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Using of geosynthetic reinforcing interlayer in road construction

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Abstract. The relevance of this work stems from the need to improve the durability and reliability of road surfaces, which are subject to intense loads, particularly from heavy vehicles, leading to the development of deformations and damage, such as cracks. This necessitates the use of reinforcement for road structure layers. The aim of this study was to determine the most effective placement of a reinforcing geosynthetic layer in the road structure to reduce the stress-strain state and increase its load-bearing capacity. Analytical methods were used for the calculations, as well as finite element numerical modelling to study the stress distribution in the layers for different reinforcing layer placement patterns. Numerical modelling revealed that geogrid reinforcement significantly reduces tensile stress in the road surface layers. The most effective placement of the geogrid is between the second and third layers of the road pavement, which, despite its primary purpose of preventing crack propagation, significantly reduces tensile stresses. The study showed that this arrangement reduces tensile stresses from 1,207 Pa to 1,011.6 Pa, representing a 20% decrease. At the same time, the use of the geogrid in the first layer increases shear stresses by 2.9%, and between the first and second layers, tensile stresses increase by almost 5%. However, overall, geosynthetics enhance the strength and durability of road pavements. Analysis of the resulting graphs confirmed that the optimal placement of the reinforcing layer corresponds precisely to the maximum tensile stress concentration, which improves structural strength, reduces deformation, and extends the service life of the pavement. The practical value of this work lies in the formulation of sound recommendations for the design of reinforced pavements, which will minimise material consumption and extend the service life of highways

Keywords: asphalt coating; reinforcement; geogrid; bonding; stress concentration; stress-strain state; cracks

Introduction

The strength and durability of the pavement structure are largely determined by the intensity of traffic loads and the influence of climatic conditions. The rapid increase in the number of heavy-duty vehicles on roads leads to higher axle loads on the pavement and contributes to the development of deformations and distress in asphalt concrete surfaces, as noted by M. Wismans *et al.* (2024) and P. Li *et al.* (2025). The works of S.A. Baran *et al.* (2021) and

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A. Raffaniello *et al.* (2022) stated, that the most common types of pavement deformations and distresses include the formation of transverse and longitudinal cracks caused by extreme tensile stresses at low sub-zero temperatures, under conditions that prevent free contraction of the upper layers. To mitigate this effect, apply transverse thermal (unloading) joints and reinforcement (longitudinal, meshes, etc.) are incorporated into the pavement structure, as emphasised by V.I. Gulyayev *et al.* (2022). Geosynthetics have recently become increasingly popular in road construction. Carbon, boron, glass, organic, ceramic, metallic, and other materials can be used as fibres. Reinforcing elements also come in various forms, including tapes, threads, strands, and meshes. Of significant practical interest is not only the selection of geosynthetic material parameters but also the placement of the reinforcing mesh to strengthen the road structure and reduce tensile stresses localised in areas adjacent to the zone of application of external distributed pressure. Therefore, it is relevant and advisable to study the integration of geosynthetics into road pavement structures, their impact on the overall strength of road structures, and the determination of the optimal geogrid placement to reduce stress and strain concentrators and increase the durability of the system.

The use of geotextile materials in the construction of road pavements and subgrades has increasingly become the subject of both international and domestic research publications. In particular, the following forms of geosynthetics for road pavements are considered: geotextiles, geogrids, geocomposites, geo-elements, geopins, and geobags (Alimohammadi *et al.*, 2020; Al-Barqawi *et al.*, 2021). Z. Yin *et al.* (2022) presented a numerical study of a geotextile-reinforced flexible pavement under static loading to evaluate the improvement due to reinforcement based on three criteria: rutting performance, placement of geosynthetic materials, and reduction in the thickness of the base layer. V.M. Pershakov *et al.* (2020) conducted an analysis of theoretical and experimental data concerning the reinforcing functions of geosynthetic interlayers and their functional interaction with other layers within the pavement structure. The study by S. Banerjee *et al.* (2024) presented the results of full-scale model tests and numerical analyses of reinforced and unreinforced pavement sections. The inclusion of geocell elements within the base layer demonstrated a significant reduction in both residual deformation and subgrade stress concentration compared with unreinforced sections across all pavement configurations. Based on the finite element method, the study by M. Huang *et al.* (2025) analysed the effect of a stress-absorbing layer on the durability of semi-rigid asphalt pavement. Thus, the analysis of recent studies and publications has demonstrated that the use of geosynthetic materials in pavement design enhances drainage properties and provides a reinforcing effect, thereby slowing down the process of crack formation. In this regard, it is highly advisable to continue research on the application of geosynthetic reinforcing layers in road construction. This study sought to identify the optimal location of a geosynthetic reinforcement layer within a pavement structure in order to minimise stress-strain responses and enhance its load-bearing performance.

Materials and Methods

To study the effect of geogrid reinforcement on the stress-strain state of the road surface, the finite element method was used. The use of numerical modelling was justified by the need to accurately reproduce the layered structure of the road and the conditions of interaction between the layers and the reinforcing element to identify zones of maximum tensile stress. Analytical methods for deriving elastic equilibrium equations and boundary conditions were additionally used. For the finite element analysis of these issues, a layered pavement structure was selected, the schematic of which is shown in Figure 1.

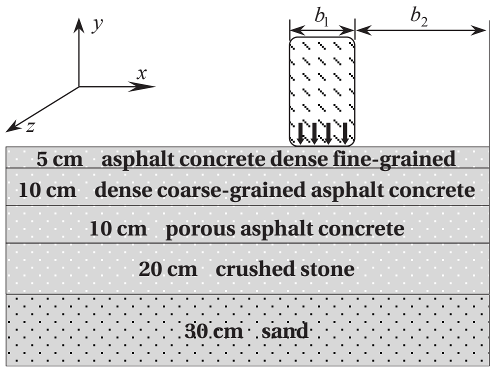

Figure 1. Structural diagram of the road surface
Source: developed by the authors

Figure 1 showed the structural layout of the road surface, illustrating the various layers of materials used in the pavement structure, including asphalt concrete, dense coarse-grained asphalt concrete, porous asphalt concrete, crushed stone, and sand. The values of the structural and mechanical parameters of the system are presented in Table 1.

Table 1. The value of the structural and mechanical parameters of the system

Number *i* layer	h_i, (m)	E_i, (Pa)	ν
I layer	0.05	$5 \cdot 10^9$	0.2
II layer	0.1	$1.4 \cdot 10^9$	0.25
III layer	0.2	$0.1 \cdot 10^9$	0.3
IV layer	0.2	$0.1 \cdot 10^9$	0.3
V layer	0.3	$0.1 \cdot 10^9$	0.35
Geogrid	0.003	$1.4 \cdot 10^{10}$	0.25

Source: developed by the authors

The data presented in Table 1 indicate a multilayer pavement structure characterised by a gradual decrease in elastic modulus from the upper layer ($5 \cdot 10^9$ Pa) to the lower layers ($0.1 \cdot 10^9$ Pa), ensuring effective stress distribution with depth. The geogrid, despite its small thickness (0.003 m), exhibits a significantly higher modulus of elasticity ($1.4 \cdot 10^{10}$ Pa), confirming its high tensile stiffness and reinforcing potential within the system. A two-dimensional formulation of the problem is considered, in which a vertical load with an intensity of p = 1,000 Pa is distributed over a section with a width of b_1 = 0.48 m (tire contact patch width), located at a distance of b_2 = 0.96 m from the edge of the road. It is assumed that the road structure consists of four layers resting on a soil foundation. Within each segment of the road, the equations of elastic equilibrium are satisfied:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0,$$
$$\frac{\partial \tau_{yz}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0,$$
$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_z}{\partial z} = 0, \quad (1)$$

where σ_x, σ_y, σ_z are the corresponding normal stresses, and τ_{xy}, τ_{yz}, τ_{zx} are the shear stresses, calculated from the following equations:

$$\sigma_i = \lambda \Delta + 2G\varepsilon_i,$$
$$\tau_{ij} = \tau_{ji} = G\gamma_{ij} = G\gamma_{ji}. \quad (2)$$

The Lame constants λ and G are expressed through the modulus of elasticity E and Poisson's ratio ν by the following formulas:

$$\lambda = \frac{\mu E}{(1+\mu)(1-2\mu)},$$
$$G = \frac{E}{2(1+\mu)}. \quad (3)$$

The symbols used in equations (2) are defined by the following expressions:

$$\Delta = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z},$$
$$\gamma_{ij} = \frac{\partial u_j}{\partial i} + \frac{\partial u_i}{\partial j},$$
$$\varepsilon_i = \frac{\partial u_j}{\partial i}, \quad (4)$$

where $i, j = x, y, z$.

The boundary conditions of zero normal and shear stresses specified on the free surfaces of the first layer and the soil mass are expressed as follows:

$$\sigma_y = 0,$$
$$\tau_{yx} = \tau_{yz} = 0. \quad (5)$$

Within the contact interaction, the stress σ_y is equal to the tire pressure p, therefore:

$$\sigma_y = -p. \quad (6)$$

The displacement continuity conditions at the interfaces of adjacent layers, as well as between the fourth layer and the soil foundation, are expressed as follows:

$$u_{i-1} = u_i, v_{i-1} = v_i,$$
$$w_{i-1} = w_i \ (i = 2,3,\ldots 5). \quad (7)$$

The finite element method was used to solve the problem. The layered system selected for the calculations was divided into three-dimensional finite elements, and the system of differential equations was replaced by a system of algebraic finite element equations formed taking into account the boundary conditions (5)-(7):

$$[K_u]\{u\} = \{q\}, \quad (8)$$

where $[K_u]$ is the stiffness matrix of the finite element model of the entire elastic body, $\{u\}$ is the vector of nodal displacements, and $\{q\}$ is the load vector.

The validity of the model is confirmed through experimental results from laboratory and in-situ testing, with findings from M.R. Sharbaf & N. Ghafoori (2021) and M. Zakarka *et al.* (2023) providing strong corroboration of the theoretical predictions regarding the reinforcing effectiveness of geogrids. It is assumed that the structural configuration of the geogrid consists of square cells formed by fibres whose modulus of elasticity and strength significantly exceed those of the materials in the pavement layers. It is also assumed that the cell dimensions are much smaller than the characteristic dimensions of the layers. Therefore, for the purpose of a qualitative analysis of the problem, the geogrid can be approximately modelled as a continuous thin elastic layer whose averaged modulus of elasticity and strength correspond to the averaged mechanical properties of the actual geogrid. By placing this equivalent layer at different positions within the layered structure, the mechanical behaviour of the reinforced pavement under a given load can be studied. For this analysis, a geogrid was selected with averaged parameter values listed in Table 1. During the simulations, the geogrid was placed within and between the upper layers, and the configuration that resulted in the minimum tensile stress at the bottom of the second layer was determined. The finite element model of the system consists of 213,236 finite elements and 319,137 nodes.

