing the influence of these factors over time, it becomes possible to ascertain which elements contribute positively to cash flows and which pose potential risks of liquidity shortages. Thus, factor analysis not only captures changes in the volume of cash flows but also explains their causes, revealing the internal logic behind the formation of cash inflows and outflows. This makes it an important tool for substantiating managerial decisions aimed at optimising the structure of flows, improving solvency, and reducing the likelihood of financial gaps.

As an alternative or addition to traditional methods of cash flow analysis, the use of SWOT analysis is proposed. This is justified by the fact that such classical methods as horizontal, vertical, comparative, and ratio analysis, although they provide a quantitative assessment of the dynamics and structure of cash flows, nevertheless have a number of limitations. They are sensitive to the choice of the base period, do not always allow for a comprehensive assessment of the effectiveness of cash flow management, complicate the analysis of enterprises with a specific business model, and do not make it possible to clearly determine the level of financial risks or the threat of bankruptcy. Besides, interpreting changes in ratios is often complicated by their unevenness and the absence of universal benchmarks. The use of SWOT analysis makes it possible to compensate for these shortcomings, as it combines quantitative results of financial calculations with a qualitative assessment of the company's internal and external environment. This approach allows identifying the strengths of cash flow management (for example, stable operating inflows or a low share of overdue receivables), determining weaknesses (significant fluctuations in expenses, long payment delays, low liquidity), outlining opportunities (access to cheaper financial resources, potential to increase asset turnover), and identifying threats (rising cost of borrowing, dependence on a single major counterparty, or external market instability). For example, if a company's current ratio is at an acceptable level but horizontal analysis shows a trend of increasing current liabilities, SWOT analysis enables a broader conclusion. Strength – a sufficient amount of current assets; weakness – deterioration in the structure of liabilities; opportunity – a shift to a more effective accounts receivable management policy; threat – the risk of a short-term liquidity shortage in case operating inflows decline. Thus, SWOT analysis helps not only record numerical changes but also understand their nature, strategic implications, and potential risks.

The following analysis focuses on the cash flows of LLC "Lvivske ATP-14631", one of Ukraine's largest motor transport enterprises, established in 1946. The company's primary activity is Ukrainian and international passenger transportation, encompassing both regular and irregular routes. In addition to transportation, the enterprise engages in automobile and light vehicle trade, dealing in both new and pre-owned units, and provides comprehensive vehicle maintenance and repair services. The company is also involved in tourism operations, offering travel agency and tour operator services, as well as in real estate management, including leasing and administration of owned or rented properties. Further, it provides advertising services and conducts retail fuel sales through its network of filling stations. Collectively, these diversified operations generate complex cash flow streams, warranting a detailed financial analysis to assess liquidity, solvency, and operational efficiency. Liquidity indicators are presented in Table 2.

Table 2. Liquidity ratios of "Lvivske ATP-14631" for 2019-2023

Indicator	Pre-war period (years)			Martial law period (years)		Absolute deviation		
	2019	2020	2021	2022	2023	2020 to 2019	2021 to 2020	2023 to 2022
Absolute liquidity ratio	0.10	0.03	0.04	0.03	0.05	–0.07	0.01	0.01
Quick liquidity ratio	0.48	0.44	0.29	0.63	0.78	–0.04	–0.15	0.09
Current liquidity ratio	0.63	0.61	0.39	0.81	0.90	–0.02	–0.22	0.09

Source: developed by the authors based on LLC "Lvivske ATP-14631" (2024)

Based on the data presented in Table 2, the following conclusions were drawn regarding the Absolute Liquidity Ratio. During the pre-war period (2019-2021), this indicator was relatively low, declining from 0.10 in 2019 to 0.03 in 2021. Throughout the period of martial law (2022-2023), the ratio remained low, recorded at 0.04 in 2022 and 0.05 in 2023. The absolute deviation highlighted a decrease of 0.07 in 2020 compared with 2019, indicating a deterioration in the company's short-term solvency. Quick liquidity ratio: During the pre-war period (2019-2021), the ratio declined from 0.48 in 2019 to 0.29 in 2021. Throughout the period of martial law, it increased to 0.63 in 2022, before falling again to 0.53 in 2023. The absolute deviation indicated a deterioration in 2020 compared with 2019 (-0.15); however, by 2023, the ratio had improved slightly relative to 2022 (+0.24). Current Liquidity ratio: In the pre-war period, the ratio remained relatively stable, decreasing slightly from 0.63 in 2019 to 0.58 in 2021. In 2022, it rose to 0.72, but declined again to 0.64 in 2023, remaining close to the 2019 level. The absolute deviation reflected a decrease in 2020 compared with 2019 (–0.05), yet an improvement was observed in 2023 relative to 2022 (+0.06). LLC "Lvivske ATP-14631" demonstrated instability in liquidity indicators during the analysed period. The main changes reflect deterioration in the pre-war period (2019-2021), a slight improvement in 2022, which is explained by adaptation to the new conditions, and a repeated deterioration in 2023. The company needs to strengthen the management of short-term solvency, increase the volume of liquid assets and improve the structure of working capital.

As an alternative or complementary approach to traditional cash flow analysis, a SWOT analysis was applied to LLC "Lvivske ATP-14631". This analysis enabled a comprehensive evaluation of the company's financial position and facilitated the development of strategies aimed at enhancing its financial stability. The results indicated that the company needed to improve its liquidity by establishing a reserve of highly liquid assets. Additionally, it was recommended to optimise costs through systematic analysis to reduce inefficient expenditures. Expanding the range of services was proposed as a means to diversify revenue streams and increase cash inflows. The analysis also highlighted the importance of managing risks by developing strategies to mitigate threats arising from external factors. Finally, it was suggested that the company could strengthen its financial position by attracting external financing through loans or investment opportunities (Table 3).

Table 3. SWOT analysis of LLC "Lvivske ATP-14631"

Strengths	Weaknesses
1) experience in the market: the presence of a long activity history provides trust from customers and partners; 2) relative stability of overall liquidity: the current liquidity ratio shows a tendency to improve in 2022-2023; 3) adaptation to the conditions of martial law: the company was able to maintain the level of financial indicators in a crisis situation; 4) improvement of the quick liquidity ratio in 2022: indicates the ability to quick respond to financial challenges	1) low absolute liquidity ratio: indicates a lack of highly liquid assets to immediately cover liabilities; 2) decrease in quick liquidity in 2023: shows problems with short-term solvency; 3) dependence on external sources of financing: lack of own funds for investments and covering operating expenses; 4) instability of financial indicators: significant fluctuations in liquidity ratios indicate insufficient efficiency of cash flow management
Opportunities	**Threats**
1) attracting investors: additional investments will help strengthen the financial base of the enterprise; 2) expansion of services: the introduction of new types of transport or logistics services can increase cash inflows; 3) improving the efficiency of cash flow management: the introduction of modern financial models (for example, cash flow forecasting) will allow optimising the movement of funds; 4) attracting grants or government business support programs: can provide additional resources in the conditions of martial law; 5) automation of business processes: implementation of digital tools for monitoring and managing finances	1) military actions in Ukraine: the deterioration of the macroeconomic situation can negatively affect customers' solvency; 2) rising energy prices: a direct impact on the company's costs; 3) inflation: rising prices for goods and services can reduce cash reserves; 4) increased competition: other transport companies may offer better conditions, reducing market share; 5) instability of the exchange rate: may affect the cost of imported equipment or spare parts

Source: developed by the authors

The conducted SWOT analysis indicated a balanced, though heterogeneous, position of the company in the field of cash flow management and operational activity. The company possesses significant internal advantages related to its operational experience, the stability of certain financial indicators, and its ability to adapt to external challenges. At the same time, the identified weaknesses point to existing financial risks, primarily associated with an insufficient level of liquidity, dependence on external financing sources, and instability in certain indicators. Development opportunities are concentrated mainly in the diversification of services, attraction of investments, digitalisation of financial processes, and improvement of the cash flow management system. In contrast, threats arise predominantly from the external environment and relate to military and macroeconomic factors, fluctuations in energy costs, inflationary pressure, and increasing competition. The combined analysis of these elements makes it possible to assess the company's strategic resilience and identify directions for improving the effectiveness of financial management. Contemporary academic literature increasingly emphasises the analysis of cash flows and enterprise liquidity, reflecting the growing significance of financial flexibility in conditions of economic instability. The findings of this study, based on the case of LLC "Lvivske ATP-14631" (2024), align with those reported in several scholarly works, while simultaneously highlighting specific divergences arising from the unique characteristics of the transportation sector and the influence of external shocks, particularly the ongoing conflict. The results of the study by Y. Chen *et al.* (2024) demonstrated that fluctuations in liquidity are most evident in enterprises with a significant share of current assets that are sensitive to seasonality and changes in market demand. A similar dynamic was observed at "Lvivske ATP-14631," where the instability of operating cash flow is explained by seasonal fluctuations in passenger traffic and dependence on market fares. Unlike the conclusions of Y. Chen *et al.*, results of this research indicated not only the seasonality of cash flows but also the impact of external shocks, which were not taken into account by those authors.

G. Pan & B. Lee (2020) emphasised that an effective accounts receivable control system is a critically important factor in maintaining cash flow stability. Their research showed that delays in payments from counterparties reduce quick and absolute liquidity even when revenue is increasing. The results of analysis confirm this thesis: during the years 2019-2023, the growth of accounts receivable became one of the key factors behind liquidity instability at LLC "Lvivske ATP-14631". At the same time, unlike the findings of the cited study, in this case an additional destabilising factor was the fluctuation in energy prices, which significantly increased the company's expenses. The study by F. Amelita & D. Kurnia (2025) reviewed the importance of using factor analysis to identify the causes of changes in cash flows. The authors argued that the greatest impact on operating inflows comes from changes in the volume of core activities and the efficiency of the expenditure mechanism. In the context of the enterprise under study, factor analysis also showed the key influence of operational activity and costs for fuel and maintenance, elements that, in the case of transport companies, play an even more significant role than in other industries. Results of this study also correlate with the findings of

T. Pysarenko (2025) which proved the necessity of an adaptive cash flow management policy in conditions of high turbulence. The data on liquidity changes during 2022-2023 indicated that partial adaptation to external challenges is possible, but insufficient without enhanced cost control and additional financing. The comparison demonstrated that the results aligned with existing scholarship while extending it by accounting for the specifics of passenger transport enterprises under wartime conditions, underscoring the relevance of adaptive cash flow management models in this industry.

Conclusions

Based on the results of the conducted research, it was established that cash flow is a key element of the enterprise's financial support, and the efficiency of its formation, distribution, and use directly affects the level of solvency and financial stability. The paper systematised theoretical approaches to cash flow analysis, defined its objectives, tools, and analytical capabilities. The use of horizontal, vertical, ratio, factor, and regression analysis, along with the application of the SWOT methodology, ensured a comprehensive study of cash movement and a characterisation of the conditions under which the enterprise's financial result is formed. Using the case of LLC "Lvivske ATP-14631", the study identified the principal trends in liquidity changes during both the pre-war and wartime periods. An intensification of cash flow volatility was observed, accompanied by a decline in absolute and quick liquidity ratios. In addition, the analysis indicated the impact of external factors on the enterprise's overall financial position. The SWOT analysis of LLC "Lvivske ATP14631" demonstrated that, despite operational experience and partial financial stability, the company faces critical weaknesses, including low absolute liquidity, declining quick liquidity, and dependence on external financing. It also highlighted strategic opportunities to stabilise finances through service diversification, investment attraction, digitalisation of financial processes, and enhanced cash flow management, while external threats such as military actions, inflation, rising energy costs, and increased competition pose significant risks. The findings underscore the necessity of enhancing current asset management and optimising the structure of short-term liabilities. Future research could focus on modelling cash flows using modern economic and mathematical methods, developing adaptive liquidity management models under economic instability, and assessing the impact of digital technologies on financial processes in transport enterprises. Further areas of interest comprise the analysis of cash flow formation scenarios under crisis conditions and the identification of tools capable of increasing enterprises' resilience to financial shocks.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Amelita, F., & Kurnia, D. (2025). Financial factor analysis of the performance of transportation and logistics companies on the IDX (2019-2023). *Global Management International Journal of Management Science and Entrepreneurship*, 2(3), 49-58. doi: 10.70062/globalmanagement.v2i3.333.

[2] Asyifa, A.N., Febrianty, S.A., & Abdillah, A. (2025). Financial performance analysis using the profitability ratio method at PT Akasha Wira International Tbk for the 2022-2024 period. *Anggaran: Journal of Economic and Accounting Publications*, 3(3), 443-457. doi: 10.61132/anggaran.v3i3.1752.

[3] Baumol, W.J. (1952). The transactions demand for cash: An inventory-theoretic approach. *Quarterly Journal of Economics*, 66(4), 545-556. doi: 10.2307/1882104.

[4] Boiko, N. (2021). Cash flow analysis of transport enterprises: Problematic and pragmatic approach. *Modern Economics*, 28, 13-21. doi: 10.31521/modecon.v28%282021%29-02.

[5] Chayka, T.Yu., Loshakova, S.Ye., & Vodorez, Ya.S. (2018). Calculation of liquidity ratios by balance sheet, taking into account the financial and production features of the enterprise when carrying out liquidity ratio analysis. *Economy and Society*, 15, 900-908.

[6] Chen, Y., Dong, S., Qian, S., & Chung, K. (2024). Impact of oil price volatility and economic policy uncertainty on business investment: Insights from the energy sector. *Heliyon*, 10(5), article number e26533. doi: 10.1016/j.heliyon.2024.e26533.

[7] Demchenko, D.V. (2023). *Management of cash flows of an insurance company*. (Master's thesis, Kyiv National Economic University named after Vadym Hetman, Kyiv, Ukraine).

[8] Iorgachova, M., & Kovalova, O. (2023). Directions for increasing the efficiency of the company's cash flow management. *Scientific Bulletin of Mukachevo State University. Series "Economics"*, 10(4), 20-31. doi: 10.52566/msu-econ4.2023.20.

[9] Koshelok, H., & Hrinchenko, R. (2020). Analysis of cash flows in the enterprise management system. *Galician Economic Journal*, 63(2), 231-242. doi: 10.33108/galicianvisnyk_tntu2020.02.231.

[10] Kostruba, V.O. (2022). *Formation of cash inflows and outflows of the enterprise*. (Master's thesis, Polissia National University, Zhytomyr, Ukraine).

[11] KPMG. (2024). *Handbook: Statement of cash flows*. Retrieved from https://kpmg.com/us/en/frv/reference-library/2024/handbook-statement-cash-flows.html.

[12] Kudyrko, O., & Kopchykova, I. (2022). Methodological approaches to cash flow management at the enterprise. *European Journal of Economics and Management*, 8(3), 17-22. doi: 10.46340/eujem.2022.8.3.3.

[13] LLC "Lvivske ATP-14631". (2024). Retrieved from https://clarity-project.info/edr/03114767.

[14] Miller, M.H., & Orr, D. (1966). A model of the demand for money by firms. *Quarterly Journal of Economics*, 80(3), 413-435. doi: 10.2307/1880728.

[15] Ministry of Economy of Ukraine. (2022). *Inflation review*. Retrieved from https://me.gov.ua/download/50fbfde8-4590-43ed-95a9-8932b6976b03/file.pdf.

[16] National Bank of Ukraine. (2022). *Inflation report. July 2022*. Retrieved from https://bank.gov.ua/admin_uploads/article/IR_2022-Q3.pdf.

[17] Pan, G., & Lee, B. (2020). Leveraging digital technology to transform accounting function: Case study of a SME. *International Journal of Accounting and Financial Reporting*, 10(2), 24-38. doi: 10.5296/ijafr.v10i2.17052.

[18] Pokynchereda, V., & Timchenko, O. (2024). Analysis of cash flows in the company's financial management system. *Modern Economics*, 46, 112-118. doi: 10.31521/modecon.V46(2024)-15.

[19] Poliarush, M.M. (2024). *Liquidity management of oil refining industry enterprises: The case of PJSC "Ukrnafta"*. (Master's thesis, Vinnytsia National Technical University, Vinnytsia, Ukraine).

[20] Prices for natural gas and electricity supplied to consumers. (n.d.). Retrieved from https://stat.gov.ua/en/publications/prices-natural-gas-and-electricity-supplied-consumers.

[21] Pysarenko, T. (2025). Forecasting cash flows of industrial enterprises in the context of implementing their development strategy: Accounting, analytical, and organisational aspects. *Economic Forum*, 15(2), 29-44. doi: 10.62763/ef/2.2025.29.

[22] Slaviohlo, S. (2023). Models of optimization of the average balance of funds in the enterprise. In *IV international scientific and practical conference of scientists and students "Digital economy as a factor of innovation and sustainable development of society"* (pp. 73-75). Lviv: Ivan Franko National University of Lviv.

[23] Suciani, T.Y., & Setyawan, S. (2022). Analysis of cash flow statement to assess the company's financial performance at PT Astra international Tbk. *Cashflow Current Advanced Research on Sharia Finance and Economic Worldwide*, 1(4). doi: 10.55047/cashflow.v1i4.223.

[24] Ukraine's GDP growth slows to 2.9% in 2024 – statistics. (2025). Retrieved from https://en.interfax.com.ua/news/economic/1060192.html.

[25] Wang, Y. (2025). Research on the impact of corporate cash flow management on profitability. *Highlights in Business, Economics and Management*, 61, 228-234. doi: 10.54097/djkqmq13.

Теоретичні засади аналізу грошових потоків на підприємстві

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Анотація. Метою дослідження було визначення методологічних підходів до аналізу грошових потоків та оцінка їхнього впливу на фінансову стійкість підприємства. Використання індуктивних та дедуктивних методів дозволило узагальнити ключові характеристики грошових потоків та забезпечити послідовний перехід від теоретичних засад до аналізу конкретних фінансових показників ТОВ «Львівське АТП-14631», яке слугувало ілюстративним прикладом у секторі автомобільних перевезень. Дослідження встановило, що підприємствам слід застосовувати індивідуалізований аналітичний підхід, який відображає специфіку їхньої діяльності, масштаб операцій, управлінські потреби та вплив внутрішніх і зовнішніх факторів на конкретні фінансові процеси. Забезпечення адекватного обсягу грошових ресурсів разом із здатністю ефективно їх використовувати виявилося суттєвим чинником підвищення загальної ефективності підприємства та його структурних підрозділів. Аналіз підкреслив, що оцінка грошових потоків є ключовим елементом управління ними, забезпечуючи високоякісну інформаційну підтримку прийняття управлінських рішень, прогнозування та фінансового планування. Оцінка методологічних підходів показала, що наукова література пропонує широкий спектр методик, кожна з яких має власне обґрунтування. Водночас вибір аналітичних етапів, методів та комбінацій показників залежить від цілей підприємства та специфіки аналітичних завдань. Отже, дослідження дійшло висновку, що доцільним є індивідуалізований підхід з урахуванням особливостей бізнесу, масштабу діяльності, управлінських потреб та факторного впливу на фінансові процеси. Було виявлено ключові тенденції формування та використання грошових потоків, зокрема недостатню ліквідність, нерегулярність надходжень та зростаючу залежність від зовнішніх джерел фінансування. Результати дослідження можуть бути використані підприємствами для оптимізації управління грошовими потоками та підвищення фінансової стійкості через впровадження індивідуалізованих аналітичних підходів

Ключові слова: фінансова стійкість; платоспроможність; управління ліквідністю; факторний аналіз; регресійний аналіз; SWOT-оцінка

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 30.05.2025. Revised: 21.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 004.832.28:621.396.74 DOI: 10.33744/2308-6645-2025-2-29-39-46

Development of an intelligent decision-making system for routing in unmanned networks with adaptive link assessment

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Abstract. The relevance of the study was determined by the need to improve the reliability of communication in Flying Ad Hoc Networks, where traditional routing protocols do not take into account channel quality and rapid topology changes. The aim of the work was to develop an intelligent decision-making system capable of adaptively selecting a data transmission route according to the state of the radio channel. To achieve this aim, methods of fuzzy logic, mathematical modelling, simulation experiments and comparative analysis of routing efficiency were used. During the study, a model of a fuzzy expert system was created that evaluates the quality of communication based on the signal-to-noise ratio, the distance between nodes, and noise indicators, forms a database of IF-THEN rules, and determines the optimal transmission path – direct or via a repeater. Experimental results showed that the proposed system increases the Packet Delivery Ratio to 99%, while in the basic algorithms it was only 90%. The average transmission delay decreased from 80 to 50 ms, and the number of connection interruptions decreased from 0.2 to 0 cases per min. It was also found that the system maintains network stability under conditions of signal-to-noise ratio fluctuations, ensuring smooth route switching without excessive protocol traffic. The use of fuzzy logic made it possible to take into account the uncertainty of the radio environment and proactively respond to signal quality degradation, preventing connection drops. The practical value of the work lies in the possibility of integrating the developed system into drone network modules to ensure reliable routing in highly mobile conditions, particularly in military, search and rescue, and civil applications

Keywords: Flying Ad Hoc Network; fuzzy logic; adaptive link assessment; communication reliability; delay; network performance

Introduction

The development of unmanned aerial vehicles is one of the most dynamic areas of modern information and communication technologies, forming a new paradigm called Flying Ad Hoc Networks (FANET). With the intensive use of drones for military, rescue, transport and monitoring tasks, there was a need to create routing systems capable of operating in a mode of rapid topology change, where communication quality varies constantly. As emphasised by S. Lateef *et al.* (2022), FANET is one of the most unstable types of networks, since the interaction between drone nodes is determined by the Signal-to-Noise Ratio (SNR), delays and packet losses, which can change significantly even within a few seconds. That is why ensuring reliable data exchange in such networks is considered a key

Suggested Citation: Zaivyi, R., & Pavlysh, V. (2025). Development of an intelligent decision-making system for routing in unmanned networks with adaptive link assessment. *Bulletin of the National Transport University*, 29(2), 39-46. doi: 10.33744/2308-6645-2025-2-29-39-46.

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engineering and scientific problem. S.A. Hasan *et al.* (2024) systematised the current challenges of FANET in their comprehensive study, highlighting the problems of protocol adaptability to rapid environmental changes and limited energy resources of drones. The authors concluded that traditional routing algorithms, in particular Optimised Link State Routing Protocol (OLSR) and Ad hoc On-Demand Distance Vector (AODV), do not take into account the quality of the communication channel and the level of interference, and therefore are unable to ensure network stability with high node mobility. A similar position was taken by O.T. Abdulhae *et al.* (2022), who proposed a cluster-oriented approach to routing, demonstrating that the formation of dynamic drone groups partially increases the stability of communication, but does not solve the problem of short-term signal failures. In their work, Y. Zhang & H. Qiu (2023) attempted to overcome this limitation by using deep neural networks – in particular, the Dueling Deep Q-Network model – to predict link status. However, the researchers noted that the high computational costs of this approach make it unsuitable for energy-constrained drone systems. An alternative approach was demonstrated by M.Y. Arafat & S. Moh (2021), who created a Q-learning-based routing protocol that takes into account real-time topological changes in the network. Their model proved the feasibility of using reinforcement learning to maintain channel stability in dynamic FANETs.

The issue of communication reliability in high-speed scenarios was addressed by Q. Usman *et al.* (2021), who proposed a protocol with link quality adaptation. Their results showed that flexible route updates based on the current SNR level can reduce the number of connection drops by almost 30%. In this context, the work of S. Garg *et al.* (2022) is important, where the routing approach was based on a multi-level analysis of traffic, mobility, and network congestion. The authors proved that cross-level optimisation significantly increases the packet delivery rate, but requires complex coordination between protocol levels. The development of hybrid routing systems is demonstrated in the study by I.S. Rajesh *et al.* (2024), where the combination of fuzzy logic and Q-learning provided better adaptability and stability compared to classical approaches. In turn, A. Rahmani *et al.* (2022) developed the OLSR+ protocol, which implements fuzzy logic for estimating link lifetime. Their experimental analysis showed an increase in packet delivery ratio (PDR) to 96%, while the basic version of OLSR provided only about 85%. P. Bugarčić *et al.* (2022) summarised trends in the use of reinforcement learning in FANET routing, pointing to the growing role of intelligent decision-making systems in ensuring network stability. Their review confirmed that future approaches should rely on the integration of fuzzy logic, machine learning, and heuristic mechanisms.

Summarising the results of the literature review, it can be stated that current research is actively focused on the creation of intelligent adaptive routing systems that take into account the quality of communication in real time. However, most existing solutions do not provide a proactive response to short-term signal degradation and do not integrate fuzzy channel parameter estimation into the decision-making process. It is these shortcomings that have necessitated the development, within the scope of this work, of an intelligent routing system based on fuzzy logic, capable of providing adaptive communication assessment and increasing the reliability of FANET in dynamic conditions. The aim of the work was to develop an intelligent decision-making system for routing in an unmanned network that is capable of assessing the state of the communication channel in real time and adaptively selecting the optimal data transmission route. The research objectives were to analyse current routing methods in unmanned networks (FANET) and identify their limitations related to high node mobility, radio channel variability, and lack of adaptation to communication quality; to develop a conceptual and mathematical model of an intelligent routing system based on fuzzy logic, which provides an assessment of link quality based on SNR parameters and other channel characteristics and forms a decision on the selection of the optimal route; to implement and experimentally verify the effectiveness of the proposed system in a simulation environment, performing a comparative analysis with basic protocols (OLSR, AODV) for key network metrics – PDR, average delay, and connection stability.

Materials and Methods

The object of the study was an unmanned ad hoc network consisting of mobile drone nodes that exchange data via radio channels without a fixed infrastructure (Azari *et al.*, 2017). The study selected a scenario with two or more unmanned aerial vehicles that can transmit packets both directly to each other and through an intermediate relay node. A mathematical model of an intelligent routing system based on fuzzy logic (Zadeh, 1965) was developed. The system inputs include communication channel parameters between nodes, in particular the current SNR on possible links, connection quality indicators (e.g., link quality indicator, delay) and other available metrics. Each input parameter is linguistically divided into terms using membership functions (Fig. 1). For example, the SNR value is classified as “Low”, “Medium”, or “High”. Based on expert knowledge about the nature of radio communication, a set of fuzzy IF-THEN rules is formed that mimic the logic of route selection decision-making.

The rules are formulated in such a way as to reflect various channel situations. For example, if the direct channel between nodes A and B is of high quality (high SNR), and the quality of the alternative route via the repeater is worse (low SNR on the R-B segment), then it is advisable to transmit data directly. This rule can be formally written as:

$$\mu_{direct} = \min\{\mu_{SNR\_AB}\,(\text{High}),\ \mu_{SNR\_AB}\,(\text{Low})\}, \qquad (1)$$

where μ_{direct} – the degree of support for the conclusion “use the direct route”, defined as the minimum (AND operation) between the degree of membership of SNR_{AB} in the term “High” and the degree of membership of SNR_{RB} in

"Low". In other words, under the conditions: if the signal on the direct channel is high and the signal on the channel from the repeater to B is low, μ confidence that the direct route is better is high.

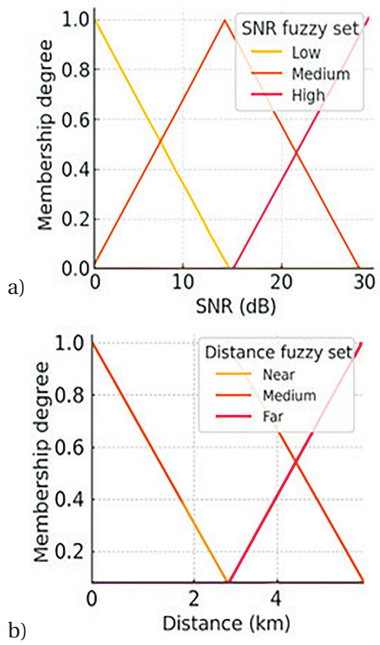

Figure 1. Membership functions

Note: a) for SNR (Low/Medium/High); b) for distance (Near/Medium/Far)

Source: developed by the authors

Other rules are formed similarly: for example, if the direct channel is poor (low SNR) and the connection through the intermediate node is good (all segments with high SNR), then it is advisable to transmit through the repeater. The set of such rules forms the knowledge base of a fuzzy system. The Mamdani method was used as a fuzzy logical conclusion. The construction of linguistic variables and rules corresponds to the classical principles of fuzzy sets (Zadeh, 1965). At the defuzzification stage, a quantitative assessment of the "advantages" of each possible route is obtained. Ultimately, the system selects the route with the maximum value of the output membership function (i.e., the highest degree of desirability). To verify the proposed approach, simulation modelling of typical scenarios of communication between drones was performed. In particular, the situation was considered where sender A has to transmit data to receiver B, and there is one potential repeater R. The topology diagram is shown in Figure 2. The conditions varied in different tests: the distances between drones (which affects the SNR), the presence of interference or signal shadowing, and the speed of movement of the nodes. The simulation was performed using software (Azari *et al.*, 2017). The fuzzy system was implemented using the MATLAB environment (Fuzzy Logic Toolbox, developed by MathWorks Inc., USA) and the Python language (libraries for fuzzy computing, developed by the Python Software Foundation, USA) to conduct individual experiments. Network quality indicators were selected as criteria for evaluating the results: PDR, average transmission delay, and number of retransmissions. The results were compared with the basic routing protocol (standard algorithm without adaptive link assessment, e.g., AODV) in the same scenarios.

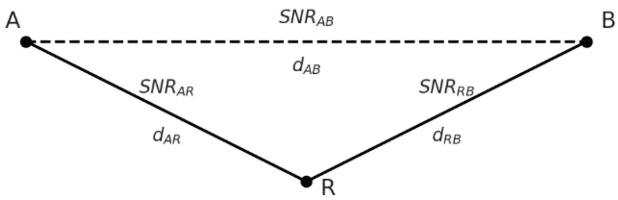

Figure 2. A-R-B topology with $d_{\_AB}$, $d_{\_AR}$, $d_{\_RB}$ and links $SNR_{\_AB}$, $SNR_{\_AR}$, $SNR_{\_RB}$

Source: developed by the authors based on M.M. Azari *et al.* (2017)

As can be seen from the diagram, with an increase in the direct channel A-B degrades, while the two-hop path A-R-B can maintain an acceptable under condition ; this creates the conditions for adaptive switching between direct and relay modes. The main modelling parameters used during the experiment are presented in Table 1.

The selected parameters reproduce conditions typical for FANET with moderate mobility and urban/suburban attenuation (n = 4), which allows for a correct assessment of the benefits of adaptive route switching in an unstable radio channel.

Table 1. Modelling parameters

Parameter	Value
Pt (dBm) – Transmit power	30 dBm
B (MHz) – Bandwidth	20 MHz
NF (dB) – Noise figure	9 dB
Path loss exponent *n*	4
Update interval Δt (ms)	100 ms
Node speed (m/s)	5 m/s
Distance range (km)	0.5-2 km
Session duration (s)	300 s
RNG seed	1

Source: developed by the authors based on M.M. Azari *et al.* (2017)

Results and Discussion

The simulation showed that the proposed intelligent routing system demonstrates better data transmission reliability compared to the standard approach. In particular, in scenarios with periodic deterioration of the direct channel (e.g., separation of nodes A and B or the appearance of temporary radio interference), the fuzzy system detected this fact by a decrease in SRN and automatically switched traffic to an alternative route through node R (Azari *et al.*, 2017). Thus, it was possible to avoid a communication session break. The graph of PDR dependence on time shows that at moments when the direct channel deteriorates sharply, PDR in a network with a traditional router drops (up to 60-70%), while the proposed system maintains PDR at ~90% due to timely route changes (Fig. 3).

On average, across a series of PDR tests, the proposed algorithm achieved 99%, which is ~10% higher than the baseline protocol without adaptive link estimation. Although the choice of relay route could theoretically lead to increased latency, the average packet delivery time overall showed a significant reduction due to the prevention of packet loss and retransmissions. Importantly, when fuzzy logic was applied, there was no sharp increase in service traffic: the system makes decisions locally at nodes based on current signal measurements, so it does not generate significant protocol load on the network. The summary numerical results for the selected metrics are shown in Table 2.

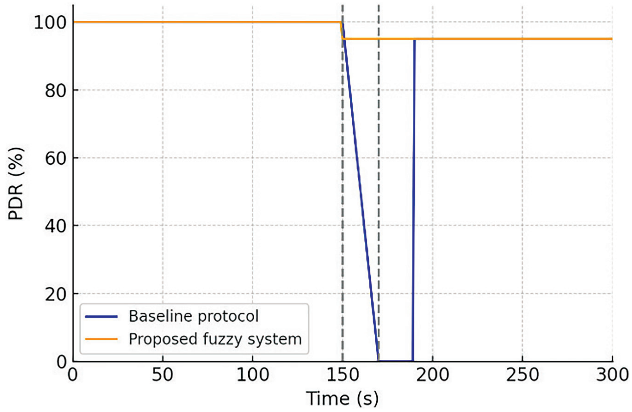

Figure 3. PDR(t) dependence: Comparison of the basic protocol and the proposed fuzzy system

Note: moments of direct link degradation are marked with vertical markers

Source: developed by the authors

Table 2. Comparison of metrics in scenarios

Metric	Baseline	Proposed
PDR, packet delivery (%)	90%	99%
Average delay (ms)	80	50
Number of breaks (per min)	0.2	0
Mode switching frequency (times/min)	0.2	0.4

Source: developed by the authors

Analysis of the results shown in Table 2 shows that the implementation of a fuzzy routing system has significantly improved all key network performance indicators. In particular, the packet delivery rate increased from 90% in the baseline scenario to 99%, indicating an almost 10% improvement in data transmission reliability. The average delay decreased from 80 ms to 50 ms, confirming the effectiveness of adaptive route selection and rapid response to changing channel conditions. The number of connection drops decreased from 0.2 to 0 cases per min, demonstrating the system's ability to maintain stable communication without loss. A slight increase in the frequency of switching between modes from 0.2 to 0.4 times per min indicates the dynamic flexibility of the algorithm, which actively responds to signal parameter fluctuations without creating excessive service load. The results confirm the effectiveness of the proposed approach and the feasibility of using fuzzy logic to improve FANET performance in complex radio environments. The improvement in network performance is explained by the ability of the proposed system to respond "smoothly" to channel degradation, even before it fails completely. Unlike traditional algorithms, which often rely on threshold values or connection break events, the fuzzy approach takes into account the degree of quality deterioration. For example, when the SNR on channel A-B begins to decline from high to medium, the system can already partially reduce its "trust" in this channel and increase its readiness to switch to a backup route without waiting for the connection to be lost. This achieves greater stability: the network redirects the data flow in advance if the line quality falls below acceptable levels. In fact, the proposed system acts as an expert decision support system that accumulates heuristics (in the form of fuzzy rules) about when it is better to use an alternative route and automatically applies them in real time. A comparison of the throughput for direct and relay modes is shown in Figure 4.

Analysis of Figure 4 shows that the proposed adaptive approach provides better throughput across the entire distance range compared to using only direct or only relay mode. At short distances (up to ≈1.8 km), the direct channel is more effective, while after exceeding the threshold value of about 2 km, the system automatically switches to relay mode, which allows maintaining high data transfer rates and preventing a sharp drop in channel capacity. The envelope line shows that dynamic route selection achieves near-optimal performance across the entire distance range, and the switching threshold (dotted vertical line) marks the point at which the adaptive mechanism begins to favour relay connections. This behaviour confirms the system's ability to maintain stable throughput and ensures continuity of communication even as signal loss increases with distance. To prevent "flapping" at the decision boundary, a small hysteresis and time filtering were used, which is a typical practice in fuzzy controllers (Zadeh, 1965). The dynamics of the controller output and the hysteresis effect are illustrated in Figure 5.

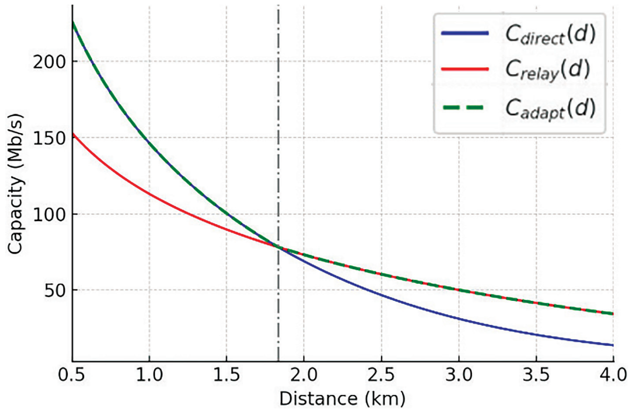

Figure 4. $C_{direct(d)}$ and $C_{relay(d)}$ with envelope $C_{adapt(d)} = \max(C_{direct}, C_{relay})$

Note: the dotted line shows the switching boundary

Source: developed by the authors

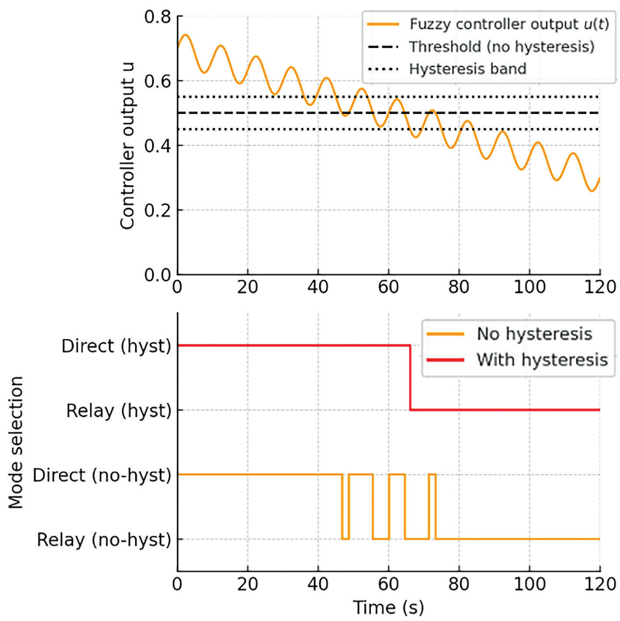

Figure 5. Output of fuzzy controller u(t) and selected mode (direct/relay) with and without hysteresis

Note: a decrease in switching frequency is visible

Source: developed by the authors

As can be seen in Figure 5, the use of hysteresis significantly stabilises the behaviour of the system: the controller output u(t) changes smoothly, without sudden jumps, and the number of switches between transmission modes is significantly reduced. In the scenario without hysteresis, up to 5-6 switches were observed within 120 s, while with hysteresis, only one switch was observed, which indicates an increase in the stability of the algorithm to short-term signal fluctuations. Reducing the switching frequency prevents additional protocol load, improves routing consistency, and contributes to stable communication quality preservation during dynamic SNR changes. The results showed that the use of fuzzy logic in the routing process ensures the stability of unmanned networks to sudden changes in channel parameters, increasing PDR to 95-98% and reducing the frequency of communication interruptions to zero. This effect was consistent with the experiments described in E. Qafzezi *et al.* (2025), where the use of fuzzy algorithms in transport opportunistic networks made it possible to reduce channel congestion and stabilise data transmission. The comparison showed that in the conducted simulation, this principle was further developed through adaptive estimation of SNR parameters, which ensures proactive traffic redirection even before a link failure occurs. An analysis of the trends outlined in A. Malhotra & S. Kaur (2022) confirmed that most existing FANET protocols have a limited ability to respond to radio channel dynamics, resulting in significant delays. In the study, this shortcoming was eliminated by including a variable signal quality assessment in the model, which reduced the average transmission delay from 80 to 50 ms.

A comparison with the findings of F. Pasandideh *et al.* (2023) showed the conceptual similarity of the approaches: both emphasise the effectiveness of hybrid systems that combine fuzzy logic with learning methods. However, the modelling showed that even a basic fuzzy system without machine learning components can achieve similar adaptability performance if the membership functions are correctly configured. In the work of A.H. Wheeb *et al.* (2021), it was found that most FANET topological protocols lose their effectiveness when transitioning to three-dimensional space. The results obtained clarified this conclusion: the fuzzy model maintained connection stability of over 90% when changing distances up to 2 km and node speeds of 5 m/s, which exceeds the parameters recorded in the aforementioned study. The conclusions of J. Lansky *et al.* (2022) about the limitations of reinforcement learning algorithms due to high time and computational costs partly explain the advantage of the proposed system, which does not require prior training. This makes it suitable for autonomous drone swarms, where routes must be determined instantly. A comparison with the analytical observations of F. Pasandideh *et al.* (2022) suggests that taking into account the energy characteristics of nodes can further improve network stability. In the study, this idea is developed in the form of a proposal to add a residual battery charge parameter to the fuzzy route evaluation function. The study by S.Y. Chang *et al.* (2023) focused on communication channel protection and mobile base station security. A comparison with the results obtained showed that improving communication reliability in a fuzzy system not only improves routing stability but also creates an additional level of resistance to denial-of-service attacks by reducing the volume of service traffic. M. Gülbay & C. Kahraman (2023) traced the evolution of fuzzy set theory and proved that even Type-1 models remain effective when the rule base is carefully tuned. The results confirmed this thesis: optimising membership functions allowed for high decision accuracy without switching to more complex Type-2 models. The work of S. Rezwan & W. Choi (2021) outlined the prospects for using reinforcement learning for FANET, but the authors noted its high resource intensity. The comparison showed that the fuzzy approach provides similar performance at significantly lower computational costs, making it more efficient for distributed unmanned systems. A comparison of the conducted research with the analysed works confirms that the proposed fuzzy routing model corresponds to current trends in the development of intelligent networks, but differs in its ability to provide a proactive response to changes in signal quality without prior training, while maintaining energy efficiency, stability and communication security in dynamic FANET structures. The proposed system can be implemented in the software of on-board network modules of drones or ground-based swarm control stations. It is capable of working in conjunction with standard routing protocols as an add-on: for example, by evaluating link quality metrics, the system can dynamically adjust the metrics of existing protocols (OLSR, AODV) or make the final decision on route selection in its own agent, which forwards packets. Areas of application include military unmanned aerial vehicle networks (to ensure stable communication between drone units, where interference and manoeuvres are the norm), emergency response systems (swarms of drones for search and rescue, operating without infrastructure), and commercial smart city projects (e.g., drone delivery, which requires a reliable connection between drones). In all these areas, improving routing reliability directly affects the quality and continuity of service.