Results and Discussion

In practice, reinforcing layers in the form of synthetic materials, so-called geogrids, are used for reinforcement. They are intended for reinforcing the road base, as a bearing layer for sections located on weak soils (Fig. 2). Their correct use turns the coating into a durable, stable structure and helps to redistribute stresses in the soil massif. Figure 2 demonstrates how the geogrid, placed beneath the crushed stone layer, helps redistribute stresses in the soil, thereby enhancing the stability and durability of the road, particularly when constructed on weak soils. Geosynthetics have been used in road construction in France since the 1960s and became more widely used in the 1980s in the United States, Canada, Israel, Belgium, Spain, the Czech Republic and Germany (Giroud *et al.*, 1985). They are consistently used in road construction in Ukraine. The use of geosynthetic materials in severely cracked road surfaces improves drainage properties and has a reinforcing effect, slowing down the crack formation process (Gaidaichuk *et al.*, 2021; Gulyayev *et al.*, 2022). Geogrid is a type of synthetic material that is heat-resistant, frost-resistant, elastic, and resistant to mechanical damage. Polyester, polypropylene, fiberglass, and high-grade polyethylene are used for its production. Geogrid modules are stacked on top of each other, and the niches are filled with crushed stone or sand with layer-by-layer compaction, after which they are covered with asphalt concrete. At the same time, the walls of the gratings prevent the displacement of the material placed in it, giving it new properties. The holes of the geogrid and the particles they are filled with form an intermediate layer that acts as a stretched membrane. This effect reduces the concentration of the concentrated vertical load from the car wheel from the base layer and distributes it inside the intermediate layer (Fig. 3). This increases the resistance to displacement and limits lateral deformations in the main layer (Kashif *et al.*, 2024). Geogrids have a wide range of applications, including the construction of road surfaces on soft and shifting soils, the stabilisation of road surfaces on roads, highways, and bridge decks, as well as the reconstruction and widening of roadways. Geogrids are also used to reinforce asphalt concrete pavements during the construction of retaining walls and soil slopes, to restore road surfaces after repairing underground utilities, and to construct and reinforce airport runways. The use of geogrids offers a range of technological and economic advantages, including the ability to reduce the thickness of asphalt concrete pavements and save money on soil improvements. Reinforcement increases the bearing capacity of weak foundations, evenly distributes mechanical loads, and prevents the propagation of thermal and fatigue cracks and the occurrence of shear deformations in pavements. These factors lead to a threefold or more increase in the service life of the pavement, a two- to threefold increase in the time between repairs, and a reduction in road surface maintenance and repair costs by more than 40%, while significantly simplifying road construction and embankment stabilisation.

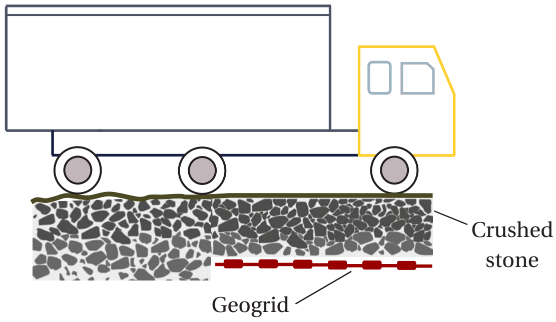

Figure 2. Geometric layout of the geogrid
Source: developed by the authors

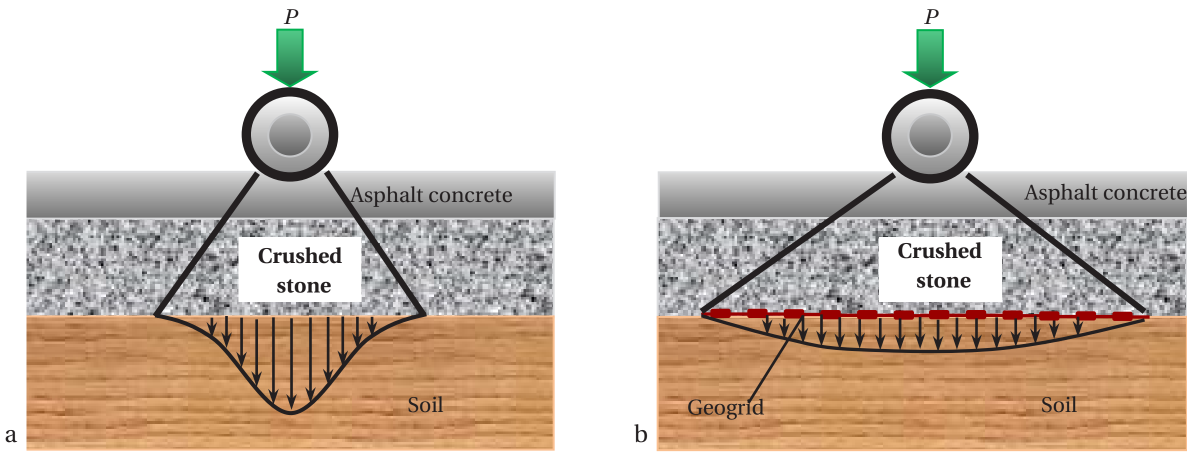

Figure 3. Concentration of concentrated vertical load from a car wheel
Note: a – without geogrid; b – with geogrid
Source: developed by the authors based on M. Al Qurishee (2017)

Depending on the type of repair work, different geogrid placement patterns are used in the pavement structure. When repairing a road section with minor cracks, a geogrid is laid to reinforce the top layer of the pavement. It is placed between the existing asphalt concrete without a levelling course and the new asphalt concrete, creating a preservative effect and absorbing horizontal stresses and deformations, thereby preventing the propagation of existing cracks into the newly laid pavement layer. To repair a road section with ruts and potholes, a geogrid is placed between the levelling course of the existing asphalt concrete and the new pavement layer. Redistributing vertical loads over a larger base area eliminates or reduces paths and potholes. When reinforcing asphalt concrete pavements on highways or airport runways, geogrids are placed between the asphalt concrete levelling layer and the cement concrete pavement. They act as a binder layer and prevent cracks due to the difference in thermal expansion coefficients between these layers. Reinforcing asphalt concrete pavements is critical at the junction of sections, as it prevents cracks from developing in the top layer. Geogrids are used to widen road surfaces at junctions, as well as to reinforce road sections after repairs to underground utilities to ensure the integrity of the roadway is restored and improve its reliability.

Using the proposed methodology, a simulation of the pavement structure depicted in Figure 3 was conducted, employing the parameter values listed in Table 1. The calculation results are shown in Figure 4 in the form of graphs of the functions $\sigma_x(y)$, $\sigma_y(y)$, $\sigma_Z(y)$, $\sigma_{xy}(y)$ in a vertical section passing through $x = const$ the centre of the load application area. Apparently, the greatest stress σ_x = -5,770 Pa occurs on the border surface of the upper layer. However, it cannot be considered the most dangerous, since it is compressed. Therefore, the tensile load σ_x = 1,207 Pa, arising on the contact edge of the second and third layers, can be considered more dangerous. The remaining components of the stress tensor have much smaller values. In connection with the noted, when reinforcing the structure, it is desirable to select such a location of the geogrid as to reduce the tensile stress σ_x on the contact surface of he second and third layers. Figure 4 shows the graphs of the functions $\sigma_x(y)$, $\sigma_y(y)$, $\sigma_Z(y)$, $\sigma_{xy}(y)$ for the case when the geogrid is installed inside the first pavement layer. Such a grid arrangement even has a negative effect, since the maximum tensile stress in the lower plane of the second layer even increased from 1,207 Pa to 1,243 Pa. At the same time, such a design scheme led to a decrease in the compressive forces in the upper layer, which were not dangerous anyway.

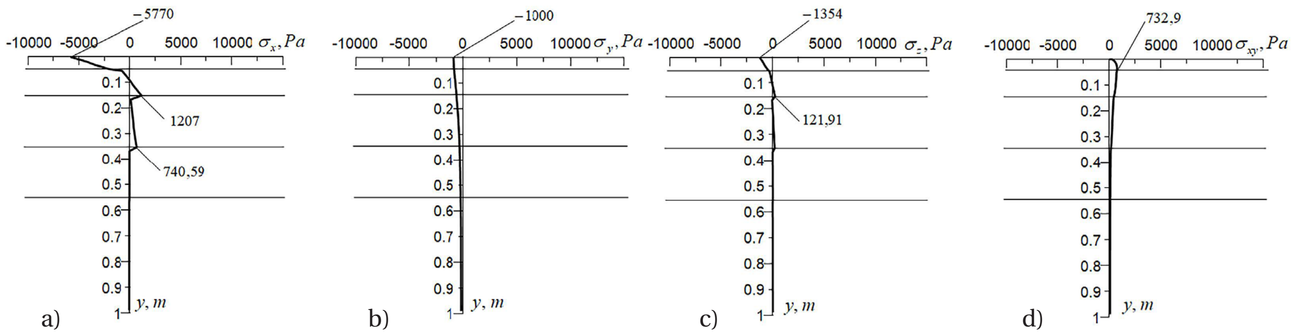

Figure 4. Graphs of stress changes (a), (b), (c), (d) in an unreinforced road structure

Source: developed by the authors

It should be noted that the stresses in the reinforcing layer significantly exceed those in the asphalt concrete. However, this does not pose a threat, as the strength of the geogrid considerably surpasses that of asphalt concrete. The case where the geogrid is located between the first and second layers is shown in Figure 5. This scheme cannot be considered rational, since the tensile stresses at the bottom of the second layer have again increased from σ_x = 1,207 Pa (without the grid) to σ_x = 1,260.3 Pa (with the grid). The geogrid placement inside the second layer has a positive effect on the lower limit of the second layer. It dropped to σ_x = 1,156.2 Pa.

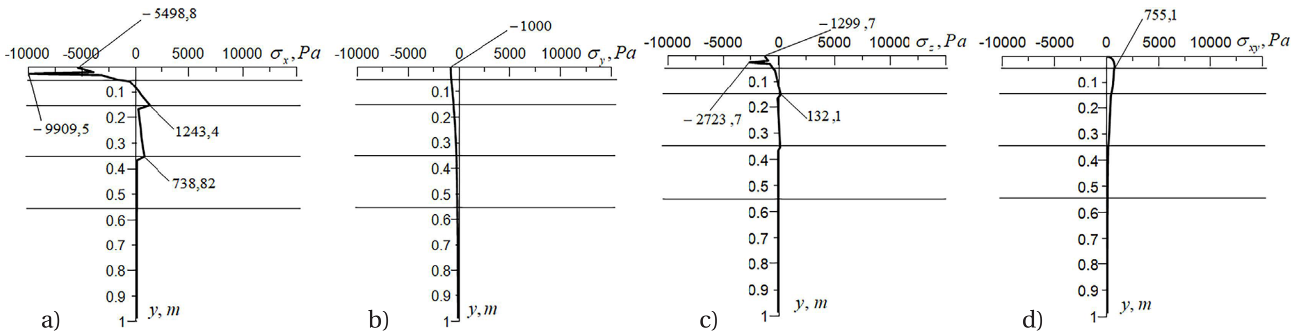

Figure 5. Graphs of changes in stresses (a), (b), (c), (d) in the road cross-section under load when the geogrid is located inside the first layer

Source: developed by the authors

Here the stress σ_x decreased from σ_x = 1,207 Pa to σ_x = 938.3 Pa. The installation of a geogrid inside the lower (third) layer also resulted in a decrease in the level of the highest tensile stresses (from 1,260.3 Pa to 1,011.6 Pa), but it was not as significant. Structural schemes were also analysed in which the geogrid was installed even lower (in the fourth layer). However, calculations showed that in this case the influence of the geogrid on the stress-strain state of the system is even less significant. Therefore, the calculation results for such a scheme are not presented here. As a conclusion to this study, it can be noted that the most rational geogrid arrangement for this structure and this stress can be considered its arrangement between the second and third layers. It should also be emphasised that although the introduction of the geogrid into the coating structure did not result (as expected) in a significant decrease in tensile stresses in the critical zones of the system, its effect on the overall strength of the coating remains important, as the geogrid, even in a closed state, prevents further crack growth and structural failure in the described area. The graphs of changes in stresses in the road cross-section under load when the geogrid is located between the first and second layers are shown in Figure 6.