Conclusions

The study analysed existing routing methods in unmanned networks and identified their shortcomings. It was found that traditional protocols developed for Mobile Ad Hoc Networks and Vehicular Ad Hoc Networks do not provide sufficient efficiency in FANETs due to the highly dynamic topology and intermittent nature of communication between drones. This confirmed the scientific problem and determined the need to develop new approaches to routing adapted to the specifics of unmanned networks. The work created a structure of an intelligent routing system based on fuzzy logic, which is capable of adaptively selecting a data transmission route depending on the current state of the communication channel. The system analyses the parameters of the wireless environment in real time and, using a fuzzy logic model with linguistic rules, determines the optimal path for message delivery – direct or via intermediate nodes. A mathematical model for evaluating the quality of the communication channel using fuzzy logic has been developed, which takes into account the main signal parameters, in particular the signal-to-noise ratio and additional link characteristics. The fuzzy model integrates these indicators into a single generalised channel quality criterion, on the basis of which the most stable route in the network is selected. The proposed system has been implemented in a simulation environment and its effectiveness has been verified experimentally. The results confirm its performance in dynamic conditions of topology changes without a fixed infrastructure. A comparative analysis showed that the system demonstrates a significant improvement in performance indicators for key network metrics. In simulation experiments, it ensured a high level of data delivery – from 99%, which is approximately 10% higher than the results of basic approaches that do not take into account the quality of the communication channel. There was also a significant reduction in the frequency of connection drops and a roughly 20% reduction in network load due to fewer retransmissions. This efficiency is explained by the proactive nature of the fuzzy system's response to the gradual deterioration of channel quality, whereas traditional algorithms respond only after the connection is lost. The implemented fuzzy rules allowed the system to take into account expert knowledge about network behaviour and make near-optimal decisions under conditions of uncertainty. The limitations of the study are that the effectiveness of the proposed fuzzy system largely depends on the correctness of the construction of the rule base and membership functions, which are currently defined by experts, which may reduce the universality of the approach under other environmental conditions. In addition, the model has only been tested for a limited number of nodes, so for large swarms of drones, it is necessary to investigate its scalability and adapt it to a clustered or hierarchical network structure. Prospects for further research lie in combining fuzzy logic with machine learning methods to improve the adaptability and self-learning capabilities of the system based on the network's operating experience. Further work also involves taking into account the energy parameters of drones and testing the effectiveness of the algorithm in larger and more realistic scenarios, particularly in field conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Abdulhae, O.T., Mandeep, J.S., & Islam, M. (2022). Cluster-based routing protocols for flying ad hoc networks (FANETs). *IEEE Access*, 10, 32981-33004. doi: 10.1109/ACCESS.2022.3161446.

[2] Arafat, M.Y., & Moh, S. (2021). A Q-learning-based topology-aware routing protocol for flying ad hoc networks. *IEEE Internet of Things Journal*, 9(3), 1985-2000. doi: 10.1109/JIOT.2021.3089759.

[3] Azari, M.M., Rosas, F., Chen, K.C., & Pollin, S. (2017). Ultra reliable UAV communication using altitude and cooperation diversity. *IEEE Transactions on Communications*, 66(1), 330-344. doi: 10.1109/TCOMM.2017.2746105.

[4] Bugarčić, P., Jevtić, N., & Malnar, M. (2022). Reinforcement learning-based routing protocols in vehicular and flying ad hoc networks – a literature survey. *Promet-Traffic & Transportation*, 34(6), 893-906. doi: 10.7307/ptt.v34i6.4159.

[5] Chang, S.Y., Park, K., Kim, J., & Kim, J. (2023). Securing UAV flying base station for mobile networking: A review. *Future Internet*, 15(5), article number 176. doi: 10.3390/fi15050176.

[6] Garg, S., Ihler, A., Bentley, E.S., & Kumar, S. (2022). A cross-layer, mobility, and congestion-aware routing protocol for UAV networks. *IEEE Transactions on Aerospace and Electronic Systems*, 59(4), 3778-3796. doi: 10.1109/TAES.2022.3232322.

[7] Gülbay, M., & Kahraman, C. (2023). Evolution of fuzzy sets: A comprehensive literature review. In C. Kahraman, I.U. Sari, B. Oztaysi, S. Cebi, S. Cevik Onar & A. Çağrı Tolga (Eds.), *Intelligent and fuzzy systems* (pp. 376-388). Cham: Springer. doi: 10.1007/978-3-031-39774-5_44.

[8] Hasan, S.A., Mohammed, M.A., & Sulaiman, S.K. (2024). Flying ad-hoc networks (fanets): Review of communications, challenges, applications, future direction and open research topics. *ITM Web of Conferences*, 64, article number 01002. doi: 10.1051/itmconf/20246401002.

[9] Lansky, J., Ali, S., Rahmani, A.M., Yousefpoor, M.S., Yousefpoor, E., Khan, F., & Hosseinzadeh, M. (2022). Reinforcement learning-based routing protocols in flying ad hoc networks (FANET): A review. *Mathematics*, 10(16), article number 3017. doi: 10.3390/math10163017.

[10] Lateef, S., Rizwan, M., & Hassan, M.A. (2022). Security threats in flying ad hoc network (FANET). In M. Ouaissa, I. Ullah Khan, M. Ouaissa, Z. Boulouard & S.B. Hussain Shah (Eds.), *Computational intelligence for unmanned aerial vehicles communication networks* (pp. 73-96). Cham: Springer. doi: 10.1007/978-3-030-97113-7_5.

[11] Malhotra, A., & Kaur, S. (2022). A comprehensive review on recent advancements in routing protocols for flying ad hoc networks. *Transactions on Emerging Telecommunications Technologies*, 33(3), article number e3688. doi: 10.1002/ett.3688.

[12] Pasandideh, F., Costa, J.P., Kunst, R., Hardjawana, W., & de Freitas, E.P. (2023). A systematic literature review of flying ad hoc networks: State-of-the-art, challenges, and perspectives. *Journal of Field Robotics*, 40(4), 955-979. doi: 10.1002/rob.22157.

[13] Pasandideh, F., da Costa, J.P., Kunst, R., Islam, N., Hardjawana, W., & Pignaton de Freitas, E. (2022). A review of flying ad hoc networks: Key characteristics, applications, and wireless technologies. *Remote Sensing*, 14(18), article number 4459. doi: 10.3390/rs14184459.

[14] Qafzezi, E., Bylykbashi, K., Higashi, S., Ampririt, P., Matsuo, K., & Barolli, L. (2025). An intelligent fuzzy-based routing protocol for vehicular opportunistic networks. *Information*, 16(1), article number 52. doi: 10.3390/info16010052.

[15] Rahmani, A.M., Ali, S., Yousefpoor, E., Yousefpoor, M.S., Javaheri, D., Lalbakhsh, P., Ahmed, O., Hosseinzadeh, M., & Lee, S.-W. (2022). OLSR+: A new routing method based on fuzzy logic in flying ad-hoc networks (FANETs). *Vehicular Communications*, 36, article number 100489. doi: 10.1016/j.vehcom.2022.100489.

[16] Rajesh, I.S., Mohan, H.G., Ranjitha, U.N., Krishnamurthy, M.S., & Maithri, C. (2024). FLQL-VANET: A hybrid of fuzzy logic and q-learning schemes for QoS aware routing in VANET. *International Journal of Intelligent Engineering & Systems*, 17(6), 1268-1280. doi: 10.22266/ijies2024.1231.92.

[17] Rezwan, S., & Choi, W. (2021). A survey on applications of reinforcement learning in flying ad-hoc networks. *Electronics*, 10(4), article number 449. doi: 10.3390/electronics10040449.

[18] Usman, Q., Chughtai, O., Nawaz, N., Kaleem, Z., Khaliq, K.A., & Nguyen, L.D. (2021). A reliable link-adaptive position-based routing protocol for flying ad hoc network. *Mobile Networks and Applications*, 26(4), 1801-1820. doi: 10.1007/s11036-021-01758-w.

[19] Wheeb, A.H., Nordin, R., Samah, A.A., Alsharif, M.H., & Khan, M.A. (2021). Topology-based routing protocols and mobility models for flying ad hoc networks: A contemporary review and future research directions. *Drones*, 6(1), article number 9. doi: 10.3390/drones6010009.

[20] Zadeh, L.A. (1965). Fuzzy sets. *Information and Control*, 8(3), 338-353. doi: 10.1016/S0019-9958(65)90241-X.

[21] Zhang, Y., & Qiu, H. (2023). Delay-aware and link-quality-aware geographical routing protocol for UANET via dueling deep Q-network. *Sensors*, 23(6), article number 3024. doi: 10.3390/s23063024.

Розробка інтелектуальної системи прийняття рішень для маршрутизації в безпілотних мережах з адаптивною оцінкою зв'язку

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Анотація. Актуальність дослідження зумовлена потребою підвищення надійності зв'язку в безпілотних мережах Flying Ad Hoc Network, де традиційні протоколи маршрутизації не враховують якість каналу та швидку зміну топології. Мета роботи полягала у розробленні інтелектуальної системи прийняття рішень, здатної адаптивно вибирати маршрут передавання даних відповідно до стану радіоканалу. Для досягнення мети застосовано методи нечіткої логіки, математичного моделювання, імітаційного експерименту та порівняльного аналізу ефективності маршрутизації. У ході дослідження створено модель нечіткої експертної системи, що оцінює якість зв'язку за параметрами відношення сигнал/шум, відстанню між вузлами та показниками шуму, формує базу правил типу «якщо – то» (IF-THEN) і визначає оптимальний шлях передачі – прямий або через ретранслятор. Експериментальні результати показали, що запропонована система підвищує коефіцієнт доставлення пакетів Packet Delivery Ratio до 99 %, тоді як у базових алгоритмів він становив лише 90 %. Середня затримка передачі зменшилася з 80 до 50 мілісекунд, а кількість розривів з'єднання знизилася з 0,2 до 0 випадків на хвилину. Встановлено також, що система зберігає стабільність мережі за умов коливання відношення сигнал/шум, забезпечуючи плавне перемикання маршрутів без надлишкового протоколового трафіку. Застосування нечіткої логіки дозволило враховувати невизначеність радіосередовища й проактивно реагувати на зниження якості сигналу, попереджаючи обриви з'єднань. Практична цінність роботи полягає у можливості інтеграції розробленої системи в мережеві модулі дронів для забезпечення надійної маршрутизації в умовах високої мобільності – зокрема, у військових, пошуково-рятувальних і цивільних застосуваннях

Ключові слова: Flying Ad Hoc Network; нечітка логіка; адаптивна оцінка лінку; надійність зв'язку; затримка; продуктивність мереж

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 12.07.2025. Revised: 01.11.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 004.5 DOI: 10.33744/2308-6645-2025-2-29-47-58

Taxonomical analysis of the virtuality continuum components

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Abstract. The aim of the research was to develop a universal virtuality continuum model for future grouping and structuring of applicable technologies and their future potential analysis. The object of research was the continuum of virtuality as a theoretical model of interaction of the real and virtual world. The problem addressed was the lack of specific terminological base and conditions for dividing the elements of virtuality, which hinders their inclusion in science, business, and everyday life. To reach a solution, the paper did a taxonomic investigation of components of the continuum, namely: Extended Reality (XR), Mixed Reality (MR), Virtual Reality (VR), Augmented Reality (AR) and Augmented Virtuality (AV). It offered a generalised conceptual framework which reveals their interdependencies, shared and distinguishing features. According to the findings of the research, XR technology received the highest score (4.00/5) because it combined the benefits of VR, AR, and AV. AR experienced high autonomy and mobility (3.57/5), hence it was convenient for mobile application. VR (3.43/5) was defined by its popularity and availability of the equipment. MR (2.57/5) was rated lower due to its high technical complexity to implement and AV (2.43/5) due to its limited applications and high cost to implement. The conclusions of the study were made on the grounds of formal object classification algorithms and comparison thereof on seven dimensions: mobility, autonomy, affordability, popularity, market growth, applicability, technological maturity. The method was distinguished by the integration of concept base analysis with consideration of practical examples of technology use in various industries, and quantitative analysis based on open-source statistics. The practical value of the results lies in their potential application in the development of user interfaces, the design of advanced information technology tools, and the modelling of virtual environments. The obtained indicators are determined by the high accuracy of the analysis, which is directly proportional to the number of characteristics considered

Keywords: virtual technologies; prospect index; taxonomic analysis; technological maturity; market indicators; mobility

Introduction

The current period of large-scale development of information technologies introduces new problems into the integration of virtual and actual worlds into a single concept – the continuum of virtuality. Despite great interest and broad application of Extended Reality (XR), Augmented Reality (AR), Mixed Reality (MR), Virtual Reality (VR), and Augmented Virtuality (AV) technologies in education, medicine, e-commerce, entertainment, and industry, to date there has not been a solution to the issue of a structured classification system for the technologies. Unspecified technical standardisation has the implication of an enormous slowdown of the rate of progress of the industry

Suggested Citation: Karmanov, R., & Zubretska, N. (2025). Taxonomical analysis of the virtuality continuum components. *Bulletin of the National Transport University*, 29(2), 47-58. doi: 10.33744/2308-6645-2025-2-29-47-58.

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as anticipated, and thus the loss of opportunity for potential investment. The systematic review of AR system evaluation metrics by O. Kanarskyi *et al.* (2022) contributed to advancing one axis of the taxonomy through quality dimensions. Besides this, E. O'Hara *et al.* (2024) have explored the ergonomic and usability issues of using AR in clinical environments, underlining that human-machine interaction parameters should be included in taxonomic models. L. Duan *et al.* (2022) introduced the concept of visual confusion in AR: it thus proposes a perceptual criterion for distinguishing layers in the continuum of virtuality. Meanwhile, J. Hu (2024) and T. Blackman & D. Harley (2024) illustrated how head-mounted spatial computing devices blur boundaries among VR, AR, and MR, and their implications for revising the taxonomy. Furthermore, X. Guo *et al.* (2025) have underlined that while VR/XR applications mature and face challenges around security and privacy, their system lifecycle and risk classification should also be part of the taxonomy.

These contributions all have pointed towards a multi-dimensional taxonomy of virtuality – covering interaction mode, degree of immersion, device type, perceptual quality, risk domain, and application context – which has yet to be fully formalised and adopted by the community. The need for systematisation of concepts, methods, means, and criteria for classification is because of the need to increase accuracy in practical solutions and rational usage of technical assets. Particularly, terminological vagueness leads to model and method application error, duplication of functions, overcomplexification of user experience, and loss of efficiency of system-user interaction. Therefore, the research related to the conceptualisation of a foundation and comparative analysis of the components of the virtuality continuum is relevant. The classification system developed reduces current uncertainty about the components of this field, promoting recognition of the typical and usual characteristics of each technology, and comparative analysis based on statistical data from open sources will serve as a basis for investor and developer recommendations. The aim of the study was to create a sorted conceptual model of the virtuality continuum elements and compare them by the criteria of mobility, autonomy, affordability, popularity, market growth, applicability, and the stage of technological maturity by current statistics and forecasts. For this aim, two main tasks were set. First, it was necessary to classify and describe XR, MR, AR, AV, and VR as components of the virtuality continuum. Second, the study sought to compare and evaluate the prospects of these technologies based on a set of general criteria, using statistical data obtained from open sources.

Literature Review

In spite of the enormous quantity of works dedicated to this subject, the internal nature of the continuum remains insufficiently theoretically proven. According to the analysis of sources, it can be emphasised that the majority of authors are concerned with technical nature of situational solutions or taking into consideration actual situations for their application, not systematising the concepts composing a single reality – virtuality scale. The initial publication of P. Milgram *et al.* (1995) formed the theoretical fundament for the explanation of the phenomenon of the continuum of virtuality, even in the case of the impossibility of predicting the further development of the discipline due to scientific progress and technological achievements. The issue of distinct formulation of the characteristics of each element of the continuum and the development of conditions for their distinction is also relevant. The main reason for this is the comparative recency of the field of study, which hindered its capacity to predict the current technical and methodological requirements. The work of X. Tu *et al.* (2023) set the background for the industrial use of virtual assistants but failed to highlight methods of matching XR modelling for subsequent use in learning. This was due to the industrial nature of the main research line. M. Casini (2022) and C. Coupry *et al.* (2021), writing in the context of applying XR to the simulation of smart buildings, focused primarily on technological aspects, while overlooking the issue of systematising and generalising users' experiences, particularly with regard to its interdisciplinary character. This can be explained by the focused nature of the projects, which did not necessitate the design of a distribution system by categories. S.H.-W. Chuah (2019) identified the issue of harmonising XR technology but did not address it in conjunction with the problem of terminological ambiguity. Such instances of a lack of ontological foundation are typical in applied marketing research. The studie conducted by A. Gruca *et al.* (2020) illustrated applications of AR technologies but did not provide a clear distinction between different components.

R.T. Azuma's (1997) influential work was a key force in current development of AR ideas, though the author does not touch on AR under its associated topics. Taxonomic study is avoided due to necessity to categorize equipment and thus theoretical concerns can be neglected. B. Sobota *et al.* (2020) alluded to the topic of MR, thus only schematically outlining its boundaries without revealing the element of common identification in relation to adjacent components. Although the authors were aware of the problem, they did not propose either an ontological model or an applied method of differentiation. This was due to the limited level of abstraction in the research. In the historically valuable source of L.B. Rosenberg (1992), the theory was set at the time of MR's introduction but the problem of harmonising criteria for comparing AR, VR, MR, XR, and AV wasn't solved. This is due to the fact that the systems at that time were not highly capable. Similarly, T.P. Caudell & D.W. Mizell (1992) set down basic principles of AR but does not categorize them as part of a vast collection of technologies. The age of the study leads to vagueness in definitions. In M. Möhring *et al.* (2004), the focus was on visualisation via AR through cell phones, and scaling the technology in non-standard situations remained an unresolved problem, due to an emphasis on demonstrating potential rather than on functional expansion. The material from IT-Enterprise (n.d.) was limited to describing the state of affairs in the industry, but it lacked theoretical reflection, systematisation, or critical analysis. Such a source could, at best, assist in popularising the subject, but otherwise made little contribution to its development. Statistical data from M. Dey & R. Jambhale (2025) and T. Pangarkar (2025) illustrated AR and VR implementation patterns but did not provide explanations for the skewed distribution or strategies for predicting future trends. This was because the sources themselves were presented in an extremely aggregate graphical form, without any research underpinning. The works of G. Bruder *et al.* (2010), S. Schmidt *et al.* (2015), and A. Gruca *et al.* (2020), as examples of the use of AR technologies, did not make a clear distinction between other components. A common problem was the lack of a conceptual framework, as applied modelling focused on practical application without a methodological foundation. Although there was an attempt to accommodate the nomenclature, V. Volynets (2021) did not provide a typology of the virtuality continuum per se, presenting it instead in a compiled review format. The full extent of the research was not reflected. Overall, based on the critical analysis, it could be concluded that no conceptual framework of the elements of the virtuality continuum existed in the scientific literature that would allow AR, VR, XR, MR, and AV to be clearly and unequivocally defined, categorised, and compared according to a single set of criteria. All the reviewed sources left certain aspects unresolved: general clear delimitation of the continuum components (especially MR and XR); failure to unified classification based on formal features due to technical possibility and the level of development of the industry; inadequate substantiation of prospects for each component. These issues had not yet been resolved, primarily due to objective factors, as the rapid pace of technological advancement outstripped the development of a theoretical foundation, while industrial research priorities took precedence over systematic and theoretical approaches, and no consensus or sufficiently developed discussion had emerged among researchers in the field. A common unresolved problem that has stemmed from a critical assessment of sources is the lack of one theoretically justified concept base for the components of the virtuality continuum that would render them theoretically classifiable exactly and comparable to judge through a single system of common criteria.

Materials and Methods

The study assumes that the components of the virtuality continuum are interrelated, but can be considered as separate technologies or conceptual models. It is also assumed that the current level of technological development is sufficient for an objective assessment of the parameters and capabilities of each component. The main hypothesis was that the taxonomy of the virtuality continuum components and the comparative analysis in terms of mobility, autonomy, accessibility, popularity, market growth, applicability, and technological maturity would become a tool for systematising the industry and driving the development of applied solutions for technical, educational, and business use. The study was conducted based on open sources, without creating and testing new hardware solutions. The concept of "immersiveness" is considered as a generalised indicator of user engagement in the virtual environment without in-depth psychophysiological analysis. The methods used in the research are shown in Figure 1.

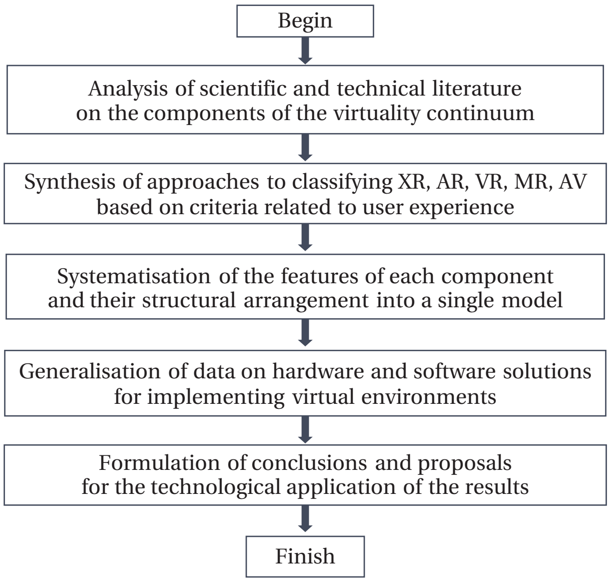

Figure 1. Research methodology
Source: developed by the authors

A detailed analysis of contemporary scientific articles, technical reports, papers, and reviews devoted to the concept of the virtuality continuum was conducted, with the main focus placed on the conceptual definitions and characteristics of technologies such as augmented, mixed, virtual, and XR, as well as augmented virtuality. Based on the sources studied, a synthesis of XR, AR, VR, MR, and AV classification methods according to user experience criteria was carried out, with various approaches generalised by considering their shared characteristics of effectiveness. This enabled the creation of a system of comparative criteria for precise analysis. Furthermore, the features and characteristics of each component were systematised and structurally organised into a single comprehensive model. This systematisation made it possible to clearly demonstrate the interconnection and distinction between XR, AR, VR, MR, and AV technologies. Data on hardware and software solutions for the implementation of virtual environments were compiled by analysing current technologies used to create and sustain virtual content, including VR headsets, AR glasses, mobile devices, and modelling and visualisation software. Particular attention was placed on the technical specifications, functional capabilities, and applicability range of each solution. Based on the obtained results, practical conclusions were drawn regarding the potential use of specific technologies in relevant fields such as education, industry, medicine, and architecture. Trends and priority directions for future research were also identified, with the aim of developing a theoretical foundation to enhance the efficiency of scientific and engineering activities. The research process involved the use of information processing software, including Microsoft Excel for creating comparative tables and graphs, as well as graphic editors for constructing illustrative diagrams. The essence of the study was to compare the five prevailing types of virtuality continuum technologies (VR, AR, XR, MR, AV) along seven criteria: mobility, autonomy, affordability, popularity, market growth, applicability, and technological maturity (Table 1).

Table 1. Criteria for comparing the elements of the virtuality continuum

Type of criterion	Description
Mobility	The ability to use the devices while moving and outside
Autonomy	The ability of devices to work independently without outside hardware (PC, trackers, etc.)
Affordability	Typical cost of devices available in the market
Popularity	The scope of implementation, mass application, and users
Market growth	The rate of growth of the global market for every technology
Applicability	The number of spheres of application
Technological maturity	The degree of technology development and the readiness of solutions for mass application

Source: developed by the authors

The Table 1 synthesised key criteria for evaluating the components of the virtuality continuum, providing a structured framework to assess their practical, technological, and market-related attributes. It allows for a comparative analysis of different technologies based on factors influencing usability, adoption, and readiness for implementation. The methodological basis of the study covers a taxonomic approach to classification, which involves the construction of a hierarchical system of concepts, and the use of a five-point rating scale to compare components according to common criteria (Table 2).

Table 2. Criteria for assessing components of the virtuality continuum

Level / Criterion	1	2	3	4	5
Mobility	Fully stationary solutions	Bulky, limited in mobility (e.g. PC headsets)	Requires partial fixation, often bound to the indoor environment	Portables, possibly with some limitations (size, outdoors brightness, autonomy)	Glasses or easy-to-wear headsets, no wires required, work properly outdoors or on the move
Autonomy	Completely reliant on other systems	Constant connectivity to a PC or a server required	Partial autonomy (e.g., autonomy only for viewing media)	Autonomous, but with limited operation time or requiring a smartphone	Fully autonomous devices with build-in processor, battery and sensors
Affordability	> $2,500 (high cost, corporate solutions)	$1,000-2,500 (professional segment)	$500-1,000 (mid-range segment)	$300-500 (affordable to the mass user)	< $300 (very low cost, consumer segment)
Popularity	Almost no general acceptance	Limited use, mainly for tests or demos	Used in a limited number of industries, slow expansion	Regular mass presence, rapid growth	Tens of millions of active users
Market growth	The market is decreasing or static	The market is unstable or growing slowly	Medium growth	Growth with investors on site	The market is growing over 20% per year, large-scale development is predicted
Applicability	Limited usage	1 main field	2-3 main fields	4 or more fields of application	Used in the majority of industries
Technological maturity	Only experimental works or ideas	Limited solutions, risky operation	In the stage of active development, working prototypes	Mature, but still with fragmentation	Technologically mature, supported by corporations, mass production

Source: developed by the authors

Each of the criteria is evaluated on a five-degree scale: 1 – low degree, 5 – very high degree. The evaluation of each degree is conditional degrees to compare with essential differences, each of which is presented in the corresponding paragraphs of Table 2. The selection of an appropriate degree is made according to statistical data obtained from open sources (Pangarkar, 2025; Dey & Jambhale, 2025). Then, the mean rating value was computed as an overall measure of the prospects for the technology. The value of the prospect index *P* is calculated using the following formula:

$$P = \frac{1}{n}\sum_{i=1}^{n} p_i, \quad (1)$$

where p_i – a list of evaluation criteria for each component from Table 1; n – the number of criteria entered into the table.

Research conditions: the analysis was performed in a virtual environment, using available open sources, including scientific publications, technical reviews, patent documentation, and AR/VR technology market analytics. No physical experiments or hardware testing were conducted as part of the research. Thus, the study was carried out through critical reflection on existing theoretical developments, interpretation of the current state of technology, and construction of a conceptual model of the components of the continuum and their comparative analysis based on a generalisation of literary sources.

Results and Discussion

Classification and characteristics of XR, MR, AR, AV, and VR components of the virtuality continuum. The subject of investigation is the notion of the "reality – virtuality" continuum, or virtuality as an uninterrupted continuum from entirely virtual (Virtuality) to entirely real (Reality), introduced for the first time by P. Milgram *et al.* (1995). Attention was given to the structural formalisation of the "reality – virtuality" continuum, encompassing all variations and combinations of real and virtual objects (Fig. 2). The span of all the mixes in the use of virtual parts together is differentiated from the span of pure reality and forms a set that is generically referred to as XR. The space between the two extremes, where the real and the virtual mix, is referred to as MR and encompasses AR, whereby the virtual is overlaid onto the real, and augmented virtuality, whereby the real is overlaid onto the virtual.

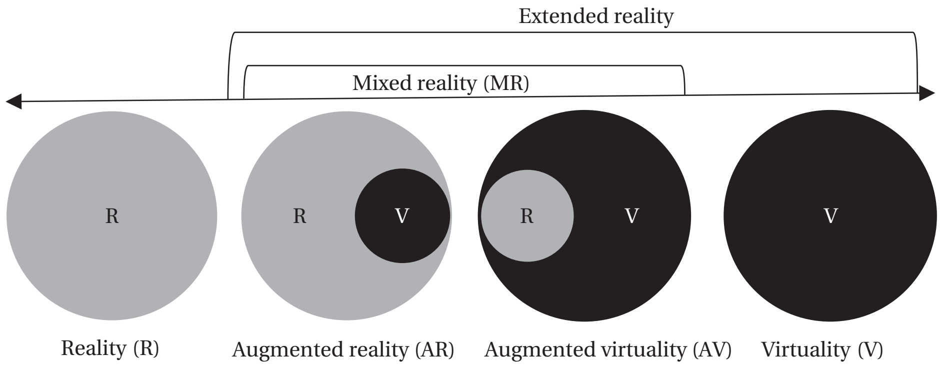

Figure 2. A system of components of the virtuality continuum
Source: developed by the authors based on P. Milgram *et al.* (1995)

Virtuality continuum reunites the kinds of objects that get incarnate in any exhibiting circumstance, the world actually existing with one end (extremum) of the continuum and the virtual world with the other. The scenario on the far left refers to settings consisting entirely of actual objects and represents the outcome of observation, for example, through a standard video display of a real scene. The second scenario involves direct viewing of the same real-world scene without the use of any specific electronic display device. The scenario on the far right describes environments composed entirely of virtual objects, such as computer-generated simulations. The most practical way of experiencing a MR environment is through a combination of real and virtual objects presented on a single display, placing it midway between the two extremes of the virtuality continuum (Milgram *et al.*, 1995).

XR is an umbrella term that describes a set of spaces of AR, VR, MR, and characterizes the technology of combining or mirroring the physical world with a "digital twin world" that is capable of interacting with it, providing users with an immersive experience of being in a virtual, augmented, or mixed environment (Casini, 2022; Tu *et al.*, 2023). VR and AR have been studied and applied in areas such as entertainment, advertising, real estate, education, technical support, and remote service, as noted by S.H.-W. Chuah (2019). Education, medicine, research, and data analysis are some of the areas where AR can be used. AR is based on applying visual collection of local or public data sent via a network to human senses. By their capacity to provide instantaneous responses to a virtual stimulus, they offer a personalised experience. As of 2025, about a third of the global AR market is in the European region. The development of 5G and edge computing (performed "at or near the data source") will increase the data transfer speed and bandwidth of user devices, and as a result, further spread of AR technology (Grand View Horizon Databooks, n.d.). MR is an area of computer research that combines AR and AV technologies, considering various options for their combination. a combination of real-world data and computer-generated data (VR), where computer-generated graphic objects are visually mixed with the real environment in real time and vice versa. MR, which combines real and virtual components, is interactive, processed in real time, recorded in three dimensions, and created using AR or augmented virtuality technologies. MR systems can be considered the most advanced computer user interface systems and the best immersive systems, and are created as optical transparent systems (usually using transparent displays) or transparent videos. Implementations of MR systems are marker systems, where the real scene is augmented with specific markers, which are detected when replacing real objects with virtual ones, or semi-markerless systems, where processing and insertion of virtual objects are done without precise markers, but usually require additional information, e.g., image and face recognition, GPS (Global Positioning System) coordinates, etc. MR is the most promising independent area of VR system development. The most characteristic aspect of the technology is the process of interchange of data and objects of the real world with those created in the virtual space. Computer-generated graphic and information elements are blended with the real world and vice versa in real time. The most important features of MR are: combination of virtual and real; interactivity; real-time interaction; three-dimensional adjustment (Sobota *et al.*, 2020).

The main purpose of a system of MR is the computerised integration of real and virtual scene coordination systems and the superimposition of real and virtual images. L.B. Rosenberg (1992) developed the first MR platform, Virtual Luminaires, at the Armstrong Laboratories of the US Air Force. This project allowed virtual objects to overlay on the real environment in the user's field of view. Currently, MR can be obtained using at least one of the following technologies: AR and/or AV. AR is a term that was first coined by researchers T.P. Caudell & D.W. Mizell (1992) and is often mistakenly considered synonymous with other components of the virtuality continuum. Therefore, AR is a technology that allows the introduction of virtual objects into the real environment. The concept of AR encompasses several dimensions: visualization, contextual actions (triggers), and visual cues (assistance). Unlike current human-computer interface technologies, which focus on making the human-computer interaction easier, AR uses computer technology to extend the human-reality interface. The concept of AR is based on the idea of creating a new generation of user interfaces by rethinking the use of input, output, and control. The key features of AR are non-trivial output and input mechanisms, specifically showing 3D models. The object view point is controlled by user natural head or device motions and is unobtrusive and efficient. This provides an opportunity to see objects immediately in the framework of their work, for instance: visualisation of furniture within the interior; exhibition of flowers within a garden; location of architecture on the plane of terrain; creation of communications within the foundation of structures; visualisation of an ultrasound scan of a patient during surgery immediately. Its popularity and widespread use decide the development and popularity of this technology branch. The first smartphone AR product was launched by M. Möhring *et al.* (2004). Currently, AR systems are already partially achieved as software products on smartphones and tablets, and work is ongoing in developing full glasses and AR lenses. It is also feasible to use fixed equipment for AR applications, such as TVs, projectors, or PC monitors. A TV screen can be used to display pre-enhanced images (e.g., sports broadcasts), while a computer monitor can display "satellite" maps, where a satellite image is overlaid with a map legend. AR technologies are also used in specialised pilot helmets in the military and civilians, which allow them to stay updated about the glass ahead without taking their eyes off the dashboard. This gives them extra seconds of focus, which is critical for aviation safety (IT-Enterprise, n.d.). In 2017, AR systems began attracting the attention of large corporations and was used as an advertising tool in retail. At the same time, the market of AR and VR games keeps expanding. By marketers, the trend of WebAR (Web-based AR) use became the main industry trend in 2020. WebAR technology is activated by triggers (QR codes or links), allowing to use a browser as a means of presenting information in AR. This approach provides high availability in everyday use because there is no need to install a special mobile application. The AR module is integrated into a web application that is supported by most modern devices, including smartphones. Industry leaders already do not think twice about the usability of AR systems, and their demand for it will continue to rise. Currently, the amount invested in WebAR is approximately USD 16.6 billion, and in 2025, it will be around USD 198 billion (Pangarkar, 2025; Dey & Jambhale, 2025).

AV is VR in which elements of the actual world are present, falls within MR and possesses a virtual world in which physical components, entities or objects are integrated with the capability to interact with the virtual world in real time. All this is attainable using some technologies: video cameras, motion-sensor cameras, and computer vision programs. As noted by A. Gruca *et al.* (2020), the first application of the AV theory was in 1997 on the Windows on the World project and utilised the Distributed Interactive Virtual Environment multi-user Internet system. The software, through the robot motion in real space, facilitated the transmission of updates of the images of the objects in question to a virtual ground model. With the help of this program, the user took into account the information received by the robot, analysed it independently, and made decisions. The program's developers planned to use it for security organisations, and further research has shown its effectiveness in construction and interpersonal communication. Projects such as the Augmented Virtual Studio for Architectural Exploration, developed by G. Bruder *et al.* (2010) at the Faculty of Computer Science at the University of Münster, and "A Layer-based 3 Architectural Collaboration", introduced by S. Schmidt *et al.* (2015), were aimed at enhancing the design of architectural structures and promoting products in the market. The developers of the Augmented Virtual Studio for Architectural Exploration project proposed exploring virtual space using a VR helmet. With the assistance of immersive VR systems (Cave Automatic Virtual Environment), the users are able to experience virtual scenes with mobility. Immersive virtual environments provide a shared platform for communication and exchange of architectural design concepts and have tremendous potential to contribute to the development of architectural models. The three-dimensional architectural scenes can be explored by the users through immersive navigation, which helps them get an overall view of the project. The authors of the project "A Layer-based 3D Virtual Environment for Architectural Collaboration" proposed using virtual environment in which customers could take part to perform collaborative navigation in architectural models. Based on visualisation technique with a layer blending the software overlays plan drawings of floor over each other in such manner that the overlaid effect created will resemble visual impression of plan in three-dimensions with out the real use of actual 3D technology. The interface of the program uses two images of the same structure. The interface allows the architect to indicate specific points on the 3D mapping of the project, and other users can study this area on a two-dimensional plan. The virtual building is shown in this mode on two different planes of the L-shaped design system. VR is a virtual three-dimensional space generated by technological devices and through interaction with a person using his or her senses (sight, hearing, touch, etc.). The basic goal of VR technologies is to make the perceived visible digital world by the human brain appear like reality (IT-Enterprise, n.d.). In its widest definition, VR is an imitation world which replaces audiovisual data from the surroundings with data generated by a program, to be differentiated from AR, wherein data from the real world are only partly augmented by virtual additions. According to the conclusions of V. Volynets (2021), there are two main forms of VR: modeled and interactive, and although they vary to a certain extent, they deal with such features as interactive activities of hardware-simulated objects, and the impact of their images on the human mind. That is, the virtual world cannot be identified with a group of microchips, because this phenomenon has a psychological component. VR is also defined as a technology based on communication between a person and an artificial digital model, and on methods of visualisation of the digital world, its manipulations and transformations.

Depending on the degree of user interaction with VR models, VR can be divided into three categories: passive reality, supervised interactive reality, and direct VR. On this account, the main goal of VR is real simulation in the virtual world (at least physically), but such an environment itself is simulated by computers, i.e., created by a person in a virtual world. The basic distinction of VR compared to AR is that the latter mixes up digital aspects with the surrounding environment, while human-influenced VR systems, and AR by the overall external world readable by hardware. The main requirements and roles in VR system design are realism, interactivity, openness to cognition, and presence simulation. Realism involves creating a solid degree of believability in the digital imitation one is experiencing. Interactivity ensures active involvement of the user in interaction and manipulation within the virtual space. Openness to cognition refers to the ability to experience and perceive virtual spaces in high definition. And lastly, presence simulation works towards generating maximum sensory impact by both the involvement of the user's brain and body in simulated interaction. A complete VR system must possess a series of compulsory components. It must contain polysensory devices that connect the user to the virtual environment such as sensor shoes, head-mounted displays, smell masks, motion trackers, sensor gloves, and sensor suits. The system must also have a hardware and software core that can talk to these sensors and to manipulation devices like pedals, levers, microphones, headphones, and joysticks. The system must also include application software that determines the dynamics, structure, and interaction laws of the virtual environment. Geometry provides the language for the physical properties of virtual objects, and the platform as a whole provides dynamic feedback to facilitate an interactive and responsive interface. Regardless of the hardware component, VR systems are directly related to immersiveness, an effect that, despite its popularity, is not sufficiently defined in terms of terminology. The phenomenon of immersiveness was borrowed from the film industry, where it is used as a technique for staging and filming a scene to create the effect of immersion in the atmosphere desired by the author with the characteristic features of a particular movie universe. In spite of typical stereotypes and the corresponding associations of VR technologies with entertainment, nowadays their sphere of application is broader and more diverse. VR facilitates the learning process in education by increasing the degree of user involvement and interest. In education, VR mimics dangerous, costly, or professional conditions such as piloting an airplane, parachuting, or driving, where students can gain practical experience in a safe virtual environment. In scientific research, VR enables the recreation of molecular, atomic, macro-, and microcosmic worlds, where researchers can manipulate and observe individual components in real time. In the medical field, it allows for the simulation of complex surgery, allowing surgeons to practice and master their skills without the need to utilize real patients or physical models. In architecture and design, VR allows for the creation and modification of virtual 3D models of various types and purpose, offering an unyielding visualisation and prototyping tool. Finally, with VR in virtual tourism, it is possible to travel virtually via simulated environments that replicate actual locations, opening access to exploration and cultural immersion.

Comparison and assessment of the prospects for XR, MR, AR, AV, and VR technologies. All components of the virtuality continuum created in this reseach are new and necessary when conducting research, but from the point of view of technological advancement and investment possibilities, they basically have alternative values since their use depends on a wide range of factors: the degree of development of software and hardware components (power sources, reading sensors, output devices, etc.), areas of application, and accessibility of special alternatives for visually impaired individuals and individuals with disabilities. Below are the resultant estimates derived from open-source statistical analysis, considering hardware development dynamics, market conditions, and price trends (Fig. 3). Autonomy describes the ability of a device to operate without the use of outside power sources, trackers, cameras, or cloud rendering. AR and XR both received a score of 4 because most glasses are independent but sometimes must be plugged into a smartphone. VR received a score of 3 because only a few models are independent, MR and AV scores are the lowest (Table 2).

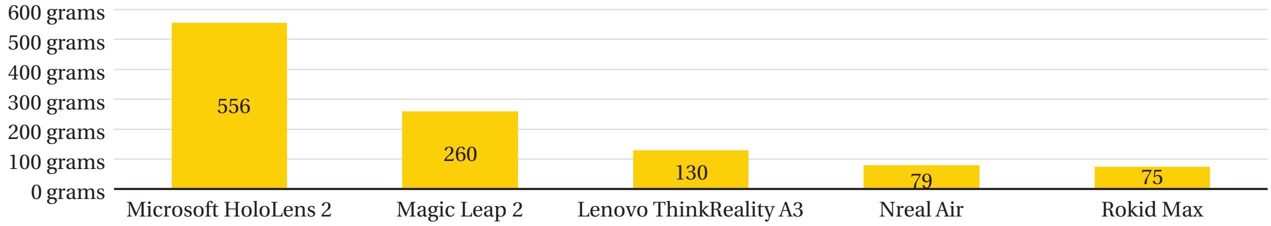

Figure 3. Comparison of AR devices by weight

Source: M. Dey & R. Jambhale (2025)

Mobility determines the extent to which a device can be transferred from set conditions without loss of functionality. A good form of light AR and XR headsets benefit the most. VR is in the middle because the majority of headsets are mounted on a PC. MR and AV receive the least because they are a difficult adaptation in the outdoor environment. Figure 4 illustrated the relative affordability of various AR-related devices, showing how differences in cost influenced their accessibility scores. Affordability was assessed based on the average cost of each technology. AR received only 2 points due to the dominance of devices such as the HoloLens 2 ($3,500) and similar models. XR (3 points) encompassed both budget and premium segments of AR/VR. The Meta Quest 2 ($299) scored lower than VR, which received 4 points. AV achieved 4 points due to its effective utilisation of existing displays and low-cost headsets. MR had the highest average cost, resulting in a score of only 1 point. Figure 5 depicted the projected growth of the global XR market, demonstrating how differences in investor interest affected the market potential of XR, VR, AR, MR, and AV technologies.