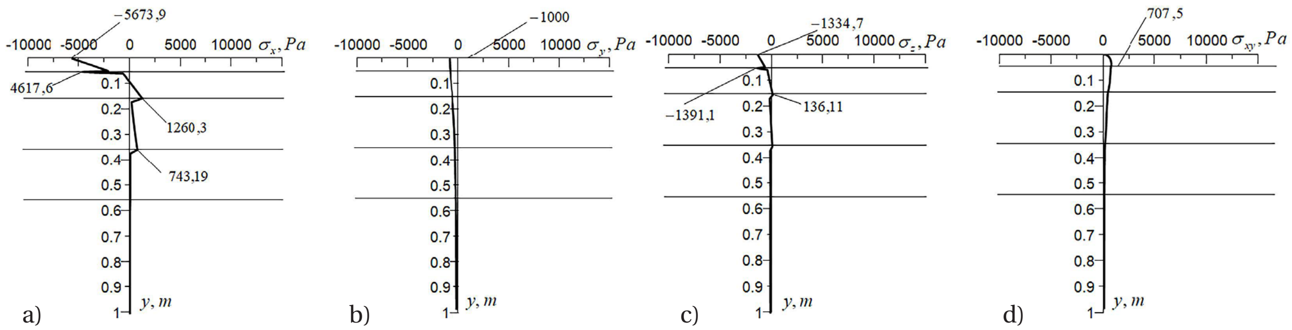

Figure 6. Graphs of changes in stresses (a), (b), (c), (d) in the road cross-section under load when the geogrid is located between the first and second layers

Source: developed by the authors

An analysis of various geogrid-reinforced road pavement designs allowed for determination the most efficient geogrid placement to minimise the most dangerous stress. When reinforcement is placed within the first layer and between the first and second layers, an increase in the critical tensile stress at the bottom of the second layer by 36-53.3 Pa is observed (Figs. 5-6). The most favourable case was when the geogrid was located in the place of maximum stress σ_x, between the second and third layers (Fig. 7).

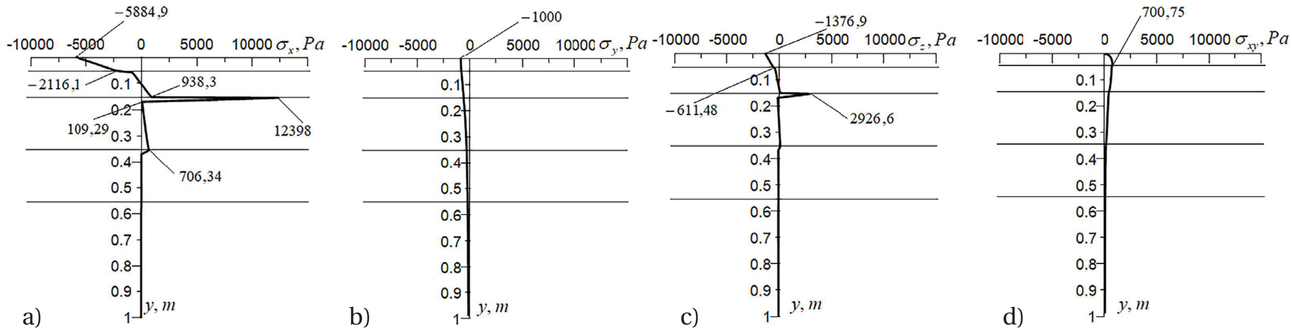

Figure 7. Graphs of changes in stresses (a), (b), (c), (d) in the road cross-section under load when the geogrid is located between the second and third layers

Source: developed by the authors

Indicating a negative impact of this placement on the overall durability of the structure. From the middle of the second layer to the middle of the third layer, a reduction in stress by 50.8 Pa to 195.4 Pa is observed compared with the critical stress value $\sigma_x = 1{,}207$ Pa. The maximum positive effect is achieved when the geogrid is placed directly in the zone of maximum tensile stress between the second and third layers. Therefore, the study clearly demonstrates the effectiveness of road pavement reinforcement, which is directly dependent on the precise placement of the geogrid in the zone where the greatest tensile stress occurs.

Previous studies confirmed the effectiveness of geosynthetic materials in improving pavement durability. In particular, the use of geogrids has been shown to reduce rutting and tensile stresses and to allow a significant reduction (20-40%) in base-layer thickness without compromising load-bearing capacity (Al Qurishee, 2017). The results obtained in the present study demonstrate that geogrid reinforcement leads to a decrease in critical stress levels, which is consistent with the findings reported by B. Hill *et al.* (2018). The authors highlighted that the inclusion of recycled materials like reclaimed asphalt pavement (RAP) in pavement construction has led to reduced performance at low temperatures, causing thermal cracking. Their previous research demonstrated that bio-binders from swine manure could mitigate the effects of RAP while enhancing the low-temperature properties of asphalt mixtures. The results of the present analysis are also consistent with the findings of P. Vishwakarma & S.R. Karumanchi (2023), who emphasised the critical importance of selecting an appropriate geogrid stiffness within the asphalt concrete layer and choosing suitable subgrade materials to optimise pavement performance and service life. Their study highlighted that maintaining the geogrid stiffness within a specific range, particularly between 100 kN/m and 400 kN/m, markedly reduces rutting depth, especially in pavements with lower subgrade modulus, thereby ensuring improved long-term performance. Compared with subgrade reinforcement approaches, the results confirm that optimal depth-wise placement of the geogrid effectively mitigates crack initiation and propagation in high-stress zones, thereby serving as a key factor in extending pavement service life. In contrast to the predominantly theoretical review presented by M. Farhan & K. Murari (2024), the present study employs finite element modelling to systematically investigate and determine the optimal depth-wise placement of geosynthetic reinforcement within the pavement structure. The results are further corroborated by the studies of M.R. Sharbaf & N. Ghafoori (2021) and M. Zakarka *et al.* (2023), providing additional evidence of the effectiveness of geosynthetic materials in enhancing pavement strength. X. Ding *et al.* (2022) demonstrated that the inclusion of geogrid reinforcement significantly improves the strength and alters the deformation behaviour of calcareous sand in maritime geotechnical structures. Their consolidated drained triaxial tests revealed that geogrid-reinforced calcareous sand (GRCS) exhibits higher strength, a shift in the deviatoric stress-strain response from slight softening to hardening, and reduced shearing dilatancy compared to unreinforced sand. D. Nie *et al.* (2023) focused on fatigue performance, the present study specifically determines that placing the geogrid between the second and third pavement layers is the most rational solution. M. Huang *et al.* (2025) demonstrated the results of a comprehensive full-scale investigation into the effectiveness of composite stabilised bases reinforced with geogrids and geotextiles in pavement structures. The findings showed that seasonal freeze-thaw cycles contribute to increased roadbed settlement. Overall, the findings of the present study, supported by previous research, confirm that geogrid reinforcement – when optimally selected in terms of stiffness and strategically placed within the pavement layers – significantly enhances structural strength, reduces critical stresses and rutting, and effectively mitigates crack initiation, thereby improving the durability and service life of pavement systems.

Conclusions

The study investigated the deformation behaviour of layered pavement structures with respect to the placement of geosynthetic reinforcement layers. It was demonstrated that the strategic incorporation of geogrid reinforcement, with optimal stiffness and depth placement, significantly enhances pavement strength, mitigates stress concentrations and rutting, and improves the overall durability and service life of the structure. The findings indicated that the most effective geogrid placement is between the second and third layers of the pavement. In this case, the tensile stress decreased from 1,207 Pa (in the unreinforced configuration) to 1,011.6 Pa, representing a significant reduction of approximately 20% in critical stress levels. In contrast, placing the reinforcing layer within the first layer of the road structure or between the first and second layers resulted in negative outcomes. When applied in the first layer, the shear stress increased by 2.9%, and when placed between the first and second layers, the tensile stresses increased by nearly 5%. Therefore, it can be concluded that the use of geosynthetic materials in pavement design is an effective method for improving the overall strength, increasing the durability, and reducing maintenance costs of road structures. It should also be emphasised that although the introduction of the geogrid into the pavement structure did not lead (as initially expected) to a substantial reduction of tensile stresses in the critical zones, its influence on the overall strength of the pavement should be considered important. Even under near-critical conditions, the geogrid prevents further crack propagation and structural failure at the affected location.

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Conflict of Interest

None.

References

[1] Al Qurishee, M. (2017). Application of geosynthetics in pavement design. *International Research Journal of Engineering and Technology*, 4(7).

[2] Al-Barqawi, M., Aqel, R., Wayne, M., Titi, H., & Elhajjar, R. (2021). Polymer geogrids: A review of material, design and structure relationships. *Materials*, 14, article number 4745. doi: 10.3390/ma14164745.

[3] Alimohammadi, H., Schaefer, V.R., Zheng, J., & Li, H. (2020). Performance evaluation of geosynthetic reinforced flexible pavement: A review of full-scale field studies. *International Journal of Pavement Research and Technology*, 14, 30-42. doi: 10.1007/s42947-020-0019-y.

[4] Banerjee, S., Manna, B., & Shahu, J.T. (2024). Behaviour of geocell reinforcement in a multi-layered flexible pavement under repeated loading. *International Journal of Geosynthetics and Ground Engineering*, 10, article number 34. doi: 10.1007/s40891-024-00541-7.

[5] Baran, S.A., Bilobrytska, O.I., Hrynchak, I.I., Kutsman, O.M., & Shevchuk, L.V. (2021). Temperature oscillations influence in asphalt concrete layers on stress-deformed condition of road pavement. *Automobile Roads and Road Construction*, 110, 11-16. doi: 10.33744/0365-8171-2021-110-011-017.

[6] Ding, X., Luo, Z., & Ou, Q. (2022). Mechanical property and deformation behavior of geogrid reinforced calcareous sand. *Geotextiles and Geomembranes*, 50(4), 618-631. doi: 10.1016/j.geotexmem.2022.03.002.

[7] Farhan, M., & Murari, K. (2024). Enhancing pavement performance through the strategic use of geosynthetics in infrastructure design. *Journal of Propulsion Technology*, 45(4), 3456-3463.

[8] Gaidaichuk, V.V., Shevchuk, L.V., & Bilobrytska, O.I. (2021). Influence of incompatibility of thermomechanical parameters of bearing layers of a bridge structure on its thermo-stressed state. *Strength of Materials and Theory of Structures*, 107, 302-313. doi: 10.32347/2410-2547.2021.107.301-311.

[9] Giroud, J.P., Ah-Line, C., & Bonaparte, R. (1985). *Design of unpaved roads and trafficked areas with geogrids: Polymer grid reinforcement*. London: Thomas Telford Limited.

[10] Gulyayev, V.I., Mozgovyy, V.V., Shlyun, N.V., & Shevchuk, L.V. (2022). Modelling negative thermomechanical effects in reinforced road structures with thermoelastic incompatibility of coating and reinforcement materials. *System Research and Information Technologies*, 2, 117-127. doi: 10.20535/SRIT.2308-8893.2022.2.09.

[11] Hill, B., Oldham, D., Behnia, B., Fini, E.H., Buttlar, W.G., & Reis, H. (2018). Evaluation of low temperature viscoelastic properties and fracture behavior of bio-asphalt mixtures. *International Journal of Pavement Engineering*, 19(4), 362-369. doi: 10.1080/10298436.2016.1175563.

[12] Huang, M., Liu, J., Pokharel, S.K., Dagenais, T., Chatterjee, A., & Lin, C. (2025). Full-scale testing and monitoring of geosynthetics-stabilized flexible pavement in Alberta, Canada. *Geotextiles and Geomembranes*, 53(1), 427-444. doi: 10.1016/j.geotexmem.2024.11.003.

[13] Kashif, M., Naseem, A., Onyelowe, K.C., Riaz, M.R., Mehboob, S.S., De Winne, P., & De Backer, H. (2024). Finite element modeling of active cracking in actively reinforced concrete pavement slab exposed to fluctuating temperature. *Scientific Reports*, 14, article number 17337. doi: 10.1038/s41598-024-68414-7.

[14] Li, P., Fu, J., Sun, L., Yue, J., & Zang, Q. (2025). Analysis of rutting formation mechanisms and influencing factors in asphalt pavements under slow-moving heavy loads. *Materials*, 18, article number 4153. doi: 10.3390/ma18174153.

[15] Nie, D., Wang, S., Sun, P., & Huang, C. (2023). Study on anti-crack effect of semi-rigid base pavement with stress absorbing layer. *Journal of Engineering and Applied Science*, 70, article number 45. doi: 10.1186/s44147-023-00217-5.

[16] Pershakov, V.M., Bieliatynskyi, A.O., & Stefashyna, N.M. (2020). Using of geosynthetic reinforcing layers in road construction. *Problems of Urban Environment Development*, 2(25), 130-149.

[17] Raffaniello, A., Bauer, M., Safiuddin, M., & El-Hakim, M. (2022). Traffic and climate impacts on rutting and thermal cracking in flexible and composite pavements. *Infrastructures*, 7(8), article number 100. doi: 10.3390/infrastructures7080100.

[18] Sharbaf, M.R., & Ghafoori, N. (2021). Laboratory evaluation of geogrid-reinforced flexible pavements. *Transportation Engineering*, 4, article number 100070. doi: 10.1016/j.treng.2021.100070.

[19] Vishwakarma, P., & Karumanchi, S.R. (2023). Modeling of semi-mechanistic approach for geo-synthetic reinforced flexible pavement design. *Proceedings of the 9ICEG 9th international congress on environmental geotechnics*, 4, 278-283. doi: 10.5 3243/ICEG2023-95.

[20] Wismans, M., van Breemen, L.C.A., Govaert, L.E., & Engels, T.A.P. (2024). The effect of thermal residual stress on the stress state in a short-fiber reinforced thermoplastic. *Journal of Materials Engineering and Performance*, 33, 4160-4169. doi: 10.1007/s11665-024-09277-x.

[21] Yin, Z., Ndiema, K.M., Lekalpure, R.L., & Kiptum, C.K. (2022). Numerical study of geotextile-reinforced flexible pavement overlying low-strength subgrade. *Applied Sciences*, 12(20), article number 10325. doi: 10.3390/app122010325.

[22] Zakarka, M., Skuodis, Š., & Dirgėlienė, N. (2023). Triaxial test of coarse-grained soils reinforced with one layer of geogrid. *Applied Sciences*, 13, article number 12480. doi: 10.3390/app132212480.

Використання геосинтетичних армуючих прошарків у дорожньому будівництві

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Анотація. Актуальність роботи обумовлена необхідністю підвищення довговічності та надійності дорожніх покриттів, які зазнають інтенсивних навантажень, зокрема від вантажного транспорту, що призводить до розвитку деформацій та ушкоджень, таких як тріщини. Це зумовлює потребу у використанні армування для шарів дорожньої конструкції. Метою дослідження було визначення найефективнішого розташування армуючого геосинтетичного шару у конструкції дороги для зменшення напружено-деформованого стану та підвищення несучої здатності покриття. Для розрахунків використовувалися аналітичні методи, а також чисельне моделювання методом кінцевих елементів для вивчення розподілу напружень у шарах при різних схемах розташування армуючого шару. Чисельне моделювання показало, що армування георешіткою значно зменшує розтягуючі напруження у шарах дорожнього покриття. Найефективніше розташування георешітки – між другим і третім шарами дорожнього полотна, що, незважаючи на основну мету запобігання поширенню тріщин, суттєво знижує розтягуючі напруження. Дослідження показало, що така конфігурація зменшує розтягуючі напруження з 1207 Па до 1011,6 Па, що становить 20 % зниження. Водночас використання георешітки в першому шарі збільшує зсувні напруження на 2,9 %, а між першим і другим шарами розтягуючі напруження зростають майже на 5 %. Однак загалом геосинтетичні матеріали підвищують міцність і довговічність дорожніх покриттів. Аналіз отриманих графіків підтвердив, що оптимальне розташування армуючого шару точно відповідає зоні максимальної концентрації розтягуючих напружень, що покращує конструкційну міцність, зменшує деформації та подовжує експлуатаційний ресурс покриття. Практичне значення роботи полягає у формулюванні обґрунтованих рекомендацій щодо проєктування армованих покриттів, що дозволяє мінімізувати витрати матеріалів і подовжити термін служби автомобільних доріг

Ключові слова: асфальтобетонне покриття; армування; георешітка; сцеплення; концентрація напружень; напружено-деформований стан; тріщини

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Research of energy efficiency indicators of a hybrid electric automotive power unit based on a spark ignition engine

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Abstract. The article examined the results of an experimental study on the energy-efficiency indicators of a hybrid electric automotive power unit based on a spark-ignition engine. The purpose of the study was to conduct a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit based on a spark-ignition engine. The research method involved experimental bench tests of a hybrid electric automotive power unit in defined operating modes to determine the regularities of changes in control parameters of the internal combustion engine, electrical subsystems, fuel economy, and environmental indicators. The experimental study of the hybrid electric automotive power unit identified regularities in energy-efficiency indicators and working-process characteristics depending on the output shaft rotational speed and power. Changes were observed in the speed and load modes of the internal combustion engine, motor generator 1, and motor generator 2, as well as in fuel consumption, the air-fuel equivalence ratio, and the ignition timing of the internal combustion engine. The state of charge of the traction battery, thermal-regime parameters of the air supply, lubrication, cooling, and exhaust systems of the internal combustion engine, motor generator 1, motor generator 2, inverter, and battery, and exhaust pollutant concentrations and their neutralisation efficiency were also analysed. Notably, a nearly direct relationship was found between the rotational speed and load of the internal combustion engine and the overall load mode of the power unit. Controlling the air-fuel mixture composition and ignition timing in all modes ensured high fuel efficiency and low emissions of harmful substances. High energy-efficiency indicators under various operating conditions were achieved due to the electric subsystem of the power unit, which provided optimal control of the speed and load mode of the internal combustion engine

Keywords: torque; hybrid transmission; operating mode; traction battery state of charge; fuel economy; environmental indicators

Introduction

The most common sources of energy in transport, particularly in the automotive sector, remain internal combustion engines (ICEs). Consequently, motor vehicles are significant consumers of fuel resources and major contributors to environmental pollution through harmful substances emitted with engine exhaust gases. The performance indicators of automotive engines depend on the nature and characteristics of their energy conversion

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processes, the fuels used, parameter regulation, and their technical condition. At the same time, these features of the working processes largely determine the level of pollutant emissions. Therefore, fuel economy indicators, as well as the energy and environmental performance of engines, can be combined into a general group of energy-efficiency indicators. Modern requirements for automotive vehicles, particularly Regulation (EU) 2019/631 (2019), emphasise substantial reductions in carbon dioxide emissions, primarily achieved through improvements in fuel economy. For this reason, continuous efforts are made to improve the working processes of automotive engines to achieve higher fuel-efficiency levels, as noted by P. Kumbar (2020) and D. Rimpas *et al.* (2025). One of the approaches to such improvement is enhancing engine efficiency under the most common operational modes. According to Y. Pan *et al.* (2025), a relevant direction in the development of automotive engines is the adjustment of their operating modes toward those that ensure high efficiency through the use of a hybrid electric drivetrain. Among such hybrid electric automotive power units, spark-ignition engines have become the most widely used. A significant number of recent studies have been devoted to determining the performance indicators of hybrid electric automotive power units. N. Sergienko *et al.* (2023) presented simulation models of the control and monitoring system and provides an investigation of the dynamic behaviour of parameters of elements of a hybrid vehicle with a series-parallel drivetrain using simulation modelling in the Matlab/Simulink environment. The analysis by O.V. Bazhynov & M.M. Kravtsov (2023) is devoted to theoretical research on methods for assessing the performance indicators of electric and hybrid vehicles during operation, with particular regard to the vehicle's average speed. The work by B. Šarkan *et al.* (2019) highlighted the significance of hybrid vehicles in urban traffic from an environmental perspective. Results obtained using an exhaust gas analyser, together with emission calculations based on engine control unit data, indicate that during urban operation the hybrid vehicle functioned in electric-drive mode for up to 75.40% of the time, while CO_2, HC, and NOx emissions were substantially lower than those of conventional vehicles of a comparable class. C. Saju *et al.* (2022) examined the issue of optimal control of hybrid vehicle drivetrain components and determined vehicle characteristics through modelling in Matlab/Simulink using the EPA HWFET (United States Environmental Protection Agency Highway Fuel Economy Test) highway driving cycle (United States) to evaluate fuel economy.

N.N. Mustafi (2021) provided an overview of modern hybrid electric vehicle technologies, including an analysis of the main configurations combining different energy sources, characteristics of hybrid system components, methods of energy storage and conversion, hybrid powertrain control strategies, environmental indicators, and the critical problems and challenges faced by contemporary hybrid power units. Among the most significant issues identified are: the efficiency, availability, and reliability of electrical energy storage systems; effective management of energy flows from various sources; efficient system architecture based on power-demand and cost considerations; efficiency and reliability of power electronics; characteristics of primary electric machines; and effective control of key hybrid power unit components. The work by Y. Wang *et al.* (2021) presented a novel hybrid power unit based on a linear free-piston engine intended for hybrid light commercial urban vehicles. The study analysed the efficiency of the proposed hybrid power unit as well as the various factors influencing its performance. M. Tomita *et al.* (2024) described new Toyota technologies aimed at enhancing Toyota Prius hybrid vehicles to increase their efficiency and reduce CO_2 emissions globally. In particular, improvements were made to traction battery capacity, transmission efficiency, internal combustion engine energy efficiency, and power-electronics performance. These advancements led to an increase in the electric-drive range to 72 km while simultaneously enhancing overall energy efficiency. The work by A.N.F. Abdelbaky *et al.* (2025) investigated the efficiency of implementing a series-parallel hybrid electric powertrain in a commercial VW (Volkswagen) Crafter vehicle equipped with a diesel engine, with respect to fuel consumption, CO_2 emissions, and driving range under standard driving cycles (New European Driving Cycle, Worldwide Harmonised Light Vehicles Test Procedure, Federal Test Procedure-75, and HWFET). The results of Matlab/Simulink modelling indicate that the average fuel consumption and CO_2 emissions are reduced by about 29%, while the driving range increases by nearly 41% when using a hybrid powertrain compared with a conventional one, provided that the nominal power and torque are similar. At the same time, the study by E.V. Rojas-Reinoso *et al.* (2024) showed that despite the declared high fuel efficiency and low CO_2 emissions, vehicles with hybrid electric powertrains may exhibit reduced fuel economy under conditions of extremely dense traffic with severe congestion. Based on the results of this study, the dependence of fuel consumption for vehicles with gasoline engines of various displacements and for a vehicle with a hybrid powertrain was analysed under conditions of overloaded urban highways in high-altitude areas. The highest fuel efficiency was demonstrated by the vehicle with the smallest analysed engine displacement of 1.2 L, whereas the hybrid vehicle showed relatively high fuel consumption under the specified driving conditions.