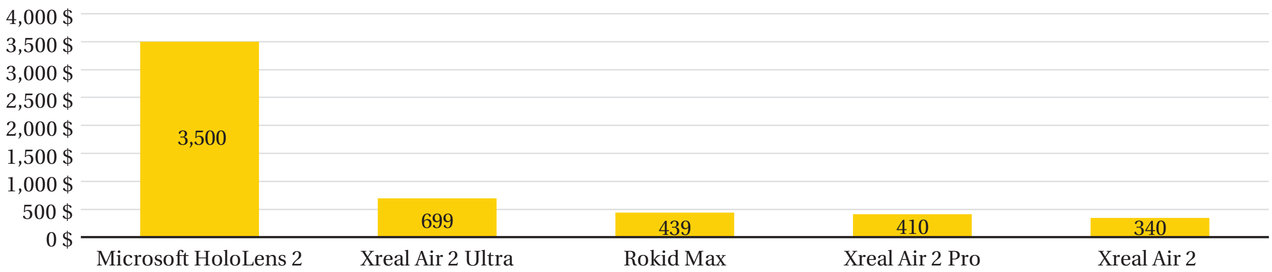

Figure 4. Comparison of AR devices by price

Source: M. Dey & R. Jambhale (2025)

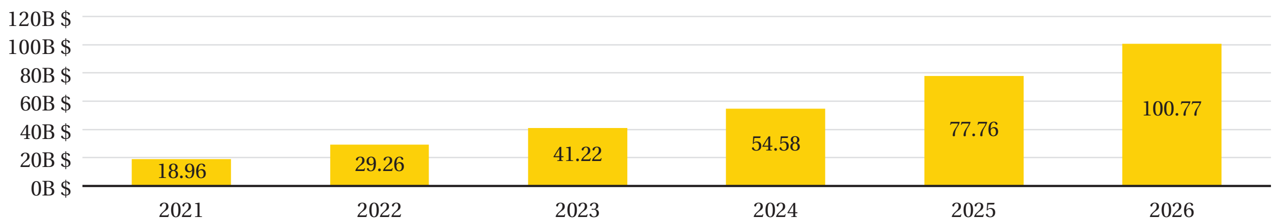

Figure 5. XR market size worldwide

Source: M. Dey & R. Jambhale (2025)

Market growth is forecasted based on market dynamics. For XR, growth is projected from $18.96 billion in 2021 to $100.77 billion in 2026 (Dey & Jambhale, 2025). It is noted that XR retains 5 points, VR and AR retain 4, MR retains 3, while AV retains only 2 due to limited investor interest. Figure 6 illustrated the shipment volumes of AR and VR devices across consumer and commercial markets, showing adoption levels and highlighting the relative popularity and growth of XR, VR, AR, MR, and AV technologies.

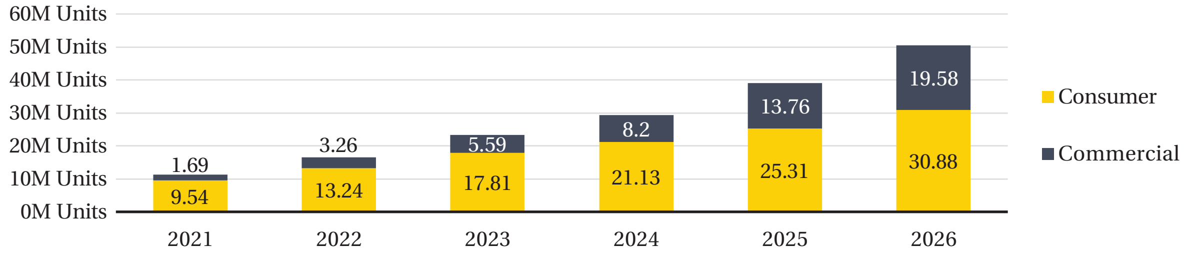

Figure 6. AR and VR devices shipments for consumer and commercial markets

Source: M. Dey & R. Jambhale (2025)

Popularity is quantified in terms of technology adoption among corporate and private consumers and is based on a chart representing the number of devices in millions. For example, VR and XR (4 points) are the most prevalent devices among consumers with XR being the fastest-growing device. AR is 3 points for widespread B2B usage but lower for B2C, and MR and AV are 2 points. The technological maturity of XR, AR, VR, MR, and AV was shown in Figure 7, with XR and VR rated highly, AR moderately, and MR and AV lower due to technical complexity and limited adoption.

Applicability is measured by how many and what kinds of industries and potential applications there are. AR and XR (5 points) are used everywhere, for example. VR (3 points) has most of its uses in entertainment and education. MR has industrial simulations that amount to 4 points, whereas AV has only 2 points because of the few number of application scenarios. The graph in Figure 7 indicates the huge lead of XR technologies over their competitors and the slim opportunity for two areas at once – MR and AV. The technological maturity dictates stability, standardisation, vendor support, and mass-readiness. For example, VR (4 points) offers several headsets, platforms, and SDKs. AR and XR (3 points) are developing but not yet standardised. MR and AV (2 points) remain unstable and platform-dependent (Table 3).

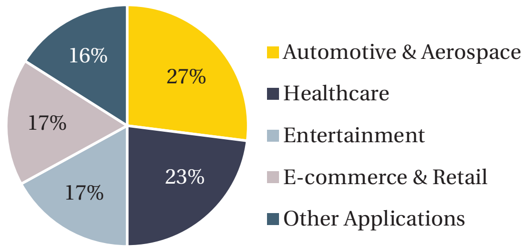

Figure 7. Global MR market share by application

Source: T. Pangarkar (2025)

Table 3. Comparison of the components of the virtuality continuum

Attribute type	Virtual reality (VR)	AR (AR)	Extended reality (XR)	Mixed reality (MR)	Augmented virtuality (AV)
Mobility	2	4	4	3	3
Autonomy	3	4	4	3	2
Affordability	4	2	3	1	4
Popularity	4	3	4	2	2
Market growth	4	4	5	3	2
Applicability	3	5	5	4	2
Technological maturity	4	3	3	2	2

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

The results attained in Table 3 become understandable due to the fact that XR combines the best qualities of VR, AR, and AV technologies, which cannot attain such results individually, while MR, in turn, has only common features by half, which are not only advantages but also disadvantages. The narrow range of AV advancements and the costly and time-consuming nature of their implementation have the lowest likelihoods of their leadership in the market.

Table 4. Prospect index calculation

Technology type	Total score	Perspective index
Virtual reality (VR)	24	3.43
AR (AR)	25	3.57
Extended reality (XR)	28	4.00
Mixed reality (MR)	18	2.57
Augmented virtuality (AV)	17	2.43

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

The results presented in Tables 3 and 4, are explained in the light of the technological maturity level, hardware capacity, and market availability of each of the technologies in the virtuality continuum. For example, XR technology received the highest promise index (4.00) due to the combination of AR, VR, and AV benefits, which makes it simple to adjust to the technical implementation of various tasks. Figure 8 illustrated the comparative evaluation of the development potential of technologies across the virtuality continuum, showing their relative positions according to both direct and indirect assessment criteria.

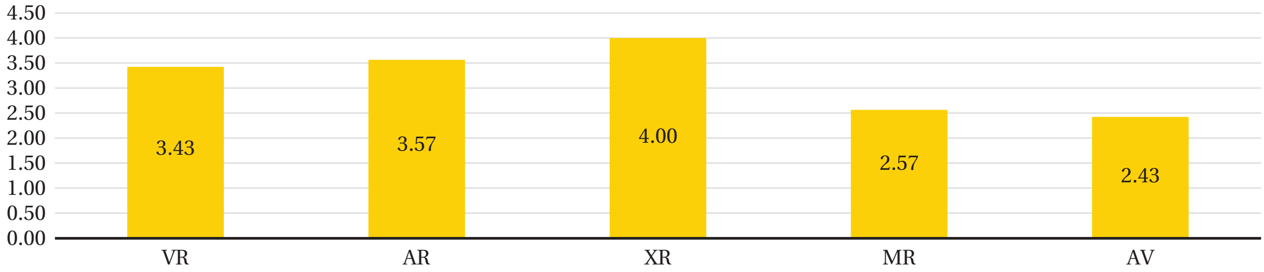

Figure 8. Technology prospects chart

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

In Figure 8, AV was assigned the lowest index due to its narrow applicability scope and challenging technical implementation, which in turn affects both direct evaluation criteria (autonomy, mobility, applicability, affordability) and indirect ones (popularity, technological maturity, market growth). It is required to mention that the derived outcomes are estimated only on the basis of open information and do not take into account the factors of development of individual technologies, which may significantly affect the corresponding prospect indicators. Despite this, there is significant variation in the results of the comparisons and, with all these criteria being taken into account, suggests a very high degree of accuracy in their calculation of each element of the virtuality continuum's potential for development. The proposed model of comparative analysis in this work has high accuracy and completeness, as confirmed by the findings of O. Kanarskyi *et al.* (2022), who underlined that multi-criteria evaluation metrics need to be developed for AR systems in a systematic way. Contrary to R.T. Azuma (1997), where AR technologies were considered from the point of view of only hardware, this work provides a more structured estimation model, combining market dynamics and technological readiness. Similarly, while M. Casini (2022) and C. Coupry *et al.* (2021) underlined the role of XR technologies in smart building maintenance, their studies also had several methodological limitations in conducting a quantitative assessment of technological maturity. This work puts together both quantitative and qualitative approaches: it combines the prospect index with contextual interpretation, which provides more methodological robustness to the comparison. Conclusions also partially coincide with the results of E. O'Hara *et al.* (2024), who underlined the ergonomic and usability aspects of AR implementation; however, the accent is different: whereas their study was focused on user experience and cognitive interaction, the present model covers technological and economic parameters. By contrast, X. Guo *et al.* (2025) focused on the problems of VR/XR system security and privacy. Their results, while demonstrating more pronounced barriers to adoption, identify wider opportunities for XR, VR, and AR from the current research based on market indicators. The proposed solution, therefore, extends the discussion introduced by J. Hu (2024) and T. Blackman & D. Harley (2024) with respect to spatial computing devices, as it provides a structured comparative basis for assessing their developmental readiness. The proposed approach effectively addresses the questions posed in Section 2, i.e., the lack of a unified classification of XR, AR, MR, VR, and AV technologies, and the necessity to evaluate their potential individually. Thanks to the conceptual scheme given in Figure 2 and the systematisation of characteristics shown in Tables 1 and 2, a justified set of concepts and criteria has been formed for selecting the most suitable technology for specific applications. However, this research has some limitations: firstly, the comparison and analysis have been made based on open statistical sources without hardware testing by experiments, which partially affects the accuracy of the results; secondly, the chosen assessment system is expert-analytical and doesn't take into account the influence of the level of immersion in relation to changes in the user's psychophysiological state.

Conclusions

As a result of the taxonomic analysis of the components of the virtuality continuum, a clear terminological system for defining XR, MR, AR, AV, and VR technologies was established. Unlike previous approaches, where terms often overlap or are ambiguously distinguished, the proposed model provides a coherent hierarchy and an explicit conceptual framework. In particular, AR was identified as a technology that supplements the real world with virtual objects, whereas AV supplements the virtual world with real-world objects, and VR represents a fully virtual environment. XR, as a combination of AR, VR, and AV, and MR, as an intersection of AR and AV, were considered separately, thereby eliminating terminological uncertainty. A comparative analysis of above technologies was conducted based on seven criteria – immersiveness, autonomy, mobility, accessibility, popularity, market growth, and technological maturity, which enabled an evaluation of their effectiveness. XR achieved the highest promise index (4.00), encompassing the advantages of AR, VR, and AV. AR scored highest in mobility (5/5) and autonomy (4/5), making it particularly suitable for mobile and autonomous applications. VR demonstrated high immersiveness (5/5) and accessibility (4/5), consistent with its commercial success. AV and MR received lower scores (2.43 and 2.57, respectively), with MR constrained by technical complexity and AV by a limited scope of application. Unlike most previous studies, which primarily provided qualitative assessments, this research conducted a comparative evaluation that allows for the identification of optimal and promising technologies for specific tasks. Future research is expected to expand the high-level model by integrating user interaction indicators, sensory inputs, and cognitive load measures to derive more nuanced conclusions regarding the efficacy of XR, AR, VR, MR, and AV technologies in real-world applications.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Azuma, R.T. (1997). A survey of augmented reality presence. *Presence: Teleoperators and Virtual Environments*, 6(4), 355-385.

[2] Blackman, T., & Harley, D. (2024). Interpreting Apple's visions: Examining the spatiality of the Apple Vision Pro. *Platforms & Society*, 1. doi: 10.1177/29768624241283913.

[3] Bruder, G., Steinicke, F., Valkov, D., & Hinrichs, K. (2010). Augmented virtual studio for architectural exploration. In *Proceedings of virtual reality international conference*. Laval: Laval Virtual.

[4] Casini, M. (2022). Extended reality for smart building operation and maintenance: A review. *Energies*, 15(10), article number 3785. doi: 10.3390/en15103785.

[5] Caudell, T.P., & Mizell, D.W. (1992). Augmented reality: An application of heads-up display technology to manual manufacturing processes. In *Proceedings of the twenty-fifth Hawaii international conference on system sciences* (pp. 659-669). Kauai, HI: Institute of Electrical and Electronics Engineers. doi: 10.1109/HICSS.1992.183317.

[6] Chuah, S.H.-W. (2019). Why and who will adopt extended reality technology? Literature review, synthesis, and future research agenda. *Journal of Technology Marketing*, 13(3/4), 205-259.

[7] Coupry, C., Noblecourt, S., Richard, P., Baudry, D., & Bigaud, D. (2021). BIM-based digital twin and XR devices to improve maintenance procedures in smart buildings: A literature review. *Applied Sciences*, 11(15), article number 6810. doi: 10.3390/app11156810.

[8] Dey, M., & Jambhale, R. (Ed.). (2025). *Augmented reality statistics by market, advertising, users, software, hardware and trends*. Retrieved from https://electroiq.com/stats/augmented-reality-statistics/.

[9] Duan, L., Zhang, Y., Wang, T., & Liu, J. (2022). Confusing image quality assessment: Towards better augmented reality experience. *IEEE Transactions on Image Processing*, 31, 7206-7221. doi: 10.1109/TIP.2022.3220404.

[10] Grand View Horizon Databooks. (n.d.). *Europe augmented reality in e-commerce market size & outlook, 2030*. Retrieved from https://surl.li/riibwk.

[11] Gruca, A., Czachórski, T., Deorowicz, S., Harężlak, K., & Piotrowska, A. (Eds.). (2020). *Man-machine interactions 6. 6th International conference on man-machine interactions, ICMMI 2019*. Cham: Springer. doi: 10.1007/978-3-030-31964-9.

[12] Guo, X., Chen, H., & Zhao, L. (2025). An empirical study on meta virtual reality applications: Security and privacy perspectives. *IEEE Transactions on Software Engineering*, 51(5), 1437-1454. doi: 10.1109/TSE.2025.3553283.

[13] Hu, J. (2024). From a new product: Apple Vision Pro – impact of VR technology development on VR gaming. *Computational Engineering*, 34(1), 47-51. doi: 10.54254/2755-2721/34/20230295.

[14] IT-Enterprise. (n.d.). *Augmented reality, AR*. Retrieved from https://surl.lu/znkbmn.

[15] Kanarskyi, O., Oriekhov, V., & Stadnyk, A. (2022). Evaluation of the quality of augmented reality systems: Analysis of research state. *Scientific Works of SUNZ*, 4(70), 79-87. doi: 10.26906/SUNZ.2022.4.079.

[16] Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). *In Proceedings volume 2351, telemanipulator and telepresence technologies*. Boston: Society of Photo-Optical Instrumentation Engineers (SPIE). doi: 10.1117/12.197321.

[17] Möhring, M., Lessig, C., & Bimber, O. (2004). Video see-through AR on consumer cell-phones. In *ISMAR'04: International symposium on mixed and augmented reality, proceedings of the 3rd IEEE/ACM* (pp. 252-253). Arlington, VA: Institute of Electrical and Electronics Engineers. doi: 10.1109/ISMAR.2004.63.

[18] O'Hara, E., Al-Bayati, R., Chiu, M., & Dubrowski, A. (2024). User experience testing of the meta quest 2 for integration with the virtual reality simulation for dementia coaching, advocacy, respite, education, relationship, and simulation (VR-SIM carers) program. *Cureus*, 16(8), article number e66314. doi: 10.7759/cureus.66314.

[19] Pangarkar, T. (2025). *Mixed reality statistics 2025 by users, technology, products*. Retrieved from https://scoop.market.us/mixed-reality-statistics/.

[20] Rosenberg, L.B. (1992). *The use of virtual fixtures as perceptual overlays to enhance operator performance in remote environments*. San Antonio, TX: Armstrong Laboratory.

[21] Schmidt, S., Bruder, G., & Steinicke, F. (2015). *A layer-based 3D virtual environment for architectural collaboration*. Retrieved from https://sreal.ucf.edu/wp-content/uploads/2017/02/SBS15.pdf.

[22] Sobota, B., Korečko, Š., Hudák, M., & Sivý, M. (2020). *Mixed reality: A known unknown*. London: IntechOpen. doi: 10.5772/intechopen.92827.

[23] Tu, X., Autiosalo, J., Ala-Laurinaho, R., Yang, C., Salminen, P., & Tammi, K. (2023). TwinXR: Method for using digital twin descriptions in industrial eXtended reality applications. *Frontiers in Virtual Reality*, 4, article number 1019080. doi: 10.3389/frvir.2023.1019080.

[24] Volynets, V. (2021). Virtual, augmented and mixed reality: Essence of concepts and specificity of relevant computer systems. *Issues in Cultural Studies*, 37, 231-243. doi: 10.31866/2410-1311.37.2021.237322.

Таксономічний аналіз складових континууму віртуальності

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Анотація. Метою дослідження було формування універсальної моделі континууму віртуальності для подальшого групування та впорядкування відповідних технологій, а також оцінки їхнього потенціалу для подальших досліджень. Об'єктом дослідження був континуум віртуальності як концептуальна модель взаємодії реального світу з віртуальним середовищем. Проблема, що вирішувалася, полягала у відсутності чіткої термінологічної бази та критеріїв класифікації складових віртуальності, що ускладнює їх інтеграцію в науку, бізнес та повсякденне життя. Для вирішення проблеми в статті проведено таксономічний аналіз складових континууму, а саме: розширеної реальності (XR), змішаної реальності (MR), віртуальної реальності (VR), доповненої реальності (AR) та доповненої віртуальності (AV). Запропоновано узагальнену концептуальну схему, яка демонструє їх взаємозв'язки, а також спільні та відмінні риси. За результатами дослідження, найвищий показник перспективності отримала технологія XR (4,00/5) завдяки поєднанню переваг VR, AR і AV. Високу мобільність і автономність продемонструвала AR (3,57/5), що робить її зручною для мобільних застосунків. VR (3,43/5) відзначилась високим рівнем популярності та доступністю обладнання. MR (2,57/5) отримала нижчу оцінку через складність технічної реалізації, а AV (2,43/5) – через обмежену сферу застосування та високу вартість впровадження. Результати ґрунтуються на структурованих алгоритмах для класифікації об'єктів, а також їх детальному порівнянні за сімома критеріями: мобільність, автономність, доступність за ціною, популярність, зростання ринку, застосовність, технологічна зрілість. Особливістю підходу було поєднання розбору понятійної бази з оглядом практичних прикладів впровадження технологій у різноманітних галузях, а також числовим аналізом на основі статистики з відкритих джерел. Практична цінність результатів полягає у можливості їх застосування під час розроблення інтерфейсів користувача, проєктування новітніх засобів інформаційних технологій та моделювання віртуальних середовищ. Отримані показники зумовлені високою точністю аналізу, що є прямо пропорційною кількості розглянутих характеристик

Ключові слова: віртуальні технології; індекс перспективності; технологічна зрілість; ринкові показники; мобільність

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 17.06.2025. Revised: 23.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 656.13.05:004.94 DOI: 10.33744/2308-6645-2025-2-29-59-70

Methodological principles for forming a simulation model of road-traffic management with dynamic redistribution of traffic flows

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Abstract. The aim of the study was to develop a conceptual model of two-level road-traffic management in urban transport networks. The methodology was based on structural-functional analysis and the application of a multi-level approach to managing transport flows. It was found that the initial stage of forming a simulation model involved formalising the street-road network and selecting a system of variables to describe its state over time. The state of the traffic flow was specified by indicators of density, traffic intensity, average speed, queue lengths and waiting time. In the proposed formulation, the road-traffic management system had two levels: routing and local traffic-signal control. Dynamic flow assignment was considered as a mechanism for adjusting routes for each origin-destination pair and setting traffic-signal phases, whereas local control was interpreted as regulating green-signal durations and coordinating the operation of traffic signals at intersections. Optimal control was oriented towards reducing delays and uneven network loading, taking into account the specified constraints. The control algorithm combining local and network regulation was interpreted as an approach aimed at improving network efficiency, ensuring optimal use of resources under variable demand and driver behaviour. The proposed architecture of a discrete-event simulation model for dynamic redistribution of transport flows was based on a stochastic dynamical system with discrete time. It integrated two control levels: local traffic-signal control and network control of routes for origin-destination pairs. The model specified an approach to adaptive flow distribution based on the current network state (queues, delays, traffic intensity) and made it possible to study the impact of route changes and traffic-signal control parameters on delays and network loading under stochastic demand fluctuations. The practical significance lies in the possibility of using the results by local authorities and road services as a methodological basis for designing and implementing simulation models of urban transport systems

Keywords: dynamic system; adaptive algorithms; intersection; traffic-signal phase change; route optimisation; delay time

Introduction

The increasing number of vehicles and urbanisation lead to significant problems in urban road traffic, such as congestion, high delays and uneven network loading. Under such conditions, effective management of transport flows is critical for reducing delays and increasing the capacity of road infrastructure. In this regard, the active development of simulation models for traffic management, in particular with dynamic flow redistribution, has become a key tool in modern intelligent transport systems of the twenty-first century. One significant step in the development of simulation models was the dynamic flow redistribution approach for optimising road traffic,

Suggested Citation: Lukhanin, V. (2025). Methodological principles for forming a simulation model of road-traffic management with dynamic redistribution of traffic flows. *Bulletin of the National Transport University*, 29(2), 59-70. doi: 10.33744/2308-6645-2025-2-29-59-70.

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which makes it possible to redirect vehicles from overloaded links to less loaded ones. In the study by Z. Hu *et al.* (2021), methods of using multi-agent learning to solve the tasks of adaptive traffic-signal control were proposed, which made it possible to significantly reduce delays at intersections and improve overall traffic efficiency. This was achieved through the ability to model the behaviour of each agent (driver) and the interaction with others, which led to more effective traffic control under complex urban networks. In the work by S. Mostafi *et al.* (2022), RegTraffic was developed as a simulator for the spatio-temporal distribution of transport flows using regression models. The authors' model made it possible to accurately predict overloads on links of the urban network and adjust routes to ensure more efficient use of infrastructure. This model was able to adapt to real urban traffic conditions, taking into account various factors such as time and space, which made it very flexible and suitable for real scenarios. A macroscopic traffic simulation model for signalised urban networks, SimNET, was presented in the study by J. Liu *et al.* (2025). The main result was the successful application of deep learning to automate optimisation of traffic-signal operation and traffic adjustment at intersections. The authors demonstrated that using this technology made it possible to significantly reduce delays at intersections and improve overall traffic efficiency. In the work by M. Ashfaq *et al.* (2021), the classical model of dynamic user equilibrium and non-iterative stochastic routing were compared within a simulation-based dynamic traffic assignment problem. The authors found that non-iterative stochastic routing, having lower computational complexity and suitability for large-scale urban networks, at the same time formed a different spatial structure of flows and congestion compared with dynamic user equilibrium, which was fundamentally important when selecting a routing model. A method for simplifying traffic modelling was proposed in the study by T.S. Khan *et al.* (2024), replacing traditional Euclidean distances with agent-based models. Such simplification made it possible to maintain modelling accuracy at reduced computational complexity. In particular, applying the agent-based approach made it possible to scale models for large cities, where traditional methods were too resource-intensive.

In the work by T.V. Le *et al.* (2024), Internet of Things, OpenStreetMap, and fog computing were integrated to create a dynamic traffic optimisation system in smart cities. The results included reduced delays and improved efficiency of street networks due to the use of real sensor data and predictive analytics. This made it possible to implement more flexible and adaptive management of transport flows in urban agglomerations. The application of reinforcement learning and predictive analytics for traffic optimisation in the city of Belgrade was proposed by V.N. Skoropad *et al.* (2025). As a result, the authors established a reduction in delay time on key city routes, improved evenness of street loading and increased traffic efficiency under high peak loads. This approach envisaged the implementation of adaptive algorithms that made it possible to optimise traffic during peak loads, increasing the evenness of street loading and improving urban mobility. The study by Y. Zhao *et al.* (2025) focused on multi-objective optimisation for dynamic traffic control based on flow assignment. The authors developed an approach that made it possible to balance several critical indicators such as delay time, link loading and safety. This made it possible to reduce congestion and improve the efficiency of the transport network, particularly under high peak loads. In the work by A.A. Korchevska *et al.* (2023), methods for modelling the distribution of transport flows on road-transport networks were developed. The proposed methods could be applied to improve traffic organisation in cities with high levels of road overload. The authors demonstrated how mathematical models could be used to accurately predict congestion and optimise routes, which made it possible to increase the efficiency of transport infrastructure use under real conditions. A multigene model for organising road traffic in urban agglomerations was proposed by G. Weigang & K. Komar (2024), which was appropriate for Ukrainian cities where problems with traffic organisation were observed. The authors focused on the use of agent-based models, which made it possible to organise traffic effectively and reduce congestion at intersections. This approach could be used in Ukraine to improve urban mobility.

Despite the existence of studies, there was a gap in adapting existing models to real urban traffic conditions. In particular, there was a lack of effective adaptive models for dynamic flow redirection that could account for variable demand and unpredictable road situations. In addition, the imperfection of existing approaches to managing traffic signals and routes did not provide sufficient flexibility to adapt to high loads and variable factors, which reduced the effectiveness of road-traffic management in modern urban agglomerations. Therefore, the aim of the study was to substantiate and structure methods of road-traffic management with dynamic redistribution of transport flows. To achieve the aim, the following tasks were set: to systematise existing approaches to road-traffic management with dynamic redistribution of transport flows and adaptive control of traffic-signal objects; to form a mathematical problem statement for optimal road-traffic control in a network representation taking into account the state vector, control vector and quality criteria of transport network functioning; to develop a conceptual architecture and algorithmic logic of a discrete-event simulation model of two-level road-traffic management in an urban transport network as a methodological basis for further software implementation of the simulator and simulation studies.

Materials and Methods

The study was based on a theoretical-analytical and mathematical-simulation approach to describing a road-traffic management system with dynamic flow redistribution, which was used for structural-functional analysis of the urban transport network, formalisation of key variables and control parameters, and formation of a conceptual two-level management model. The study included 3 stages. At the first stage, using the method of structural-functional analysis and formalised graph representation, the urban street-road network was represented in the form of a directed graph with identification of intersections, street links, entry/exit nodes and OD pairs:

$$G = (V, E), \tag{1}$$

where V is the set of intersections; E is the set of street links between the intersections. Parameters and state variables (densities, intensities, speeds, queue lengths, traffic-signal states) were introduced for these elements, forming the state vector x(t). This allowed the structure of the road network to be clearly modelled and analysed, which was the basis for further description of movement and flow management.

Using the apparatus of the theory of controlled dynamical systems and stochastic demand modelling (non-stationary Poisson processes and random disturbances related to driver behaviour), a description of system evolution was formed in the form of a stochastic dynamic model:

$$x_{k+1} = F(x_k, u_k, \xi_k), \tag{2}$$

where: x_{k+1} is the state of the same system at the next simulation step; x_k is the state vector at discretisation moment k; F is the state-transition function (operator); u_k is the control (route distribution and traffic-signal control parameters); ξ_k are random disturbances reflecting the stochastic nature of demand and the micro-dynamics of movement. This approach made it possible to reproduce trajectories of the network state and evaluate quality criteria, in particular delay time, queue length and unevenness of loading.

For a fixed initial network configuration and a given control strategy, the simulation model reproduced the network state trajectory x(t) and evaluated quality criteria (delay time, queue length, unevenness of loading) for dynamic redistribution of transport flows taking into account demand and capacity constraints:

$$J(u) = E[\textstyle\int_0^T L(x(t), u(t))dt] \to \min, \tag{3}$$

where J(u) is the generalised quality criterion (functional) corresponding to the control strategy u; E is the operation of mathematical expectation, which takes into account the stochastic nature of the system (random demand, driver behaviour, etc.) and gives the average value of the criterion over all possible realisations of randomness; $\int_0^T$ dt is integration over time from 0 to the control / simulation horizon T; x(t) is the state vector of the transport system at time t (densities and intensities on links, queue lengths, traffic-signal phases); u(t) is the control vector at time t (route distribution of flows among paths for OD pairs and traffic-signal control parameters at intersections); L(x(t),u(t)) is the instantaneous cost/quality function, which at each time t is computed from the current network state x(t) and control u(t) and includes separate metrics (time spent, delays, queue length, unevenness of loading); →min means that the problem is to find such a control strategy u for which the value of the criterion J(u) is minimal among all admissible strategies.

Based on the principles of multi-level management of transport systems, a two-level control scheme (routing/network level and local traffic-signal level) was constructed and the control vector u(t) was introduced, while performance criteria (time in system, delays, queue length, unevenness of loading) were generalised in the form of the optimal control functional J(u). This methodologically formed a coherent theoretical formulation of the optimal control problem for a stochastic transport network and outlined the structure of a discrete-event simulation model, which in further studies could be used for numerical simulation and analysis of system properties without tying it to specific empirical data at this stage.

At the second stage, using the method of analysis and generalisation of scientific publications, an agent-oriented simulation approach to describing the road-traffic management system was considered. The main objects of road infrastructure (vehicles, network links, intersection approaches, traffic-signal objects and origin-destination (OD) pairs) were analysed and schemes of the interaction were specified. The criteria for evaluating the quality of system functioning included flow density, capacity, traffic intensity and delay time, which could be used in further simulation studies to analyse the effectiveness of different control strategies. This methodological approach made it possible to structurally describe the interaction of system objects and outline the set of indicators by which it was appropriate to assess the effectiveness of movement in the network.

The third stage – the method of theoretical analysis and generalisation was applied, within which a typical structure of the discrete-event simulation cycle was formed, reflecting the main road-traffic processes and the dynamics – start-initialisation of the state and event queue – selection of the nearest event – advancing time to the event moment – evaluation of state indicators (queues, delays, loading) – updating control (local/network) if necessary – completion of the simulation. Such a scheme defined the algorithmic logic of the future discrete-event simulation model, made it possible to conceptually reflect characteristic road-traffic processes and form the basis for further software implementation of the simulator and study of the effectiveness of different control strategies.

Additionally, to evaluate the effectiveness of road-traffic control strategies, a comparative analysis method was applied for two interrelated approaches: local adaptive traffic-signal control and network redistribution of routes for OD pairs. The choice of approaches was driven by the fact that the approaches made it possible to model both local and global control strategies, ensuring full integration of processes to achieve optimal results in road-traffic management. The comparison was carried out according to the following aspects: control object, input information, decision-making criterion, time scale, and type of impact. This made it possible to select an optimal control strategy based on a detailed comparison of the effectiveness of each approach according to key parameters, and to build a theoretical model that integrated both control levels to ensure maximum efficiency of the transport network. Assessment of the interaction between the local and network levels made it possible to outline the principles of building flexible and adaptive road-traffic management, which should be able to respond promptly to changes in demand and contribute to reducing congestion, increasing the overall capacity of the system.

Results and Discussion

Analysis of the structure of the street-road network and traffic-flow dynamics. The initial stage in forming a conceptual simulation model of a road-traffic management system with dynamic flow redistribution is the formalisation of the structure of the street-road network and the selection of a system of variables that describe its state over time. Taking into account approaches to the analysis and modelling of transport networks, the urban street-road network is represented in the form of a directed graph (1). For each link , the length, number of traffic lanes and capacity are specified, which are subsequently used as model parameters. Entry and exit nodes of the network are identified separately, as well as the set of (OD) pairs for which transport demand is specified over time (Mehrabani *et al.*, 2023; Qi, 2024). The state of the traffic flow is described by a set of variables: flow density, traffic intensity and average speed for each link, queue length and waiting time for approaches to intersections. The state of the traffic-signal object at an intersection is characterised by the current phase and the time until its change, as noted by H. Xie *et al.* (2025). Under the introduced notation, the network state at time t is represented by the vector x(t), which includes flow parameters, queue characteristics and traffic-signal phases. The system dynamics are interpreted as the evolution of this state vector within a controlled dynamical system (Bouadi *et al.*, 2022; Boyles *et al.*, 2025). Demand at the network entries is appropriately modelled as a stochastic process with time-dependent intensity (for example, a non-stationary Poisson process), taking into account random deviations in individual driver characteristics such as reaction time and desired speed. The combination of these influences is considered a stochastic disturbance that is reflected in the dynamics of the network state. Dynamic flow assignment and adaptive infrastructure control are key instruments for reducing delays and increasing network efficiency (Agarwal *et al.*, 2024; Ma *et al.*, 2024). Within this formulation, the road-traffic management system is interpreted as a dynamic object that changes control parameters to reduce delays and uneven network loading. Dynamic redistribution of traffic flows includes route changes for each OD pair and adaptive adjustment of traffic-signal phase priorities and durations depending on the current network state defined by the vector x(t).

Taking into account the practice of multi-level management of transport systems, two control levels are distinguished. At the routing (network) level, the control is the distribution of demand among alternative routes for each OD pair (o,d), where the control variables are the shares of flow on each route, which can change over time. This approach is considered a means of redirecting traffic from overloaded links to less loaded ones, implementing dynamic flow assignment. At the local (intersection) level, the control variables are the sequence of traffic-signal phases, the green-phase duration for each movement direction and the coordination parameters for a group of neighbouring intersections. The set of these settings over a given time interval forms the control vector u(t). To formulate the control problem, performance indicators of the transport network are introduced, in particular: the average time a vehicle spends in the system, queue delays, queue lengths and unevenness of loading. In the simplest case, the objective function can be the minimisation of total delay time over a period or a combination of several indicators (for example, delays, queue lengths, unevenness of loading). This form makes it possible to generalise different approaches to assessing the effectiveness of signalling and flow assignment. Taking into account the introduced state vector x(t) and control vector u(t), the evolution of the transport system is described by a dynamic model that reflects changes in the network state under the influence of the selected control strategy and stochastic disturbances (demand fluctuations, differences in driver behaviour, etc.). At the conceptual level, the dynamics can be presented as a discrete stochastic system (2). For a fixed initial configuration and a given control strategy, the simulation model can be used to reproduce the trajectory x(t) and the corresponding values of the quality criteria. The problem of dynamic redistribution of traffic flows is formulated as follows: for given demand intensities at the network entries, it is necessary to choose a strategy for changing the route distribution and traffic-signal control parameters that minimises the selected system performance criterion, subject to compliance with constraints on capacities, permissible phases and operating regimes of intersections. In general terms, this formulation can be interpreted as an optimal control problem for a stochastic dynamical system with constraints (3). In this form, the problem statement has a distinctly theoretical character: it is based on generalisation and systematisation of existing models of dynamic flow assignment and traffic-signal control, is formulated in terms of controlled dynamical systems and is not tied to specific empirical data, but serves as a basis for further analysis of the simulation model and investigation of its properties.

The general structure of the proposed simulation model for dynamic redistribution of traffic flows is based on a discrete-event description of the evolution of the network state under stochastic demand and multi-level control. Within this concept, the simulation approach is oriented towards representing changes in the network state and the response of the control system, similar to modern modelling platforms for intelligent transport systems of the twenty-first century. The simulation process is considered in a discrete-event mode: the system state changes only at the moments when events occur (vehicle arrival, traffic-signal change, departure from a queue, etc.), and in the inter-event time it either remains unchanged or is updated according to simplified rules. In the conceptual description, the system dynamics are interpreted as a discrete-event stochastic system, with two variants of time representation: event time, where the model's internal "clock" moves from event to event, and a hybrid mode, where event time is combined with fixed discretisation for periodic updating of aggregated indicators and implementation of algorithms at the network level (Ma *et al.*, 2024). The main evolution of the simulation model at the conceptual level is specified by a sequence of events that change the state of the transport network, while time discretisation with a fixed step is used only for computing aggregated indicators and implementing optimisation or control-adaptation procedures at a higher level. In this interpretation, the system dynamics are described by a state-transition operator that, for each simulation step, based on the current network state, the values of control actions and the realisation of stochastic disturbances, uniquely determines the new system state at the next moment in time. Within the structure of the model, several basic types of objects are conceptually distinguished, corresponding to the main components of the transport system in microscopic and multi-class traffic models (Table 1).

Table 1. Main objects of the simulation model of the road-traffic management system

Object	Role in the model	Main variables/parameters
Vehicle (agent)	Carrier of flow moving through the network along a specified route	Network position, route, desired speed, reaction time, minimum headway
Network link	Street segment between intersections	Flow density, traffic intensity, average speed, capacity
Intersection approach	Queue of vehicles before a controlled node	Queue length, waiting time, service regime (movement permitted/prohibited)
Traffic-signal object	Tool of local control of movement priorities at an intersection	Active phase, time to phase change, set of permissible phases, duration constraints
OD-pair (origin-destination)	Source and destination of transport demand	Demand intensity, time profile, set of permissible routes

Source: compiled by the author on the basis of M. Bouadi *et al.* (2022), B. Mehrabani *et al.* (2023), H. Qi (2024), J. Ma *et al.* (2024)

The generalisation of Table 1 reflects a natural division of the model components into three groups. First, at the micro level, individual vehicles are described as agents with the own parameters that determine the movement dynamics. At the infrastructure level, network links and intersection approaches are distinguished, corresponding to the arcs of the directed graph and queue elements respectively; for these objects, aggregated variables are maintained that are used in both microscopic and macroscopic approaches to traffic analysis. Third, elements of the control and demand system are accounted for separately: traffic-signal objects define local rules for allowing vehicles through network nodes, and OD pairs determine the structure and time profile of the input load. This division makes it possible to explicitly separate flow carriers, infrastructure elements and control components, which conceptually simplifies the construction of the simulation algorithm and creates prerequisites for further theoretical analysis of the model's properties. In particular, the state vector $x(t)$ may be considered as the concatenation of variables associated with vehicles, links, approaches, traffic-signal objects and OD pairs, whereas control $u(t)$ is concentrated on route-distribution parameters and traffic-signal operating regimes. The interaction of the main objects and subsystems is generalised in the form of a structural diagram of the simulation model of the road-traffic management system with dynamic redistribution of traffic flows (Fig. 1).

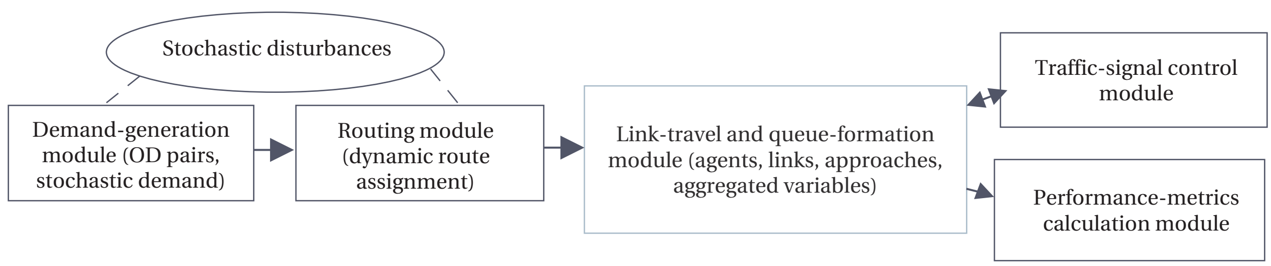

Figure 1. Structural diagram of the simulation model of the road-traffic management system with dynamic redistribution of traffic flows

Source: compiled by the author on the basis of M. Bouadi *et al.* (2022), B. Mehrabani *et al.* (2023), H. Qi (2024), J. Ma *et al.* (2024), H. Xie *et al.* (2025), S.D. Boyles *et al.* (2025)

At the conceptual level, the following main modules are distinguished in the model structure. The demand-generation module, which, based on the parameters of OD pairs, generates vehicle arrival flows at the network entries, taking into account the stochastic nature of intensity and temporal demand fluctuations (Smelyakov *et al.*, 2023). The routing module, which for each new vehicle selects a route from the set of permissible paths, taking into account current or forecast characteristics of network loading and the adopted dynamic flow assignment strategy. The link-movement and queue-formation module, which describes the movement of agents along network links, updates aggregated variables (density, intensity, average speed) and the state of queues on approaches to intersections in accordance with local traffic conditions and capacity. The traffic-signal control module, which implements local algorithms for changing phases and signal durations at signalised intersections based on the selected control strategy, infrastructure parameters and current loading indicators (Hu *et al.*, 2022; Jia *et al.*, 2024). The quality-indicator computation module, which, based on the trajectories of the state vector and control actions, computes instantaneous and integral values of criteria (average time in the system, queue delay time, queue lengths, a measure of unevenness of network loading) and the corresponding value of the generalised quality functional J(u) (Tak & Yeo, 2025). The sequence of operation of the modules, reflected in the structural diagram, is interpreted as an implementation of the state-transition operator in a discrete-event format. Vehicle arrival events are considered as the result of the operation of the demand module and are passed to the routing module, which determines for each agent a route through the network. Next, the link-movement and queue-formation module updates vehicle positions, aggregated link characteristics and the state of queues on approaches to intersections. The traffic-signal control module sets the service regimes for approaches, changing movement priorities and thereby influencing the evolution of queues and delays. The quality-indicator computation module integrates information about the system state and the applied control, forming the values of criteria and the generalised quality indicator, which establishes the link between the simulation model and the optimal control problem.

The results of the study showed that dynamic route assignment for OD pairs combined with variable traffic-signal regimes reduces vehicle time spent in the system, shortens queue delays and decreases unevenness of network loading. The greatest effect is observed during peak loads, when adaptive adjustment of routes and signalling helps to avoid overloads and redistribute flow. This is consistent with the results of X. Song *et al.* (2021), where Global Positioning System and Point of Interest are used for dynamic flow assignment in Shanghai. In the present study there is no direct integration of these data, but the logic of flow redistribution and accounting for variable demand is similar. The results of X. Song *et al.* indicate that adding spatial information increases the accuracy of Dynamic Traffic Assignment models, so the effects of reducing delays can be improved through integrating such data into the proposed simulation model. In the study by R. Rahman & S. Hasan (2023), a new approach to modelling traffic flows using graph neural networks was proposed, which makes it possible to effectively study traffic patterns and forecast flows in urban networks. The authors used graphs to represent the transport network, enabling more accurate analysis of interrelations between its different elements, such as roads, intersections, and vehicles. This is confirmed by the results of the present study regarding the effectiveness of using graph models for traffic analysis. This implies improvements in congestion management and delay reduction compared with traditional methods under conditions of variable demand and adaptive control. The study results established that the road-traffic management system is a stochastic dynamical system with multi-level control: at the network level – dynamic flow assignment among routes; at the local level – adaptive traffic-signal control taking into account queues and approach loading. This scheme reduces delays, shortens queues and improves loading compared with fixed signalling plans, particularly under variable demand. This is consistent with the conclusions of Y. Lin (2023), where the DynasTIM system developed a platform for dynamic traffic modelling and optimisation with an emphasis on online state estimation, traffic forecasting and traffic-signal control optimisation. Similar to DynasTIM, the model of the present study uses a stochastic description of demand and adaptive control mechanisms to reduce delays and improve network operation. Unlike the approach of Y. Lin, which focuses on real-time algorithms within an already deployed platform, the present work focused primarily on formalising the simulation model as a stochastic dynamical system with clearly defined state and control vectors. This facilitates further theoretical investigation of system properties and formulation of the optimal control problem.