The analysis of these and other recent studies in the field of hybrid electric automotive power units demonstrates the significant interest of researchers and automotive developers in such transport energy-supply technologies. Leading global automotive companies have already developed and continue to refine hybrid vehicle components. However, substantial unresolved critical issues remain concerning the efficiency, reliability, and cost of hybrid electric power units. In Ukraine, the development of hybrid electric vehicle technologies is at an early stage, prompting further research in this direction, particularly the study of existing technologies, their efficiency, and features of implementation. This will enable the introduction and development of such power units in the domestic automotive sector to enhance energy efficiency and environmental safety. A primary step in studying existing hybrid power units is experimental laboratory research, which makes it possible to determine the main operational characteristics of these units and the regularities of controlling their operating modes. The aim of the work was a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit featuring a spark-ignition engine. To achieve this objective, the following tasks were carried out:

1. Development of a structural and functional diagram of an experimental setup and justification of the technical characteristics of the equipment necessary for conducting experimental research on a hybrid electric motor unit for a vehicle.

2. Conducting experimental bench tests to determine energy efficiency indicators and study the features of the working processes of a hybrid electric motor unit of a car based on an internal combustion engine.

3. Conducting a comprehensive analysis and scientific discussion of the results of experimental studies of the energy efficiency indicators of a hybrid electric motor unit for a car, with an assessment of their practical and theoretical significance.

Materials and Methods

The object of the experimental research was the hybrid electric power unit of a Toyota Prius vehicle equipped with a 1NZ-FXE spark-ignition engine (4FS 7.5/8.47) with a rated power of 57 kW, featuring electronically controlled fuel injection, variable valve timing, and an exhaust-gas (EG) aftertreatment system with a three-way catalytic converter (Fig. 1). The setup was installed in the Engine Testing Laboratory of the Department of "Engines and Heating Engineering" at the National Transport University (Ukraine). The subject of the study was the influence of operating modes on the energy efficiency indicators of a hybrid electric automotive power unit based on a spark-ignition engine.

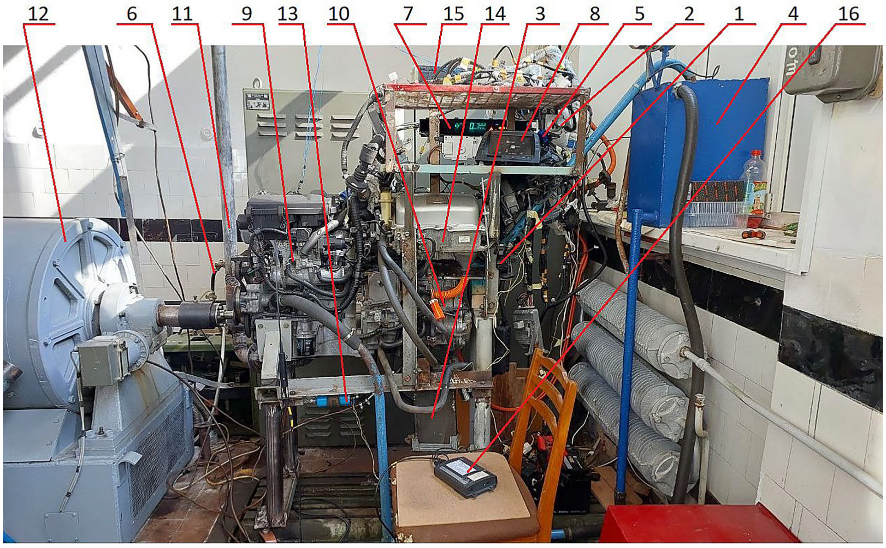

Figure 1. A hybrid electric power unit equipped with a Toyota 1NZ-FXE engine

Note: 1 – accelerator pedal with a device for fixing its position; 2 – transmission mode selector; 3 – inverter and transmission cooling system; 4 – ICE cooling system; 5 – diagnostic device for connection to the OBD (on-board diagnostics) data-reading system; 6 – exhaust gas sampling system; 7 – instrument panel; 8 – energy flow monitor; 9 – ICE; 10 – hybrid transmission; 11 – exhaust and exhaust-gas aftertreatment system; 12 – electric load machine; 13 – fuel supply system; 14 – inverter; 15 – high-voltage traction battery; 16 – oil temperature measurement device

Source: authors' photo

Figure 1 depicts a hybrid electric power unit featuring an engine, highlighting key components like energy monitoring, cooling systems, and diagnostic tools. It demonstrates the integration of traditional ICE technology with hybrid systems, ensuring optimised performance, fuel efficiency, and emissions control. The experimental setup also includes other components not shown in Figure 1, in particular: a brake pedal, a control panel for the load machine, a power unit control system, a device for displaying OBD system parameters, and gas analysis equipment for determining the composition of the exhaust gases. A brief technical specification of the power unit is provided in Table 1.

Table 1. Brief technical specifications of the experimental research object

No.	Parameter name	Parameter value
1	Engine model	1NZ-FXE
2	Number of cylinders	4
3	Firing order	1-3-4-2

Table 1, Continued

No.	Parameter name	Parameter value
4	Cylinder arrangement	inline
5	Displacement, L	1.497
6	Cylinder bore and stroke, mm	75/84.7
7	Compression ratio	13
8	Number of intake/exhaust valves per cylinder, pcs	2/2
9	Rated power, kW	57 at 5,000 min^{-1}
10	Maximum torque, Nm	111 at 4,200 min^{-1}
11	Fuel type	gasoline A-95
12	Fuel injection system	port fuel injection
13	Variable valve timing system	hydraulically controlled camshaft drive clutch
14	Ignition system	electronic, with individual ignition coils and knock control
15	Exhaust gas aftertreatment system	three-way catalytic converter
16	Hybrid system type	series-parallel
17	Traction battery type	nickel-metal hydride (NiMH)
18	Battery voltage, V	201.6
19	Traction battery capacity, kWh	1.31
20	Battery mass, kg	40.3
21	Battery power, kW	21
22	Inverter voltage range, V	200…500
23	Type of MG1 and MG2 motor-generators	AC motors with permanent-magnet rotors
24	Rated power of MG1, kW	33
25	Rated power of MG2, kW	50 at 1,200…1,540 min^{-1}
26	Maximum torque of MG2, Nm	400 at 0…1,200 min^{-1}
27	Hybrid transmission	single planetary gearset for power-split
28	Planetary gearset ratio	-2.6
29	Final drive ratio	4.113
30	Maximum system power, kW	82 at ≥ 85 km/h
31	Maximum system torque, Nm	478 at ≤ 22 km/h

Note: MG – motor generator
Source: developed by the authors based on Toyota Motor Sales (2004), R.H. Staunton *et al.* (2006), Toyota Motor Europe (n.d.)

The power unit consists of two main parts: the ICE and its associated systems, and the electrical subsystem. The ICE is an inline four-cylinder gasoline engine with a four-valve valve train, spark ignition, and a relatively high geometric compression ratio, operating on an Atkinson cycle with a high expansion ratio. The electrical subsystem of the hybrid power unit is based on a series-parallel configuration with a nickel-metal hydride high-voltage battery, two synchronous alternating current electric machines (MG1, and MG2), and a planetary gear set for power splitting. The schematic diagram of the experimental setup is shown in Figure 2.

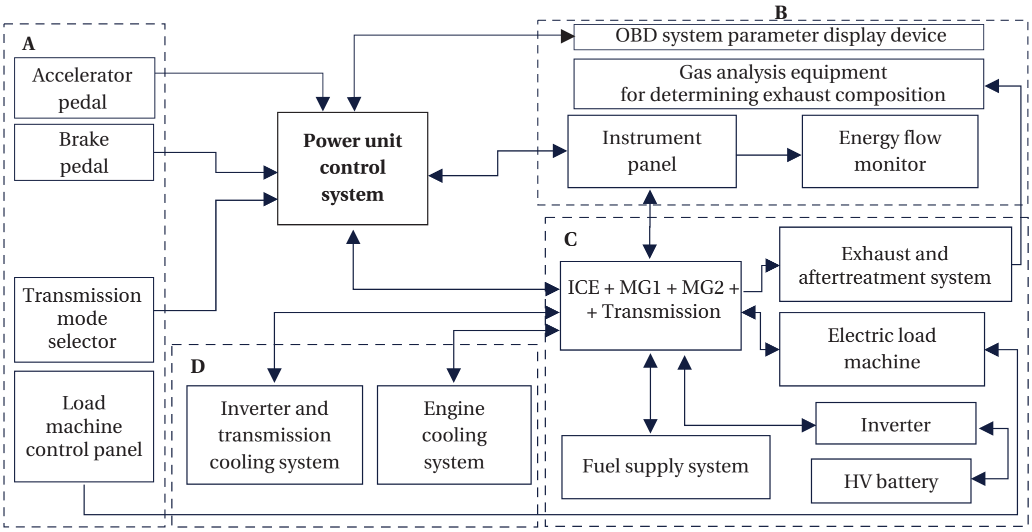

Figure 2. Diagram of the experimental setup
Source: developed by the authors

The structure of the experimental setup comprises four subsystems: the test control subsystem (A), the information subsystem (B), the power subsystem (C), and the thermal management subsystem (D). The test control subsystem (A) consists of the accelerator and brake pedals, the transmission mode selector, and the control panel of the load unit. The information subsystem (B) includes devices for data display and acquisition, namely the OBD system parameters interface, gas analysis equipment for determining exhaust gas composition, the instrument panel, and the energy flow monitor. The power subsystem (C) comprises the ICE, the hybrid transmission with MG1 and MG2, the fuel supply system of the ICE, the high-voltage battery, the inverter, the exhaust and exhaust-gas aftertreatment system, and the electric load machine. The operating modes of the power unit components are controlled by the control system. Measurement accuracy was evaluated based on the absolute or relative errors of the respective instruments and sensors listed in Table 2.

Table 2. Specifications of the instruments and equipment used during the experiment

No.	Measured parameter	Unit	Measuring instruments	Error
Brake test bench parameters				
1	Brake test bench	–	SAK-670 with electric brake machine GPF a17h, 250 kW, max 3200 min^{-1}	–
2	Rotor speed	min^{-1}	Pulse device for measuring rotational speed	±1
3	Torque	N·m	Dynamometric link with strain-gauge sensor	0.01%
Fuel consumption measurement system parameters				
4	Fuel mass	kg	Electronic scales MERA VM–2/3	±0.0005
5	Time	s	Stopwatch	±0.01
Power unit control system parameters				
6	Power unit control parameters	–	Device for connection to engine control system (OBDII), laptop	–
7	Crankshaft speed	min^{-1}	Hall-effect rod sensor	±0.25
8	Mass air flow	g/s	Hot-wire air flow meter	±0.01
9	Intake manifold air temperature	°C	Temperature sensor with thermistor	±1
10	Ignition timing advance	°CA	Individual ignition coil	±0.5
11	Coolant temperature	°C	Temperature sensor with thermistor	±1
12	Throttle valve opening angle	deg	Potentiometric throttle position sensor	±0.1
13	Oil pressure in lubrication system	kgf/cm^2	Low-pressure warning sensor	±0.01
14	Exhaust gas temperature	°C	Thermistor in wideband λ-sensor housing	±1
15	Excess air ratio	–	Wideband λ-sensor before catalytic converter	±0.001
16	Vehicle speed	km/h	Half-shaft rotation speed sensor	±1
17	Inverter temperature MG1/MG2	°C	Thermistor in MG1/MG2 inverter housing	±1
18	MG1/MG2 speed	min^{-1}	Inductive sensors	±1
19	MG1/MG2 torque	N·m	Equivalent electric current meter	±0.125
20	Traction battery state of charge	%	Battery current and voltage meters	±1
21	MG1/MG2 temperatures	°C	Thermistor in MG1/MG2 housing	±1
22	Traction battery temperature (1,2,3)	°C	Thermistors 1, 2, 3 in battery housing	±1
Lubrication system condition parameters				
23	Engine oil temperature in oil pan	°C	Bosch BEA 030 temperature meter	±1
Exhaust gas composition				
24	O_2 concentration in exhaust gases	vol.%	Multicomponent gas analyser Bosch BEA 060	±0.010
25	*CO* concentration in exhaust gases	vol.%		±0.001
26	CO_2 concentration in exhaust gases	vol.%		±0.010
27	C_mH_n concentration in exhaust gases	ppm		±1.0
28	NO_x concentration in exhaust gases	ppm		±1.0
29	Excess air ratio (λ) from exhaust gas composition	–		±0.001
Ambient conditions				
30	Atmospheric pressure	Pa	Barometric aneroid ND-49-A	±100
31	Air temperature	°C	Mercury thermometer	±0.1%
32	Relative humidity	%	Hair hygrometer	±2.5

Source: developed by the authors

Table 2 presented brief specifications of the instruments and equipment used in the study. The measuring equipment includes instruments for measuring the rotational speed and torque at the output shaft of the power unit using the SAK-670 test bench with the GPF a17h electric brake machine; fuel consumption by the weight method; parameters of the power unit control system by means of the corresponding built-in sensors and by reading the obtained values from the onboard OBD system using an appropriate adapter and a laptop; oil temperature in the ICE lubrication system using a Bosch BEA 030 sensor; exhaust gas composition using a Bosch BEA 060 multicomponent gas analyser; and ambient environmental parameters. During the experimental studies, the following parameters were measured using the specified equipment: output shaft rotational speed n; torque on the output shaft of the power unit M; engine crankshaft rotational speed n_e; throttle opening degree φ_{thr}; hourly fuel consumption G_{fuel}; hourly air consumption G_{air}; intake manifold air temperature t_{in}; excess air ratio α; ignition timing advance θ; engine coolant temperature t_{cool}; oil temperature t_{oil}; exhaust gas temperature t_{EG}; traction battery state of charge S_{ch}; rotational speed of MG1 n_{MG1}; torque of MG1 M_{MG1}; rotational speed of MG2 n_{MG2}; torque of MG2 M_{MG2}; MG1 temperature t_{MG1}; MG2 temperature t_{MG2}; MG1 inverter temperature $t_{inv.MG1}$; MG2 inverter temperature $t_{inv.MG2}$; traction battery temperatures t_{B1}, t_{B2}, t_{B3}; exhaust gas concentrations of O_2 (C_{O2}), CO (C_{CO}), CO_2 (C_{CO2}), C_mH_n (C_{CmHn}), and NO_X (C_{NOx}); and the equivalent vehicle speed V_a. The parameters of the power unit control system, determined by reading them from the onboard OBD system during measurements at each test point, were accumulated in the corresponding data file with a time interval of approximately 1 s. For further analysis, the arithmetic mean values of these parameters over the time interval corresponding to each test mode were used. The experimental research programme included determining a series of load characteristics of the hybrid power unit at output shaft rotational speeds of 250 min^{-1}, 500 min^{-1}, and 750 min^{-1}. The load characteristics were determined by measuring the specified parameters under steady-state conditions with selected loads ranging from minimum to maximum at a given rotational speed, such that the number of test points made it possible to establish the nature of the dependence of the corresponding parameter on the load, as specified in ISO 15550:2016 (2016).

The rotational speeds of the power unit output shaft were selected so as to uniformly cover the range of variation of this parameter under operating conditions, which are determined by the vehicle speed. The equivalent vehicle speed V_a, km/h, during bench testing of the power unit can be determined from relationship:

$$V_a = \frac{3.6 \cdot \pi \cdot n \cdot r_w}{30}, \tag{1}$$

where n is the rotational speed of the output shaft, min^{-1}; r_w is the rolling radius of the wheel, m.

The rolling radius of the wheel can be approximately determined from the geometric dimensions of the tire using relationship:

$$r_w = \frac{d}{2} + \lambda_t \cdot \frac{h}{B} \cdot B, \tag{2}$$

where d is the rim diameter, m; $\frac{h}{B}$ is the ratio of the tire profile height to its width; B is the tire section width, m; λ_t is the radial deformation of the tire profile, which can be assumed as $\lambda_t = 0.9$ (Sakhno *et al.*, 2004).

For the Toyota Prius 2004 vehicle, on which the investigated power unit is installed, the parameters of the standard P185/65R15 tires specified in relationship (2) are as follows: $d = 15$ inches or 0.381 m; $\frac{h}{B} = 0.65$; B = 0.185 m (Toyota Motor Sales, 2004). Therefore, the rolling radius is $r_w = 0.299$ m. For the specified rotational speeds of the power unit output shaft, the corresponding equivalent vehicle speeds of 28.2 km/h, 56.3 km/h, and 84.5 km/h were determined using relationship (1). These speeds practically divide the speed range of 0…120 km/h uniformly, which is defined for M1 category vehicles during compliance testing with environmental standards in accordance with Regulation No 83 of the Economic Commission for Europe of the United Nations (UNECE) (2015). This allows the performance indicators of the power unit to be evaluated under these Regulations in further studies. Fuel consumption was determined by the weight method using the electronic scales and the stopwatch (Table 2). The measurement procedure involved determining the time required for the power unit to consume a specified mass of fuel (the fuel dose mass was selected to ensure a minimum measurement time of at least 30 s) under steady-state operating conditions at each test point.

The value of the hourly fuel consumption G_{fuel}, kg/h, is determined from relationship:

$$G_{fuel} = \frac{\Delta G_{fuel}}{\tau_{fuel}} \cdot 3.6, \tag{3}$$

where ΔG_{fuel} is the mass of the fuel dose whose consumption time is measured, g; τ_{fuel} is the time required to consume the measured fuel dose, s.

All measuring equipment was verified for accuracy prior to testing using reference instruments in order to achieve the required measurement accuracy in accordance with ISO 15550:2016 (2016). At this stage of the research, all the above-mentioned energy efficiency indicators were measured directly using the equipment specified in Table 2. The measured parameters of the power unit constitute the basis for further analysis and modelling of the vehicle's energy efficiency performance under driving cycle conditions. Within the scope of this study, it is intended to evaluate the patterns of variation of the measured power unit parameters as a function of its effective power. The effective power N at the output shaft of the power unit, kW, is determined by relationship:

$$N = \frac{M \cdot n}{9550}, \tag{4}$$

where M is the torque at the output shaft, N·m; n is the rotational speed of the power unit output shaft, min^{-1}.

The errors of direct measurements are specified in Table 2. The errors of indirect measurements were determined in accordance with generally accepted calculation formulas. In this case, the relative errors in measuring the hourly fuel consumption and the power of the power unit are equal to the sums of the relative errors of the directly measured parameters included in equations (3) and (4), as determined from Table 2. According to the results of the evaluation, all errors of direct and indirect measurements are within the permissible limits for engine testing as specified in ISO 15550:2016 (2016).

Results and Discussion

The energy-efficiency indicators of an automotive power unit include fuel-economy indicators, as well as energy and environmental indicators, which are described by fuel consumption and emissions of harmful substances with exhaust gases under the main operating modes. In modern engines, these indicators substantially depend on the engine's air consumption, the concentrations of pollutants in combustion products, and the efficiency of the exhaust-gas aftertreatment system. Therefore, the experimental bench studies of the energy-efficiency indicators of the hybrid electric automotive power unit are aimed at determining the mass flow rates of fuel and air, the concentrations of harmful substances in the exhaust gases, and establishing the operating parameters of the electrical components in different operational modes, which define the speed parameters and load levels of the energy-source components. The results of the study of the ICE parameters under the above-mentioned operating modes of the hybrid power unit are presented in Figure 3.

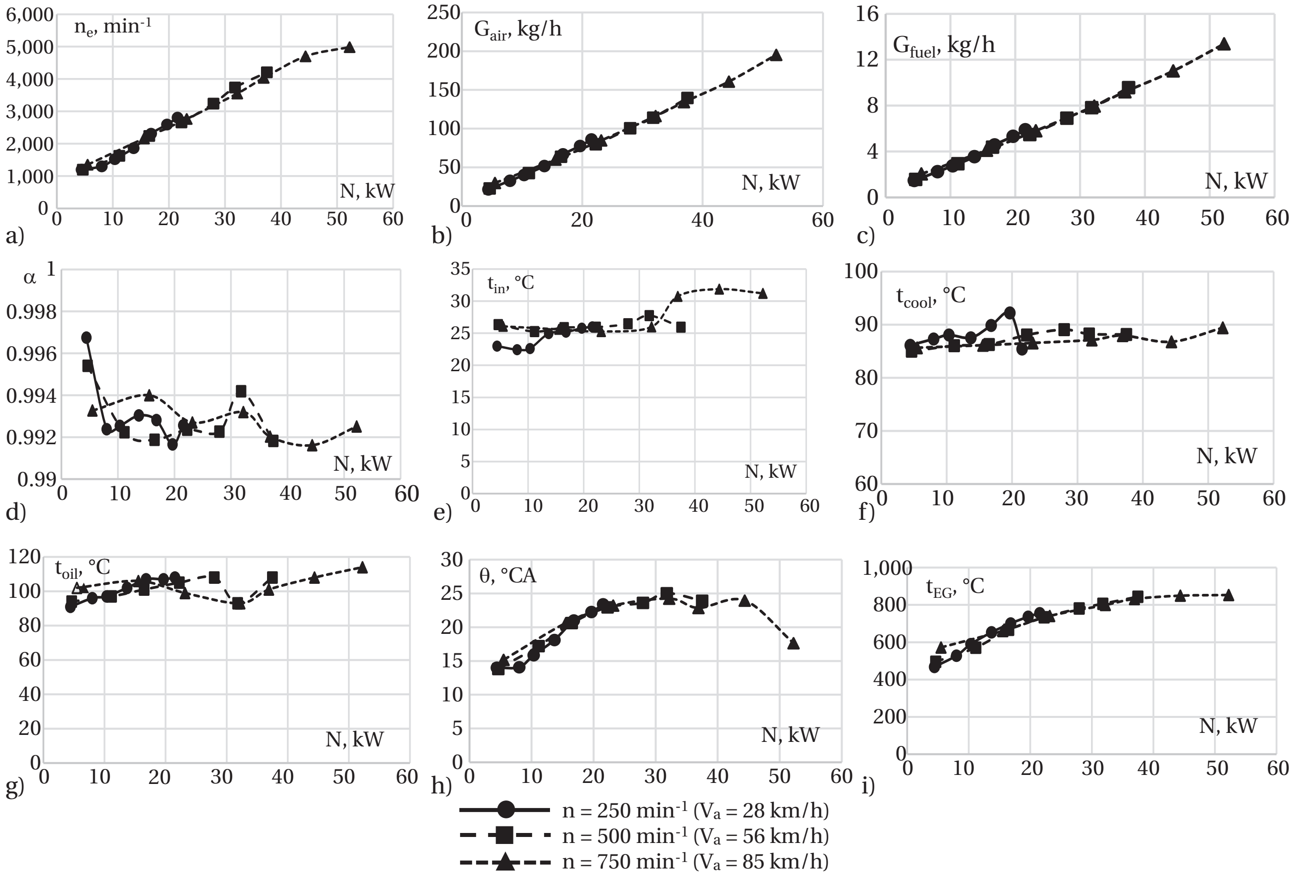

Figure 3. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured ICE parameters)