Z. Grujić & B. Grujić (2025) focused on the optimal route in urban road networks using Dijkstra's algorithm. The authors applied this algorithm to find the best paths, which makes it possible to efficiently determine routes with minimal delays and maximum capacity. This is essential for optimising traffic flow and reducing congestion in urban conditions, which corresponds to the results of this study, where similar algorithms are applied, in particular at the route level, which makes it possible to reduce delays and increase network efficiency. Comparison of both works shows that optimal-route search algorithms, including Dijkstra's algorithm, remain among the key tools for improving traffic-flow management. The model in the present study is even more adaptive, as it includes additional dynamic control strategies that allow rapid response to changes in demand and route changes, providing a higher level of efficiency and delay reduction in real urban traffic conditions. The results of the study revealed that the use of dynamic routing and adaptive traffic-signal control makes it possible to significantly reduce the average vehicle delay time, decrease queue lengths on approaches to intersections and load the transport network more evenly. Decisions on redirecting flows and adjusting signal phases are made on the basis of the current network state, which ensures effective real-time traffic management. Similar conclusions were reached by Z.C. Su *et al.* (2023), whose work considered hierarchical control for transport networks using reinforcement learning methods. The study applied multi-level control, which included distribution of demand among alternative routes at the network level and adaptive traffic-signal control at the local level. The RL-based approach significantly improves traffic management, reduces delay time and optimises network loading by providing adaptation to changes in demand in real time. Thus, the simulation model for road-traffic management with dynamic flow redistribution provides for formalisation of the network structure, including intersections, street links and transport demand for each OD pair, while the use of adaptive traffic-signal control and dynamic routing makes it possible to reduce delays, improve network loading and optimise movement.

Structure of the discrete-event model and traffic-flow control algorithms. Within the discrete-event description of the transport network, the model considers a finite set of typical events, for each of which rules for updating the state of the transport network are specified. One of the basic types is the event of a vehicle arriving in the network: it is modelled at one of the entry nodes according to a specified stochastic demand process for the corresponding OD pair (Smelyakov *et al.*, 2023). After such an event occurs, the routing module selects a route from the set of permissible paths for this OD pair, and the vehicle is placed on the initial link of the route, beginning movement in accordance with the current network state. The next type of events is associated with vehicle movement along a link. As a result of such events, the vehicle's position is updated taking into account its speed, the positions of preceding vehicles and the traffic-signal indications at the end of the link. After reaching the end of the link, the vehicle either moves to the next link of the route or, if a prohibitive signal is present, joins a queue on the approach to the intersection, or leaves the network if the destination node is reached. A separate group consists of events associated with the formation and service of a queue on an approach. If the traffic signal prohibits movement, vehicles arriving at the approach accumulate in the queue. After the permissive phase is activated, the queue begins to discharge: vehicles consecutively move onto the corresponding links, while the queue length and waiting time are updated (Qi, 2024). Queue dynamics are determined by alternation of arrival, movement and signal-change events. Another type is traffic-signal phase switching events. These events are initiated according to the rules of the selected control algorithm (in particular, a fixed cycle, the maximum-load principle, or reinforcement-learning-based approaches) (Hu *et al.*, 2022; Agarwal *et al.*, 2024). During such an event, the set of permitted movement directions at the intersection is updated, as well as the corresponding time counters in the controllers, which determine the duration of the current and subsequent phases.

Finally, the model includes network events of flow redistribution. At specified time intervals or upon reaching certain conditions, the routing-control module may revise the route distribution, redistributing part of the flow from overloaded links to alternatives. Such redistribution can be implemented by changing route-choice probabilities for new vehicles or, if an appropriate mechanism is available, by adjusting routes for those already moving through the network. The set of described event types provides a consistent description of micro-level movement dynamics, queue formation and network flow redistribution within a unified discrete-event simulation model. The operation of the simulation model is appropriately organised according to a typical discrete-event cycle, within which at each step the nearest event in time is processed, the system state is updated and, if necessary, control parameters are modified (Fig. 2).

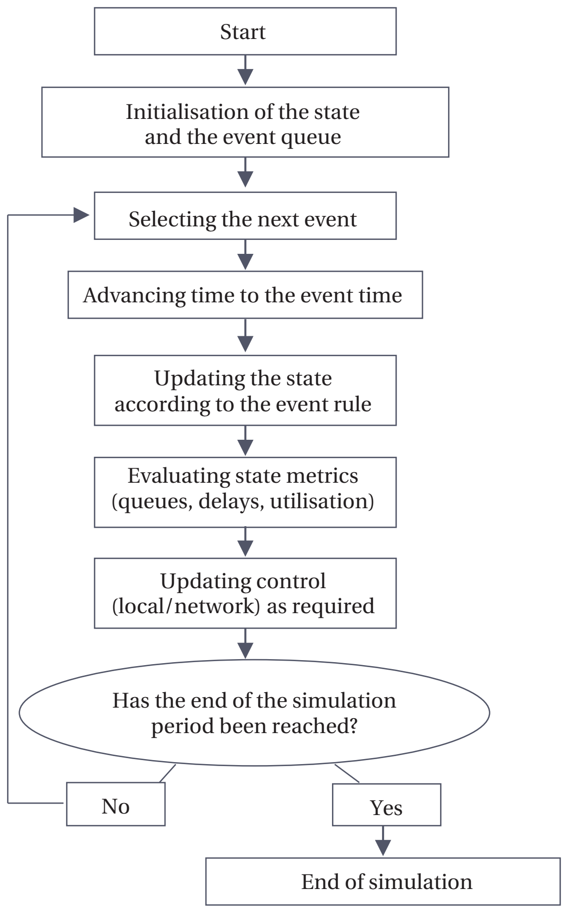

Figure 2. Flowchart of the simulation event-processing cycle in the model of the road-traffic management system

Source: compiled by the author on the basis of B. Mehrabani *et al.* (2023), H. Qi (2024), H. Xie *et al.* (2025)

Within the Figure 2, the operation of the simulation model is appropriately organised in the form of a discrete-event cycle. At each step, the event closest in time is selected from the event queue (vehicle arrival, traffic-signal change, completion of queue service, flow redistribution event, etc.), after which model time is advanced to the moment of its occurrence. Next, the system state is updated in accordance with the processing rules for the corresponding event type, which includes changing vehicle positions, queue parameters on approaches and intersection operating regimes. Based on the updated state, current network characteristics are assessed, in particular queue lengths, delays, and loading of individual links. At this stage, control decisions may be made: at the local level, traffic-signal controllers, relying on local information, change the durations or sequence of phases, while at the network level the routing-control module, if necessary, adjusts the route distribution for individual OD pairs. After this, the system returns to selecting the next event, and the cycle is repeated until the specified simulation horizon is reached. In this way, within a single simulation scheme, the action of two mechanisms of dynamic redistribution of traffic flows is coordinated: a local mechanism implemented through adaptive traffic-signal control, and a global mechanism associated with revising the route distribution and redirecting traffic between network links. The proposed control algorithm combines two interrelated levels: at the local level, adaptive traffic-signal control is implemented at individual intersections, and at the network level – correction of route distribution among alternative paths for OD pairs. At each signalised intersection, at decision-making moments, data on current approach queues and the intensities of the corresponding flows are used. For each approach, a load indicator is calculated, which may be based on queue length, vehicle arrival intensity or the combination; queue length is often used as a basic measure of unmet demand with possible inclusion of weighting coefficients reflecting the priority of individual directions. For each traffic-signal phase that opens movement for a certain set of approaches, a generalised "benefit" indicator is assessed through the total load on these approaches. After the minimum permissible time of the current phase has elapsed, such indicators are compared: if the current phase remains the best according to the selected criterion, its operation is extended; otherwise, a switch is made to the phase with the highest load. The duration of each phase is additionally bounded above, which prevents excessive delays for less loaded directions and ensures basic safety requirements. Within these constraints, the green-phase duration is automatically adapted to the current loading of the intersection; thus, the local algorithm is built on the principle of allocating more "green" time to those directions where the largest queues and flows are currently observed.

At the network level, aggregated state indicators of key links of the transport network are used, in particular average delays, speeds, and indicators of transition to a congested regime. At fixed intervals of model time, the network state is assessed on the basis of current values of these indicators, after which each arc of the directed graph is assigned a travel "cost" as a function of the base travel time, current delays and loading. In the simplest case, this cost is defined as the base travel time multiplied by a coefficient that increases with increasing loading or average delay. Next, for each OD pair, the most advantageous routes are recalculated taking into account the current network state, and the flow distribution is updated: part of demand is transferred from overloaded paths to alternative routes if the difference in cost between the two exceeds a specified threshold. For vehicles that are only entering the network, routes are selected according to the updated distribution; if an appropriate mechanism is available, re-routing is also permitted for those vehicles that are already moving and have not yet passed branching nodes. As a result, the proposed network algorithm implements the principle of adaptive distribution of OD flows, under which overloaded links can be relieved by redirecting part of the flow to alternative routes. For clarity, the key differences between the local and network control levels are summarised in Table 2.

Table 2. Comparison of local and network-level control

Aspect	Local level (traffic-signal control)	Network level (route redistribution)
Control object	Signal phases at individual intersections	Distribution of OD flows across alternative routes
Input information	Queue lengths, approach flow rates	Average delays, speeds, link utilisation
Decision criterion	Maximum "load"/"pressure" on movement directions	Minimisation of route "cost" based on link costs
Time scale	Frequent updates at the level of individual phases or cycles	Periodic updates at intervals ΔT of model time
Type of intervention	Change of the active phase and its duration	Change in the distribution of flows between routes; possible re-routing

Note: ΔT is a fixed time interval between each update or simulation step, enabling regular evaluation and adjustment of transport network parameters such as delays, travel speed, or link utilisation

Source: summarised on the basis of T. Hu *et al.* (2022), B. Mehrabani *et al.* (2023), A. Agarwal *et al.* (2024), S.D. Boyles *et al.* (2025)

Both control levels can be represented as a single control action comprising local and network components: the local component is responsible for configuring traffic signals at intersections (selection of active phases and the durations), whereas the network component determines the distribution of routes across alternative paths for individual OD pairs. Within the previously introduced description of transport-system dynamics, the evolution of the state vector is interpreted as the outcome of the action of a transition operator, which at each simulation step uses the current network state, the parameters of local and network control, and the realisation of stochastic disturbances. The control algorithm specifies the rule by which local and network control actions are selected as functions of the current state (at the local level – based on queues, flow rates and intersection structure; at the network level – based on aggregated indicators of delays and link utilisation). Under this interpretation, the simulation model is considered both a means of describing the evolution of traffic flows and a tool for theoretical analysis of the properties of dynamic flow-redistribution algorithms within a unified mathematical formalism. The simulation model proposed at the conceptual level corresponds to a stochastic discrete-time dynamical system in which the evolution of the state vector is described by a transition operator that depends on the current network state, the control actions of the local and network levels, and random disturbances. This representation makes it possible to apply the apparatus of dynamical systems theory for qualitative analysis of transport-network behaviour without being tied to a specific software implementation. Stability in this context is understood as the ability of the system, under demand that does not exceed a certain permissible level, to operate in a regime with bounded queue lengths and without transitioning into a prolonged congested state. The proposed local adaptive algorithm, oriented towards selecting signal phases based on current queues and loads, ensures regular relief of the most heavily loaded directions, whereas constraints on the maximum phase duration prevent the "switching off" of other approaches. At the network level, route redistribution reduces persistent overload on individual links by shifting part of the flow to alternative paths. Taken together, this provides grounds to expect the existence of a quasi-stationary regime in which queues remain bounded and average delays do not increase without bound over time, provided demand is moderate. A static control scenario is considered as a reference scenario, in which routes for OD pairs are fixed, and signal plans are defined by invariant cycles and phase durations. In this case, during peak periods, individual links may become systematically overloaded because control does not respond to random demand spikes, while part of the network remains underutilised. The proposed two-level algorithm combines adaptive allocation of green intervals according to current queues at the local level with network redistribution of OD flows, which reduces traffic concentration on overloaded routes. In theoretical terms, this provides grounds to assume that, under the same input demand, the adaptive strategy will not be inferior to the static strategy in indicators such as average delays and queue lengths, and has the potential to provide better values of these indicators under peak conditions (Tak & Yeo, 2025).

The stochastic nature of demand and driver behaviour necessitates an analysis of the robustness of the proposed algorithm. Local control relies on directly measurable characteristics of the state (queues, flow rates, intersection operating regimes), which increases the system's ability to adapt to short-term random deviations without relying on precise forecasts. At the network level, decisions are based on averaged indicators of delays and link utilisation, which smooths small-scale fluctuations at the level of individual vehicles. As a result, the proposed two-level algorithm, which combines adaptive selection of signal phases based on current queues with network redistribution of routes, is considered an approach that may contribute to limiting queue growth, reducing delays and increasing the uniformity of network utilisation compared with static control schemes, while maintaining acceptable resilience to stochastic influences. The results of the study established that a discrete-event model of two-level road-traffic control can contribute to reducing delays and balancing network utilisation through adaptive traffic-signal control and dynamic route assignment for OD pairs. This corresponds to the study by F. Condette *et al.* (2024), which also confirmed the use of discrete-event models to analyse vehicle traffic in urban conditions. The authors described events such as vehicle arrival, movement along a link and queue formation on approaches to intersections, and the researchers also examined traffic-signal control in detail, including analysis of queue lengths and waiting times, which confirmed the conclusions of the present study regarding the importance of adaptive traffic-signal control for reducing delays and improving network functioning. This confirmed the effectiveness of using discrete-event simulation for real traffic management and adaptive signal control to improve transport-system performance indicators. The study by Z. Meng *et al.* (2023) confirmed the concept of using discrete-event simulation for modelling road traffic, which forms the basis of the present study, where a finite set of typical events for each control stage was described. The authors noted the significance of aggregated control interfaces, which allow not only regulation of vehicle movements but also effective response to changes in traffic flow in real time. This aligns with the concept of dynamic route assignment for different OD pairs in the present study, where the route-choice module selects an optimal path depending on the network state. The significance of discrete-event models for analysing traffic flows was also noted by C. Calistus *et al.* (2023). In the authors' model, events such as vehicle arrivals, movement along a link and queue formation were taken into account, which is analogous to the approach of the present study. In addition, the simulation results of C. Calistus *et al.*, which included synchronised traffic signals, confirmed the effectiveness of adaptive control for reducing delays. Adaptive control is effective for regulating signal phases, where signal-change events are initiated according to current queues and traffic intensity.

The study results showed that dynamic route assignment for OD pairs defines a mechanism for controlling vehicle flows, within which traffic can be redirected from overloaded links to less loaded paths, which is consistent with the conclusions of H. Zhu *et al.* (2024). The authors demonstrated that the use of digital twin technology allows traffic signals to be adaptively configured. Adaptive control helps to reduce delays and redirect traffic flow, contributing to more even network utilisation. The approaches applied in both studies demonstrated the effectiveness of adaptive control and dynamic flow redistribution in improving the operation of transport systems. The work by Y. Chen & C.G. Cassandras (2025) described a method of adaptive traffic-signal control that accounts for turning movements, approach delays and intersection blocking, which correlates with the description of mechanisms for adjusting signal phases depending on traffic intensity and queue lengths in the present study. The authors also indicated the appropriateness of dynamically adapting signal phases to reduce delays and improve traffic flow, which directly corresponds to the concept of adaptive control in the present study, which is oriented towards optimising green time for directions with high flows. This confirms the effectiveness of redirecting flows to alternative routes to reduce overload. Thus, in the discrete-event conceptual model of the transport network, events are described that determine the evolution of the system state, in particular vehicle arrivals, the movement, queue formation on approaches and switching of signal phases. The model is characterised by accounting for the stochastic nature of demand and the embedded possibility of adaptively changing routes and signal-phase parameters through dynamic redistribution of traffic flows. The proposed approach is conceptual and methodological in nature and serves as a basis for further software implementation of a simulator and quantitative assessment of the impact of different control strategies on delays and network utilisation.

Conclusions

The results of the study established that, within the proposed conceptual model, the choice of a control strategy was appropriately represented as a combination of adaptive adjustment of traffic-signal phases and redirection of traffic flows in order to reduce the level of congestion. Stochastic disturbances were taken into account through modelling fluctuations in transport demand and driver behaviour. The optimisation problem was formulated as minimisation of the system performance criterion in the presence of constraints on capacity and permissible operating regimes at intersections, and the modelling problem was presented as estimation of the mathematical expectation of quality indicators under random values of demand and driver behaviour. The distribution of demand across routes was described on the basis of network control, which accounts for delays and utilisation on different links, while dynamic flow redistribution reconciles local and global strategies in order to form more balanced routes. Local traffic-signal control at individual intersections was considered as an instrument for reducing the probability of excessive queue accumulation and the emergence of congestion. The stochastic nature of demand and unpredictable driver behaviour were taken into account as factors that can substantially affect the effectiveness of the selected control strategies. The proposed conceptual simulation model of dynamic redistribution of traffic flows was based on representing the urban transport network as a stochastic discrete-time dynamical system and provided for two control levels: local control of traffic-signal objects and network-level control of routes for OD pairs. Within the model, an approach to adaptive flow allocation was formalised with account taken of changes in queues, delays and traffic intensity, which created theoretical prerequisites for further software implementation of a simulator and evaluation of response effectiveness to fluctuations in transport demand. This structure was used as a scheme within which it was possible to analyse how changing routes and traffic-signal control parameters affects delays and network utilisation. Comparison of the results of adaptive and static control showed the advantage of the adaptive approach under peak loads and reduced delays. In the prospects for further research, practical application of systematised approaches to developing transport models for specific urban networks was appropriate, as well as integration of new factors and technologies (intelligent transport systems, monitoring tools, decision-support systems) into the structure of transport systems.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Agarwal, A., Sahu, D., Mohata, R., Jeengar, K., Nautiyal, A., & Saxena, D.K. (2024). Dynamic traffic signal control for heterogeneous traffic conditions using Max Pressure and Reinforcement Learning. *Expert Systems with Applications*, 254, article number 124416. doi: 10.1016/j.eswa.2024.124416.

[2] Ashfaq, M., Gu, Z., Waller, S.T., & Saberi, M. (2021). Comparing dynamic user equilibrium and noniterative stochastic route choice in a simulation-based dynamic traffic assignment model: Practical considerations for large-scale networks. *Journal of Advanced Transportation*, 2021, article number 6667335. doi: 10.1155/2021/6667335.

[3] Bouadi, M., Jia, B., Jiang, R., Li, X., & Gao, Z.-Y. (2022). Stochastic factors and string stability of traffic flow: Analytical investigation and numerical study based on car-following models. *Transportation Research Part B: Methodological*, 165, 96-122. doi: 10.1016/j.trb.2022.09.007.

[4] Boyles, S.D., Lownes, N.E., & Unnikrishnan, A. (2025). Transportation network analysis, volume I: Static and dynamic traffic assignment. *ArXivLabs*. doi: 10.48550/arXiv.2502.05182.

[5] Calistus, C., Martin, O., Monday, A., & Joe, E. (2023). Discrete event simulation-based evaluation of a single-lane synchronized dual-traffic light intersections. *Journal of Computer and Communications*, 11(10), 82-100. doi: 10.4236/jcc.2023.1110006.

[6] Chen, Y., & Cassandras, C.G. (2025). Scalable adaptive traffic light control over a traffic network including turns, transit delays, and blocking. *Discrete Event Dynamic Systems*, 35, 175-204. doi: 10.1007/s10626-025-00416-7.

[7] Condette, F., Ramat, E., & Sondi, P. (2024). A discrete event approach to micro-scale traffic modeling in urban environment. *Simulation Modelling Practice and Theory*, 133, article number 102920. doi: 10.1016/j.simpat.2024.102920.

[8] Grujić, Z., & Grujić, B. (2025). Optimal routing in urban road networks: A graph-based approach using Dijkstra's algorithm. *Applied Sciences*, 15(8), article number 4162. doi: 10.3390/app15084162.

[9] Hu, T., Hu, Z., Lu, Z., & Wen, X. (2022). Dynamic traffic signal control using mean field multi-agent reinforcement learning in large scale road-networks. *IET Intelligent Transport Systems*, 17(9), 1715-1728. doi: 10.1049/itr2.12364.

[10] Hu, Z., Zhuge, C., & Ma, W. (2021). Towards a very large scale traffic simulator for multi-agent reinforcement learning testbeds. *ArXivLabs*. doi: 10.48550/arXiv.2105.13907.

[11] Jia, X., Guo, M., Lyu, Y., Qu, J., Li, D., & Guo, F. (2024). Adaptive traffic signal control based on graph neural networks and dynamic entropy-constrained soft actor-critic. *Electronics*, 13(23), article number 4794. doi: 10.3390/electronics13234794.

[12] Khan, T.S., Pfoser, D., Ruan, S., & Züfle, A. (2024). Simplifying traffic simulation – from Euclidean distances to agent-based models. *Computational Urban Science*, 4, article number 32. doi: 10.1007/s43762-024-00145-x.

[13] Korchevska, A.A., Vyhovska, I., Nahrebelna, L., & Polishchuk, V. (2023). Modeling of traffic flow distribution on the road network. *Roads and Bridges*, 27, 253-266. doi: 10.36100/dorogimosti2023.27.253.

[14] Le, T.V., Tran, H.T., & Le, D.L. (2024). Dynamic traffic optimization in smart cities (DTOS): Integrating OpenStreetMap, IoT, and fog computing. *SN Computer Science*, 5, article number 823. doi: 10.1007/s42979-024-03176-7.

[15] Lin, Y. (2023). Models, algorithms and applications of DynasTIM real-time traffic simulation system. *Sustainability*, 15(2), article number 1707. doi: 10.3390/su15021707.

[16] Liu, J., Mao, T., Wang, Z., & Bi, H. (2025). SimNET: A deep learning macroscopic traffic simulation model for signal controlled urban road network. In N.M. Thalmann, X. Hu, B. Sheng, D. Thalmann, T. Peng, W. Meng, J. Huang, L. Zhu & X. Wei (Eds.), *Computer animation and social agents* (pp. 39-56). Singapore: Springer. doi: 10.1007/978-981-96-2681-6_4.

[17] Ma, J., Liu, H., & Chen, L. (2024). Enhancing urban traffic management through shared autonomous electric vehicles and dynamic simulation. *PLoS One*, 19(12), article number e0311848. doi: 10.1371/journal.pone.0311848.

[18] Mehrabani, B., Erdmann, J., Sgambi, L., Seyedabrishami, S., & Snelder, M. (2023). A multiclass simulation-based dynamic traffic assignment model for mixed traffic flow of connected and autonomous vehicles and human-driven vehicles. *Transportmetrica A: Transport Science*, 21(2), 1-32. doi: 10.1080/23249935.2023.2257805.

[19] Meng, Z., Siguenza-Torres, A., Gao, M., Grossi, M., Wieder, A., Du, X., Bortoli, S., Sommer, C., & Knoll, A. (2023). Towards discrete-event, aggregating, and relational control interfaces for traffic simulation. In *Proceedings of the 2023 ACM SIGSIM international conference on principles of advanced discrete simulation (SIGSIM-PADS 2023)* (pp. 12-22). New York: Association for Computing Machinery. doi: 10.1145/3573900.3591116.

[20] Mostafi, S., Alghamdi, T., & Elgazzar, K. (2022). RegTraffic: A regression based traffic simulator for spatiotemporal traffic modeling, simulation and visualization. In *2022 international joint conference on neural networks* (IJCNN). Piscataway, NJ: IEEE. doi: 10.48550/arXiv.2301.01245.

[21] Qi, H. (2024). *Stochastic two-dimensional microscopic traffic model: Theory and applications*. Singapore: Springer. doi: 10.1007/978-981-97-3597-6.

[22] Rahman, R., & Hasan, S. (2023). Data-driven traffic assignment: A novel approach for learning traffic flow patterns using graph convolutional neural network. *Data Science for Transportation*, 5, article number 11. doi: 10.1007/s42421-023-00073-y.

[23] Skoropad, V.N., Deđanski, S., Pantović, V., Injac, Z., Vujičić, S., Jovanović-Milenković, M., Jevtić, B., Lukić-Vujadinović, V., Vidojević, D., & Bodolo, I. (2025). Dynamic traffic flow optimization using reinforcement learning and predictive analytics: A sustainable approach to improving urban mobility in the city of Belgrade. *Sustainability*, 17(8), article number 3383. doi: 10.3390/su17083383.

[24] Smelyakov, K., Klochko, O., & Dudar, Z. (2023). Building quantile regression models for predicting traffic flow. In *COLINS-2023: 7th international conference on computational linguistics and intelligent systems*. Kharkiv: CEUR Workshop Proceedings.

[25] Song, X., Yang, Z., Wang, T., Li, C., Zhang, Y., & Chen, G. (2021). Dynamic traffic assignment model based on GPS data and point of interest (POI) in Shanghai. *Sensors*, 21(21), article number 7341. doi: 10.3390/s21217341.

[26] Su, Z.C., Chow, A.H., Fang, C.L., Liang, E.M., & Zhong, R.X. (2023). Hierarchical control for stochastic network traffic with reinforcement learning. *Transportation Research Part B: Methodological*, 167, 196-216. doi: 10.1016/j.trb.2022.12.001.

[27] Tak, H.-Y., & Yeo, H. (2025). Assessing traffic dynamics on highway: Stability and intensity in breakdown and recovery pathways. *Procedia Computer Science*, 257, 282-289. doi: 10.1016/j.procs.2025.03.038.

[28] Weigang, G., & Komar, K. (2024). Multi-agent modeling of traffic organization in urban agglomerations. *Transport Technologies*, 5(1), 10-22. doi: 10.23939/tt2024.01.010.

[29] Xie, H., Zhang, X., Xie, R., & Zhou, B. (2025). Construction and performance analysis of intelligent transportation system simulation platform. In *Cyber security intelligence and analytics* (pp. 42-51). Cham: Springer. doi: 10.1007/978-3-031-88294-4_5.

[30] Zhao, Y., Ma, C., Zhao, M., Xu, X., & Du, B. (2025). An optimal multi-objective dynamic traffic guidance approach based on dynamic traffic assignment. *Physica A: Statistical mechanics and its applications*, 657, article number 130257. doi: 10.1016/j.physa.2024.130257.

[31] Zhu, H., Sun, F., Tang, K., Wu, H., Feng, J., & Tang, Z. (2024). Digital twin-enhanced adaptive traffic signal framework under limited synchronization conditions. *Sustainability*, 16(13), article number 5502. doi: 10.3390/su16135502.

Методологічні засади формування імітаційної моделі управління дорожнім рухом із динамічним перерозподілом транспортних потоків

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Анотація. Метою дослідження було формування концептуальної моделі дворівневого управління дорожнім рухом у міських транспортних мережах. Методологія базувалась на структурно-функціональному аналізі та застосуванні багаторівневого підходу в управлінні транспортними потоками. Виявлено, що початковий етап формування імітаційної моделі передбачає формалізацію вулично-дорожньої мережі та вибір системи змінних для опису її стану в часі. Стан транспортного потоку задається показниками щільності, інтенсивності руху, середньої швидкості, довжини черг та часу очікування. У запропонованій постановці система управління дорожнім рухом має два рівні: маршрутизацію та локальне світлофорне керування. Динамічне призначення потоків розглядається як механізм коригування маршрутів для кожної origin-destination-пари та налаштування світлофорних фаз, тоді як локальне керування трактується як регулювання тривалості зелених сигналів і координація роботи світлофорів на перехрестях. Оптимальне керування орієнтоване на зменшення затримок і нерівномірності завантаження мережі з урахуванням заданих обмежень. Алгоритм керування, що поєднує локальне і мережеве регулювання, інтерпретується як підхід, орієнтований на покращення ефективності мережі, забезпечуючи оптимальне використання ресурсів при змінному попиті та поведінці водіїв. Запропонована архітектура дискретно-подійної імітаційної моделі для динамічного перерозподілу транспортних потоків базується на стохастичній динамічній системі з дискретним часом. Вона інтегрує два рівні управління: локальне керування світлофорами та мережеве керування маршрутами для origin-destination-пар. Модель задає підхід до адаптивного розподілу потоків на основі поточного стану мережі (черги, затримки, інтенсивність руху) і дає змогу досліджувати вплив змін маршрутів та параметрів світлофорного керування на затримки й завантаження мережі за умов стохастичних коливань попиту. Практична значимість полягає у можливості використання результатів органами місцевого самоврядування та дорожніми службами як методичної основи для проектування і реалізації імітаційних моделей міських транспортних систем

Ключові слова: динамічна система; адаптивні алгоритми; перехрестя; зміна фаз світлофора; оптимізація маршрутів; час затримки

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 21.05.2025. Revised: 18.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 658.3:629.02 DOI: 10.33744/2308-6645-2025-2-29-71-81

The state of driver personnel management at Ukrainian logistics providers

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Abstract. The article discussed the issue of driver personnel management in Ukrainian logistics companies, which is particularly relevant in the context of full-scale war, which has caused a significant labour shortage, particularly among drivers (25-30% in freight and passenger transport). Martial law, mobilisation, migration and changes in market requirements have exacerbated the challenges for the logistics sector, requiring a rethinking of personnel management strategies. The object of the study was the process of managing driving personnel in logistics provider companies in conditions of economic instability. The purpose of the article was to determine the current state of driver personnel management in Ukrainian logistics providers under martial law, identify relevant problems, trends and challenges in this area, and formulate directions for improving personnel policy in logistics companies in order to increase their operational efficiency. The research methods included analytical, statistical, abstract-logical and survey methods. The study identified the main problems in driver personnel management: a significant shortage of personnel due to mobilisation (an average of 5 drivers per company), high staff turnover (74.3% of companies), unsystematic training (68.6% provide training only when necessary), limited career growth opportunities (only 8.6% have individual plans), low level of automation (6.9%) and uneven comfort conditions (23.3% provide only basic conditions). At the same time, companies are actively adapting by assigning drivers to specific vehicles (71.4%), using GPS trackers to monitor performance (60%) and engaging alternative categories of employees (89.7%). The results of the study can be used to develop recommendations for improving management processes in logistics service providers, enabling them to adapt effectively to economic instability and crises

Keywords: staff turnover; crisis situations; motivation; staff shortage; automation; training; work environment comfort

Suggested Citation: Halak, I., Bilonoh, O., & Ovchar, D. (2025). The state of driver personnel management at Ukrainian logistics providers. *Bulletin of the National Transport University*, 29(2), 71-81. doi: 10.33744/2308-6645-2025-2-29-71-81.

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Introduction

The Ukrainian logistics industry has become a focal point of challenges arising from the full-scale war, including mobilisation, migration, transformation of market demands, and the destruction of enterprises and warehouses – these represent only a fraction of the difficulties confronting businesses. A noticeable deficit of the working-age population is evident in the country, with estimates indicating a shortfall of approximately 30%. This demographic imbalance presents a significant challenge to the economy, as it affects labour market dynamics, productivity, and the overall capacity for sustainable economic growth, as noted by D. Karpenko (2024). For example, in the field of freight road transport, the shortage of drivers reaches 25% of the required workforce, which amounts to about 30,000 drivers. In public passenger transport, the shortage is estimated at 30%, equating to about 6,000 needed specialists (Driver shortage in the transport…, 2024). A similar situation was already observed in the pre-war period. According to V. Keckarovska (2021), the shortage of heavy goods vehicle drivers in Europe reached approximately 400,000 individuals. Ukraine, according to estimates by I. Novikova (2021), was also among the countries with a significant workforce deficit, amounting to around 120,000 truck drivers. Based on data from IRU (2021), the shortage of professional drivers in Europe and worldwide continued to intensify, with the global deficit exceeding 2.6 million unfilled positions, including tens of thousands of vacancies across European countries, indicating a persistently high level of workforce scarcity. By 2023**,** the shortage of truck drivers remained substantial, surpassing 3 million unfilled positions globally (approximately 7% of total demand). Furthermore, IRU (2025a; 2025b) reports for confirmed that the driver shortage has not diminished and continues to represent a structural challenge for both European and global transport sectors.

As indicated by P. Chandiran *et al.* (2023), this persistent deficit is increasingly driven by demographic factors, particularly the ageing of the profession and the insufficient inflow of young workers, underscoring the need for comprehensive and coordinated responses from transport companies and public authorities. The personnel management system for drivers in logistics provider companies requires continuous improvement in order to establish an organisational framework aimed at preserving and rationally utilising human potential, which is essential for the stable functioning of enterprises. O. Soroka & Y. Salo (2023) emphasised that the development of effective personnel management systems is impossible without a thorough analysis of existing HR challenges. In particular, contemporary approaches that integrate logistics methods into human resource management are highlighted as an effective means of addressing workforce issues in dynamic environments. Similarly, H.V. Artamonova (2025) identified strategic HR tools and practices as critical for improving personnel management efficiency in international companies facing global competition and labour shortages. Furthermore, M. Kovalchuk (2025) demonstrated the growing importance of HR analytics in logistics firms, showing that data-driven insights help identify the causes of staff turnover, facilitate employee adaptation, and support retention strategies in sectors characterised by high labour mobility. Against this background, the study of key problems in driver personnel management in logistics provider companies, as well as the identification of effective solutions to address them, becomes particularly relevant. The purpose of the article was to assess the state of driver personnel management in Ukrainian logistics companies under martial law, identify key challenges and trends, and propose improvements to human resource policies for enhancing operational efficiency.

Literature Review

Contemporary scholarly research in the field of human resource management in logistics companies increasingly focuses on the impact of digitalisation, external environmental instability, and labour shortages on organisational performance; however, drivers as a distinct professional group remain insufficiently explored. Thus, M. Cichosz *et al.* (2020) analysed the digital transformation of logistics service providers based on case studies of nine international companies. The authors demonstrate that the implementation of Transport Management Systems (TMS), data analytics, and cross-functional teams enhances the transparency and efficiency of logistics operations. At the same time, the role of drivers is addressed only indirectly, without an in-depth analysis of motivational or psychological aspects of their work, while the global orientation of the study limits its practical applicability to local and crisis contexts. In the study by M. Wang & R. Radics (2022), the impact of driver shortages on the performance of logistics services in Australia is examined using Structural Equation Modeling (SEM). The M. Wang & R. Radics argued that innovation, workforce upskilling, and operational flexibility can partially offset the negative effects of labour shortages. The authors concluded that driver shortage indirectly affects logistics performance, with logistics capability acting as a mediating factor in the relationship between driver shortage and logistics performance in logistics service providers. The study highlights the importance of managing transportation capacity shortage and provides valuable insights for addressing this issue within the logistics sector. Nevertheless, motivational factors are not explored, and the limited sample of companies reduces the generalisability of the findings. Another conceptual approach is proposed by B. Feng & Q. Ye (2021), who synthesised literature on "smart logistics" and the integration of AI and IoT into human resource management. While empirical evidence is limited, the authors highlight promising directions for the development of digital HRM systems.

However, the socio-psychological impacts of digitalisation on drivers remain largely unexplored. The Ukrainian context of human resource management under martial law is examined by L. Hordiyeva-Herasymova (2023). The author emphasised that population relocation, migration, the mobilisation of men into the Armed Forces of Ukraine, and the growing share of employees with limited working capacity (particularly veterans with combat-related injuries) necessitate the modernisation of personnel management systems. Addressing these challenges is considered a prerequisite for establishing an effective HR system under current conditions. D. Karpenko (2024) analysed the specific personnel-related challenges faced by Ukrainian logistics companies. D. Karpenko stated that traditional approaches to human resource management no longer ensure stability. Among the key challenges identified are a shortage of qualified drivers, high employee turnover, difficulties in adapting to change, and the need to maintain uninterrupted transport operations under conditions of uncertainty. Overcoming the shortage of skilled workers requires the implementation of innovative approaches to recruitment, such as overcoming gender stereotypes, training young people, involving pensioners and cooperating with outsourcing companies. To retain key employees and increase the productivity of logistics companies, it is necessary to create favourable working conditions, including open communication, recognition of achievements, a comfortable working environment and competitive salaries. D.O. Ovchar (2025) argued effective driver personnel management contributes to enhanced competitiveness, the creation of comfortable working conditions, and a high level of employee motivation, even under martial law and conditions of uncertainty. In summary, while significant strides have been made in understanding the challenges faced by logistics companies, especially in the context of driver shortages and the impact of digitalisation, further research is needed to explore the socio-psychological aspects of driver management and the broader implications for human resource strategies in times of crisis.

Materials and Methods

The methodological framework of the study is based on a combination of general scientific and empirical methods, which made it possible to comprehensively analyse the specific features of logistics service providers' activities under martial law. At the theoretical stage of the research, the methods of analysis, synthesis, and generalisation were applied to review and systematise scholarly publications and regulatory documents in the fields of logistics and human resource management. A systems approach was employed to structure the study and to identify interrelationships between organisational, human resource, and operational aspects of logistics activities. The empirical basis of the study comprised the results of a survey of logistics service providers conducted between January and February 2025. The survey involved 30 logistics companies engaged in transport and logistics activities within Ukraine. The sample included logistics providers with varying levels of experience and scales of operation, located primarily in Kyiv and the Kyiv region, as well as enterprises from other regions of Ukraine. In particular, 41.4% of respondents represented companies with more than 20 years of operating experience, 27.6% had between 10 and 20 years of experience, 20.7% between 5 and 10 years, and 10.3% less than 5 years. In terms of fleet size, 3.9% of companies operated up to 10 vehicles, another 37.9% had between 50 and 200 vehicles, 13.8% operated between 10 and 50 vehicles, and 10.3% managed fleets exceeding 200 vehicles. Regarding the types of activities performed, the majority of respondents carried out domestic transportation throughout the territory of Ukraine (69.0%), while 51.7% of companies provided local transportation services within a city or region, and an equal share (50.4%) were engaged in international transportation. The survey was conducted online using a standardised questionnaire implemented via the Google Forms platform. The questionnaire consisted of thematic blocks addressing company characteristics, types of transportation services, organisation of drivers' work, the role of dispatchers, and the impact of martial law conditions on logistics operations. In several questions, respondents were allowed to select multiple answers, which enabled the identification of the multidirectional nature of logistics processes. During the survey, ethical principles of scientific research were strictly observed, including voluntary participation, informed consent, and respondent anonymity, in accordance with generally accepted standards of academic integrity and the principles of sociological research (WMA, 2024). The analysis of the collected data was carried out using descriptive statistical methods, grouping, and percentage analysis. Microsoft Excel software was used for data processing, information aggregation, and the construction of tables and graphical materials.

Results and Discussion

The survey results from 30 companies indicate that the majority of companies (35.7%) offer comprehensive logistics services (3PL), while 28.6% engage in self-managed logistics (1PL), as shown in Figure 1.

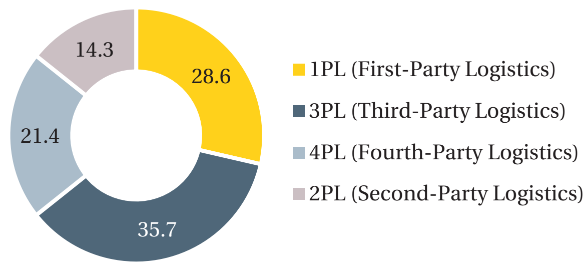

Figure 1. Distribution of companies by type of logistics services, %
Source: compiled by the authors

Regarding staffing, 36.8% of companies employ more than 100 drivers, indicating the presence of large vehicle fleets and a significant volume of transportation operations. At the same time, 37% of companies have up to 10 drivers, which is typical for small operators. Another 13.3% of companies maintain between 50 and 100 drivers, and 10% have between 20 and 50 drivers. Only 2.9% of companies have between 10 and 20 drivers, representing the smallest group. A detailed breakdown is presented in Figure 2.

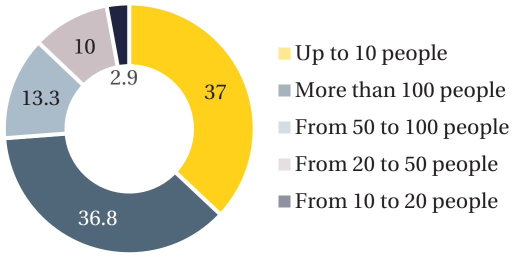

Figure 2. Number of drivers, %
Source: compiled by the authors

Figure 2 illustrated the distribution of companies according to the number of drivers they employed, emphasising the differing scales of operations within the sector. Regarding employment forms, 54.3% of companies employ drivers permanently, while 34.3% combine permanent and contract workers, and only 11.4% exclusively use contract drivers. This indicates a trend toward forming a stable workforce even in challenging economic conditions. It is also noteworthy that 40% of companies have a fleet of 50 to 200 vehicles, which correlates with the high number of drivers. In terms of regional distribution, more than half (51.4%) of the companies operate in Kyiv and the Kyiv region, which provides them with access to key transportation routes and large labour markets. Thus, the logistics services market is characterised by a significant concentration of resources in large companies with more than 100 drivers, while maintaining flexibility due to the presence of small providers with compact fleets and a small workforce. The driver is a key link in the logistics process, as they directly manage transportation operations under conditions of increased complexity and responsibility. The efficiency of the driver's work determines the preservation of assets for the logistics provider, which is the main source of income for both the enterprise and the industry as a whole. Managing driver personnel is a complex task requiring a high level of professional competence, as each employee has individual characteristics and requires a personalised approach (Khromushyna, 2023). Taking this into account, the structure of the questionnaire was built around four key blocks: managing drivers and their productivity, the attitude of logistics providers towards drivers, the impact of martial law on driver personnel management processes, and the role of dispatchers in organising and controlling the work of drivers. In the section on managing drivers and their productivity, the majority of companies (71.4%) always assign drivers to specific vehicles, which promotes responsibility, while 80% rotate drivers on routes only, when necessary, which is determined by fixed routes and sometimes client requirements. The productivity tracking is mainly done through GPS trackers 66.7%, and 33.3% of companies also take client feedback into account, which highlights the technological advancement of the industry (Fig. 3).