Note: a – crankshaft rotational speed; b – hourly air consumption; c – hourly fuel consumption; d – excess air ratio; e – intake air temperature; f – coolant temperature; g – oil temperature; h – ignition timing advance; i – exhaust gas temperature

Source: developed by the authors

As can be seen from the dependencies of the engine crankshaft rotational speed n_e, there is an almost linear relationship between n_e and the power of the power unit N (Fig. 3a). In higher-speed operating modes of the power unit, a higher engine rotational speed is achieved at correspondingly higher output power. In low-load modes, the curves of n_e for different output shaft rotational speeds n overlap. Thus, there is a direct relationship between the load mode of the power unit and the engine rotational speed n_e. The influence of the power unit load on the ICE load is also confirmed by the dependencies of hourly air consumption G_{air} (Fig. 3b) and the associated hourly fuel consumption G_{fuel} (Fig. 3c). A nearly linear effect of load on G_{air} and G_{fuel} is observed; the curves of G_{air} and G_{fuel} for different n overlap. Therefore, the dependence of the ICE load mode on the hybrid power unit load is also practically linear. The measured values of the excess air ratio α (Fig. 3d) indicate that the control system maintains a stoichiometric air-fuel mixture across all operating modes of the power unit. The thermal operating conditions of the ICE systems are characterised by the intake manifold air temperature t_{in} (Fig. 3e), engine coolant temperature t_{cool} (Fig. 3f), oil temperature t_{oil} (Fig. 3g), and exhaust gas temperature t_{EG} (Fig. 3i). These dependencies confirm that the thermal operating conditions of these systems remained within acceptable limits during the tests. The ignition timing advance θ dependencies (Fig. 3h) characterise the engine control unit (ECU) algorithm for controlling this parameter. Up to an external load of 20 kW and, correspondingly, $n_e \leq 2{,}500$ min^{-1}, θ increases significantly from 14° CA to 23° CA with increasing *N*. This corresponds to θ adjustment to compensate for combustion duration in crank-angle degrees under rising n_e, ensuring the highest cycle efficiency. At loads of $N \approx 20\ldots45$ kW and at corresponding n_e values in the range of 2,500…4,700 min^{-1}, θ remains within 23…25° CA. This reflects θ correction under medium-load conditions to ensure optimal cycle efficiency and to minimise NO_X emissions. At loads above 45 kW and with increasing rotational speed up to the nominal 5,000 min^{-1}, θ sharply decreases to 17° CA. This corresponds to θ correction at high load conditions to prevent knock combustion. The results of the study of the electrical component parameters under the investigated operating modes of the hybrid power unit are presented in Figure 4.

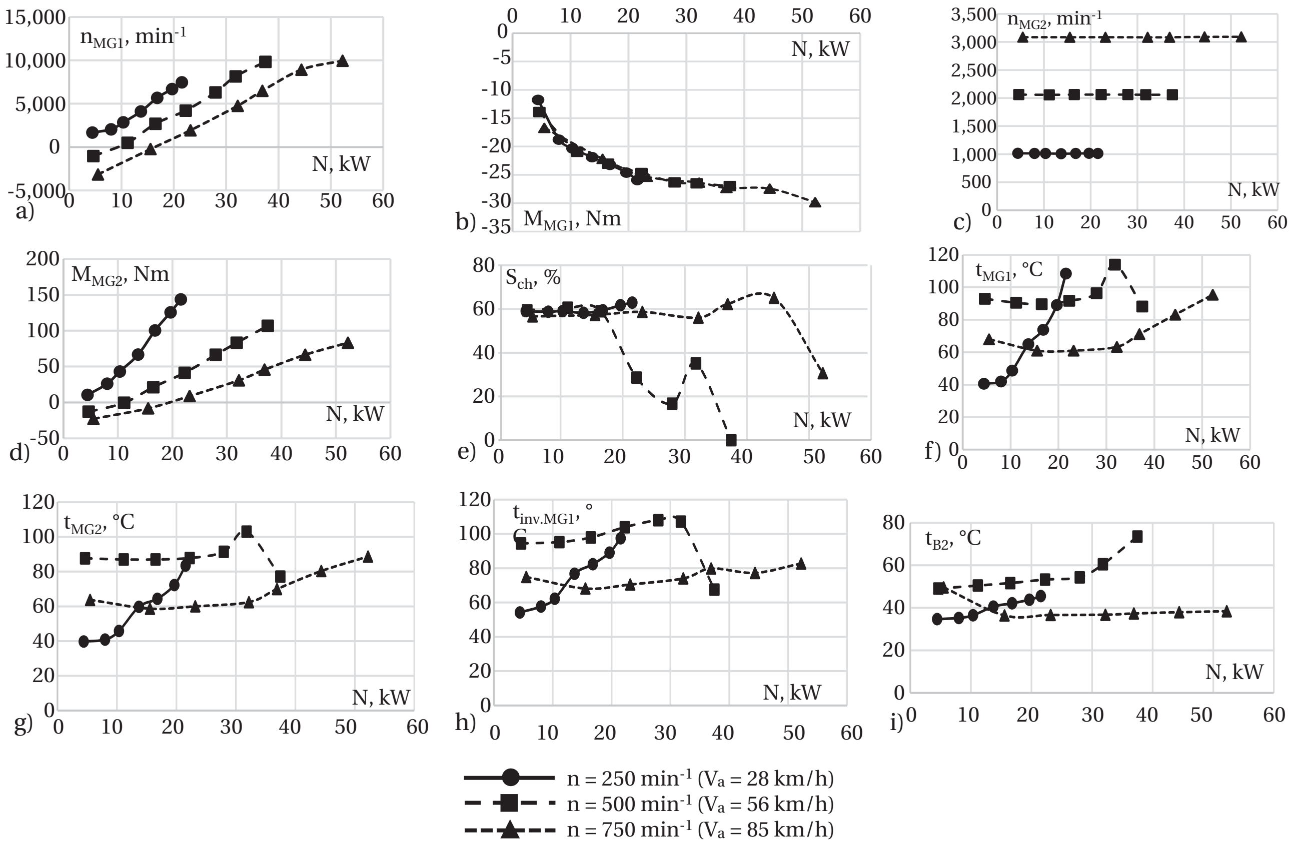

Figure 4. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured parameters of the electrical components)

Note: a – MG1 rotor speed; b – MG1 torque; c – MG2 rotor speed; d – MG2 torque; e – traction battery state of charge; f – MG1 temperature; g – MG2 temperature; h – MG1 inverter temperature; i – traction battery temperature

Source: developed by the authors

The rotational speed of MG1, n_{MG1} (Fig. 4a), varies according to nearly linear dependencies similar to those of n_e, because MG1 is kinematically linked to the ICE through the planetary gearset and serves as the regulator of the ICE crankshaft speed. The maximum n_{MG1} value is 10,000 min^{-1}. At the same time, the rotational speed of MG2, n_{MG2} (Fig. 4c), does not depend on the external load, since MG2 is connected to the output shaft of the hybrid power unit through a fixed gear ratio; therefore, n_{MG2} is determined exclusively by the vehicle speed. The MG1 torque M_{MG1} (Fig. 4b) depends on the rotational speed and direction of rotation n_{MG1}, which in turn are determined by the required gear ratio of the hybrid transmission depending on vehicle speed (MG2 rotational speed n_{MG2}) and external load. If the required n_{MG1}, determined by the planetary gearset relationships, is opposite to the ICE direction of rotation ($n_{MG1} < 0$), as observed at loads up to 10 kW for n = 500 min^{-1} and up to 15 kW for n = 750 min^{-1}, then MG1 operates in motor mode. The mechanical energy generated by MG1 is added to the ICE energy, and as the absolute value of n_{MG1} decreases, the absolute value of M_{MG1} increases, since in this case M_{MG1} is the driving torque. If the required $n_{MG1} > 0$, then MG1 operates in generator mode, consuming mechanical energy, and with increasing n_{MG1}, the absolute value of M_{MG1} increases, because M_{MG1} in this case represents resisting torque. To maintain the energy balance of the hybrid power unit (supplying mechanical energy and consuming generated electrical energy during generator operation) under operating modes without involving the traction battery, both motor-generators MG1 and MG2 must operate cooperatively: one in motor mode, the other in generator mode. Therefore, in modes with *N* < 10 kW at

$n = 500$ min^{-1} and $N < 15$ kW at $n = 750$ min^{-1}, when MG1 operates in motor mode, MG2 operates in generator mode. The resisting torque of MG2 (Fig. 4d) in generator mode is related to the torque of MG1 in motor mode (and vice versa) in such a way that when reduced to the same shaft (MG1 or MG2), the torques satisfy the conditions:

$$\left|M_{MG1}^{red(G)}\right| > \left|M_{MG2}^{red(M)}\right|,$$
$$\left|M_{MG2}^{red(G)}\right| > \left|M_{MG1}^{red(M)}\right|. \quad (5)$$

The difference between these torques is related to the efficiency of converting mechanical energy into electrical energy in the generator and electrical energy into mechanical energy in the motor, and it determines the overall efficiency of the hybrid transmission. The traction battery state of charge S_{ch} (Fig. 4e) remains at approximately 60% in most of the investigated modes and decreases under high-load conditions. This is associated with prolonged operation of the power unit at sustained high loads, where charging the battery becomes impossible (due to high mechanical power demand, thermal condition of the battery), as well as with potential loss of battery capacity as a result of long-term use. The temperature modes of MG1 (Fig. 4f), MG2 (Fig. 4g), the inverter (Fig. 4h), and the traction battery (Fig. 4i) remain within permissible limits. A battery temperature above 50°C (Fig. 4i) leads to a reduction in charging-discharging efficiency, as can be seen in Figure 4e. The environmental performance of the power unit is described by the measured concentrations of pollutants and other substances in the exhaust gases before and after the catalytic converter (Fig. 5).

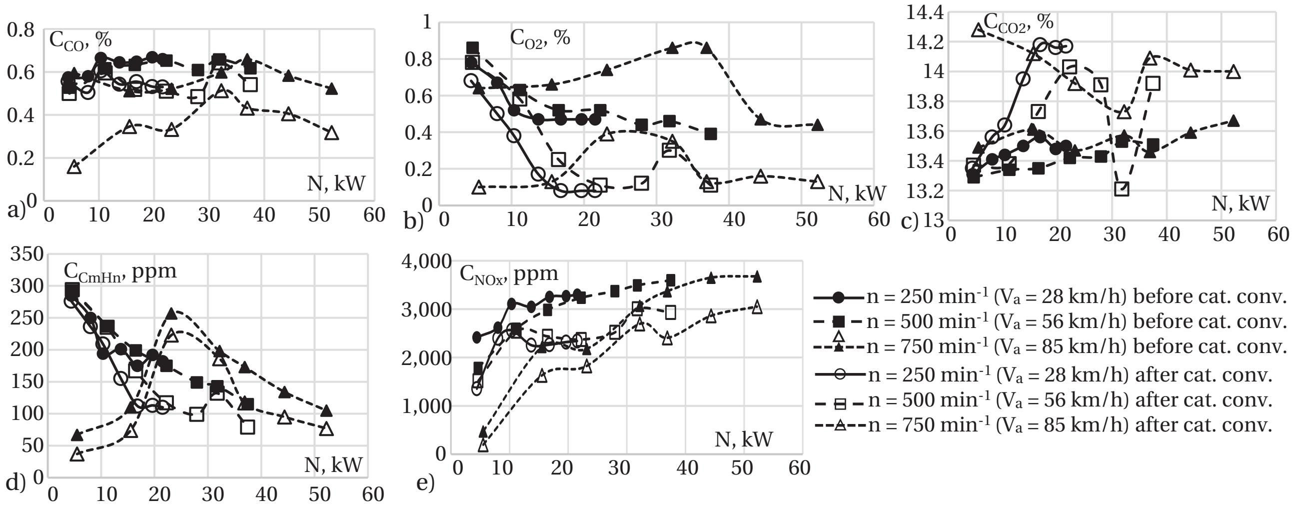

Figure 5. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured environmental indicators)