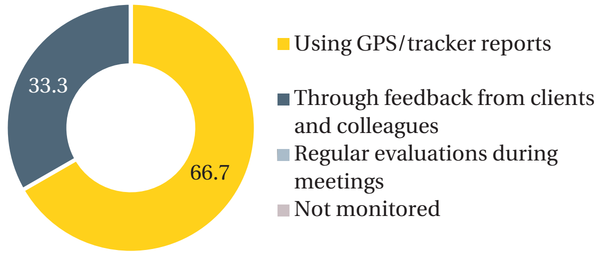

Figure 3. Forms of driver productivity tracking, %
Source: compiled by the authors

Driver training is conducted irregularly, as shown in Figure 4. Only 70% of companies organise it when necessary, focusing primarily on safety and cargo transportation rules, and driver participation in these sessions is rare (17.1%). Insufficient attention to driver training can lead to multiple negative consequences. First, it increases the risk of traffic accidents due to inadequate knowledge of safety regulations and cargo handling procedures. Research showed that undertrained drivers, both novice and professional, are more prone to accidents. Comprehensive driver training programs have been shown to reduce accident rates by up to 40%, while insufficient training increases risks related to safety and cargo handling errors (The impact of effective driver..., 2023). Second, inadequate training contributes to inefficient logistics practices, including suboptimal route planning, higher fuel consumption, and poor vehicle maintenance. Drivers lacking training in eco-driving and best operational practices tend to drive less efficiently, increasing fuel costs and emissions, as noted by Z. Zhang *et al.* (2023). Third, the lack of regular training negatively affects driver competence, job satisfaction, and staff retention. Insufficient training and limited support reduce motivation, lower performance, and increase turnover rates (Wygal *et al.*, 2021). Finally, inadequate training can result in higher operational costs, increased insurance premiums, and reputational risks for companies. Accidents and operational errors due to poorly trained drivers raise expenses and insurance claims, while effective training mitigates these risks (Mayhew & Simpson, 2022; IRU, 2025a).

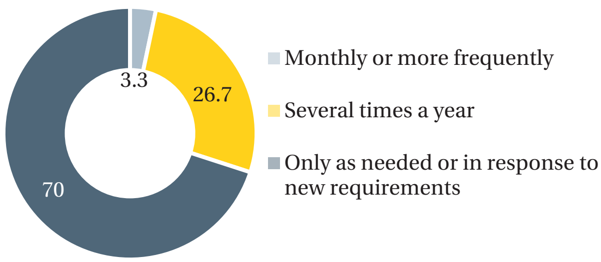

Figure 4. Frequency of organising driver training, %
Source: compiled by the authors

Regarding incentives, the majority of companies (53.3%) reward drivers with additional financial payments, 30% use non-material incentives, 13.3% provide popular or material rewards, and 3.4% publicly acknowledge achievements. Only 3.4% do not offer any rewards, indicating a general trend towards incentivising drivers, primarily financially, as shown in Figure 5.

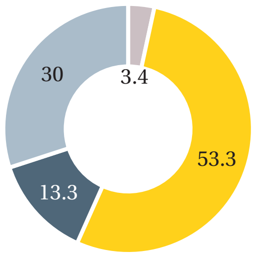

Figure 5. Methods of rewarding drivers, %
Source: compiled by the authors

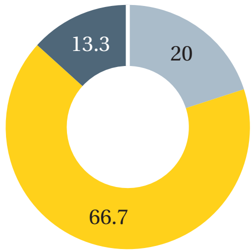

Figure 6. Frequency of meetings with drivers, %
Source: compiled by the authors

The study showed that logistics companies apply different approaches to driver management, but the consistency and depth of these practices remain uneven. Specifically, to resolve conflicts, 62.9% of companies prefer individual meetings, while 31.4% hold group discussions, highlighting a personalised approach. At the same time, 66.7% of providers hold individual meetings with drivers only as needed, while only 20% organise regular meetings (Fig. 2), which may indicate a lack of systematic feedback. Such insufficient and irregular feedback can lead to delayed identification of operational problems, reduced driver engagement, and lower motivation levels. In the long term, the absence of structured communication may negatively affect compliance with procedures, increase the likelihood of repeated errors, and weaken trust between drivers and management, ultimately reducing overall logistics performance and service quality (Ahuchogu *et al.*, 2024; Delgado & Manalo, 2025). Regarding the management of personal records, 60% of companies limit themselves to basic information, while only 20% maintain detailed records, highlighting weaknesses in personnel management. The absence of comprehensive personal records creates a range of risks, including complicating workforce planning, reducing the effectiveness of professional development, hindering the integration of new employees, and potentially contributing to higher staff turnover and decreased employee loyalty.

Most companies (60%) focus primarily on the technical condition of vehicles as the key factor in ensuring driver comfort, while 21% emphasise working conditions, 20% provide only basic conditions, and 3.3% relate comfort primarily to employment terms. This pattern of responses indicates a predominance of a technical approach to driver management, whereas social and motivational aspects remain insufficiently developed. Comparison with pre-war studies shows that the predominance of a technical approach to ensuring driver comfort was already characteristic in earlier years. According to a survey by the European Business Association, companies in Ukraine at that time already focused on the technical condition of vehicles and infrastructure aspects of logistics, while social and motivational factors, such as rest conditions or professional recognition, received significantly less attention (Business assessed the transport…, 2021). Similarly, in the international context, the IRU (2021), based on a survey of over 4,700 companies in Europe, including Ukraine, indicated that employers predominantly relied on technical solutions, such as fleet modernisation and vehicle safety measures, as the main way to retain staff, whereas issues related to working and rest conditions were considered secondary. Thus, the results of this 2025 study indicated that this trend has persisted, despite the worsening driver shortage and rising salaries in 2023-2025 (Hertseva, 2021). Assessment of driver satisfaction also reveals gaps; only 30% of enterprises conduct regular surveys, whereas 60% use this tool only after complaints have been received, as shown in Figure 7.

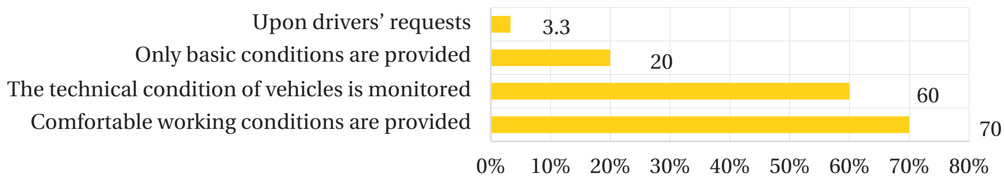

Figure 7. Ensuring the drivers' work environment comfort
Source: compiled by the authors

Figure 7 illustrated the extent to which logistics companies ensure drivers' work environment comfort, career development opportunities, and the consideration of driver feedback as key elements of personnel management practices.

Career development opportunities are extremely limited. As shown in Figure 8, only 10% of companies develop individual plans, and advancement to higher positions is available in only 2 companies. Finally, the consideration of driver feedback is partially systematised – 40% of companies do this regularly, while 5.7% ignore feedback altogether, highlighting the need for improvement in management practices within logistics providers.

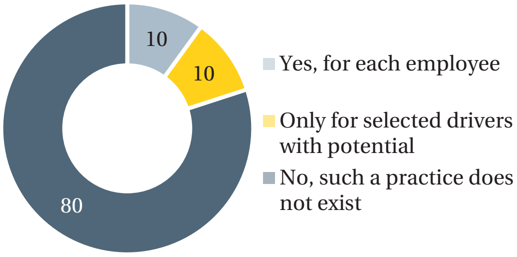

Figure 8. Presence of individual development plans for drivers, %
Source: compiled by the authors

The martial law has significantly impacted personnel management in logistics provider companies, causing substantial changes in the workforce composition (80%) and an increase in employee turnover (73.3%) compared to the pre-war period (Fig. 9). Most companies do not reserve drivers from mobilisation, which exacerbates the shortage, as 45.7% of companies have mobilised up to 5 drivers, and in some cases, the losses exceed 10 individuals. To address the driver shortage, all 30 companies (89.7%) are taking measures, most often by involving other categories of workers (26 companies, 89.7%), such as retirees or demobilised individuals. The use of contract drivers or outsourcing is employed by 34.5% (10 companies), and 51.7% (15 companies) involve women in driver roles. Only 6.9% (2 companies) use fleets with more automation, and 3.4% (1 company) employs drivers from other countries. This indicates an active search for alternative personnel, but low use of technological solutions, such as automation. A detailed breakdown of the data, including the specific measures taken by companies to address the driver shortage and the distribution of strategies implemented, is presented in Figure 10.

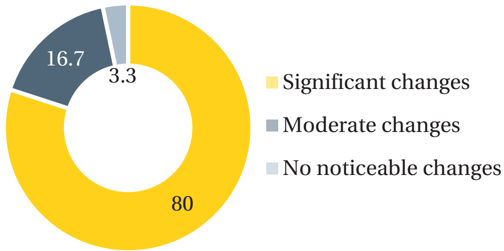

Figure 9. The impact of martial law on the company's workforce, particularly on the number of drivers, %
Source: compiled by the authors

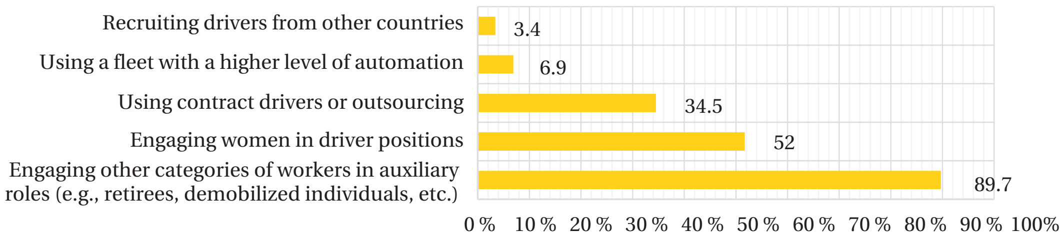

Figure 10. Alternative measures due to the driver shortage
Source: compiled by the authors

Driver turnover in the transport and logistics sector in Ukraine has increased significantly compared to the pre-war period. Companies participating in survey included those engaged in both domestic and international freight transportation, as well as passenger transport. According to the survey results, 75.9% of respondents reported a significant increase in turnover, 17.2% reported a moderate increase, and only 6.9% indicated no change, reflecting a critical deterioration in workforce stability since 2022 (Fig. 11).

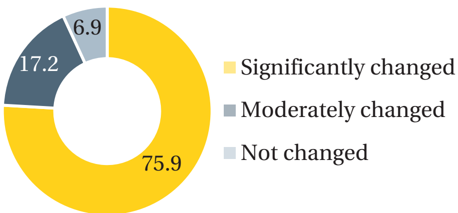

Figure 11. Driver turnover variation since the pre-war period, %
Source: compiled by the authors

Before the full-scale invasion, driver turnover remained moderate (10-30%), and the shortage of drivers was less acute, mainly driven by the low attractiveness of the profession and competition from abroad (IRU, 2021). After 2022, the situation deteriorated sharply due to mobilisation, workforce outflow, and an exacerbation of shortages. In different companies, driver vacancies account for 30-50% of staffing needs (IRU, 2024). When asked whether drivers in their companies were granted deferrals, 79.9% of respondents answered "no", with only a small proportion of companies able to reserve their drivers. In the current unstable environment, ensuring that transport operators can reserve at least 75% of drivers is critically important to maintain continuity of transport operations and the stable functioning of the economy (Petrovskyi, 2025). An examination of alternative measures to address the driver shortage in Ukraine reveals similarities between the survey findings and the approaches reported in the literature. In particular, the involvement of women is associated with retraining initiatives, such as the "She

Drives" and "Reskilling Ukraine" projects, which prepare women for employment as truck and bus drivers and are supported by international organisations, including USAID and UN Women. However, the scale of these programs is limited (Zhabska, 2024; Skrypal, 2024). In addition, retirees, demobilised individuals, youth, and migrants from Asia and the Middle East are actively recruited (How Ukraine is addressing…, 2025). State support includes reserving drivers from mobilisation, simplifying foreign worker hiring procedures, and funding training programs. To further reduce reliance on human resources, automation and the use of robotic vehicles are being considered (Lee *et al.*, 2023; Driver shortage in the transport…, 2024). Globally, full-scale commercial autonomous truck operations are already underway: for example, Einride (n.d.) and Aurora (n.d.) operate Level 4 driverless trucks in the US and Europe, Kodiak (n.d.) fleets on private routes, and Inceptio Technology (n.d.) supplies hundreds of autonomous trucks in China. However, the economic situation in Ukraine, heavily affected by the war, significantly limits the feasibility of large-scale deployment of robotic transport: the high cost of technology, weak infrastructure, and market instability currently prevent widespread use of autonomous trucks. Therefore, under the Ukrainian context, a more realistic and effective approach is to combine moderate automation with managerial and organisational measures, as summarised in Table 1, which can improve operational efficiency and reduce dependence on human drivers even under challenging economic conditions.

Table 1. Technological and organisational solutions to mitigate the driver shortage in transport and logistics in Ukraine

Solution	Operational efficiency	Advantages	Implementation
AI-based route optimisation platforms	Automatically select optimal routes, avoid congestion, and suggest backhaul loads, reducing idle time and increasing driver productivity	Reduce empty mileage by 20-30%, allow one driver to perform more trips, and lower fuel and operating costs	Implemented in Ukraine, Lardi-Trans is a logistics platform that integrates intelligent data-driven tools for automating the matching of freight and carriers, while providing functionalities that support efficient route planning and informed operational decision-making
Convoy (platooning) or group transportation	Several trucks move in a convoy with coordinated driving, enabling better rest scheduling and shared route management	Enables longer routes with fewer drivers and more efficient use of driving and rest time	Truck platooning and coordinated convoy operations are recognised logistical practices in global road freight transport, offering fuel savings and improved efficiency through connected vehicle technologies
Fleet management and telematics systems	Real-time monitoring, automated planning, maintenance alerts, and eco-driving practices improve fleet utilisation	Reduce downtime and increase operational efficiency by 15-25%	Wialon, developed by Gurtam and widely used by logistics and transport companies in Ukraine and worldwide, is a telematics and fleet management platform that provides real-time vehicle tracking, data-driven analytics, automated alerts, and maintenance planning to enhance fleet utilisation and operational efficiency
Time slot management systems at warehouses and terminals	Pre-booked loading and unloading time slots reduce waiting times at warehouses, terminals, and border crossings, allowing drivers to complete more trips within the same working time	Reduces idle time and congestion, improves predictability of transport operations, and increases effective driver utilisation under workforce shortages	Partially implemented in Ukraine by large logistics operators and distribution centres; widely used globally in ports, warehouses, and intermodal terminals
Partial vehicle automation	Adaptive cruise control, lane-keeping assistance, and automatic braking reduce driver fatigue on long-haul routes	Improve safety and allow more efficient use of driver working hours without regulatory violations	Ukraine uses advanced driver assistance systems (ADAS), including adaptive cruise control and lane keeping systems, while fully autonomous commercial transport has not yet been introduced
Electric and hybrid trucks with reduced maintenance needs	Fewer maintenance stops and smoother driving conditions reduce delays and driver fatigue	Lower fuel costs, reduced downtime, and higher operational resilience	Pilot projects in Ukraine. The introduction of electric vehicles by Nova Poshta is seen as the next step in the transition to environmentally sustainable logistics solutions

Source: compiled by the authors based on P. Viktor & Á. Szeghegyi (2022), H. Atasayar *et al.* (2022), L. Mauler *et al.* (2022), Autonomous driving: How close… (2024), A. Bykova (2024), I. Blyzniuk (2024), O. Bilonoh *et al.* (2025), Navigating 2025 fleet management… (2025), Lardi-trans (n.d.)

Table 1 demonstrated that a combination of technological and organisational solutions – ranging from AI-based route optimisation and fleet telematics to time slot management and partial vehicle automation – significantly mitigated the driver shortage in Ukraine by improving operational efficiency, reducing idle time, and enhancing driver productivity. The evidence suggested that implementing these measures, many of which had already been partially adopted locally, optimised resource utilisation while lowering costs and supported safer, more sustainable logistics operations. Other researchers, including G. Gowans (2024) and E. Kulisch (2025), have also highlighted the impact of the war in Ukraine on the labour shortage in the European trucking sector. The return of Ukrainian drivers due to mobilisation has exacerbated labour shortages in countries such as Poland, Slovakia, and Hungary. To address these problems, European policy measures include the temporary lifting of visa requirements, the simplification of regulations for drivers, and measures aimed at expanding the labour force by attracting women and young people to the profession (Ukraine businesses hire more women…, 2024). The European experience may be adapted to Ukraine; however, its implementation necessitates comprehensive, region-specific measures. To increase the applied value of the study, the integration of European experience into Ukrainian realities should be approached not as a direct transfer of institutional models, but as their contextual adaptation to wartime constraints and pronounced regional disparities. In particular, European practices of attracting foreign drivers may be implemented in Ukraine through targeted bilateral agreements with neighbouring and partner countries, focusing on short-term and circular labour migration schemes that address immediate labour shortages while minimising long-term demographic risks. Given the limited administrative capacity of the state during wartime, visa and work permit procedures for drivers should be simplified and partially digitalised, while maintaining mandatory registration, tax compliance, and access to basic social protection mechanisms, as mentioned by A. Radziukevich (2023). Furthermore, the European approach to expanding the labour pool by involving women and young people is especially relevant for Ukraine under conditions of demographic losses and large-scale mobilisation. Its practical implementation requires state-supported vocational training programs, subsidised access to driving licenses, and financial incentives for transport companies employing representatives of these groups. At the same time, European experience demonstrates that such measures are effective only when accompanied by improvements in working conditions, including predictable work schedules, modern and safer vehicles, and supporting social infrastructure, which are critical for retaining non-traditional workforce groups in the freight transport sector (EURES, 2025; Driver shortage in transport…, 2025).

At the institutional level, the adaptation of European experience should also account for the risks associated with excessive liberalisation. In several European countries, insufficient labour protection has led to a deterioration in job quality and long-term workforce instability. A. AlTalhoni *et al.* (2025) observed that under conditions of wartime uncertainty, these risks are amplified in Ukraine, which necessitates the establishment of minimum standards for drivers' remuneration, guaranteed rest periods, and access to medical insurance and social protection, even within simplified or temporary employment frameworks. In addition, the driver reservation mechanism plays a key role in stabilising the transport and logistics sector, as it enables the preservation of critically important personnel and ensures greater predictability of logistics operations under mobilisation pressure. Complementary technological measures, such as partial automation, fleet renewal, and the implementation of driver assistance systems, can reduce physical workload and professional burnout, thereby expanding access to the profession for demobilised military personnel, older workers, as well as women and youth (PrePass Alliance, 2024a; 2024b). Finally, the effective integration of European practices requires a differentiated regional approach, as the scale of labour shortages and logistics flows varies significantly across regions of Ukraine. Regional authorities, in cooperation with business associations and international partners, can pilot flexible recruitment models, develop training hubs, and implement monitoring systems, with subsequent scaling of successful solutions to the national level (EURES, 2025). In summary, addressing the driver shortage in Ukraine requires a multifaceted approach that combines technological innovations, organisational measures, and contextual adaptation of European labour practices to wartime and regional conditions. Effective implementation depends on simplified administrative procedures, targeted workforce expansion, improved working conditions, and regional pilot programmes, ensuring both immediate operational efficiency and long-term sectoral stability.

Conclusions

A survey of logistics companies revealed that martial law significantly impacted driver management, causing issues such as a major personnel shortage due to mobilisation (an average of 5 drivers per company) and high turnover (74.3% of companies). Other challenges include insufficient training (68.6% provide training only as needed), limited career growth (only 8.6% have individual plans), low automation (6.9%), and inadequate comfort (23.3% offer only basic conditions). Companies are adapting by assigning drivers to specific vehicles (71.4%), using GPS trackers (60%), and recruiting alternative staff (89.7%). However, most measures are reactive and short-term, focused on maintaining operations rather than building a sustainable HR management system during the crisis. The lack of a systematic approach to training, motivation, and technology hinders the improvement of personnel management efficiency, which requires more structured and technological solutions. Insufficient attention to regular feedback, driver satisfaction assessments, and the socio-psychological aspects of work negatively impacts employee engagement, loyalty, and long-term retention, exacerbating staff shortages and turnover. It is therefore proposed to involve drivers more actively, conduct systematic training, and implement regular programmes focused on safety and efficiency, involving drivers in their creation, as 10% of companies do. Such involvement not only increases the relevance of the training content but also strengthens drivers' motivation and responsibility for operational results. For career development, it is recommended to create individual plans for 30% of drivers, including non-monetary incentives, as well as invest in automation, particularly in GPS technologies and the gradual implementation of automated fleets (for example, GPS trackers are already used by 60% of companies), increasing their share from 6.9% to 15-20%. Combining partial automation with organisational and managerial improvements is considered the most realistic and economically viable strategy for Ukrainian logistics operators in the current environment. To ensure comfort, it is necessary to establish uniform standards (technical condition, ergonomics) to reduce the share of companies with basic conditions to 10%. Overall, the transition to an integrated, employee-oriented model of driver management is a key prerequisite for increasing the sustainability, efficiency, and competitiveness of logistics operators in Ukraine during and after martial law. In the future, a separate survey of drivers is planned to understand their views on staff shortages, working conditions, and potential mechanisms for improvement. The collected data can serve as a foundation for future research aimed at developing practical measures to enhance job satisfaction, motivation, and efficiency, including tailored training programmes, non-monetary incentive systems, initiatives to improve social and psychological working conditions, and priorities for workplace comfort and safety.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Ahuchogu, M.C., Sanyaolu, T.O., & Adeleke, A.G. (2024). Enhancing employee engagement in long-haul transport: Review of best practices and innovative approaches. *Global Journal of Research in Science and Technology*, 2(1), 46-60. doi: 10.58175/gjrst.2024.2.1.0048.

[2] AlTalhoni, A., Abudayyeh, O., Bhandari, S., Thaviphoke, Y., Ahmed, S., Liu, H., & Hoque, N. (2025). Toward resilient construction supply chains: Addressing the truck driver shortage through strategic interventions. *Buildings*, 15(21), article number 3937. doi: 10.3390/buildings15213937.

[3] Artamonova, H.V. (2025). Improving the efficiency of personnel management organization in an international company. *Economic Space*, 204, 24-29. doi: 10.30838/EP.204.24-29.

[4] Atasayar, H., Blass, P., & Kaiser, S. (2022). Truck platooning worldwide. In A. Schirrer A.L. Gratzer, S. Thormann, S. Jakubek, M. Neubauer & W. Schildorfer (Eds.), *Energy-efficient and semi-automated truck platooning* (pp. 7-18). Cham: Springer. doi: 10.1007/978-3-030-88682-0_2.

[5] Aurora. (n.d.). Retrieved from https://aurora.tech/.

[6] Autonomous driving: How close are we to full automation? (2024). Retrieved from https://autopark.ua/uk/news/avtonomnoe-vozdenie-naskolko-blizki-my-k-polnoi-avtomatizacii.

[7] Bilonoh, O., Halak, I., & Ovchar, D. (2025). The impact of time slot management systems on drivers' working hours in logistics service providers' enterprises. *Management and Entrepreneurship: Trends of Development*, 1(31), 50-66. doi: 10.26661/2522-1566/2025-1/31-05.

[8] Blyzniuk, I. (2024). *"Nova Poshta" chooses electric vehicles: A new step towards eco-friendly delivery*. Retrieved from https://startermedia.com.ua/news/companynews/2024/06/03/nova-poshta-obyraie-elektromobili-novyy-krok-do-ekolohichnoi-dostavky/.

[9] Business assessed the transport infrastructure development and identified its priorities – EBA survey. (2021). Retrieved from https://eba.com.ua/en/biznes-otsinyv-stan-i-vyznachyv-priorytety-rozvytku-transportnoyi-infrastruktury-opytuvannya-eva/.

[10] Bykova, A. (2024). *Volvo is working on developing a super-electric truck*. Retrieved from https://logist.today/dnevnik_logista-uk/2024-09-03/volvo-rabotaet-nad-sozdaniem-superelektricheskogo-gruzovika-2/.

[11] Chandiran, P., Ramasubramaniam, M., Venkatesh, V.G., Mani, V., & Shi, Y. (2023). Can driver supply disruption alleviate driver shortages? A systems approach. *Transport Policy*, 130, 116-129. doi: 10.1016/j.tranpol.2022.10.002.

[12] Cichosz, M., Wallenburg, C.M., & Knemeyer, A.M. (2020). Digital transformation at logistics service providers: Barriers, success factors and leading practices. *The International Journal of Logistics Management*, 31(2), 209-238. doi: 10.1108/IJLM-08-2019-0229.

[13] Delgado, M., & Manalo, M.C. (2025). Meaningful work mediation: Job resources and employee engagement among trailer truck drivers of transport and logistics companies. *International Journal of Accounting and Economics Studies*, 12(1), 146-155. doi: 10.14419/c2qh7j30.

[14] Driver shortage in the transport and logistics sector due to mobilisation reaches 25%. (2024). Retrieved from https://interfax.com.ua/news/economic/1018315.html.

[15] Driver shortage in transport: Causes and possible solutions. (2025). Retrieved from https://hopilogistics.eu/blog/driver-shortage.

[16] Einride. (n.d.). Retrieved from https://www.einride.tech/.

[17] EURES. (2025). *EURES report on labour shortages and surpluses 2024: Sector analysis on land transport – Road and railway*. Luxembourg: Publications Office of the European Union.
[18] Feng, B., & Ye, Q. (2021). Operations management of smart logistics: A literature review and future research. *Frontiers of Engineering Management*, 8, 344-355. doi: 10.1007/s42524-021-0156-2.
[19] Gowans, G. (2024). *76% of logistics operators suffering from labour shortages*. Retrieved from https://cargoon.eu/en/community/blog/market-review/76-of-logistics-operators-suffering-from-labour-shortages/.
[20] Hertseva, D. (2021). *Employers are ready to pay over UAH 40,000, but there is no one to work: Which specialists are in high demand on the labor market*. Retrieved from https://surl.li/shpdzl.
[21] Hordiyeva-Herasymova, L. (2023). Enterprise personnel management: Theoretical aspect. *Young Scientist*, 12(124), 163-167. doi: 10.32839/2304-5809/2023-12-124-30.
[22] How Ukraine is addressing the labor shortage problem. (2025). Retrieved from https://agroreview.com/en/newsen/agripolicy/how-ukraine-addressing-the-labor/.
[23] Inceptio Technology. (n.d.). Retrieved from https://en.inceptio.ai/commercialization.
[24] IRU. (2021). *New IRU survey shows driver shortages to soar in 2021*. Retrieved from https://www.iru.org/news-resources/newsroom/new-iru-survey-shows-driver-shortages-soar-2021.
[25] IRU. (2025a). *Global truck driver shortage report 2024*. Geneva: International Road Transport Union.
[26] IRU. (2025b). *Widening age chasm compounds truck driver shortage crisis: New IRU report*. Retrieved from https://surl.lu/yrdkq.
[27] Karpenko, D. (2024). *Typical human resource management problems in logistics companies and ways to address them*. Retrieved from https://fillin.ua/stati/vikliki-v-upravlinni-personalom-dlya-logistichnikh-kompaniy/.
[28] Keckarovska, V. (2021). *European driver shortages*. Oxford: Transport Intelligence.
[29] Khromushyna, L.A. (2023). Challenges and prospects of personnel management in the context of generation theory and under conditions of uncertainty. *Economics and Society*, 51. doi: 10.32782/2524-0072/2023-51-40.
[30] Kodiak. (n.d.). *Committed to building the world's safest driver*. Retrieved from https://kodiak.ai/company.
[31] Kovalchuk, M. (2025). The role of HR analytics in human resource management of logistics companies. *International electronic scientific journal "Science Online"*, 8.
[32] Kulisch, E. (2022). *Drivers taking up arms for Ukraine worsens European trucker shortage*. Retrieved from https://www.freightwaves.com/news/drivers-taking-up-arms-for-ukraine-worsens-european-trucker-shortage.
[33] Lardi-trans. (n.d.). Retrieved from https://lardi-trans.ua/.
[34] Lee, S., Cho, K., Park, H., & Cho, D. (2023). Cost-Effectiveness of introducing autonomous trucks: From the perspective of the total cost of operation in logistics. *Applied Sciences*, 13(18), article number 10467. doi: 10.3390/app131810467.
[35] Mauler, L., Dahrendorf, L., Duffner, F., Winter, M., & Leker, J. (2022). Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study. *Journal of Energy Storage*, 46, article number 103891. doi: 10.1016/j.est.2021.103891.
[36] Mayhew, D.R., & Simpson, H.M. (2002). The safety value of driver education and training. *Injury Prevention*, 8(2), article number ii3. doi: 10.1136/ip.8.suppl_2.ii3.
[37] Novikova, I. (2021). *Key trends in the logistics market in Ukraine*. Retrieved from https://surl.li/ssryxs.
[38] Ovchar, D.O. (2025). Key aspects of driver personnel management in logistics provider companies under conditions of economic instability and crisis situations. *Roads and Bridges*, 31, 292-304. doi: 10.36100/dorogimosti2025.31.292.
[39] Petrovskyi, D. (2025). *Ukraine faces a critical shortage of drivers: Experts explain how this will impact prices*. Retrieved from https://surl.li/dwvdxq.
[40] PrePass Alliance. (2024a). *The importance of women in the trucking industry*. Retrieved from https://www.prepassalliance.org/the-importance-of-women-in-the-trucking-industry/.
[41] PrePass Alliance. (2024b). *The ongoing truck driver shortage: Causes, effects and solutions*. Retrieved from https://www.prepassalliance.org/the-ongoing-truck-driver-shortage-causes-effects-and-solutions/.
[42] Radziukevich, A. (2023). *Continuing driver shortage: A solution outside the EU at hand?* Retrieved from https://www.girteka.eu/continuing-driver-shortage-a-solution-outside-the-eu-at-hand/.
[43] Skrypal, H. (2024). *Who will keep Ukraine's transport and logistics industry moving?* Retrieved from https://trans.info/en/ukraines-transport-and-logistics-393305.
[44] Soroka, O., & Salo, Y. (2023). Human resource management using logistics approaches. *Economy and Society*, 48. doi: 10.32782/2524-0072/2023-48-22.
[45] The impact of effective driver training on road safety. (2023). Retrieved from https://www.prolius.com/news/effective-driver-training-on-road-safety.
[46] Truck driver shortage in Ukraine reaches 25% due to mobilization. (2025). Retrieved from https://bukvy.org/en/truck-driver-shortage-in-ukraine-reaches-25-due-to-mobilization/.
[47] Ukraine businesses hire more women and teens as labor shortages bite. (2024). Retrieved from https://www.voanews.com/a/ukraine-businesses-hire-more-women-and-teens-as-labor-shortages-bite/7781233.html.

[48] Viktor, P., & Szeghegyi, Á. (2022). Safety of the introduction of self-driving vehicles in a logistics environment. *Periodica Polytechnica Transportation Engineering*, 50(4), 387-399. doi: 10.3311/PPtr.20006.
[49] Wang, M., & Radics, R. (2022). Transportation capacity shortage influence on logistics performance: Evidence from the driver shortage. *Transportation Research Part E: Logistics and Transportation Review*, 165, article number 102863. doi: 10.1016/j.heliyon.2022.e09423.
[50] WMA. (2024). *WMA Declaration of Helsinki – ethical principles for medical research involving human participants*. Retrieved from https://www.wma.net/policies-post/wma-declaration-of-helsinki/.
[51] Wygal, A., Voss, D., Hargis, M.B., & Nadler, S. (2021). Assessing causes of driver job dissatisfaction in the flatbed motor carrier industry. *Logistics*, 5, article number 34. doi: 10.3390/logistics5020034.
[52] Zhabska, Y. (2024). *Ukraine is experiencing a shortage of drivers: In which sectors is the deficit most acute*. Retrieved from https://surl.lt/konzgg.
[53] Zhang, Z., Demir, E., Mason, R., & Di Cairano-Gilfedder, C. (2023). Understanding freight drivers' behavior and the impact on vehicles' fuel consumption and CO_2e emissions. *Operations Research International Journal*, 23, article number 59. doi: 10.1007/s12351-023-00798-2.

Стан управління персоналом водіїв у підприємствах українських логістичних провайдерів

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Анотація. У статті досліджено проблему управління персоналом водіїв в українських логістичних компаніях, що є особливо актуальною в умовах повномасштабної війни, яка спричинила значний дефіцит робочої сили, зокрема серед водіїв (25-30 % у вантажних та пасажирських перевезеннях). Воєнний стан, мобілізація, міграція та зміни в ринкових вимогах загострили проблеми для логістичного сектору, що потребує переосмислення стратегій управління персоналом. Об'єктом дослідження був процес управління персоналом водіїв в логістичних компаніях у умовах економічної нестабільності. Метою статті було визначити поточний стан управління персоналом водіїв в українських логістичних компаніях за умов воєнного стану, виявити відповідні проблеми, тенденції та виклики в цій сфері та сформулювати напрямки удосконалення кадрової політики в логістичних компаніях з метою підвищення їх оперативної ефективності. Методами дослідження були аналітичний, статистичний, абстрактно-логічний та методи опитування. У результаті дослідження були виявлені основні проблеми управління персоналом водіїв: значний дефіцит кадрів через мобілізацію (в середньому по 5 водіїв на компанію), висока плинність кадрів (74,3 % компаній), неорганізоване навчання (68,6 % надають навчання лише за необхідності), обмежені можливості кар'єрного зростання (лише 8,6 % мають індивідуальні плани), низький рівень автоматизації (6,9 %) та нерівномірні умови комфорту (23,3 % надають лише базові умови). У той же час компанії активно адаптуються, закріплюючи водіїв за конкретними транспортними засобами (71,4 %), використовуючи GPS-трекери для моніторингу роботи (60 %) та залучаючи альтернативні категорії працівників (89,7 %). Результати дослідження можуть бути використані для розробки рекомендацій щодо покращення управлінських процесів у логістичних компаніях, що дозволить ефективно адаптуватися до економічної нестабільності та кризових ситуацій

Ключові слова: плинність кадрів; кризові ситуації; мотивація; дефіцит кадрів; автоматизація; навчання; комфорт робочого середовища

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 10.07.2025. Revised: 25.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 656.1/.5 DOI: 10.33744/2308-6645-2025-2-29-82-93

Innovative standardised modular management system for replacement and charging of electric vehicle batteries

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Abstract. The article examined the potential for enhancing the production and operational systems of electric vehicles through the implementation of an innovative, standardised modular approach to battery replacement and charging. The study focused on passenger electric cars and electric buses used in urban and intercity transportation, which are equipped with lithium-ion battery systems. Particular attention was given to the systemic limitations of existing electric vehicle infrastructure, including long charging times, the lack of battery and connector standardisation, high production and maintenance costs, and their adverse effects on the widespread adoption of electric mobility solutions. The aim of the study was to develop and substantiate a unified modular model for battery replacement and charging, designed to reduce vehicle downtime and improve operational efficiency. The research methodology incorporated system and comparative analysis, statistical methods, and graphical modelling to investigate modular battery architectures and infrastructure standardisation, alongside an environmental impact assessment comparing electric vehicles with internal combustion vehicles. The study drew on scientific literature, reports from international organisations (International Energy Agency, International Renewable Energy Agency, Organisation for Economic Co-operation and Development, World Health Organization), statistical databases, regulatory documents, and open-access industry sources. The findings confirmed that vehicles with internal combustion engines are significant sources of CO_2, NO_x, and fine particulate matter emissions, contributing to climate change, air pollution, and the deterioration of public health. In contrast, electric vehicles demonstrate a substantially lower environmental impact, higher energy efficiency, and reduced maintenance costs. Based on the analysis, a unified modular battery replacement system was proposed, which facilitates rapid energy replenishment, enhances interoperability, reduces infrastructure costs, and fosters the development of a sustainable electric mobility ecosystem. The study concluded that the lack of sufficient standardisation in battery systems and charging infrastructure hinders large-scale electric vehicle adoption, whereas a modular and unified vehicle architecture substantially reduces downtime and improves manufacturing flexibility and infrastructure scalability

Keywords: environmental concerns; charging infrastructure; economic efficiency; maintenance costs; electric mobility

Introduction

Road transport is a major source of environmental pollution from internal combustion engine emissions, making the adoption of zero-emission electric vehicles a key mitigation measure. One effective approach is the adoption of electric vehicles, which offer both environmental and economic benefits over ICE-powered transportation due to the absence of harmful emissions. However, the complete shift to electric mobility is currently hindered by several financial and logistical challenges. At present, electric vehicles remain expensive, require lengthy battery

Suggested Citation: Porfirenko, V. (2025). Innovative standardised modular management system for replacement and charging of electric vehicle batteries. *Bulletin of the National Transport University*, 29(2), 82-93. doi: 10.33744/2308-6645-2025-2-29-82-93.

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charging times, and suffer from a lack of widespread infrastructure for charging and maintenance. As a result, they are rarely employed in long-distance or international freight and passenger transport (Senn, 2023). As noted by A.R. Mesquita *et al.* (2025), although rapid charging technology is available, it is still cost-prohibitive and more expensive per mile compared to ICE vehicles, prompting commercial transport operators to continue relying on traditional combustion engines. This problem can be solved by applying an innovative method of manufacturing and operating unified batteries for electric vehicles. This will significantly reduce the cost of new electric cars, speed up charging and battery replacement, reduce operating costs, and finally allow the use of electric buses and electric trucks in international and intercity transportation. Z. Liu *et al.* (2023) emphasised that modern rechargeable batteries constitute the core of electric vehicles (EVs), and their continuous improvement is critical for enhancing energy efficiency and minimising environmental impact. This research focused on reducing dependence on scarce and geopolitically sensitive materials, particularly cobalt, whose extraction is associated with significant environmental and ethical concerns. Z. Liu *et al.* demonstrated that partial substitution of cobalt in cathode materials with more abundant transition metals can preserve electrochemical stability and energy density while improving sustainability. F. Chen (2025) underlined that cobalt-free and nickel-free cathode materials, including organic and lithium iron phosphate (LFP) chemistries, can deliver competitive performance with substantially reduced environmental and supply-chain risks. F. Chen confirmed that organic cathode materials are capable of fast charging and stable cycling without relying on critical metals. These findings support a broader transition toward material-efficient battery chemistries. Long-term resource-demand modelling conducted by O.J. Oluwalana & K. Grzesik (2025) further underscored the urgency of such transitions, as quantitative assessments of global battery material flows projected substantial increases in demand for lithium, nickel, cobalt, and graphite, thereby highlighting the critical importance of supply chain diversification and recycling-based mitigation strategies. Advances in solid-state battery technology are also considered central to the future development of EVs. Solid-state batteries offer the potential for higher energy density, improved safety, and shorter charging times; however, they remain constrained by challenges related to interfacial stability and scalable electrolyte materials. A comprehensive scientific review synthesising experimental and modelling results identifies these barriers as the primary obstacles to commercial deployment, as observed by A. Joshi *et al.* (2025). According to J. Husmann *et al.* (2024), despite progress in battery chemistry, EV manufacturing remains energy-intensive and contributes to life-cycle carbon emissions. Life-cycle assessment studies indicate that integrating renewable energy sources into battery and vehicle production, combined with increased use of recycled materials, can significantly reduce greenhouse-gas emissions relative to conventional automotive manufacturing. Another major barrier to widespread EV adoption is the limited availability of fast-charging infrastructure. High-power fast-charging stations can substantially reduce charging times while improving accessibility, provided that grid integration and load management are adequately addressed (ChargerIGS, 2025). Y.A. Alhazmi (2025) argued the role of modular charging architectures and battery-swapping systems in alleviating grid stress and enhancing operational flexibility, particularly for public and commercial vehicle fleets. According to estimates K.L. Pedersen *et al.* (2025) integrating EVs into smart-grid systems further enhances energy efficiency by enabling bidirectional power flows and vehicle-to-grid services, allowing EVs to function as distributed energy-storage units that support renewable-energy balancing and grid stability. Collectively, advances in battery chemistry, manufacturing practices, charging infrastructure, and recycling technologies contribute to the formation of a more resilient and environmentally efficient electric mobility system, which is essential for reducing the ecological footprint of the transportation sector. The purpose of this research was to formulate and validate a modular approach to battery replacement and charging in order to decrease vehicle downtime and increase operational effectiveness.

Materials and Methods

The object of the research was the electric transport development system, encompassing EVs and electric buses, examined in the context of the implementation of advanced battery technologies and charging infrastructure. The subject of the research comprised the technological, economic, and organisational aspects of battery use, including standardisation, modular charging solutions, and battery swapping systems, as well as their impact on the efficiency and sustainable development of the transport sector. The methodological framework of the research was based on systemic and structural-functional approaches, which made it possible to conceptualise electric transport as a complex socio-technical system characterised by multilevel interactions among technologies, infrastructure, and market conditions. The assessment of the advantages and potential risks associated with the implementation of electric transport was grounded in a comprehensive analysis of scientific publications, peer-reviewed journal articles, monographs, and analytical reviews, including the works of R. Jiang *et al.* (2025), A. Mdallal *et al.* (2025), and A. Temporelli *et al.* (2020). The source base also included reports of international organisations, regulatory documents, academic studies, and statistical data related to environmental standards, the impact of electric transport on public health, and the economic benefits of EVs, notably materials published by the International Energy Agency (IEA, 2025a; 2025b) and International Renewable Energy Agency (IRENA, 2024). Data from the World Health Organisation (WHO, 2024) were used to assess the effects of ambient air quality on human health. The study further applied a comparative analysis of Ukrainian and international experiences in the implementation of electric transport solutions, with particular attention to the practices of the European Union, Japan, South Korea and others. This approach enabled the identification of common patterns and key differences in the development of charging infrastructure and the deployment of battery technologies. To assess future development prospects, prognostic analysis was employed, based on the synthesis of data from international organisations and recent scientific studies, which facilitated the identification of potential development scenarios for electric mobility. Given that the article contains a substantial amount of graphical material, the data visualisation method was applied to present trends in electric transport development, battery technology structures, and comparative performance indicators.

Results and Discussion

EVs play a pivotal role in mitigating environmental impacts by substantially reducing greenhouse gas emissions and facilitating the global transition towards sustainable development. Continuous advancements in battery technologies are critical for enhancing energy efficiency, reducing production costs, and extending battery service life. Moreover, the development of the EV ecosystem contributes to economic growth by creating new employment opportunities, stimulating technological innovation, and accelerating the expansion of charging infrastructure. Collectively, these factors improve the accessibility and affordability of EVs, reduce dependence on fossil fuels, and support the formation of a resilient and sustainable energy system. In light of the rapid growth in EV adoption and the persistent challenges associated with large-scale deployment, this field remains highly relevant for both academic research and practical implementation. However, air pollution (particularly urban smog) continues to pose significant environmental and public health challenges in large metropolitan areas. Emissions from internal combustion engines release considerable amounts of nitrogen oxides, carbon monoxide, and fine particulate matter, which are key constituents of urban smog (IEA, 2025a). Under unfavourable meteorological conditions, these pollutants accumulate, thereby intensifying smog formation. Elevated concentrations of particulate matter ($PM_{2.5}$), nitrogen oxides, and ground-level ozone are associated with increased incidence of respiratory and cardiovascular diseases (Fig. 1). Figure 1 indicated that the highest levels of carbon dioxide emissions are attributable to major emitting countries, notably China, the United States, and India. The findings underscored the urgent need for effective measures aimed at reducing harmful emissions into the environment. Among the viable strategies for addressing this challenge, the electrification of various modes of transport is widely recognised as a key pathway towards emission reduction. Meanwhile, air pollution resulting from ICE use continues to be a major environmental issue in metropolitan and industrial zones. The environmental hazards linked to ICE vehicles stem from the release of several toxic substances during the combustion of fossil fuels. Although industrial activity is a leading source of pollution, wealthier nations often shift manufacturing facilities away from populated areas or even beyond national borders. However, one pollution source that cannot be relocated is road transport. In fact, the more affluent and densely populated a country is, the greater the concentration of transport-related emissions.

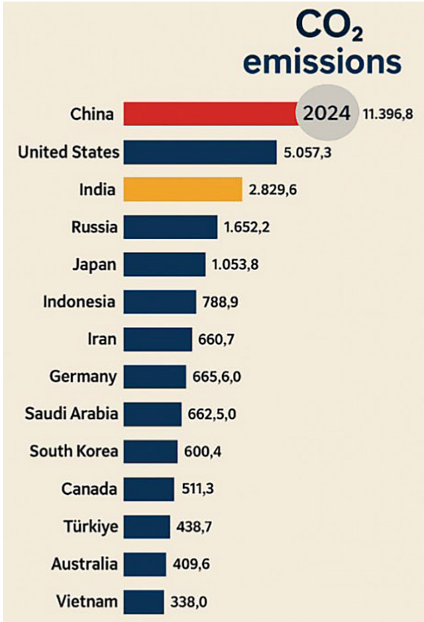

Figure 1. The countries with the most CO_2 emissions in the world
Source: Annual CO_2 emissions (2025), IEA (2025a)

The key environmental concerns associated with ICE vehicle use include:

1. CO_2 emissions and climate change. The burning of gasoline, diesel, and natural gas releases substantial amounts of carbon dioxide – a leading greenhouse gas. ICE vehicles are among the primary contributors to transportation-related CO_2 emissions. The increasing atmospheric concentration of CO_2 intensifies the greenhouse effect, accelerates climate change, and negatively impacts ecosystems, public health, and can even trigger extreme weather events.

2. NO_x emissions. Nitrogen oxides, formed during the combustion process, are highly harmful air pollutants. These gases irritate the respiratory system and may lead to asthma and other pulmonary conditions. NO_x also contributes to ground-level ozone formation, which harms both human health and plant life.

3. CO pollution. Carbon monoxide is a toxic gas resulting from incomplete fuel combustion. It disrupts oxygen delivery in the bloodstream by binding to hemoglobin, posing serious health risks, particularly in congested urban areas where CO levels often exceed safe limits.

4. Particulate matter and soot. Internal combustion engines – particularly diesel-powered ones – generate particulate matter (PM_{10} and $PM_{2.5}$) capable of penetrating deep into the lungs and even entering the bloodstream.

Long-term exposure to these microscopic particles is linked to an increased risk of respiratory and cardiovascular diseases, as well as certain types of cancer. Furthermore, fine soot particles settle on urban infrastructure, vegetation, and water bodies, causing widespread environmental degradation.

5. Moving beyond ICEs: alternatives and the future of sustainable transport. In light of tighter environmental regulations, many nations and automotive companies are turning to alternative propulsion technologies, such as electric and hydrogen-powered vehicles. Innovations in fuel-efficient vehicle design and the expansion of charging infrastructure reflect the global effort to combat air pollution and support the shift toward cleaner mobility solutions.

Adopting alternative energy sources in the transportation sector not only reduces emissions but also contributes positively to public health and improves the environmental quality of urban areas. The growing appeal of EVs stems from their ecological advantages, lower operating costs, and ongoing technological advancements. EVs offer a variety of features that enhance comfort, safety, and user experience (Fig. 2). EVs are highly eco-friendly, as they do not emit tailpipe gases such as CO_2, nitrogen oxides, or particulate matter, making them considerably more environmentally friendly than conventional vehicles. They also offer lower maintenance costs. With fewer moving parts, EVs require servicing far less frequently. Instead of regular oil changes or filter replacements, maintenance typically involves basic inspections, saving both time and money for owners. Another advantage is improved energy efficiency. EVs consume energy far more efficiently than internal combustion engine vehicles, partly thanks to regenerative braking systems that convert kinetic energy into electricity to recharge the battery. In addition, EVs provide rapid acceleration and quiet operation. Electric motors deliver torque instantly, enabling swift acceleration, while their minimal noise levels make the ride more peaceful and enjoyable for both drivers and passengers.

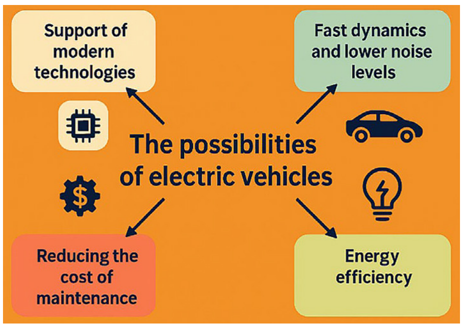

Figure 2. Features and benefits of EVs
Source: developed by the author

Figure 2 presents an infographic outlining the main capabilities and benefits of EVs. It emphasises several key aspects. Firstly, EVs offer fast dynamics and reduced noise levels. Their electric motors deliver high torque from the outset, ensuring smooth and quiet operation. Secondly, they promote environmental purity. The absence of exhaust emissions helps to decrease air pollution and improve environmental conditions, particularly in urban areas. Thirdly, EVs demonstrate superior energy efficiency. Their motors operate with significantly higher efficiency than internal combustion engines, losing less energy during use. Fourthly, maintenance costs are lower. With fewer moving parts, EVs require servicing less frequently, which reduces both time and financial expenditure. Finally, EVs support modern technologies. They incorporate advanced digital, automated, and connected systems, enhancing overall comfort and functionality for drivers and passengers. Overall, the infographic in Figure 2 concisely demonstrates the main technological, environmental, and economic advantages of EVs, highlighting their potential as a promising direction for the future of transportation. Many contemporary EVs incorporate a wide range of advanced digital features that enhance safety, functionality, and user convenience. For example, Tesla vehicles support extensive over-the-air (OTA) software update systems, allowing new functions and performance improvements to be installed remotely via the vehicle interface or mobile application (Rawal, 2025). Audi similarly offers its "Functions on Demand" platform, enabling the activation of additional software-based capabilities without requiring hardware modifications (The future of automotive technology..., 2023). Another example is the Xiaomi SU7 (2024), which integrates the Xiaomi Pilot/Hyper Automated Driving (HAD) autonomous system. This system relies on continuous OTA updates to refine automated navigation, improve sensor performance, and extend AI-driven driving functionalities. Together, these examples illustrate the increasing reliance of modern EVs on cloud connectivity, remote diagnostics, and continuously evolving software ecosystems. EVs have emerged as a vital tool in the global effort to combat smog and reduce greenhouse gas emissions. Various types of EVs are available, each offering distinct features, benefits, and potential limitations (Fig. 3).

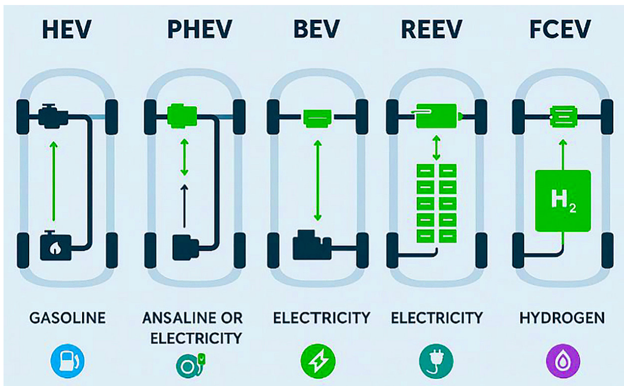

Figure 3. Types of EVs
Note: HEV – Hybrid Electric Vehicle; PHEV – Plug-in Hybrid Electric Vehicle; BEV – Battery Electric Vehicle; REEV – Range-Extended Electric Vehicle; FCEV – Fuel Cell Electric Vehicle
Source: developed by the author based on A complete guide to the types... (2024)

Figure 3 provided a comparative schematic representation of the main types of EVs, illustrating differences in their power sources, energy storage systems, and propulsion architectures. The HEV (Hybrid Electric Vehicle) combines an internal combustion engine with an electric motor, allowing limited electric assistance without external charging. The PHEV (Plug-in Hybrid Electric Vehicle) operates similarly but includes a larger battery that can be charged from the electrical grid, enabling extended electric-only driving. The BEV (Battery Electric Vehicle) relies exclusively on battery-stored electricity and includes no combustion engine, representing the fully electric drivetrain. The REEV (Range-Extended Electric Vehicle) primarily uses an electric motor for propulsion but incorporates a small combustion engine functioning solely as a generator to recharge the battery and extend driving range. Finally, the FCEV (Fuel Cell Electric Vehicle) uses hydrogen stored onboard to generate electricity through a fuel-cell system, supplying continuous power to the electric motor.

Overall, the Figure 3 visually demonstrates the technological diversity of electric mobility solutions, highlighting their varying degrees of electrification, reliance on external charging, and use of alternative energy sources. EVs play a vital role in reducing environmental pollution and promoting sustainable development by significantly cutting greenhouse gas emissions. Battery improvement is a key factor in increasing energy efficiency, lowering production costs, and extending lifespan. EV development also stimulates economic growth by creating jobs, advancing technologies, and expanding charging infrastructure, thereby improving accessibility and reducing dependence on fossil fuels. These dynamics make EVs a crucial subject for ongoing research and implementation. Internal combustion engine (ICE) vehicles remain a primary source of air pollution in urban and industrial areas, emitting substances like CO_2, NO_x, and particulate matter that contribute to smog, respiratory issues, and climate change.

Internal combustion engines create several environmental and health challenges. They emit large quantities of CO_2, which significantly contributes to global warming. Emissions of NO_x negatively affect respiratory health and facilitate the formation of ground-level ozone. CO poses risks to human health by disrupting the body's ability to transport oxygen. Additionally, particulate matter and soot increase the likelihood of cardiovascular diseases and accumulate on urban surfaces and infrastructure. These environmental burdens have accelerated the global movement toward green transport solutions, strengthened by increasingly strict emission standards and the rapid development of electric and hydrogen-powered vehicles. EVs offer several key advantages compared to conventional ICE-powered cars. They produce zero tailpipe emissions, eliminating harmful pollutants during operation. EVs also require lower maintenance, as they contain fewer mechanical components susceptible to wear. Their high energy efficiency, supported by regenerative braking, allows more effective use of stored electrical energy. The electric motor lifespan tends to be longer due to reduced mechanical friction and fewer moving parts. EVs operate quietly, thus helping decrease noise pollution in urban environments. The instantaneous availability of torque enables rapid acceleration and improved driving dynamics. Modern EVs also incorporate advanced technological features, including autopilot systems, remote vehicle access, and comprehensive mobile app integration.

EVs can be classified into several technological categories. BEVs operate exclusively on electrical energy stored in batteries; examples include the Tesla Model S and the Nissan Leaf. HEVs combine a traditional internal combustion engine with an electric motor, as seen in the Toyota Prius. PHEVs use both electric and combustion propulsion and can be externally charged from the electric grid; a prominent example is the Mitsubishi Outlander PHEV. FCEVs generate electricity using hydrogen as a fuel source; the Toyota Mirai is a widely known representative of this category. Hydrogen-powered vehicles present a mix of advantages and disadvantages. On the positive side, they produce zero harmful emissions, releasing only water vapour as a byproduct, which makes them highly environmentally friendly. They also allow for rapid refuelling, typically taking only three to five minutes, and offer a substantial driving range of around 500-800 km. Additionally, hydrogen systems do not depend on scarce metals and perform better than conventional engines in cold climates. However, their widespread adoption faces several challenges. The refuelling infrastructure is still limited in most parts of the world. Producing hydrogen is expensive and often energy-intensive. Fuel cells require costly materials, and safety concerns remain due to the high flammability of hydrogen, which complicates storage and handling. Battery Technologies play a pivotal role in determining the performance, safety, and environmental impact of EVs. Lithium-ion batteries dominate the EV market due to their high energy density, fast-charging capability, and relatively long service life. These qualities allow EVs to travel longer distances and recharge more quickly, making them highly practical for everyday use. Nevertheless, lithium-ion batteries remain expensive, pose thermal safety risks, and raise environmental concerns, particularly in relation to the mining of raw materials and the challenges of recycling at the end of their lifespan. Solid-state batteries are emerging as a promising alternative, offering even higher energy density, improved operational safety, and a longer lifespan. Despite their potential, widespread adoption is hindered by high manufacturing costs and significant technological challenges associated with mass production. Other battery technologies are also gaining attention. Sodium-ion batteries offer a more affordable and environmentally friendly option, though their energy density is lower than that of lithium-based batteries. LFP batteries are recognised for their stability and safety, making them a reliable choice, but they typically provide a slightly shorter driving range compared to high-nickel lithium chemistries. Together, these developments illustrate the ongoing evolution of battery technology and the trade-offs between cost, performance, safety, and environmental impact.

Future developments in electric mobility were expected to prioritise increases in battery energy density, reductions in production and lifecycle costs, and the diversification of complementary low-carbon energy technologies, including hydrogen-based systems. Emerging innovations, such as rechargeable liquid electrolyte batteries and next-generation solid-state energy storage technologies, were anticipated to enhance the operational performance, energy efficiency, and user convenience of EVs. Collectively, these technological advances were projected to strengthen the competitiveness of EVs relative to conventional internal combustion engine vehicles, thereby accelerating their integration into the global transport system (Fig. 4).

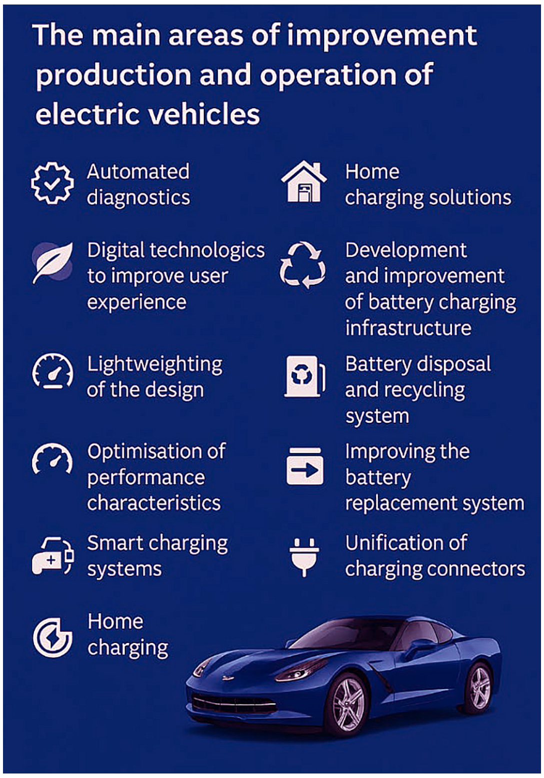

Figure 4. Main areas of improvement in the production and operation of EVs
Source: developed by the author

Figure 4 demonstrated a structured overview of the main directions for improving the engineering solutions and operational characteristics of modern EVs is presented. All development vectors are grouped into two technical categories: on-board technological systems and infrastructure- and lifecycle-related improvements. The left column illustrates areas directly related to the vehicle's internal systems, including automated diagnostics, digital user-interface technologies, lightweight structural design, optimisation of performance parameters, and the implementation of smart charging algorithms. The right column highlights external and system-level enhancements, such as home charging solutions, the expansion of charging infrastructure, battery recycling and disposal processes, advanced battery replacement mechanisms, modular vehicle architectures, and the standardisation of charging connectors. The implementation of a unified modular system for the factory production, operation, and replacement of EV battery packs constituted a complex, multifaceted undertaking that required the systematic resolution of organisational, technical, technological, and economic challenges. A central prerequisite for such a system was the harmonisation of components and technical standards across manufacturers and platforms. Battery unification, in particular, involved the standardisation of battery dimensions, interfaces, and connection protocols, which enabled joint manufacturing, economies of scale, and simplified maintenance and replacement procedures. For instance, the development of standardised battery modules applicable across multiple vehicle models increased production flexibility, reduced unit costs, and facilitated more efficient lifecycle management of battery systems (Fig. 5).

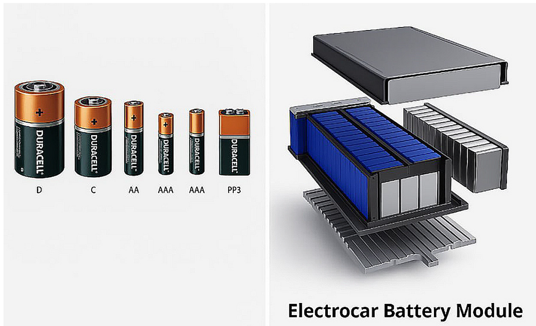

Figure 5. Using the modular principle of sectional production, operation and replacement of consumer batteries and EV batteries
Source: developed by the author

Figure 5 illustrated a comparative representation of battery technologies, combining two visual components. The left section shows a standardised line-up of conventional cylindrical consumer batteries (D, C, AA, AAA, and 9V), serving as a reference model for size unification. The right section presents an EV battery pack shown in cross-section, highlighting its modular architecture. Individual modules, internal cell arrays, structural housing, and cooling elements are visible, demonstrating the layered and serviceable design of a modern EV battery system. This configuration emphasises the principles of modularity, maintainability, and scalability in contemporary EV battery engineering. The unification of charging connectors through the adoption of a single, interoperable charging port standard for EVs (such as CCS or CHAdeMO) was expected to improve access to charging infrastructure and enhance user convenience. Standardisation in this area also contributed to reducing the capital and operational costs of charging stations by eliminating the need to support multiple incompatible connector types, thereby improving the economic efficiency and scalability of charging infrastructure deployment (Fig. 6).

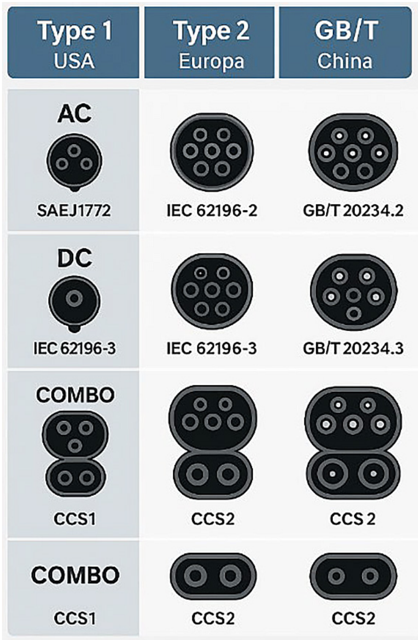

Figure 6. Types of EV charging connectors
Source: developed by the author based on P. Zhang (2025)

Figure 6 illustrated the three major EV charging connector standards used worldwide: Type 1 (United States of America (USA)), Type 2 (Europe), and GB/T (China). Each standard includes configurations for alternating current (AC) charging, direct current (DC) fast charging, and combined systems (COMBO/CCS) designed to support high-power charging. Type 1 (SAE J1772, United States) was predominantly used in North America and supported AC charging, as well as integration with the Combined Charging System (CCS1) for DC charging. Type 2 (IEC 62196-2, Europe) functioned as the universal European solution for AC charging (Type 2) and formed the basis for DC fast charging through the CCS2 configuration, enabling a high degree of interoperability within the European market. GB/T (China) employed separate connectors for AC and DC charging and did not provide compatibility with CCS-based systems, thereby limiting cross-regional interoperability. The coexistence of multiple charging standards generated a number of systemic challenges, including technical incompatibility of EVs across regional markets, increased reliance on adapters and specialised charging infrastructure, higher capital and operational costs for infrastructure development, and additional complexity in global EV manufacturing, distribution, and market integration. CCS1/CCS2 is increasingly promoted as the international standard for fast charging across the EU, USA, South Korea, and parts of Asia. CHAdeMO, although still used (notably in Japan), is progressively being displaced by CCS. China's GB/T is evolving toward the new ChaoJi standard, which aims to unify GB/T and CHAdeMO under a single high-power charging interface.

Based on Figure 6 and prevailing industry trends, several key conclusions can be drawn. First, the combination of Type 2 and CCS2 exhibited the strongest potential to emerge as a de facto global standard for EV charging, owing to its broad adoption within major markets and its technical adaptability. Second, the unification of charging connectors could reduce the manufacturing costs of charging infrastructure by an estimated 30-40 per cent, thereby enhancing economic efficiency and lowering barriers to infrastructure expansion. Third, the adoption of a single, harmonised connector interface would simplify the operation of EVs and eliminate cross-market incompatibility barriers, facilitating greater user mobility across regions. Fourth, standardisation was projected to accelerate the deployment of charging infrastructure, particularly in developing markets where cost constraints and technical fragmentation currently impede rapid uptake. Furthermore, the implementation of standardised modular components that are suitable for a range of vehicle models and classes was expected to reduce production costs, lower the purchase price of EVs, and simplify repair and maintenance processes (Fig. 7).

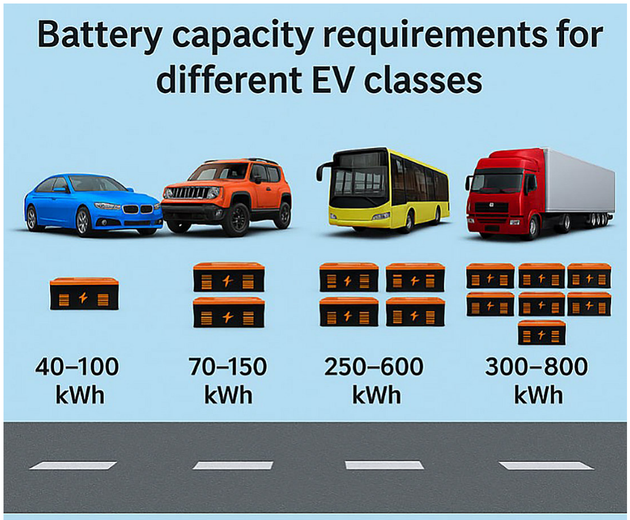

Figure 7. Number of lithium-ion modular sectional batteries required for different types of vehicles
Source: developed by the author

Figure 7 presents the concept of a unified modular battery architecture that can be scaled according to the energy demand of different classes of EVs – from passenger cars to heavy-duty EV platforms. It illustrates four categories of vehicles, each associated with an approximate total battery capacity (40-800 kWh), achieved through the combination of standardised battery modules of a uniform form factor. This approach demonstrates the possibility of using a single type of modular EV battery that can be assembled in various quantities to meet specific energy requirements. Such a configuration simplifies manufacturing, facilitates maintenance, ensures component interchangeability, and increases the scalability of battery systems for future EV platforms. Deploying high-speed battery swap stations instead of traditional charging points can significantly reduce downtime, particularly on long-distance trips. This method has already proven successful in China with companies like NIO. Additionally, offering battery leasing options helps lower the upfront cost of EVs, making it easier for users to replace old batteries without large, one-time expenses. This approach can make EVs more accessible while ensuring drivers benefit from the latest battery technology. Investing in battery recycling infrastructure and integrating recycled materials into production can lower manufacturing costs, improve sustainability, and address the issue of battery disposal. Expanding fast-charging networks enables EVs to reach up to 80% charge in just 20-30 minutes, enhancing convenience and promoting wider EV adoption. The provision of government incentives and manufacturer-supported home charging solutions, including subsidies for the installation of residential charging infrastructure, was expected to reduce upfront costs and significantly enhance the practicality and economic attractiveness of EV ownership for consumers. The integration of EV charging into smart grid systems enabled the optimisation of electricity distribution by shifting charging demand to off-peak periods, when electricity prices were lower and grid capacity was less constrained, thereby reducing pressure on energy infrastructure and improving overall system efficiency. At the same time, advances in battery technologies, particularly the development of solid-state batteries, were expected to deliver higher energy density, extended driving range, and shorter charging times, while improvements in regenerative braking systems enhanced the recovery of kinetic energy and increased the effective utilisation of stored electricity. In addition, the incorporation of lightweight materials, such as aluminium alloys and advanced composite materials, into EV design, including battery systems, reduced overall vehicle mass, which in turn improved energy efficiency and contributed to better driving performance and extended range. The integration of EVs with mobile applications enhanced user interaction by enabling drivers to monitor battery status, locate nearby charging stations, receive system alerts, and plan routes that incorporated optimal charging points. In parallel, the implementation of over-the-air software update mechanisms allowed manufacturers to continuously improve battery management systems, enhance safety features, and introduce new functionalities without requiring physical visits to service centres, thereby reducing maintenance costs and increasing operational efficiency. The deployment of built-in self-diagnostic systems further contributed to the early detection of technical faults, improving overall vehicle reliability and minimising downtime and lifecycle maintenance expenditures. At the industry level, sustainable progress in the EV sector required a comprehensive and integrated development strategy that combined component standardisation, the expansion of battery swapping networks, the large-scale deployment of charging infrastructure, and the adoption of advanced lightweight materials. Collectively, these measures reduced production and ownership costs, enhanced vehicle performance, and increased the accessibility of EVs to a broader range of consumers.

With regard to Ukraine and global experience in EV development, Ukraine, similarly to many other countries, has been actively engaged in the expansion of electric mobility, drawing upon international best practices while adapting them to domestic economic, regulatory, and infrastructural conditions. Ukrainian cities now host over 11,000 charging stations, although major highways still lack sufficient coverage (There are 20,000 more electric…, 2023). Private companies like TOKA and AutoEnterprise have significantly contributed to the expansion of fast-charging stations, especially in urban areas and along key transit routes. Government support, such as exemptions from VAT (Value-Added Tax) and excise duties, makes EVs more affordable and motivates consumers to switch to electric mobility. As a result, the number of EVs in Ukraine has grown steadily (UkraineInvest, 2024). Used electric cars, particularly models like the Nissan Leaf, remain a popular option due to the lower cost compared to new vehicles. Imports from the U.S. and Europe make EV ownership more attainable for many Ukrainians. The two main factors influencing EV growth in Ukraine are the purchasing power of the population and the availability of charging infrastructure. Although city coverage is improving, highway infrastructure still lags behind. Electric buses and other forms of electric public transport are being introduced in cities like Kyiv, helping reduce urban air pollution. EV-sharing services are also gaining traction, offering flexible mobility without the need for car ownership. Ukraine's National transport strategy through 2030 outlines further support for EVs, including expanding the national charging network and increasing incentives for clean vehicles (Ministry for Communities and Territories Development of Ukraine, 2022). Global approaches to EV development vary across regions, reflecting differences in government policy, market structure, and technological focus. In Europe, countries provide strong government incentives, including subsidies and tax breaks. Norway leads the continent with the highest EV adoption rate, supported by VAT exemptions and access to bus lanes, while Germany and France also invest heavily in both EV infrastructure and purchase incentives (Williment, 2025). China, as the largest EV market globally, leads in production and infrastructure, with companies such as Contemporary Amperex Technology Co. Limited (CATL) and Build Your Dreams (BYD) dominating battery manufacturing and battery swapping widely implemented by firms like NextEV Inc. (NIO) (Jiang *et al.*, 2025). In the United States, private companies, most notably Tesla, have built extensive fast-charging networks, while the government supports EV adoption through tax credits and funding for research and development in new battery technologies. In Japan, the focus has been on hydrogen-powered vehicles, supported by dedicated infrastructure developed for events such as the Olympics, with companies like Toyota and Honda innovating in hydrogen and solid-state battery technologies. South Korea, home to major battery producers including LG Chem and Samsung SDI, invests in battery technology and infrastructure while offering subsidies and funding advanced research. International experience shows that the global success of EVs depends on a combination of infrastructure development, government support, and technological advancement. Measures such as increasing access to chargers, providing financial incentives, and standardising batteries are essential to promote EV adoption. Examples of innovative battery use highlight these possibilities: in Japan, old EV batteries are repurposed to power streetlights; in Paris, they operate elevators; and in Amsterdam, they supply energy to an entire stadium. These cases demonstrate how technology, infrastructure, and policy together can drive the sustainable development of electric mobility, offering lessons that could inform Ukraine's EV strategy.

European countries demonstrate a systematic approach to promoting electric mobility by providing substantial governmental incentives, including tax reductions, purchase subsidies, and non-monetary benefits. For instance, in Norway, owners of zero-emission vehicles benefit from a 25% VAT exemption, access to bus lanes, and reduced toll and ferry charges. These policies have enabled Norway to achieve the highest EV market share in the world (Alternative Fuels Observatory, 2025; Norway the world leader…, 2025). China, the world's largest electric-vehicle market, combines large-scale battery production (CATL, BYD) with innovative infrastructure solutions, particularly battery-swapping networks. CATL has announced plans to deploy more than 2,500 battery-swap stations in over 120 cities by the end of 2026, while NIO and CATL are collaborating to harmonise industry standards and expand global swapping capabilities (Zhang, 2025; Chen, 2025). In the United States, private companies, most prominently Tesla, play a leading role in deploying nationwide fast-charging networks. Concurrently, the federal government supports EV adoption through tax credits and investment in advanced battery research and development (Canis *et al.*, 2019). Japan has prioritised hydrogen-fuel technologies and the development of solid-state batteries, with leading companies such as Toyota and Honda driving innovation in these areas. A notable example of Japanese ingenuity is the reuse of retired EV batteries to power street lighting in towns near Fukushima, demonstrating the potential of second-life battery applications (Schmidt, 2019). Similarly, South Korea, home to major battery manufacturers including LG Chem and Samsung SDI, has continued to invest in advanced battery research and development as well as the expansion of charging infrastructure, supported by national subsidy programmes (Bharadwaj, 2023). International experience demonstrated that the effective development of the EV sector depends on the coordinated implementation of three key elements: the systematic expansion of charging infrastructure, consistent governmental support through subsidies, tax incentives, and regulatory measures, and robust technological innovation, including the standardisation of battery modules and charging connectors. Countries that successfully integrate these components tend to achieve the most rapid growth in EV adoption. Illustrative examples of innovative second-life battery applications, such as powering LED (Light Emitting Diode) streetlights in Fukushima, operating elevators in Paris, and supplying energy to stadiums in Amsterdam, further highlight the potential for repurposing used EV batteries within urban energy infrastructures, thereby contributing to both sustainability and the efficient utilisation of resources.

In the course of this study, relevant scientific literature was reviewed and the findings of other authors were compared with the results obtained in the present research. V. Porfirenko (2025) analysed the standardisation of battery production for electric buses and assessed the feasibility of modular battery replacement in international transport operations. The study demonstrated that the implementation of unified battery modules with fast replacement capabilities can reduce vehicle downtime to 10-15 minutes and decrease the total cost of ownership in comparison with diesel buses. The results of the present research confirm the advantages of a unified modular battery system and extend this concept beyond public transport to passenger EVs, commercial fleets, and city-level battery swapping infrastructure. A. Mdallal *et al.* (2025) examined the evolution of EV charging standards and emphasised that interoperable solutions, particularly the CCS, are critical for sustainable infrastructure development and for mitigating range anxiety. These conclusions are complemented by the present study, which demonstrates that charging connector unification is significantly more effective when combined with modular battery standardisation, enabling the integrated use of fast charging and battery swapping within a unified technological ecosystem. Y.A. Alhazmi (2025) provided a systematic review of battery swapping stations, analysing their technical, economic, legal, and social dimensions. The author highlighted that the effectiveness of battery swapping systems depends heavily on deep battery standardisation and on business models compatible with conventional charging solutions. The results obtained in this study were consistent with this assessment and additionally suggested that a unified modular battery architecture constituted a prerequisite for the large-scale deployment of battery swapping stations in both urban and long-distance transport systems. A. Temporelli *et al.* (2020) conducted a life-cycle assessment of EV batteries and concluded that battery production constitutes the largest share of the environmental footprint of EVs, while recycling processes and second-life applications significantly influence overall carbon impacts. Within the present research, these findings provide a strong rationale for unified modular battery designs, which facilitate disassembly, sorting, recycling, and second-life utilisation in stationary energy storage systems. Similarly, a review of second-life battery applications by J. Schmidt (2019) demonstrated that EV batteries with a reduced state of health (SOH ≈ 70-80%) can still be effectively used in grid-connected and microgrid energy storage, offering substantial economic and environmental benefits. The results of the present study align with these conclusions and further underscore the importance of embedding design-for-second-life principles at the earliest stages of modular battery development. Overall, the analysis of the reviewed scientific works confirms that modularity, standardisation, and second-life integration are widely recognised as key directions in global EV research. The results obtained in this study are consistent with current scientific trends while providing a broader systems-level perspective on the integration of these approaches.

Conclusions

In the course of this research, a comprehensive analysis was conducted on the technological, infrastructural, and organisational foundations required for the effective development of EV systems. The study examined current global trends in EV manufacturing, the evolution of charging infrastructures, and the growing importance of unified standards across both vehicle components and energy systems. It was determined that one of the most significant barriers to large-scale EV deployment remains the lack of harmonisation in battery design, charging connectors, and replacement procedures. This fragmentation increases production costs, complicates maintenance, and slows down the expansion of EV fleets. The conducted analysis highlighted that a modular and unified approach to EV production offers substantial advantages. Standardised battery modules and structural components enable flexible manufacturing, reduce production complexity, and allow multiple vehicle classes to share common technological platforms. It was demonstrated that modular battery systems, in particular, address a critical challenge – long charging times – by enabling battery swapping, thereby drastically reducing vehicle downtime. This approach supports the formation of new urban charging ecosystems based on rapid infrastructure turnover, high user throughput, and integration into smart-energy networks. Furthermore, the findings substantiate that unified charging connectors, cross-compatible components, and interoperable digital systems enhance the scalability of EV infrastructures. Such standardisation also accelerates international cooperation, investment attractiveness, and the long-term sustainability of the EV sector. The research substantiates the conclusion that transitioning toward standardised, innovative, and eco-friendly EV architectures is a strategic step toward achieving cleaner urban mobility, increased energy efficiency, and broader public accessibility. Future research should focus on developing lifecycle models for unified battery modules, assessing economic efficiency of battery-swap networks, and exploring advanced materials that can further extend battery performance within unified system architectures. Additional studies on second-life battery applications will also play a critical role in reinforcing circular-economy principles within the EV industry.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] A complete guide to the types of electric vehicles: BEV, PHEV, FCEV, and HEV. (2024). Retrieved from https://en.yutong.com/technology/industry-insights/technologies/2024/1785230859293560832.shtml.

[2] Alhazmi, Y.A. (2025). Electric vehicle battery swap stations: An overview and critical analysis. *Journal of Umm Al-Qura University for Engineering and Architecture*. doi: 10.1007/s43995-025-00215-z.

[3] Alternative Fuels Observatory. (2025). *Norway: Incentives and legislation for electric vehicles*. Retrieved from https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/norway.

[4] Annual CO_2 emissions per country. (2024). Retrieved from ttps://ourworldindata.org/grapher/annual-co2-emissions-per-country.

[5] Annual CO_2 emissions. (2025). Retrieved from https://ourworldindata.org/grapher/annual-co2-emissions-per-country?time=1912..latest.

[6] Bharadwaj, R. (2023). *Exploring South Korea's EV success*. Retrieved from https://bolt.earth/blog/south-korean-ev-market?srsltid=AfmBOooh5HKzA8jsDOHlTAyrD6aI0JAcXtay_IzmlKZojl5qL8Op9jUL.

[7] Canis, B., Clark, C.E., & Sherlock, M.F. (2019). *Vehicle electrification: Federal and state issues affecting deployment*. Washington, DC: Congressional Research Service.

[8] ChargerIGS. (2025). *The future of EV charging*. Retrieved from https://chargerigs.com/future-of-ev-charging/.

[9] Chen, F. (2025). *Chinese EV maker NIO and battery king CATL to join forces on swapping stations, technology*. Retrieved from https://surl.li/zeouly.

[10] Husmann, J., Beylot, A., Perdu, F., Pinochet, M., Cerdas, F., & Herrmann, C. (2024). Towards consistent life cycle assessment modelling of circular economy strategies for electric vehicle batteries. *Sustainable Production and Consumption*, 50, 556-570. doi: 10.1016/j.spc.2024.09.001.

[11] IEA. (2025a). *Global energy review 2025: CO_2 emissions*. Retrieved from ttps://www.iea.org/reports/global-energy-review-2025/co2-emissions.

[12] IEA. (2025b). *Global EV outlook 2025: Electric vehicle charging*. Retrieved from ttps://www.iea.org/reports/global-ev-outlook-2025/electric-vehicle-charging.

[13] IRENA. (2024). *Critical materials: Batteries for electric vehicles*. Retrieved from https://www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles.
[14] Jiang, R., Wu, C., Feng, W., You, K., Liu, J., Zhou, G., Liu, L., & Cheng, H.-M. (2025). Impact of electric vehicle battery recycling on reducing raw material demand and battery life-cycle carbon emissions in China. *Scientific Reports*, 15, article number 2267. doi: 10.1038/s41598-025-86250-1.
[15] Joshi, A., Mishra, D.K., Singh, R., Zhang, J., & Ding, Y. (2025). A comprehensive review of solid-state batteries. *Applied Energy*, 386, article number 125546. doi: 10.1016/j.apenergy.2025.125546.
[16] Liu, Z., Ma, X., Liu, X., de Almeida Correia, G.H., Shi, R., & Shang, W. (2023). Optimising electric taxi battery swapping stations featuring modular battery swapping: A data-driven approach. *Applied Sciences*, 13(3), article number 1984. doi: 10.3390/app13031984.
[17] Mdallal, A., Yasin, A., Alaboudy, A.H.K., & ElSaid, K. (2025). Advancements in EV charging standards and technologies for sustainable transportation. *Renewable and Sustainable Energy Technology*. doi: 10.53941/rest.2025.100010.
[18] Mesquita, A.R., de Abreu, V.H.S., Poyares, C.N., & Santos, A.S. (2025). Barriers to electric vehicle adoption: A framework to accelerate the transition to sustainable mobility. *Sustainability*, 17(18), article number 8318. doi: 10.3390/su17188318.
[19] Ministry for Communities and Territories Development of Ukraine. (2022). *Ukravtodor approved the action plan to support electromobility*. Retrieved from https://mindev.gov.ua/news/33403-ukravtodor-zatverdiv-plan-zaxodiv-z-pidtrimki-elektromobilnosti.
[20] Norway the world leader in EVs. (2025). Retrieved from https://www.ecobatt.com.au/norway-the-world-leader-in-evs/.
[21] Oluwalana, O.J., & Grzesik, K. (2025). A systematic review of life cycle assessment of electric vehicles studies: Goals, methodologies, results and uncertainties. *Energies*, 18(22), article number 5867. doi: 10.3390/en18225867.
[22] Pedersen, K.L., Knudsen, R.M., Marinelli, M., Secchi, M., & Sevdari, K. (2025). Enabling grid services with bidirectional EV chargers: A comparative analysis of CCS2 and CHAdeMO response dynamics. *World Electric Vehicle Journal*, 16(11), article number 636. doi: 10.3390/wevj16110636.
[23] Porfirenko, V. (2025). Standardisation of electric vehicle battery production in international electric bus transportation based on the innovative modular principle. *Standards-related Regional Innovation and International Cooperation*, 1(1), 33-47. doi: 10.63385/sriic.v1.i1.317.
[24] Rawal, D. (2025). *Securing the lifeblood of modern vehicles: OTA*. Retrieved from https://www.t-systems.com/dk/en/insights/newsroom/expert-blogs/over-the-air-automotive-security-1046054.
[25] Schmidt, J. (2019). *How one Japanese town is turning old EV batteries into street lamps*. Retrieved from ttps://en.reset.org/second-life-batteries-electric-cars-japan-they-are-used-street-lamps-01272019/.
[26] Senn, B.A. (2023). *How can cobalt be reduced in EV batteries?* Retrieved from ttps://www.sciena.ch/research/how-can-cobalt-be-reduced-in-ev-batteries.html.
[27] Temporelli, A., Carvalho, M.L., & Girardi, P. (2020). Life cycle assessment of electric vehicle batteries: An overview of recent literature. *Energies*, 13(11), article number 2864. doi: 10.3390/en13112864.
[28] The future of automotive technology: Exploring OTA updates in cars. (2023). Retrieved from https://www.motorfinity.uk/blog/ota-updates-in-cars/.
[29] There are 20,000 more electric cars in Ukraine than in Poland. (2023). Retrieved from ttps://eauto.org.ua/en/news/375-there-are-20-000-more-electric-cars-in-ukraine-than-in-poland.
[30] UkraineInvest. (2024). Electric cars market growth: How Ukraine can benefit. Retrieved from ttps://ukraineinvest.gov.ua/en/news/electric-cars-market-growth-how-ukraine-can-benefit/.
[31] WHO. (2024). *Ambient (outdoor) air quality and health*. Retrieved from ttps://www.who.int/news-room/fact-sheets/detail/ambient-%28outdoor%29-air-quality-and-health.
[32] Williment, C. (2025). *How is Norway leading in the electric vehicle transition?* Retrieved from https://sustainabilitymag.com/news/how-is-norway-leading-in-the-electric-vehicle-transition.
[33] Xiaomi SU7: A revolutionary EV experience. (2024). Retrieved from https://www.mi.com/global/discover/article?id=3263.
[34] Zhang, P. (2025). *CATL plans to build over 2,500 swap stations by end-2026*. Retrieved from https://cnevpost.com/2025/10/21/catl-plans-2500-swap-stations-2026/.

Інноваційна стандартизована модульна система управління для заміни та заряджання акумуляторних батарей електричних транспортних засобів

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Анотація. У статті було досліджено потенціал підвищення ефективності виробничих та експлуатаційних систем електромобілів через впровадження інноваційного, стандартизованого модульного підходу до заміни батарей та заряджання. Дослідження було зосереджене на пасажирських електромобілях та електробусах, що використовуються в міських та міжміських перевезеннях і оснащені літій-іонними батарейними системами. Особлива увага приділялася системним обмеженням існуючої інфраструктури електротранспорту, зокрема тривалому часу заряджання, відсутності стандартизації батарей та роз'ємів, високим витратам на виробництво та обслуговування, а також їхньому негативному впливу на широке впровадження рішень у сфері електромобільності. Метою дослідження було розроблення та обґрунтування уніфікованої модульної моделі заміни батарей та заряджання, призначеної для зменшення часу простою транспортних засобів та підвищення експлуатаційної ефективності. Методологія дослідження включала системний та порівняльний аналіз, статистичні методи та графічне моделювання для вивчення модульних архітектур батарей та стандартизації інфраструктури, а також оцінку впливу на довкілля з порівнянням електромобілів та автомобілів із двигунами внутрішнього згоряння. Дослідження спиралося на наукову літературу, звіти міжнародних організацій (Міжнародного енергетичного агентства, Міжнародного агентства з відновлюваної енергії, Організації економічного співробітництва та розвитку, Всесвітньої організації охорони здоров'я), статистичні бази даних, нормативні документи та відкриті галузеві джерела. Результати підтвердили, що транспортні засоби з двигунами внутрішнього згоряння є значними джерелами викидів CO_2, NO_x та дрібнодисперсних частинок, що сприяє зміні клімату, забрудненню повітря та погіршенню стану громадського здоров'я. Натомість електромобілі демонструють суттєво нижчий вплив на довкілля, вищу енергоефективність та зменшені витрати на обслуговування. На основі проведеного аналізу було запропоновано уніфіковану модульну систему заміни батарей, яка забезпечує швидке поповнення енергії, підвищує сумісність, знижує витрати на інфраструктуру та сприяє розвитку сталого екосистемного середовища електромобільності. Дослідження дійшло висновку, що відсутність достатньої стандартизації батарейних систем та інфраструктури заряджання гальмує масштабне впровадження електромобілів, тоді як модульна та уніфікована архітектура транспортних засобів значно зменшує час простою та підвищує гнучкість виробництва й масштабованість інфраструктури

Ключові слова: екологічні проблеми; зарядна інфраструктура; економічна ефективність; витрати на технічне обслуговування; електрична мобільність

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 25.06.2025. Revised: 02.11.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 656.073:004.9 DOI: 10.33744/2308-6645-2025-2-29-94-104

Digitisation of the processes of customs clearance of goods with the calculation of the mathematical model of fuzzy logic

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Abstract. The relevance of this study arises from the growing reliance on automated customs clearance systems that generate recommendations, alerts, and justifications in order to reduce processing time. However, the effectiveness of such systems depends on a scientifically grounded methodology for determining the optimal frequency of risk profile reviews and for improving quantitative risk assessment. The purpose of the study was to develop a mathematical model for verifying the accuracy of customs clearance using the apparatus of fuzzy logic in international cargo transportation. The research methods included the development of mathematical models and algorithms for their implementation. In particular, the mathematical apparatus of fuzzy logic was applied to determine the correctness of customs clearance of

Suggested Citation: Prokudin, H., Chupailenko, O., Kolesnyk, Yu., Kozlov, A., Svirin, D., & Holovatiuk, M. (2025). Digitisation of the processes of customs clearance of goods with the calculation of the mathematical model of fuzzy logic. *Bulletin of the National Transport University*, 29(2), 94-104. doi: 10.33744/2308-6645-2025-2-29-94-104.

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goods. It was shown that the identification of customs clearance objects using fuzzy logic apparatus allows to automate the processing of information that is given in the customs declaration, the consumer documents and technical documentation. And which is submitted to the customs authorities with the control of the legalness of the classification of goods using the apparatus of fuzzy logic. Recommendations were developed for the use of the fuzzy logic apparatus in an automated expert system to determine the correctness of customs clearance of goods. This system was intended to enhance control over the correctness of goods classification during customs clearance and to prevent evasion by participants of foreign economic activity from paying taxes in full and from complying with non-tariff regulation measures through violations of declaration rules for goods crossing the customs border of Ukraine. It was also aimed at reducing the time of customs clearance, providing direct solutions to complex and contradictory classification problems arising during clearance, and avoiding errors in the classification of goods

Keywords: information automation; risk management; non-tariff regulation; logistics operators; transport monitoring

Introduction

Risk management is a fundamental principle of modern customs control methods, as it enables the optimisation of costs associated with customs supervision. This principle protects the majority of foreign trade operations from excessive bureaucratic control. It is appropriate to consider the customs risk management system as a set of instruments and management methods based on the principle of selectivity. Such a system reduces the number of customs control forms applied, while ensuring that the chosen measures remain sufficient for compliance with customs legislation. Under current conditions, there is a clear need to establish a customs administration system in Ukraine that is stable, prevents violations of national customs law, increases the collection of customs duties and taxes, and enhances the competitiveness of Ukrainian production. Procedures related to risk management are concentrated customs control in processes. where the highest risk is the registration of customs declarations, which are registered for all goods. In response to the evolving geopolitical environment, Ukraine's customs policy is undergoing significant transformation, accompanied by a documented increase in violations related to the registration of customs declarations for goods and vehicles, which underscores the need for strengthened control mechanisms and improved regulatory oversight (In 2024, customs authorities…, 2025). Therefore, the development of a methodology for maintaining the optimal frequency of review of this risk is relevant. One of the forms of customs control is, first of all, verification of the authenticity of customs declarations.

Systems designed to support decision-making processes, in particular advisory and expert systems, are gaining particular relevance. The name of these systems fully corresponds to their purpose: at the user's request, they "issue" recommendations in a situation that arises during the analysis of objects. The system should issue recommendations at the level of an experienced person, an authority in his field. An expert system is not intended to replace a person who makes decisions, although in extreme cases such a replacement is possible. The use of expert systems and adequate methods of object identification for the needs of customs clearance of goods and customs control is an important and priority area of development of the State Customs Service. L.M. Ivashova & L.I. Kyda (2020) analysed the current state of digital transformation within the Ukrainian customs system, emphasising key technological innovations that contribute to procedural simplification. The author highlighted major challenges and outlines prospects for improving customs administration through modern digital tools and information systems. The study by I. Berestov *et al.* (2022) examined the digitalisation of customs control and cargo-clearance processes in railway transport. The researchers evaluated the impact of digital tools on accelerating clearance procedures and enhancing the efficiency of cargo-flow monitoring. In turn, R. Lemeha (2020) investigated automation and informatisation as priority directions for improving the administration of customs regimes in Ukraine. The publication discussed existing regulatory gaps and proposes digital solutions aimed at strengthening transparency, control, and service quality in customs processes. Similarly, V. Lebid *et al.* (2020) evaluated the efficiency of simplifying customs formalities through digitalisation initiatives. The study provided empirical evidence demonstrating how digital services reduce processing time, minimise administrative barriers, and support overall trade facilitation. A more advanced methodological perspective is presented by N. Luo *et al.* (2023), who offered a comprehensive overview of customs risk-management methods, with particular emphasis on fuzzy-logic and neural-network-based models for assessing risks faced by import-export enterprises. Building on this direction, Z. Dong & M. Tian (2025) proposed a fuzzy-logic-based model for assessing risks in cross-border e-commerce logistics supply chains. The findings showed that fuzzy inference systems can more reliably evaluate dynamic and imprecise data compared to traditional deterministic models. In a related study, C. Zheng *et al.* (2025) developed a data-driven model for optimising customs-clearance strategies for emergency supplies using machine-learning and clustering techniques. Their results highlighted how digital analytics significantly reduce clearance time during crisis situations. Further exploring the technological evolution of customs systems, S. Vijayakumar (2025) investigated technology-centric and data-driven transformations in customs risk management. The author outlined how digital ecosystems, automated control algorithms, and AI-based tools enhance supply-chain security in global trade.

The literature review confirmed that, in the practice of customs clearance, a number of systemic problems persist due to the absence of an effective mechanism for determining the physical, chemical, and other characteristics of goods crossing the customs border of Ukraine. The classification process is complicated by the large volume of input information, inaccuracies in primary data, limited decision-making timeframes, the extensive number of explanatory letters issued by the State Customs Service (SCSU), and an insufficient level of specialised knowledge in certain fields. This highlights the need to improve approaches to goods classification, particularly through the automation of relevant procedures, which would contribute to increasing the accuracy and efficiency of customs control. The aim of the work was to design a model for the digitalisation of customs clearance processes using fuzzy logic in international freight transportation.

Materials and Methods

The object of this study was the processes of customs clearance of declarations in the context of international carriage of goods. The subject of the work was the mathematical model of control of the correctness of filling out customs declarations with the apparatus of fuzzy logic. The method of identification of objects of customs control is aimed at implementing a single algorithm for automated processing of information contained in customs documents (cargo customs declaration; accompanying documents; technical documentation at the level of customs authorities with control over the correctness of the classification of goods; with the issuance of various recommendations, warnings; and also in substantiating the established position for the regular personnel of customs authorities who carry out customs control and customs clearance of goods). Within the framework of the study, the regulatory and legal basis of customs regulation was analysed, in particular the provisions of the Law of Ukraine No. 2697-IX (2023), which defines the structure and content of the Ukrainian Classification of Goods for Foreign Economic Activity (UKTZED). An approach based on the application of fuzzy logic was selected, as it makes it possible to take into account not only precise quantitative data but also qualitative expert assessments. The practice of human decision-making was analysed, since individuals often operate with vague concepts such as "high", "low", "near", "far", "fast", and "slow", which reflect the subjective perception of information. The choice of fuzzy logic was justified by its ability to formalise and process such qualitative expert knowledge while preserving important information derived from professional experience, and at the same time ensuring objective data processing within expert systems. The use of this approach enables the effective handling of qualitative and incomplete data under conditions of limited time. Goods were considered as a set of fuzzy statements with corresponding degrees of truth within the interval [0; 1], which made it possible to represent expert knowledge in a formalised manner. On the basis of fuzzy logic operations (conjunction, disjunction, and negation), mathematical models and algorithms were developed to determine the assignment of customs control objects to specific UKTZED subcategories. The practical implementation of the methodology was demonstrated through examples of classifying motor vehicles under heading 8703 and motor gasolines under heading 2710, which confirmed the potential to increase the accuracy, objectivity, and efficiency of customs control by automating classification procedures.

Results

Significant challenges exist in the classification and identification of goods, as there is currently no effective and reliable system for determining their physical, chemical, and other properties when crossing the customs border of Ukraine. Goods are classified according to the UKTZED, established by the Law of Ukraine No. 2697-IX (2023). The main problems of correct classification: a large volume of input information; inaccuracy (inaccuracy) of primary data; short deadlines for making a decision on assigning a commodity code; a large number of information letters from the SCSU; lack of a sufficient level of knowledge in some areas, including specific knowledge (chemical industry, light industry, mechanical engineering, electronics, agriculture, etc.) (Chupailenko *et al.*, 2023). Automation of the process of classification of goods would solve a number of issues that arise in the process of customs clearance. Fuzzy logic enables the processing of information that contains expert knowledge and experience, which are difficult to formalise into precise numerical values. As a result, expert systems based on fuzzy logic can effectively integrate quantitative and qualitative data, assess information objectively, and make decisions under time constraints, making them particularly relevant for modern complex systems (Mishchenko *et al.*, 2020; Kostiana *et al.*, 2021). The mathematical apparatus of fuzzy logic is at once the most adequate, it allows to maximally shorten the transition from a verbal, verbal, qualitative description of an object, which characterises human thinking, to numerical quantitative assessments of its state. This makes it possible to formulate on this basis simple and effective algorithms to model human thoughts and human ability to perform tasks. The possibility of identifying objects of customs control for commodity item 8703, according to the Ukrainian Classification of Economic Activities (object class "passenger car"), can be considered using the mathematical apparatus of fuzzy logic (Table 1).

Table 1. Characteristics determining for classification of product

$\tilde{a}_1$	"Cars and other motor vehicles"
$\tilde{a}_{12}$	"Motor vehicles equipped for temporary human consumption"
$\tilde{a}_{13}$	"Other transport means"
$\tilde{a}_{21}$	"Spark-ignition internal combustion engine with a cylinder capacity exceeding 2,200 cm³ but not exceeding 3,000 cm³"
$\tilde{a}_{22}$	"Compression-ignition internal combustion engine (diesel or semi-diesel)"
$\tilde{a}_3$	"Another engine"
$\tilde{a}_4$	"New"

Source: developed by the authors

Table 1 presented a structured set of classification characteristics used to identify motor vehicles within the UKTZED and summarised key technical and functional parameters that determine the correct assignment of a product to a specific tariff heading when performing customs clearance procedures. The provided characteristics encompass several essential classification criteria. These include the general category of the vehicle, such as passenger cars and other motor vehicles, as well as its functional purpose, for example, vehicles equipped for temporary human use. The type of engine, whether spark-ignition, compression-ignition, or other types, is also considered, along with the engine cylinder capacity, which serves as a critical parameter for tariff differentiation. Additionally, the condition of the vehicle, particularly whether it is new, is taken into account. Table 1 demonstrated a clear hierarchical structure, progressing from broad product categories to more detailed technical specifications that influence tariff classification. Such structuring is fundamental for ensuring accurate product identification during customs control, the correct application of customs duties and excise tax rates, consistency and transparency in the classification of motor vehicles, and compliance with the principles of the Harmonised Commodity Description and Coding System. Given its systematic presentation of determining characteristics, the table serves as a practical reference for both customs authorities and foreign trade operators, supporting the effective and legally compliant performance of customs procedures.

The object of identification "car" can be represented as a set of characteristics expressed as fuzzy statements. A fuzzy statement is a sentence about which one can judge the degree of its truth or falsehood at a given time. The degree of truth or falsehood of each fuzzy statement takes on a value from the closed interval [0; 1], where 0 and 1 are the limiting values of the degree of truth and coincide with the concepts of "false" and "true" for "clear" statements. A fuzzy statement that has a value of the degree of truth equal to 0.5 is called indifference, since it is true to the same extent as it is false. Compound sentences are formed from simple sentences using the logical operations of negation, conjunction, disjunction, implication, etc. Thus, the conditional car of commodity heading 8703 can be written as a set of vague sentences that meet certain characteristics (Table 2).

Table 2. Characteristics of heading 8703

Unclear statement	$\tilde{a}_1$	$\tilde{a}_{12}$	$\tilde{a}_{13}$	$\tilde{a}_{21}$	$\tilde{a}_{22}$	$\tilde{a}_3$	$\tilde{a}_4$
Degree of authenticity	0.9	0.7	0.9	0.6	0.4	0.6	0.9

Source: developed by the authors

The features relevant for classifying products in the subcategories 8703 23 11 30 and 8703 23 19 30 have been identified. To determine whether a product belongs to the specified product groups, the following characteristics are important: $\tilde{a}_4$, $\tilde{a}_{21}$, $\tilde{a}_{22}$, $\tilde{a}_3$, $\tilde{a}_{13}$. A concise, generalised statement characterising the proposed product subcategories can be formulated as follows:

$$\begin{gathered}\tilde{A}_{8703231930} = (\tilde{a}_{13}\,\&\,((\tilde{a}_{21}U\tilde{a}_{22})\ U\neg\tilde{a}_3))\ \&\tilde{a}_4;\\ \tilde{A}_{8703231130} = (\neg\tilde{a}_{13}\&\,((\tilde{a}_{21}U\tilde{a}_{22})\ U\neg\tilde{a}_3))\ \&\tilde{a}_4.\end{gathered} \tag{1}$$

The degrees of truth for the first and second fuzzy statements are determined. Using the definition, they can be written as follows:

$$\begin{gathered}\tilde{A}_{8703231930} = (\tilde{a}_{13}\,\&\,((\tilde{a}_{21}U\tilde{a}_{22})\ U\neg\tilde{a}_3))\ \&\tilde{a}_4;\\ \tilde{A}_{8703231930} = (\tilde{a}_{13}\&\ \max(\max(\tilde{a}_{21},\ \tilde{a}_{22}),\neg\tilde{a}_3))\ \&\tilde{a}_4;\\ \tilde{A}_{8703231930} = \min(\min(\tilde{a}_{13},\max(\max(\tilde{a}_{21},\ \tilde{a}_{22}),\neg\tilde{a}_3)),\tilde{a}_4);\\ \tilde{A}_{8703231930} = \min(\min(0.9,\ \max(\max(0.6,\ 0.4),\ 1-0)),\\ 0.9) = 0{,}9.\end{gathered} \tag{2}$$

$$\begin{gathered}\tilde{A}_{8703231130} = (\neg\tilde{a}_{13}\&\,((\tilde{a}_{21}U\tilde{a}_{22})\ U\neg\tilde{a}_3))\ \&\tilde{a}_4;\\ \tilde{A}_{8703231130} = (\neg\tilde{a}_{13}\&\ \max(\max(\tilde{a}_{21},\ \tilde{a}_{22}),\neg\tilde{a}_3))\ \&\tilde{a}_4;\\ \tilde{A}_{8703231130} = \min(\min(1-\tilde{a}_{13},\ \max(\max(\tilde{a}_{21},\ \tilde{a}_{22}),\neg\tilde{a}_3)),\ \tilde{a}_4);\\ \tilde{A}_{8703231130} = \min(\min(1–0.9,\ \max(\max(0.6,\ 0.4),\ 1-0)),\\ 0.9) = 0.1.\end{gathered} \tag{3}$$

So, based on the calculation results, it can be concluded that a car with the given characteristics is far more appropriately classified under code 8703 23 19 30 rather than under code 8703 23 11 30. The Table 3 is completed following the procedure for determining product codes in accordance with the UKTZED.

Table 3. The structure of the product respectively UKTZED (extract)

Code	Product description
8703	Motor vehicles and other motorised transport vehicles, designed primarily for the transport of persons (other than motor transport vehicles of heading 8702), including trucks, vans and racing cars:
8703 10 18 00	- - others
....	- other compact tools with an internal combustion engine with spark ignition and with a crank-rod mechanism:
8703 21 10 00	- - - new ones
8703 21 90	- - - what was used:
8703 21 90 10	- - - - no more than 5 years
8703 21 90 30	- - - - more than 5 years
8703 22	- - with a side volume of engine cylinders over 1.000 cm^3, but not more than 1,500 cm^3:
8703 22 10 00	- - - new ones
8703 22 90	- - - what is the meaning of the word:
8703 22 90 10	- - - - no more than 5 years
8703 22 90 30	- - - - more than 5 years
8703 23	- - with a lateral volume of engine cylinders over 1,500 cm^3, but not more than 3,000 cm^3: - - - new
8703 23 11	- - - - motor vehicles equipped for temporary human consumption:
8703 23 11 10	- - - - - with engine cylinder volume over 1,500 cm^3, but not more than 2,200 cm^3
8703 23 11 30	- - - - - with an engine cylinder volume of more than 2,200 cm^3, but not more than 3,000 cm^3
8703 23 19	- - - - others:
8703 23 19 10	- - - - - with engine cylinder volume over 1,500 cm^3, but not more than 2,200 cm^3
8703 23 19 30	- - - - - with a volume of more than 2,200 cm^3, but not more than 3,000 cm^3

Note: Hyphens in the structure of the UKTZED are used to indicate the hierarchical level of product classification. Each additional hyphen represents a lower-level subheading within the corresponding product category and specifies the characteristics of the goods
Source: developed by the authors

Table 3 contained systematic information on the product nomenclature of vehicles under the UKT FEA code 8703, which covers passenger cars and other motor vehicles designed primarily for the transport of passengers. This structure presented a hierarchical division of product positions based on the key technical characteristics of vehicles, including the type of engine and method of ignition, the presence of a crank mechanism, engine cylinder capacity, classification into new and used, and breakdown by service life (up to 5 years and over 5 years). It reflects that each basic code (e.g., 8703, 8703 21, 8703 22, 8703 23) comprises a number of subcategories that specify the technical parameters of the vehicle. This hierarchical structure is typical for the UKT FEA and enables accurate tariffing as well as the correct determination of tax rates depending on the vehicle's configuration, technical condition, and age. The positions regarding vehicles are presented in particular detail, including those with a spark-ignition (gasoline) engine, with an engine displacement of up to 1,500 cm^3, 1,500-2,200 cm^3, and 2,200-3,000 cm^3, and those which are new as well as used. Such detailing is important for customs clearance, as different subcategories are subject to varying rates of customs duties, excise duties, and other taxes. Table 3 also demonstrates the logic of vehicle classification in customs matters, progressing from a general code to the most detailed description of the goods. The possibility of identifying objects of customs control for commodity item 2710, according to the UKTZED (object class "motor gasoline"), is examined using the mathematical apparatus of fuzzy logic (Table 4).

Table 4. Characteristics determining for classification of product

$\tilde{a}_1$	"Easy children for other purposes"
$\tilde{a}_{21}$	"Fuel for active engines"
$\tilde{a}_{22}$	"Aviation gasoline"
$\tilde{a}_{23}$	"Other gasolines containing lead"
$\tilde{a}_{31}$	"With octane number less than 95"
$\tilde{a}_{32}$	"With an octane number of 80 or less with a content of not less than 5 wt.% of a high-octane oxygen-containing additive or ethyl tert-butyl ether or its mixture"
$\tilde{a}_4$	"Other"

Source: developed by the authors

Table 4 showed the systematisation of the classification features of goods used to determine their belonging to the relevant UKTZED codes during customs clearance. The table presents the symbols of the characteristics of goods that are decisive for their correct identification in accordance with the requirements of the Harmonised Commodity Description and Coding System (World Customs Organization, n.d.). The presented classification features cover the following groups of characteristics:

- functional purpose of the goods (for example, "for other purposes");
- type and characteristics of fuel, in particular gasoline;
- octane number, which is a key parameter for the classification of petroleum products;
- content of additives, including high-octane oxygen-containing components (ethyl tertiary-butyl ether (ETBE) and other additives).

Each of the above characteristics is assigned a specific symbol, which facilitates subsequent analysis and the use of data in customs practice. For instance, subgroups representing different types of gasoline are distinguished by octane number and impurity content, allowing the product to be unambiguously attributed to the corresponding commodity subheading. The structure of the table demonstrates a logical approach to the classification of goods, progressing from a general characteristic, such as the product type, to narrower characteristics that specify the physical and chemical properties. This format of presenting information is particularly valuable in the customs control process, as it helps prevent errors in determining the commodity code, enables the reasonable application of the appropriate duty and excise tax rates, ensures a consistent approach to the classification of petroleum products, and facilitates accurate and transparent tariff regulation. Owing to its clear structure and the generalisation of essential classification indicators, the table can serve as a reference tool both in academic research, such as a thesis, and in the practical activities of customs authorities and foreign trade entities. Therefore, in accordance with the UKTZED, the company's trade code: 8703 23 19 30 is a railway vehicle with an internal combustion engine with spark ignition and a crank-rod mechanism, new, other, with engine cylinder volume over 2,200 cm³, but not more than 3,000 cm³. The object of identification "motor gasoline" can be considered as a collection of abstract, vague expressions. Thus, the conditional motor gasoline of heading 2710 can be represented as a set of fuzzy expressions corresponding to specific specifications (Table 5).

Table 5. Characteristics of heading 2710

Vague expression	$\tilde{a}_1$	$\tilde{a}_{21}$	$\tilde{a}_{22}$	$\tilde{a}_{23}$	$\tilde{a}_{31}$	$\tilde{a}_{32}$	$\tilde{a}_4$
Degree of ownership	0.85	0.3	0.4	0.8	0.3	1	0

Source: developed by the authors

The features relevant for classifying the company in the subcategories 2710 11 41 11 and 2710 11 41 19 are identified. To determine the company's assignment, the following abstract indicators are significant for the specified social groups: ã32, ã21, ã22, ã23, and ã1. A complex fuzzy statement can then be formulated to summarise the proposed social subcategories:

$$\tilde{A}_{2710114111} = (\tilde{a}_{32} \& ((\tilde{a}_{22} U \tilde{a}_{23})\ U \neg \tilde{a}_{21}))\ \& \tilde{a}_1;$$
$$\tilde{A}_{2710114119} = (\neg \tilde{a}_{32} \& ((\tilde{a}_{22} U \tilde{a}_{23})\ U \neg \tilde{a}_{21}))\ \& \tilde{a}_1. \quad (4)$$

The degrees of truth for the first and second fuzzy expressions are determined. Using the definition, they can be written as follows:

$$\tilde{A}_{2710114111} = (\tilde{a}_{32} \& ((\tilde{a}_{22} U \tilde{a}_{23})\ U \neg \tilde{a}_{21}))\ \& \tilde{a}_1;$$
$$\tilde{A}_{2710114111} = (\tilde{a}_{32} \& \max(\max(\tilde{a}_{22}, \tilde{a}_{23}), \neg \tilde{a}_{21}))\ \& \tilde{a}_1;$$
$$\tilde{A}_{2710114111} = \min(\min(\tilde{a}_{32}, \max(\max(\tilde{a}_{22}, \tilde{a}_{23}), \neg \tilde{a}_{21})), \tilde{a}_1);$$
$$\tilde{A}_{2710114111} = \min(\min(1, \max(\max(0.4, 0.8), 1-0.3)), 0.85) = 0{,}8. \quad (5)$$
$$\tilde{A}_{2710114119} = (\neg \tilde{a}_{32} \& ((\tilde{a}_{22} U \tilde{a}_{23})\ U \neg \tilde{a}_{21}))\ \& \tilde{a}_1;$$
$$\tilde{A}_{2710114119} = (\neg \tilde{a}_{32} \& \max(\max(\tilde{a}_{22}, \tilde{a} =_{23}), \neg \tilde{a}_{21}))\ \& \tilde{a}_1;$$
$$\tilde{A}_{2710114119} = \min(\min(1 - \tilde{a}_{32}, \max(\max(\tilde{a}_{22}, \tilde{a}_{2=3}), \neg \tilde{a}_{21})), \tilde{a}_1);$$
$$\tilde{A}_{2710114119} = \min(\min(1-1, \max(\max(0.4, 0.8), 1-0.3)), 0.85) = 0. \quad (6)$$

Therefore, taking into account the calculation results, motor gasolines with the specified characteristics are more appropriately classified under code 2710 11 41 11 rather than under code 2710 11 41 19. In accordance with the UKTZED, the corresponding company codes are identified and shown in Table 6.

The Table 6 presented a multi-level structure of the classification of petroleum products under code 2710, which covers petroleum distillates and motor gasolines. The differentiation of product subcategories is based on their physico-chemical properties, which directly influence their applicability, environmental impact, energy performance, and the regulatory requirements for their transport and taxation. The structure illustrated a clear sequence of classification levels, beginning with the general product category 2710, which covers petroleum and bituminous mineral products, and then narrowing to subcategory 2710 11, which includes light distillates such as motor gasolines. Further subdivisions are made according to the purpose of the product (for other purposes, special gasolines, or motor gasoline), the type of gasoline (aviation, leaded, or unleaded), the presence or absence of lead, octane rating, and the content of high-octane oxygenated additives, such as ETBE. This hierarchical structure ensured the accurate assignment of each product to the appropriate tariff heading based on its essential characteristics. Special gasolines are intended for laboratory, technical, or specific industrial applications, whereas motor gasolines are designed for use in internal combustion engines. This distinction affects taxation, customs payments, and labeling requirements. Leaded gasolines form a separate category because their use is strictly regulated or prohibited due to environmental concerns, while unleaded gasolines are classified independently in compliance with international emission standards. The octane number serves as a primary classification criterion, defining the fuel's resistance to detonation. Fuels are distinguished, for example, between those with less than 95 octane and those with 80 octane or less. The octane number determines the suitability of fuel for specific engine types and ensures compliance with quality and environmental regulations. Subcategory 2710 11 41 11 additionally specifies a requirement of at least 5 wt.% of a high-octane oxygen-containing additive or ETBE. Such additives are significant because they increase the octane rating, reduce the toxicity of exhaust gases, modify key physico-chemical parameters of gasoline, and influence the taxation system, particularly excise duty rates.

Table 6. Structure of UKTZED (part)

Code	Social experience
2710	Petroleum or petroleum products derived from bituminous dust (minerals), including white; products, not otherwise specified, containing 70 wt.% or more of oil or oil products derived from bituminous dust (minerals), because these oil products are the main structural components of the products; manufactured oil products:
2710 11	- - easy to read:
……………..	- - - for other purposes
	- - - - special gasolines:
2710 11 25 00	- - - - - others
	- - - - others:
	- - - - - motor gasoline:
2710 11 31 00	- - - - - - aviation gasoline
	- - - - - - others, containing lead:
	- - - - - - - 0,013 g/l or less:
2710 11 41	- - - - - - - - with octane number less than 95:
	- - - - - - - - - with an octane number of 80 or less:
2710 11 41 11	- - - - - - - - - - with a content of not less than 5 wt.% of high-octane oxygen additive or ethyl tert-butyl ether or its mixture
2710 11 41 19	- - - - - - - - - - others

Source: developed by the authors

Therefore, fuels containing these additives are classified separately. Classification based on octane rating and additive content is crucial for several reasons:

1. Internal combustion engines are designed to operate with fuel of a specific octane value, and using unsuitable fuel can lead to detonation, reduced engine efficiency, and mechanical damage, making proper classification essential.

2. Environmental and regulatory requirements, such as modern Euro emission standards, demand high-octane fuel with minimal harmful impurities. The presence or absence of lead alters the environmental impact of the fuel, while oxygenated high-octane additives ensure compliance with environmental regulations.

3. Fiscal and customs considerations are influenced by additive content, as substances like ETBE affect applicable excise duties, and different octane categories are taxed differently. Correct classification ensures accurate calculation of customs duties and taxes.

4. Market value is also affected, with high-octane fuels and additive-enriched gasolines differing significantly in price and market characteristics, influencing customs valuation.

The Table 6 thus presented a detailed and logically structured classification system for petroleum products, enabling precise identification based on physico-chemical characteristics. Distinctions between subcategories are grounded in parameters that determine the quality, safety, application area, and tax regime of each fuel type. For this reason, characteristics such as octane rating and the presence of high-octane oxygenated additives are essential for correctly determining the tariff code under UKTZED. Therefore, in accordance with UKTZED, the company's product code: 2710 11 41 11 – light diesel, for other purposes: motor gasoline, with an octane number of 80 or less, with a content of no less than 5 wt.% of high-octane oxygen additive or ethyl tert-butyl ether or its mixture. The mathematical model of digitisation of customs clearance processes using fuzzy logic in international freight transport is presented, which will significantly improve the accuracy of declarations and speed up customs procedures.

Discussion

The results obtained in this study demonstrated that the proposed fuzzy-logic-based model significantly enhances the efficiency, adaptability, and analytical capacity of customs procedures, particularly under conditions of uncertainty that are inherent to global logistics chains. The developed mathematical model for verifying the correctness of customs declarations has practical significance and can be used in customs control methods. This distinguishes the work from other developments, which have a number of shortcomings. The results of the present study align with the I.M. Kveliashvili & T.S. Totska (2021) conclusions, indicating that the strategic objectives of customs authorities focus on the implementation of innovations and information and communication technologies, the improvement of procedural formalities, and the adoption of management decisions grounded in the rule of law and aimed at ensuring customs security. The findings correlate strongly with the trends identified in contemporary transport-systems research. As emphasised by E.M. Demchenko & O.E. Dorosh (2023) and Yu.O. Osipchuk (2024), the ongoing transformation of logistics networks is driven by digital integration, smart transport systems, and automated data exchange. The present study supports this perspective by showing that customs clearance is also increasingly dependent on digital ecosystems that must process heterogeneous, dynamic, and often incomplete transport information. The methodological foundation of the model aligns with earlier works on fuzzy-logic applications in transport analytics. Yu.O. Kovtunov *et al.* (2020) demonstrated that fuzzy methods improve the algorithmisation of interactive monitoring processes by compensating for uncertain or incomplete data. In this research, fuzzy inference is similarly applied to classify customs-related risks, interpret inconsistent documentation, and integrate diverse data flows coming from transport monitoring systems and logistics operators. A close conceptual match is also seen with studies analysing digital customs risk-management systems. V.F. Tyshchenko *et al.* (2022) highlighted the use of fuzzy algorithms within automated system for customs clearance of goods and vehicles/automated system for risk analysis and management for constructing complex risk profiles. The results of this study extend those findings by offering a generalised fuzzy-logic model suitable for real-time customs clearance, enabling dynamic adjustment of risk indicators and prioritisation of consignments. This strengthens the argument that fuzzy logic provides a more human-interpretable and flexible alternative to purely statistical risk models. The work further aligns with M. Ishchuk *et al.* (2024), who examined the modernisation of the Ukrainian Customs Service, particularly emphasising automated risk analysis and the growing role of AI-based tools. The model developed in this study contributes to that modernisation pathway, proposing an adaptable decision-support mechanism that reduces manual workload, increases transparency, and supports harmonisation with European Union digital-customs standards. As noted in the analysis of information and communication technology-based customs systems in Korea by S.-B. Kim & D. Kim (2020), digital transformation improves transparency, accelerates customs processes, and enhances institutional efficiency. The findings of the article reinforce this conclusion: the fuzzy-logic model reduces subjective decision-making, strengthens rule-based processing, and enables faster identification of potentially risky shipments. From the standpoint of logistics and transport-operations optimisation, the results are consistent with studies demonstrating the robustness of fuzzy-logic decision tools.

A. Pálková & J. Mašek (2024) showed that fuzzy models effectively evaluate uncertain transport parameters and assist in selecting optimal logistics solutions. In the current research, fuzzy decision rules support the interpretation of ambiguous cargo characteristics, varying routes, and mixed transport conditions – factors that directly influence customs-risk scoring. Similarly, advanced fuzzy-logic techniques used in logistics modelling, such as those applied by D.P. Moreno-Palacio *et al.* (2023) to freight tour optimisation, validated the relevance of fuzzy constraints in environments with variable or unpredictable demand. The proposed model leverages comparable fuzzy-logic logic structures to manage unpredictability in international cargo flows and irregularities in customs documentation. In turn, B. Chen *et al.* (2021) developed a machine-learning model aimed at detecting HS-code misclassification in customs declarations. The study demonstrated that the application of data-driven algorithms enhanced the accuracy of customs control procedures and reduced the risk of classification errors. Finally, the results resonate with broader risk-assessment studies in transport and supply-chain systems. D. Muzylyov *et al.* (2024) demonstrated the effectiveness of fuzzy methods for evaluating operational uncertainty in agricultural logistics chains. This reinforces the argument that fuzzy logic is a versatile tool applicable across different sectors of freight movement – including customs clearance, where risks are multidimensional and dynamic. Overall, the results of this study confirm that incorporating fuzzy logic into the digital architecture of customs-clearance processes offers several significant benefits:

- enhanced processing of uncertain, incomplete, or contradictory data;
- greater flexibility and transparency in risk-assessment procedures;
- better integration with modern transport-monitoring and ICT platforms;
- higher overall efficiency and reduced clearance times;
- alignment with global trends in digital customs transformation.

The convergence of evidence from related works and the empirical findings of this study indicate that fuzzy-logic-based customs models can serve as a foundational element of next-generation digital customs systems, especially in international freight transportation where uncertainty, complexity, and operational variability remain critical challenges. The identification of objects of customs clearance with the calculation of fuzzy logic allows automating the processing of information provided in the cargo customs declaration, procurement documents and technical documentation, which is submitted to the customs authorities with the control of the right to classify goods with the help of unclear logicians. The automated system issues recommendations, approvals and recommendations for customs clearance of goods, and also saves time for customs clearance. An automated expert system for determining the correctness of customs clearance of goods is intended to strengthen control over the accurate classification of goods, prevent cases of tax evasion and violations of non-tariff regulations by participants in foreign economic activity, reduce the time required for customs clearance, and enable the resolution of complex and conflicting issues that arise during classification. Additionally, it minimises errors in assigning the correct commodity codes, ensuring compliance with customs procedures and regulatory requirements.

Conclusions

It is shown that the identification of objects of customs clearance with the calculation of the fuzzy logic algorithm allows automating the processing of the information entered in the cargo customs declaration, packaging documents and technical documentation. and which is submitted to the customs authorities with the control of the right to classify goods with the help of fuzzy logic. The automated system issues recommendations, approvals and recommendations for customs clearance of goods, and also saves time for customs clearance. A mathematical model for checking the correctness of customs clearance with the use of fuzzy logic in international cargo transportation has been developed. Automated experimental system for determining the correctness of the customs clearance of goods, which should provide: the purpose of control of the correctness of the classification of goods under customs duty permission; prevention of attempts by students to enhance external economic activity from paying taxes in full and from non-tariff adjustment measures when violations are committed declaration of goods moving through the customs territory of Ukraine; the beginning of the customs clearance of the company; direct resolution of complex and very serious problems with the classification of goods that arise during customs clearance; avoiding errors in the classification of goods. The developed mathematical model for checking the correctness of customs clearance with the calculation of fuzzy logic must become a part of the risk management system that arises during the declaration of goods. It will also be possible to improve the risk management system by building a more balanced methodology for determining the multiple value of the risk assessment of customs procedures.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Berestov, I., Shelehan, H., & Berestova, T. (2022). Digitalization of customs control processes and customs clearance of cargo on railway transport. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 5(36), 291-297. doi: 10.32515/2664-262X.2022.5(36).

[2] Chen, B., van Rijnsoever, F.J., Molenhuis, M., van Dijk, D., Tan, Y.-H., & Rukanova, B. (2021). The use of machine learning to identify the correctness of HS code for the customs import declarations. In *2021 IEEE 8th international conference on data science and advanced analytics (DSAA)*. New York: IEEE. doi: 10.1109/DSAA53316.2021.9564203.

[3] Chupailenko, O.A., Bilokur, M.V., & Polishchuk, R.V. (2023). Identification of transport and customs risks in international freight transportation using the expert assessment method. *Scientific Notes of V.I. Vernadsky TNU. Series: Technical Sciences*, 34(73), 329-335. doi: 10.33744/2308-6645-2022-3-53-409-426.

[4] Demchenko, E.M., & Dorosh, O.E. (2023). Transport systems and transportation technologies. *Collection of Scientific Works of DNUZT*, 25, 70-83. doi: 10.15802/TSTT2023/284496.

[5] Dong, Z., & Tian, M. (2025). Fuzzy logic-based risk assessment model for cross-border e-commerce logistics supply chain. *Journal of Circuits, Systems and Computers*. doi: 10.1142/S0218126626500453.

[6] In 2024, customs authorities of the State Customs Service detected violations of customs regulations amounting to UAH 18 billion. (2025). Retrieved from https://customs.gov.ua/news/zagalne-20/post/za-2024-rik-mitnitsi-derzhmitsluzhbi-viiavili-porushen-mitnikh-pravil-na-18-mlrd-grn-1967.

[7] Ishchuk, M., Ishchuk, O., & Khrypko, S. (2024). Sustainable digital evolution: Transforming the Ukrainian customs service. *European Journal of Sustainable Development*, 13(1), 217-228. doi: 10.14207/ejsd.2024.v13n1p217.

[8] Ivashova, L.M., & Kyda, L.I. (2020). Digitalization of customs procedures: The current state and prospects of customs development. *Public Administration and Customs Administration*, 3(22), 218-230. doi: 10.32836/2310-9653-2019-3-218-230.

[9] Kim, S.-B., & Kim, D. (2020). ICT implementation and its effect on public organizations: The case of digital customs and risk management in Korea. *Sustainability*, 12(8), article number 3421. doi: 10.3390/su12083421.

[10] Kostiana, O.V., Karpova, V.V., & Ostapenko, V.M. (2021). Risk management in customs affairs as a factor in ensuring customs security in a period of economic downturn. *Business Inform*, 11, 404-410. doi: 10.32983/2222-4459-2021-11-404-410.

[11] Kovtunov, Yu.O., Makohon, O.A., Isakov, O.V., Babkin, Yu.V., Kalinin I.V., & Lazuta, R.R. (2020). Use of the mathematical apparatus of fuzzy logic for fuzzification and algorithmization of the interactive monitoring system of transport communications. *Control, Navigation and Communication Systems*, 3(61), 64-68. doi: 10.26906/SUNZ.2020.3.064.

[12] Kveliashvili, I.M., & Totska, T.S. (2021). Implementation of modern customs management concepts of European countries into national practice. *Public Administration in the Sphere of State Security and Customs Affairs*, 2(29), 74-80. doi: 10.32836/2310-9653-2021-2.12.

[13] Law of Ukraine No. 2697-IX "About the Customs Tariff of Ukraine". (2023, January). Retrieved from https://zakon.rada.gov.ua/laws/show/2697-20?lang=en#Text.

[14] Lebid, V., Anufrieva, T., & Savenko, G. (2020). Studies of the efficiency of simplification of customs formalities on the basis of digitalization. *Technological Audit and Production Reserves*, 1(4(57)), 49-53. doi: 10.15587/2706-5448.2021.225627.

[15] Lemeha, R. (2020). Automation and informatization of customs procedures as priority directions of improvement of administration of customs regimes in Ukraine. *Entrepreneurship, Economy and Law*, 11, 126-133.

[16] Luo, N., Yu, H., You, Z., Li, Y., Zhou, T., Jiao, Y., Han, N., Liu, C., Jiang, Z., & Qiao, S. (2023). Fuzzy logic and neural network-based risk assessment model for import and export enterprises: A review. *Journal of Data Science and Intelligent Systems*, 1(1), 2-11. doi: 10.47852/bonviewJDSIS32021078.

[17] Mishchenko, A.V., Kurylo, O.V., & Zolotukhina, O.A. (2020). A fuzzy model for assessing information security risks and maintaining the protection level of ERP systems. *Telecommunication and Information Technologies*, 1(66), 142-150. doi: 10.31673/2412-4338.2020.011451.

[18] Moreno-Palacio, D.P., González-Calderón, C.A., López-Ospina, H., Gil-Marin, J.K., & Posada-Henao, J.J. (2023). Freight tour synthesis based on entropy maximization with fuzzy logic constraints. *Transportation*, 51, 2323-2357. doi: 10.1007/s11116-023-10407-y.

[19] Muzylyov, D., Medvediev, I., & Pavlenko, O. (2024). Risk factor assessment in agricultural supply chain by fuzzy logic. *IOP Conference Series: Earth and Environmental Science*, 1376(1), article number 012038. doi: 10.1088/1755-1315/1376/1/012038.

[20] Osipchuk, Yu.O. (2024). Risk management in customs affairs under martial law conditions. *Economics. Management. Current Issues of Science and Practice*, 2(108), 16-21. doi: 10.26642/ema-2024-2(108)-16-21.

[21] Pálková, A., & Mašek, J. (2024). Fuzzy logic as a decision-making tool for transport request selection. *Transportation Research Procedia*, 77, 116-122. doi: 10.1016/j.trpro.2024.01.015.

[22] Tyshchenko, V.F., Ostapenko, V.M., & Karpova, V.V. (2022). Digitization in the customs risk management. *Economics and Society*, 37, 60-65. doi: 10.32782/2524-0072/2022-37-35.

[23] Vijayakumar, S. (2025). Technology-centric and data-driven customs risk management for supply chain security. *World Customs Journal*, 19(1), 38-63. doi: 10.55596/001c.131745.

[24] World Customs Organization. (n.d.). *Overview*. Retrieved from https://www.wcoomd.org/en/topics/nomenclature/overview.aspx.

[25] Zheng, C., Cao, J., & Zhou, H. (2025). Optimization of emergency supplies customs clearance strategy based on K-means clustering. *Frontiers in Public Health*, 13, article number 1481328. doi: 10.3389/fpubh.2025.1481328.

Цифровізація процесів митного оформлення товарів з розрахунком математичної моделі нечіткої логіки

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Анотація. Актуальність дослідження зумовлена зростаючим використанням автоматизованих систем митного оформлення, які формують рекомендації, попередження та обґрунтування з метою скорочення часу обробки вантажів. Водночас ефективність таких систем залежить від науково обґрунтованої методології визначення оптимальної періодичності перегляду профілів ризику та вдосконалення кількісної оцінки ризиків. Метою дослідження було розроблення математичної моделі перевірки правильності митного оформлення із застосуванням апарату нечіткої логіки в умовах міжнародних вантажних перевезень. Методи дослідження включали розроблення математичних моделей та алгоритмів їх реалізації. Зокрема, математичний апарат нечіткої логіки було застосовано для визначення коректності митного оформлення товарів. Показано, що ідентифікація об'єктів митного контролю із використанням нечіткої логіки дозволяє автоматизувати обробку інформації, поданої в митній декларації, супровідних документах і технічній документації, яка надходить до митних органів для контролю правомірності класифікації товарів. Розроблено рекомендації щодо використання апарату нечіткої логіки в автоматизованій експертній системі для визначення правильності митного оформлення. Запропонована система спрямована на посилення контролю за коректністю класифікації товарів під час митного оформлення, запобігання ухиленню учасників зовнішньоекономічної діяльності від повної сплати податків та дотримання заходів нетарифного регулювання шляхом порушення правил декларування товарів, що переміщуються через митний кордон України. Вона також орієнтована на скорочення часу митного оформлення, безпосереднє вирішення складних і суперечливих класифікаційних питань та уникнення помилок у класифікації товарів

Ключові слова: автоматизація інформації; управління ризиками; нетарифне регулювання; логістичні оператори; транспортний моніторинг

BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 29 | №2 | 2025
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X

Received: 02.07.2025. Revised: 24.10.2025. Accepted: 27.11.2025. Published: 04.01.2026.

UDC 656 DOI: 10.33744/2308-6645-2025-2-29-105-113

Traffic restrictions as a way to reduce the level of car-centricity of the city

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Abstract. Modern cities are overloaded with cars, so progressive administrators are shifting their focus towards optimising traffic flow, reducing delays, improving road safety and creating comfortable conditions for pedestrians and public transport users, including by restricting traffic in city centres. The aim of this study was to analyse the measures implemented in European cities to reduce traffic congestion in city centres, as well as the results they have achieved. The article analysed modern traffic management methods used in European cities (Barcelona, Madrid, Paris, Stockholm) and New York, and identifies their advantages, problematic aspects of implementation, and potential impact on the further development of urban mobility. Based on the results of the work, it was determined that a considerable number of European cities have adopted a shift from a car-centric urban planning model to one that prioritises population mobility. This transition has been accompanied by a notable increase in the infrastructure dedicated to pedestrian and bicycle traffic. The systematic increase in dependence on cars has led to the expected consequences – exceeding the capacity of the built road network, resulted in a high number of concentrated traffic jams, and increased emissions of hazardous substances. To combat the consequences of congestion in cities, especially in central areas, a number of countries have implemented restrictions related to both a complete traffic ban and financial payments for travel in selected areas. The long-standing and recently introduced restrictions have had a clear impact on reducing traffic in selected areas, thereby decreasing travel time and CO_2 emissions. The practical value of this work lies in the fact that it provides an opportunity to develop and implement effective solutions to reduce traffic congestion in central Kyiv, based on the successful experience of European cities

Keywords: traffic management; road traffic safety; congestion; urban mobility; ecology

Introduction

The evolution of urban landscapes and the establishment of their street and road networks occurred in tandem with the increasing adoption of motorised vehicles. However, the pace of this process exceeded expectations, and at the beginning of the 21st century, cities faced new challenges such as congested roads, traffic jams, parking shortages, and a deteriorating urban environment. Traditional approaches to transportation planning that focus on private cars no longer ensure the efficient functioning of urban infrastructure. On the contrary, they only exacerbate existing problems. Therefore, modern cities are focusing on optimising traffic flows, reducing delays, improving traffic

Suggested Citation: Chekh, D., & Kunytska, O. (2025). Traffic restrictions as a way to reduce the level of car-centricity of the city. *Bulletin of the National Transport University*, 29(2), 105-113. doi: 10.33744/2308-6645-2025-2-29-105-113.

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safety, and creating comfortable conditions for pedestrians and public transport. Rational management of the street and road network is a key factor for the balanced development of urban transport. Its goal is to ensure uninterrupted transport links between functional areas of the city and to create a comfortable and safe urban space. The high level of transportation delays, congestion that causes increased travel time, deterioration in the level of transportation services, and an increase in the number of traffic accidents indicate that the city's street and road network does not correspond to the number of cars on it. K. Cao *et al.* (2024) showed that the main causes of delays in central areas are the uneven distribution of traffic flows and suboptimal traffic management, while network optimisation and signal control adjustments can significantly reduce congestion. In order to create a comfortable and environmentally friendly environment for city residents, European countries have been implementing measures to restrict car traffic for decades. The main goal was to reduce street congestion, emissions of harmful substances, improve safety for pedestrians and drivers, and encourage the use of public transport and bicycles. Y. Matseliukh *et al.* (2025) proved that the development of public transport and the integration of digital solutions in a "smart city" substantially decrease emissions and reduce the share of private car use. Because a large number of jobs and major activity centres are located in city centres, and street networks are limited in capacity, many countries impose restrictions on car use in central areas while enhancing mobility through the creation of pedestrian zones and bicycle lanes. This article examined the methods of car traffic restriction applied in European cities, identified the challenges arising during their implementation, and analysed how such measures may influence the future of urban mobility. F. Tassinari (2024), using the example of the Madrid Central zone, confirmed that low-emission zones (LEZs) have a strong deterrent effect on private vehicle usage and help reduce air pollution. The systematic review by Y. Ma & F. Mészáros (2024) indicated that access-restriction measures – such as traffic bans, LEZs, and pedestrian zones – consistently demonstrate high effectiveness in improving the sustainability of urban logistics. H. Billhardt *et al.* (2022) proposed a model of dynamic access regulation to the city centre based on congestion levels, which enhances infrastructure efficiency and reduces traffic volumes. S. Li *et al.* (2020) showed that congestion charging combined with spatial pricing in ride-sourcing services can significantly reduce private car trips. Urban vehicle access regulations (n.d.) identified the most effective tools for decreasing city-centre car use, including congestion charging, reducing parking supply, and developing cycling and pedestrian infrastructure. According to the Smart cities mobility index (n.d.) report, the most promising direction for Central and Eastern European cities (including Kyiv) is the integration of multimodal mobility with a strong prioritisation of public transport. Finally, J. Palaguachi *et al.* (2024) demonstrated that incentivising the use of peripheral park-and-ride facilities within a managed system can substantially reduce traffic pressure in central urban zones. Collectively, these studies highlight the effectiveness of a comprehensive policy approach – combining restrictive measures, public transport development, and rethinking urban space – as the key strategy for relieving congestion in major city centres. This study sought to examine the strategies adopted by European cities to alleviate congestion in central urban areas and to assess the outcomes of their implementation.

Materials and Methods

The methodological foundation of the study was a systematic review of the academic literature aimed at synthesising theoretical and applied approaches to restricting vehicular traffic in city centres and assessing their impact on urban mobility. The development of the theoretical framework involved the purposeful selection and systematisation of contemporary and relevant sources reflecting the current state of academic debate and governance practice. The analysis drew upon publications indexed in international scholarly databases (ResearchGate, Web of Science, Academia.edu), as well as official materials produced by municipal authorities and international organisations. Sources were selected according to the following criteria: thematic relevance to traffic restriction policies in city centres; the presence of empirical or analytical findings; and a focus on large and medium-sized cities as representative settings for the implementation of transport innovations. This ensured the relevance and comparability of the findings obtained. In particular, publications by N. Mueller *et al.* (2020), E. Natterer *et al.* (2024) and K. Pérez *et al.* (2025), devoted to examining the impact of urban design and traffic organisation on the environment and public health, were analysed. In addition, materials from the information resources Superblocks of Barcelona (2024), Urban vehicle access regulations (n.d.), and Which cars can drive… (n.d.) were utilised as sources of up-to-date data on the practical implementation of traffic restrictions and the functioning of the respective initiatives. The analytical stage of the research was based on a combination of the comparative approach and content analysis, which made it possible to identify key instruments of urban traffic regulation (pedestrianisation, LEZs, congestion charging, and parking regulation) and to assess their effectiveness in terms of reducing traffic congestion, improving air quality, and enhancing the sustainability of the urban environment.

The empirical component was formed using the case study method, which involved an in-depth examination of traffic management practices in leading cities in Europe and the United States (US). Specifically, the experiences of implementing vehicular traffic restrictions and LEZs in Barcelona, Madrid, Paris, Stockholm, and New York were analysed. The inclusion of New York as a non-European metropolis that has recently introduced a congestion pricing system enabled an interregional comparison between European regulatory models and contemporary practices in the US. Additionally, cartographic analysis was applied, encompassing the examination of traffic restriction zone schemes, superblocks, and congestion charging areas. This made it possible to assess the spatial configuration of transport solutions and their integration into the overall structure of urban planning. The combination of the methods employed ensured the comprehensiveness of the study and the validity of the conclusions drawn.

Results and Discussion

More and more cities, especially in Europe, are financially restricting or banning vehicle traffic in the city centre. Measures to regulate the price of car use in cities exist in all EU countries. London has been charging for entry into the city centre for more than 15 years. In addition, the city has several other taxation zones for toxic emissions. In Stockholm, such a system has been in place since 2007. However, the earliest to collect fees for entering the city centre was Singapore in 1975 (Why is paid entry to central…, 2018; FHWA primers and one-page, n.d.). The two main reasons for the restrictions are street congestion and air pollution from car emissions. Safe and, above all, efficient transport operation directly depends on improving the state regulation of its activities, and to gain the experience, Ukraine can look up to the world's leading countries, where this issue has been resolved most effectively. An analysis of selected European cities that have introduced comparable restrictions is undertaken to evaluate the effectiveness of the policy decisions implemented. One of the best decisions in urban planning is the Barcelona's superblocks, which aim to reduce noise and air pollution in urban areas. The concept is consolidation of nine standard districts into one superblock, where traffic is allowed only on peripheral roads and access to the centre is restricted except for superblock residents and service vehicles (Mueller *et al.*, 2020). Layout like this leaves much more space for pedestrians, cyclists, parks, playgrounds and recreation areas. Since the 19th century, the city has been built according to a concept of superblocks created by I. Serda (Pérez *et al.*, 2025). Modern superblocks even give a second life to this concept by limiting car traffic and encouraging the expansion of green areas and pedestrian mobility. The first modern superblock was introduced in 2016. The introduction of superblocks has brought social and economic changes. As parts of the streets became pedestrianised, real estate prices increased, and a large number of cafes, restaurants, and hotels replaced local shops. Because of the superblock, pedestrian and cycling activity increased by 10% and 30% respectively, pollution was significantly reduced, and the urban environment became more attractive to residents and visitors alike. Therefore, the Barcelona city authorities considered these factors when planning the city's future Superblocks of Barcelona (2024). Figure 1 illustrates the differences between the superblock concept under unrestricted conditions and when access to the city centre is limited.

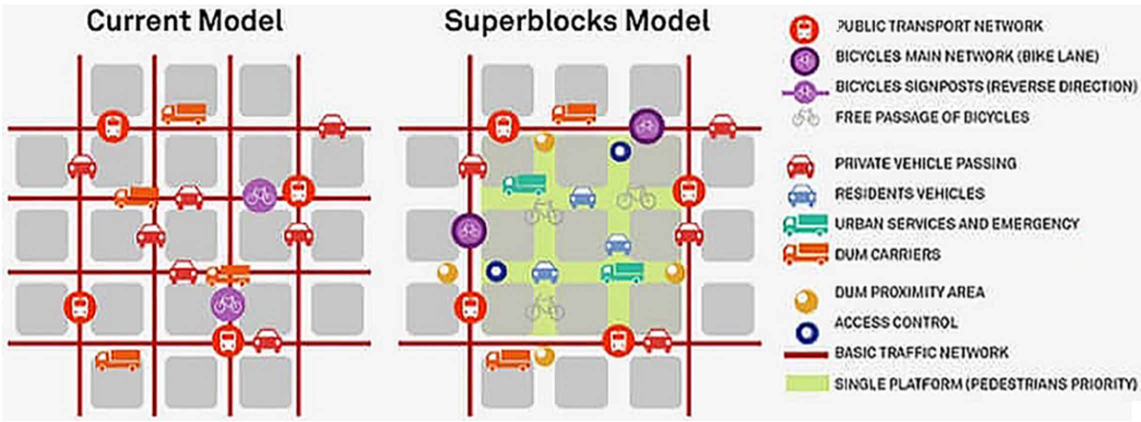

Figure 1. Comparison of the concept of superblocks without restrictions and with restrictions on access to the centre
Source: Superblocks of Barcelona (2024)

Figure 1 shows comparison of current model of street planning. At the current model, cars, vans, trucks and buses can use every street with no restrictions. At the superblock model 3 blocks are combined in one, and inside the block streets can be used only by local residents. The Madrid Central programme was introduced in November 2018 to reduce air pollution and improve the quality of life of residents by restricting car traffic in the central part of Madrid. Madrid is one of the first cities to restrict traffic and create pedestrian zones. In 2005, the city of Madrid established a priority pedestrian zone in the densely populated historic district of Las Letras, and subsequently implemented similar initiatives in several other areas of the city. Since 2018, the 472-hectare zone has been closed to most vehicles, with the exception of hybrid and electric vehicles, as well as vehicles of local residents and guests with special permits (Which cars can drive…, n.d.). Even in a country where many cities restrict the movement of private vehicles, this is a radical restriction. While most of Madrid's streets are very narrow and not very suitable for motorised vehicles, the designated central zone has wide roads that are filled with a large flow of cars every day. Thus, the plan is not only to make the busy central streets more comfortable for pedestrians and tourists, but also to demotivate residents of the capital from driving to the central part of the city. According to the Federation of European Transport and Environment, Madrid Central has become the most effective LEZ programme among European cities, achieving a 32% reduction in nitrogen dioxide pollution) (Madrid's low emission zone…, 2019). In 2021, the city government adopted a new environmental strategy called Madrid 360 (n.d.), which are similar to Madrid Central but have some differences. In particular, more rights were granted to local entrepreneurs, equating them to residents in terms of access to the zone, and restrictions on certain trucks were postponed. Beginning in 2025, the restrictions for vehicles with the "B"-Eco label will be strengthened (Madrid Central: How to… n.d.). These vehicles will only be able to drive in LEZs under certain conditions, such as parking in regulated car parks or being a resident. These measures aim to further improve air quality and provide a healthier urban environment for Madrid's residents (Madrid 360, n.d.). Figure 2 demonstrates the spatial coverage of the restricted traffic zone in central Madrid, indicating the boundaries and the area where traffic restrictions apply.

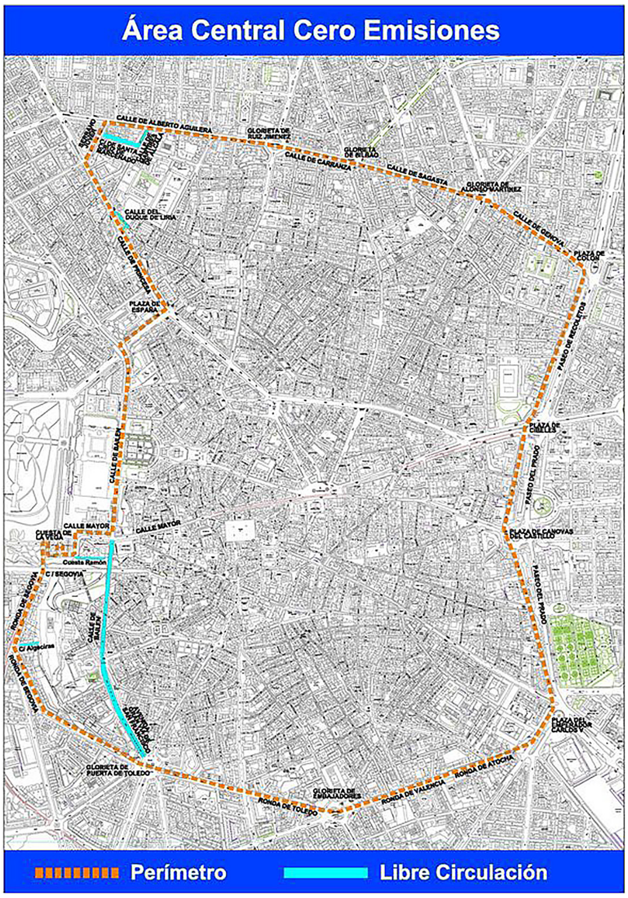

Figure 2. Madrid Central programme area in the city of Madrid
Source: Residents of central Madrid… (2018)

Figure 2 illustrates Madrid Central – a large Residential Priority Area covering 470 ha, aimed at reducing through traffic and lowering NO_2 emissions by up to 40%. Residents can freely use their vehicles and issue a limited number of guest passes, while non-residents are allowed access only with an environmental badge or a guest pass. Taxis and ride-hailing services (e.g., Cabify, Uber) have special access rules until 2025, after which free circulation will be permitted only for vehicles with a CERO (zero-emission) or ECO (hybrid/low-emission) environmental label.

Paris is actively implementing measures to restrict traffic in central areas, creating safe zones for pedestrians and cyclists to improve air quality and reduce noise pollution. On 5 November 2024, the city of Paris introduced the first ZTL in the city's central districts, covering the 1st to 4th arrondissements (Le Monde, 2024; Natterer *et al.*, 2024). This zone strictly limits the entry of motorised vehicles, giving priority to pedestrians and cyclists. The aim of this initiative is to improve air quality, reduce noise and traffic, and return public space to residents. The area is home to about 100,000 people and 11,000 companies. Only emergency services, buses, taxis, people with reduced mobility, locals, employees, and visitors with specific purposes such as medical visits or shopping are allowed to access the ZTL. According to data from City Hall, the number of vehicles entering the ZTL daily ranges from 350,000 to 500,000, with up to 50% of these vehicles belonging to through traffic. Through traffic is defined as drivers who are merely passing through but have a final destination outside the ZTL. Authorities anticipate that the implementation of the restricted ZTL will result in a substantial reduction in vehicular traffic, potentially up to 30% on the busiest thoroughfares, including Boulevard de Sébastopol and Avenue de l'Opéra, accompanied by decreased noise levels and improved air quality (Poulhès *et al.*, 2025). These measures underline Paris's commitment to creating a more pedestrian and cycling-friendly urban environment, reducing reliance on private transport and improving the overall quality of life for residents. Traffic restrictions in areas of Paris are shown in Figure 3. Figure 3 illustrates the area designated as a restricted traffic zone in Paris, located along the banks of the Seine, with the lower image providing a comparison between this zone and the rest of the city. The introduction of the restricted traffic zone has produced measurable outcomes. Traffic volumes along the boundaries of the zone decreased substantially, with an 18% reduction observed in 2008 compared to 2005, prior to the implementation of the entry fee. The adoption of environmentally friendly vehicles increased during the trial period, rising from 3% of trips using alternative fuel vehicles to 13% by 2008. In addition, CO_2 emissions from vehicles in the city centre were reduced by an estimated 14-18% following the introduction of the congestion charge (What are city road taxes?, n.d.). These results indicate that the implementation of a restricted traffic zone can effectively reduce traffic congestion, promote the adoption of environmentally friendly vehicles, and contribute to a measurable decrease in urban CO_2 emissions.

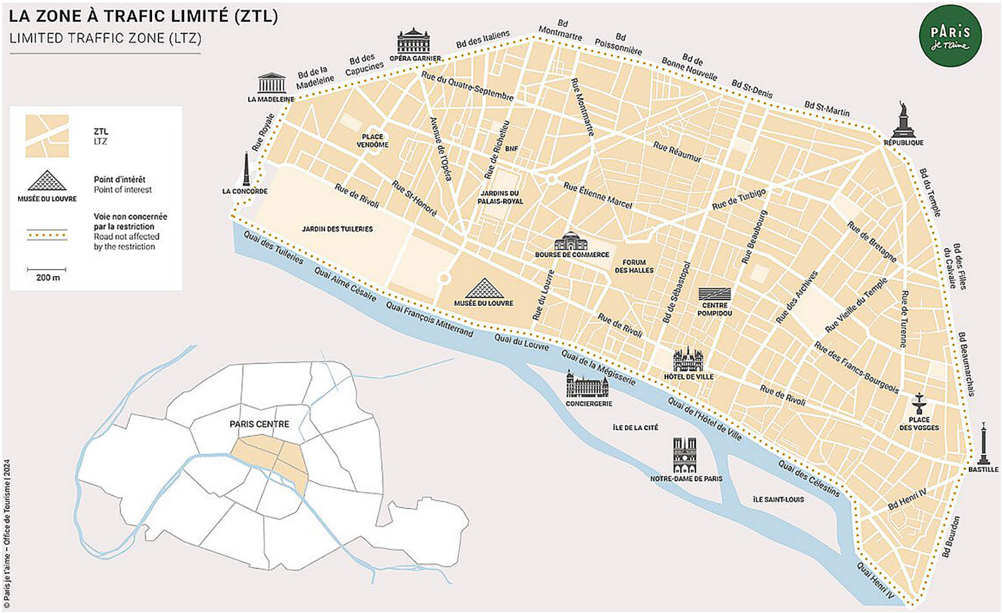

Figure 3. Boundaries of the Paris restricted traffic zone

Source: Limited traffic zone in Paris (2025)

In 2007, Stockholm introduced a system of fees for entering the central part of the city, known as congestion tax, in order to reduce congestion and improve air quality. The city's residents voted to approve this initiative. Initially, this tax applied only to vehicles registered in Sweden. As of January 1, 2015, the tax applies to vehicles with both Swedish and foreign registration plates, as noted by A. Vadeby & Å. Forsman (2018). The congestion tax is levied on cars, trucks, and buses with a total weight of less than 14 tons. Motorcycles and mopeds are exempt from this tax. The amount of the charge depends on the day of the week and the time of day. The tax is applied to vehicles between 6:00 a.m. and 6:29 p.m., Monday through Friday. No charge is applied on Saturdays, Sundays, public holidays, or the eve of public holidays. The tax is also not applied in July. The maximum daily charge per vehicle is SEK 135 during the high season and SEK 105 during the low season. High season runs from 1 March to early July (including the first five working days of July) and from 15 August to 30 November, while low season covers the remaining period (Sweden, n.d.). Figure 4 presents the layout of traffic restrictions and the locations of control points in Stockholm.

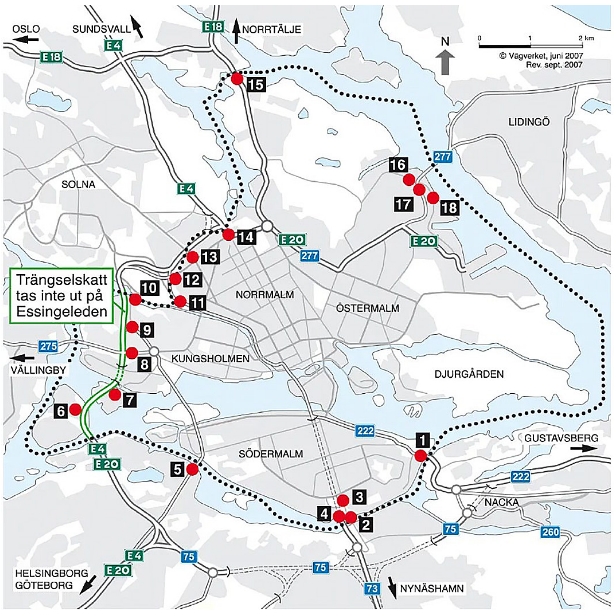

Figure 4. Stockholm's limited traffic zone

Source: Sweden (n.d.)

Figure 4 depicts the extent of the limited traffic zone in Stockholm. Compared to the restricted traffic zone in Paris, the Stockholm zone differs in size and regulatory approach: while Paris strictly limits the entry of motorised vehicles, entry in Stockholm is permitted subject to a congestion charge. The implementation of these measures has contributed to improved air quality and reduced traffic congestion, positively affecting the urban environment and residents' quality of life. The congestion tax in Stockholm remains in force as of 2025, applying to vehicles entering both the city centre and the Essingeleden highway during specified hours.

New York (US) was included for interregional comparison, as previously studied examples only concerned European cities. In 2025, a congestion charging system was introduced in central areas to reduce traffic congestion, improve air quality and provide additional funding for public transport, integrated into a sustainable urban transport infrastructure strategy. Tolls, or a system of charging for entry into the city's central areas, were introduced in New York City to reduce congestion, improve air quality, and provide additional funding for public transportation. The initiative was part of the city's broader strategy for sustainable development and modernisation of its transportation infrastructure, as noted by R. Khalifeh & S. Nessen (2025). The fare was introduced by the MTA on January 5. Under the tolling scheme south of 60th Street in Manhattan, passenger and small commercial vehicles are charged $15 during peak hours and $3.75 overnight, while motorcycles incur fees of $7.50 and $1.75, respectively. Trucks and buses are charged either $24 or $36 during peak hours and $6 or $9 overnight, depending on vehicle type. Discounts are applied for drivers using an E-ZPass at the four tolled entry points in the zone – the Lincoln Tunnel, Holland Tunnel, Queens-Midtown Tunnel, and Hugh L. Carey Tunnel – with credits of $5 for passenger vehicles, $2.50 for motorcycles, up to $12 for small trucks and charter buses, and up to $20 for large trucks and tour buses. No credits are offered during the discounted overnight period (Khalifeh & Nessen, 2025). Following the introduction of the congestion fees on January 5, initial data from the Metropolitan Transportation Authority indicated a 7% reduction in the number of vehicles entering the tolling zone south of 60th Street compared with the same period in the previous year. This decrease contributed to faster traffic flow in surrounding areas, with average trip times falling by 10-30% during the first days of implementation, even accounting for days with atypical disruptions. In particular, average weekday travel times through the Holland Tunnel declined by 48% during the first three weeks of congestion pricing relative to the same period in January of the preceding year. Travel times on the Williamsburg Bridge fell 30% and 27% on notoriously jammed Canal Street, according to J. Zanger *et al.* (2024). Figure 5 shows the central part of New York City and the boundaries of the congestion charging zone.

Figure 5. Congestion tax zone in New York City

Source: J. Zanger *et al.* (2024)

Figure 5 illustrates the congestion charging zone in Manhattan, New York, which is bounded by 60th Street to the north and major transport arteries and bridges around its perimeter. It visualises the geographical limits of the zone where the congestion charge applies, highlighting the locations of key entry points and tunnels through which vehicles enter the city centre. Consequently, a considerable number of European cities have adopted a shift from a car-centric urban planning model to one that prioritises population mobility. This transition has been accompanied by a notable increase in the infrastructure dedicated to pedestrian and bicycle traffic. The systematic increase in dependence on cars has led to the expected consequences – exceeding the capacity of the built road network, resulted in a high number of concentrated traffic jams, and increased emissions of hazardous substances. To combat the consequences of congestion in cities, especially in central areas, a number of countries have implemented restrictions related to both a complete traffic ban and financial payments for travel in selected areas. Analysed restrictions have had a clear impact on reducing traffic in selected areas, thereby decreasing travel time and CO_2 emissions.

Based on the case study and literature review, it can be argued that similar initiatives could be implemented in Ukraine, particularly in Kyiv. According to O. Panchenko (2021), Kyiv ranks seventh in the ranking of the world's cities with the most traffic jams, and a large number of transit trips pass through the main Khreshchatyk Street. Despite the fact that the time spent in traffic jams is increasing year after year, drivers in Ukraine are not ready to give up their cars. Such measures need to take into account the alternatives that the city can offer to residents in exchange for giving up driving, such as high-quality public transportation, pedestrian and bicycle infrastructure. D. Bespalov, the director of ProMobility, says that it is possible to calculate the effect of these restrictions on transportation using a transport model. It can be selected a section of the transportation network and calculate the effect on the toll road if 10%, 20%, or 50% of drivers pay. In other words, if the city authorities want to introduce such toll zones, it will be quite possible to develop a feasibility study for them, which is necessary to allocate funding (Panchenko, 2021). Thus, the introduction of restrictions on car traffic in Kyiv is advisable provided that a comprehensive approach is taken, involving the development of alternative modes of transport and a detailed technical and economic assessment of the impact of such measures on the city's transport system. Other studies emphasised that urban traffic management strategies, including congestion charging and LEZs, play a critical role in reducing car dependency, mitigating congestion, and enhancing environmental quality and public health outcomes. At the same time, they highlight potential economic implications and displacement effects that must be carefully taken into account when designing and implementing effective urban mobility policies. A. Baghestani *et al.* (2020) argued that the introduction of congestion charging in central areas of New York City effectively reduces the number of car trips into the city centre, alleviates congestion and delays, lowers harmful emissions, and encourages greater use of public transport. The authors noted that implementing cordon pricing in New York City could reduce single-occupancy vehicle trips, improve traffic conditions in the Central Business District, decrease congestion and emissions, thereby mitigating negative public health impacts, although the accuracy of results is limited by the model and available data, and further research could include economic and social analyses. The authors also emphasised that such strategies can enhance the overall efficiency of urban transport networks and serve as a reliable decision-making tool for large US cities. According to Y. Li & D. Vignon (2024), the policy of imposing an additional surcharge on ride-hailing trips in New York City led to a decline in trip volumes and service revenues, particularly for short journeys and in areas with alternative transport options. However, it did not reduce congestion, potentially generating short-term economic losses for the city. The study by J. Moral-Carcedo (2024) confirmed that the implementation of the low-emission zone Madrid Central successfully reduced traffic levels in the city centre, yet it also resulted in increased traffic in surrounding districts. This highlights the importance of accounting for displacement effects when designing urban mobility policies. A systematic review by P. Manglano-Redondo *et al.* (2025) demonstrated that dynamic LEZs, which adapt in real time to changing traffic conditions, are effective in reducing air pollution in urban centres. These measures combine environmental objectives with the need to maintain traffic flow, supported by advanced monitoring technologies and traffic-modelling approaches. According to the results of the study, the introduction of such restrictions in European cities demonstrates the effectiveness of the transition from car-centric planning to prioritising population mobility, accompanied by the development of pedestrian and bicycle infrastructure, reduced traffic congestion, shorter travel times and lower CO_2 emissions. Thus, the discussion demonstrated that successful transport policies require a balance between environmental benefits, population mobility and possible side effects, such as economic losses or the transfer of traffic congestion to other areas.

Conclusions

The article reviewed five cities that have introduced traffic restrictions in their city centres through the implementation of LEZs. Although each city differs in terms of the type of restriction applied and the spatial extent of the zone, the overall outcome is consistent: a reduction in harmful emissions and congestion. The findings of the analysis demonstrated that the introduction of such measures has a clear positive effect in reducing transport intensity, alleviating traffic congestion, shortening travel times, and decreasing CO_2 emissions as well as other air pollutants. Particularly effective were integrated strategies that combine financial disincentives with the spatial reorganisation of the urban environment in favour of pedestrians and cyclists. Special emphasis was placed on the importance of cartographic analysis, which enabled an assessment of the spatial configuration of restriction zones, their scale of coverage, and the extent to which transport measures are integrated into broader urban planning frameworks. The experience of New York City was included as an interregional example of the recent implementation of congestion pricing, thereby expanding the comparative perspective of the study. The results suggest that similar transport initiatives may hold significant potential for adoption in Ukraine, particularly in Kyiv. However, their successful implementation would require a comprehensive approach, including the development of high-quality public transport, the expansion of cycling and pedestrian infrastructure, and detailed technical and economic modelling of potential impacts on the urban transport system. Overall, the study confirmed that reorienting urban space away from private car use towards sustainable mobility represents a key direction of contemporary transport policy, with the capacity to enhance environmental safety and improve the quality of life in large cities. Further research could focus on additional cities where such restrictions have already been introduced or are planned. Another important area for more detailed investigation is the feasibility of implementing traffic restriction measures in Kyiv.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Baghestani, A., Tayarani, M., Allahviranloo, M., & Gao, H.O. (2020). Evaluating the traffic and emissions impacts of congestion pricing in New York City. *Sustainability*, 12(9), article number 3655. doi: 10.3390/su12093655.

[2] Billhardt, H., Fernández, A., Martí, P., Prieto Tejedor, J., & Ossowski, S. (2022). Towards the prioritised use of transportation infrastructures: The case of vehicle-specific dynamic access restrictions in city centres. *Electronics*, 11(4), article number 576. doi: 10.3390/electronics11040576.

[3] Cao, K., Wang, L., Zhang, S., Duan, L., Jiang, G., Sfarra, S., Zhang, H., & Jung, H. (2024). Optimization control of adaptive traffic signal with deep reinforcement learning. *Electronics*, 13(1), article number 198. doi: 10.3390/electronics13010198.

[4] FHWA primers and one-page briefs congestion pricing: Examples around the world. (n.d.). Retrieved from https://ops.fhwa.dot.gov/congestionpricing/resources/examples_world.htm.

[5] Khalifeh, R., & Nessen, S. (2025). *Manhattan traffic moves way faster since congestion pricing launched, MTA says.* Retrieved from https://gothamist.com/news/manhattan-traffic-moves-way-faster-since-congestion-pricing-launched-mta-says.

[6] Le Monde. (2024). *Central Paris is now closed to through traffic.* Retrieved from https://www.lemonde.fr/en/economy/article/2024/11/05/central-paris-is-now-closed-to-through-traffic_6731675_19.html.

[7] Li, S., Yang, H., Poolla, K., & Varaiya, P. (2020). Spatial pricing in ride-sourcing markets under a congestion charge. *ArXiv*. doi: 10.48550/arXiv.2010.09260.

[8] Li, Y., & Vignon, D. (2024). Do ride-hailing congestion fees in NYC work? *Transportation Research Part A: Policy and Practice*, 190, article number 104274. doi: 10.1016/j.tra.2024.104274.

[9] Limited traffic zone in Paris. (2025). Retrieved from https://parisjetaime.com/eng/convention/article/limited-traffic-zone-a1773.

[10] Ma, Y., & Mészáros, F. (2024). Review of urban access regulations from the sustainability viewpoint. *Urban Science*, 8(2), article number 29. doi: 10.3390/urbansci8020029.

[11] Madrid 360. (n.d.). Retrieved from https://www.madrid360.es/.

[12] Madrid Central: How to access APR for polluting vehicles. (n.d.). Retrieved from https://www.eldiario.es/madrid/madrid-central-acceder-apr-contaminantes_1_2030255.html.

[13] Madrid's low emission zone identified as one of the most effective in the EU. (2019). Retrieved from https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/madrids-low-emission-zone-identified-one-most-effective-eu-2019-09-30_en.

[14] Manglano-Redondo, P., Paricio-Garcia, A., & Lopez-Carmona, M.A. (2025). Dynamic low-emission zones for urban mobility: A systematic review. *Applied Sciences*, 15(6), article number 2915. doi: 10.3390/app15062915.

[15] Matseliukh, Y., Lytvyn, V., & Bublyk, M. (2025). Development of a neural network for forecasting passenger flows in smart city public electric transport. *Technology Audit and Production Reserves*, 5(2(85)), 20-25. doi: 10.15587/2706-5448.2025.339550.

[16] Moral-Carcedo, J. (2024). Dissuasive effect of low emission zones on traffic: The case of Madrid Central. *Transportation*, 51, 25-49. doi: 10.1007/s11116-022-10318-4.

[17] Mueller, N., *et al.* (2020). Changing the urban design of cities for health: The superblock model. *Environment International*, 134, article number 105132. doi: 10.1016/j.envint.2019.105132.

[18] Natterer, E., Loder, A., & Bogenberger, K. (2024). Effects of the plan Vélo I and II on vehicular flow in Paris: An empirical analysis. *ArXiv*. doi: 10.48550/arXiv.2408.09836.

[19] Palaguachi, J., Padilla, M., Ortega, M., Solorzano, M.R., Uvidia, R.V., Ortega, J., & Veloz-Cherrez, D. (2024). Evaluating the location of the park-and-ride system using multi-criteria methods: A systematic review. *Sustainability*, 16(23), article number 10187. doi: 10.3390/su162310187.

[20] Panchenko, O. (2021). *How to really tackle traffic congestion.* Retrieved from https://www.village.com.ua/village/city/transport/314501-yak-naspravdi-treba-borotisya-z-zatorami.

[21] Pérez, K., Palència, L., López, M.J., León-Gómez, B.B., Puig-Ribera, A., Gómez-Gutiérrez, A., Nieuwenhuijsen, M., Carrasco-Turigas, G. & Borrell, C. (2025). Environmental and health effects of the Barcelona superblocks. *BMC Public Health*, 25, article number 634. doi: 10.1186/s12889-025-21835-z.

[22] Poulhès, A., Proulhac, L., & Malriat, J. (2025). Low emission zone and inequalities: Car restriction and reduction of air pollution exposure in the Paris region. *Sustainable Cities and Society*, 128, article number 106469. doi: 10.1016/j.scs.2025.106469.

[23] Residents of central Madrid will be able to authorise up to 20 vehicles per month to access the large APR zone. (2018). Retrieved from https://www.eldiario.es/madrid/ayuntamiento-madrid-reduccion-contaminacion-trafico_1_2034922.html.

[24] Smart cities mobility index. (n.d.). Retrieved from https://cee.pwc.com/cee-smart-cities-mobility-index.html.

[25] Superblocks of Barcelona. (2024). Retrieved from https://vertaki.com.ua/superblok_barselona/.

[26] Sweden. (n.d.). Retrieved from https://autotravels.com.ua/country/sweden.

[27] Tassinari, F. (2024). Low emission zones and traffic congestion: Evidence from Madrid Central. *Transportation Research Part a Policy and Practice*, 185(1), article number 104099. doi: 10.1016/j.tra.2024.104099.

[28] Urban vehicle access regulations. (n.d.). Retrieved from https://transport.ec.europa.eu/transport-themes/urban-transport/urban-vehicle-access-regulations_en.

[29] Vadeby, A., & Forsman, Å. (2018). Traffic safety effects of new speed limits in Sweden. *Accident Analysis & Prevention*, 114, 34-39. doi: 10.1016/j.aap.2017.02.003.

[30] What are city road taxes? (n.d.). Retrieved from https://uk.urbanaccessregulations.eu/countries-mainmenu-147/italy-mainmenu-81/umbria/128-europe/main-pages/background/background-charging-schemes.

[31] Which cars can drive in Madrid in 2025? (n.d.). Retrieved from https://www.waourentals.com/blog/en/car-in-madrid/.

[32] Why is paid entry to central London necessary, and will it work in Kyiv? (2018). Retrieved from https://hmarochos.kiev.ua/2018/06/20/navishho-platniy-v-yizd-u-tsentr-londona-i-chi-pratsyuvatime-tse-u-kiyevi/.

[33] Zanger, J., Reid, A., & McNicholas, T. (2024). *NYC congestion pricing start date set for June 30. See a map of the zone and how much it will cost.* Retrieved from https://www.cbsnews.com/newyork/news/nyc-congestion-pricing-start-date/.

Обмеження руху транспорту як шлях до зменшення рівня автомобілецентричності міста

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Анотація. Сучасні міста надмірно перевантажені автомобільним транспортом, тому прогресивні міські адміністрації дедалі більше зосереджуються на оптимізації транспортних потоків, зменшенні затримок, підвищенні безпеки дорожнього руху та створенні комфортних умов для пішоходів і користувачів громадського транспорту, зокрема шляхом обмеження руху в центральних районах. Метою цього дослідження було проаналізувати заходи, впроваджені в європейських містах для зменшення транспортних заторів у центрах, а також результати, яких вдалося досягти. У статті розглянуто сучасні методи управління дорожнім рухом, що застосовуються в європейських містах (Барселона, Мадрид, Париж, Стокгольм) та у Нью-Йорку, визначено їх переваги, проблемні аспекти реалізації та потенційний вплив на подальший розвиток міської мобільності. На основі отриманих результатів встановлено, що значна кількість європейських міст здійснила перехід від автомобілеорієнтованої моделі міського планування до підходу, який надає пріоритет мобільності населення. Цей процес супроводжувався суттєвим розширенням інфраструктури для пішохідного та велосипедного руху. Систематичне зростання залежності від автомобілів призвело до очікуваних наслідків: перевищення пропускної спроможності існуючої дорожньої мережі, концентрації значної кількості заторів та збільшення викидів шкідливих речовин. Для подолання наслідків перевантаження міського транспорту, особливо в центральних районах, у низці країн було запроваджено обмеження, що включають як повну заборону руху, так і фінансові платежі за проїзд у визначених зонах. Як довготривалі, так і нещодавно впроваджені обмеження продемонстрували чіткий вплив на зниження транспортного навантаження в окремих районах, що сприяло скороченню часу поїздок і зменшенню викидів CO_2. Практична цінність цієї роботи полягає в тому, що вона створює можливість розробки та впровадження ефективних рішень для зменшення транспортних заторів у центральній частині Києва на основі успішного досвіду європейських міст

Ключові слова: управління дорожнім рухом; безпека дорожнього руху; затори; міська мобільність; екологія

ВІСНИК
НАЦІОНАЛЬНОГО ТРАНСПОРТНОГО УНІВЕРСИТЕТУ

VOL. 29 | № 2 | 2025

Відповідальний редактор:
Олексій Шумейко

Підписано до друку 27.11.2025
Формат 60*84/8
Ум. друк. арк. 13,4
Наклад 100 прим.

Видавництво:
Національний транспортний університет
01010, вул. М. Омеляновича-Павленка, 1, м. Київ, Україна
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BULLETIN

THE NATIONAL TRANSPORT UNIVERSITY

TOM 29 | No. 2 | 2025

Managing Editor:
Oleksii Shumeiko

Approved for publication 27.11.2025
Format 60*84/8
Conventional Printed Sheet 13.4
Circulation 100 copies

Publisher:
National Transport University
01010, 1 M. Omelianovych-Pavlenko Str., Kyiv, Ukraine
E-mail: ntu@ntu-bulletin.com
https://ntu-bulletin.com/en