Note: a – CO concentrations in the exhaust gases; b – O_2 concentrations in the exhaust gases; c – CO_2 concentrations in the exhaust gases; d – C_mH_n concentrations in the exhaust gases; e – NO_x concentrations in the exhaust gases

Source: developed by the authors

The variation in concentrations of different substances in the exhaust gases for this engine is determined primarily by the air-fuel mixture composition, described by α (Fig. 3d), and by the load. Since, according to Figure 3d, the air-fuel mixture composition in all investigated modes is nearly stoichiometric ($\alpha \approx 1$), the concentrations of O_2 in the exhaust gases before the catalytic converter (Fig. 5b) vary only slightly and remain within the range of 0.4…0.9%. This, in turn, results in changes in the pre-catalyst concentrations of CO (Fig. 5a) within 0.5…0.7% and CO_2 within 13.3…13.7% (Fig. 5c). Concentrations of C_mH_n in the exhaust gases (Fig. 5d) before the catalytic converter change from 300 to 100 ppm as α decreases from 0.997 to 0.992. The concentrations of NO_X in the exhaust gases (Fig. 5e) before the catalytic converter at low loads strongly depend on α: when the mixture is leaned from $\alpha = 0.993$ to $\alpha = 0.997$, C_{NOx} increases from 500 to 2,400 ppm. With a further increase in load, C_{NOx} increases from 2,500 to 3,600 ppm. After treatment by the catalytic converter, the concentrations of O_2, CO, C_mH_n, and NO_X in the exhaust gases decrease significantly, while the concentration of CO_2 increases. The degree of concentration change is determined by the neutralisation reactions, the efficiency of which depends on the size and placement of the catalytic converter. The obtained relatively low neutralisation efficiencies for CO, C_mH_n, and NO_X are explained by the non-standard design of the exhaust aftertreatment system. Based on the measured parameters of the hybrid power unit, it becomes possible to determine the following: MG1 power, MG2 power, ICE torque, ICE power, specific effective fuel consumption, cycle air consumption, volumetric efficiency of the ICE cylinders, ICE efficiency, hybrid transmission efficiency, hybrid power unit efficiency, and the transmission ratios of the hybrid transmission from MG1 and from the engine. According to the results of the experimental study of the energy efficiency indicators and the features of the operating processes of the hybrid electric automotive power unit based on a spark-ignition engine, the following dependencies were established as functions of the output shaft speed and the power of the power unit: speed and load modes of the ICE, MG1, and MG2; fuel consumption, air-fuel ratio, ignition timing of the ICE; traction battery state of charge; temperature regime parameters of the air supply, lubrication, cooling, and exhaust systems of the ICE, MG1, MG2, the inverter, and the traction battery; pollutant concentrations in the exhaust gases and the efficiency of their neutralisation.

The obtained results have formed the basis for further determination of the efficiency of individual components of the power unit and refinement of the mathematical model of the hybrid vehicle's motion in order to study the influence of individual parameters of its power unit on fuel economy and environmental performance. These results can also be compared with related studies by other authors. A theoretical generalisation and a new solution to an important applied scientific problem – enhancing the operational efficiency of hybrid vehicles through the rational use of the ICE and electric motors – is presented by O.P. Smyrnov (2016). According to the obtained research results (Fig. 3c), at a power unit output of 5.3 kW (which, under the conditions of this study, corresponds to the power at the driving wheels), the fuel consumption is about 1.7 kg/h. This correlates fairly well with the results reported in the study by O.P. Smyrnov (2016) and, at the same time, differs due to the apparently more efficient design configuration of the power unit and the different experimental conditions. The study by V. Dvadnenko *et al.* (2022) considered an improved control algorithm for the traction induction motor of a mild hybrid vehicle by increasing the efficiency of regenerative braking in order to improve economic and environmental parameters. O.V. Bazhynov *et al.* (2018) focused on substantiating the efficient use of electric and hybrid vehicles to support their widespread introduction into production and to minimise the environmental hazards posed by existing ICEs. A mathematical model for evaluating vehicle quality based on the key consumer indicators is presented, and the influence of electric components in electric and hybrid vehicles on overall and environmental safety indicators is analysed. According to the results of this study, relationships between environmental safety criteria and the vehicle speed of conventional and hybrid vehicles have been established. For example, at the above-considered speed of 55 km/h, the environmental safety criterion for the Toyota Prius hybrid vehicle was about 0.5. In the present study, the NO_X concentration, which is proposed by O.V. Bazhynov *et al.* (2018) as a basis for determining the environmental safety criterion, is about 200 ppm (Fig. 5e), which corresponds to 0.15 g/km at the given speed and, according to the calculation methodology, yields an environmental safety criterion of approximately 2.5. Such a discrepancy between the results of this study and those reported by O.V. Bazhynov *et al.* (2018) is primarily explained by the efficiency of the exhaust aftertreatment system, which exhibits low efficiency under the conditions of the present study, as discussed above. The study by Kh. Maush (2017) focused on developing a concept for converting a vehicle equipped with an ICE and a manual transmission into a hybrid vehicle. Experimental research was conducted to select a suitable traction electric motor for the conversion, complemented by mathematical modelling and experimental evaluation of the economic characteristics of the converted hybrid vehicle under urban driving conditions. Based on the results of the mathematical modelling of fuel economy and emissions for both conventional and hybrid vehicles operating under driving-cycle conditions, it was determined that the hybrid vehicle's fuel consumption is 28% lower, while emissions of regulated pollutants are reduced by 48%. Experimental studies have further indicated a reduction in fuel consumption by a factor of 2 to 3 compared with the baseline vehicle. According to the results, it is not possible to assess how the type of power unit (hybrid electric or conventional) affects fuel consumption or pollutant emissions in a driving cycle or under real urban driving conditions. At the same time, it is possible to compare the hourly fuel consumption obtained at the same power output of the power unit in hybrid and conventional configurations. As has been determined above, at a power output of 5.3 kW, the hourly gasoline consumption of the considered hybrid power unit is 1.7 kg/h. For the compared conventional gasoline power unit, as reported by S.V. Sosida (2023), at a power output of 5.3 kW and an engine speed of 2,400 min-1, the gasoline consumption was 2.2 kg/h. Thus, it can be concluded that the fuel consumption of the hybrid electric power unit under steady-state driving conditions is reduced by 23% compared to the conventional gasoline power unit. This result correlates well with that obtained in Kh. Maush (2017). Mathematical modelling of fuel economy indicators and CO_2 emissions under transient operating conditions was performed by I. Taymaz & M. Benli (2014) for a conventional commercial vehicle and a hybrid vehicle designed on its basis. The results showed that, at the same performance level, the hybrid vehicle emits nearly 30% less CO_2. A comparison of the obtained result on the effect of using a hybrid power unit on CO_2 emissions with the results of this study can be carried out in a manner analogous to the comparison of the effect on fuel consumption described above. The measured CO_2 concentrations for a load of 5.3 kW of the hybrid power unit are about 13.4% (Fig. 5c), whereas for the conventional gasoline power unit they are about 13% (Sosida, 2023). Since the CO_2 concentration for the hybrid power unit is higher by approximately 3% compared to the conventional one, while the fuel consumption, as indicated above, is lower by 23%, the CO_2 emissions are reduced by about 20% when using the hybrid power unit under steady-state driving conditions at a vehicle speed of 55 km/h. This also correlates fairly well with the results reported in (Taymaz & Benli, 2014). The differences in the obtained effects on CO_2 emissions are explained by different emission determination conditions, different types of vehicles, and other factors. R.H. Staunton *et al.* (2006)

focused on determining the energy-efficiency indicators of elements of the Toyota Prius II hybrid transmission – specifically the electric motor, inverter, and mechanical gear – based on experimental bench tests of the components. Based on the results of study of R.H. Staunton and this research, the efficiency of energy transfer from the ICE to the output shaft through the electric hybrid transmission can be determined for a given power unit load, for example, 16.5 kW at a vehicle speed of 56 km/h. In this operating mode, MG1 produces a resisting torque of about 23 N·m (Fig. 4b) at 2,700 min^{-1} (Fig. 4a), corresponding to 6.5 kW, to generate electrical energy, which in MG2 produces a torque of 22 N·m (Fig. 4d) at 2000 min^{-1} (Fig. 4c), corresponding to 4.6 kW. Thus, in order to obtain an output shaft power of 16.5 kW, the ICE produces 18.4 kW, and the transmission efficiency is 0.89. At the same time, according to the authors, the efficiency for the specified operating mode was 0.87, which correlated with the results of this study.

Conclusions

The study provided a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit based on a spark-ignition engine. The assessed indicators include component operating parameters, fuel consumption, and exhaust gas pollutant concentrations under specific control system settings and thermal conditions. Following this methodology, an experimental setup was created at the Engine Testing Laboratory of the Department of Engines and Heating Engineering, National Transport University, using a Toyota Prius hybrid power unit with a 1NZ-FXE engine. The test bench setup with an electric brake machine simulated various speed and load conditions and measured OBD parameters, fuel consumption, temperatures, and exhaust gas composition. Bench tests showed a nearly direct relationship between the power unit load and the ICE speed and load modes. As the power unit's speed and load varied, the control system maintained a stoichiometric air-fuel mixture and engine thermal conditions within permissible limits. The ignition timing was adjusted to maximise cycle efficiency at low and medium loads, reduce NO_x emissions at medium loads, and prevent knock at high loads. MG1 speed varied almost linearly with vehicle speed and load, while MG2 speed depended solely on power unit speed. MG1 and MG2 torques adjusted to maintain the energy balance in modes without traction battery involvement, with one machine operating as a motor and the other as a generator depending on MG1 rotation. In this case, the resisting torque in generator mode is always greater than the driving torque in motor mode, and their difference determines the efficiency of the hybrid transmission. The state of charge of the traction battery is about 60% and decreases under high-load conditions due to the influence of the thermal regime and capacity degradation. The composition of the exhaust gases under various operating modes of the power unit is determined primarily by the air-fuel mixture composition of the ICE and the load. However, due to the use of a non-standard exhaust aftertreatment system design, its efficiency is reduced. The research results align with related studies on the impact of power unit type on fuel consumption, CO_2 emissions, and hybrid transmission efficiency. Compared with a conventional power unit, the hybrid unit reduces fuel consumption by approximately 23%, CO_2 emissions by approximately 20%, and achieves a transmission efficiency of 0.89. However, the low efficiency of the non-standard exhaust aftertreatment system used in the experiments led to lower environmental performance than reported by other authors. Future work will focus on developing a mathematical model of the hybrid vehicle to evaluate energy efficiency under driving-cycle conditions.

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Conflict of Interest

None.

References

[1] Abdelbaky, A.N.F., Babangida, A., Kunya, A.B., & Szemes, P.T. (2025). Development and fuel economy optimization of series-parallel hybrid powertrain for van-style VW crafter vehicle. *Energies*, 18(14), article number 3688. doi: 10.3390/en18143688.

[2] Bazhynov, O.V., & Kravtsov, M.M. (2023). Determining the quality index of electric and hybrid vehicles. *Ukrainian Journal of Civil Engineering and Architecture*, 5, 19-26. doi: 10.30838/j.bpsacea.2312.241023.19.989.

[3] Bazhynov, O.V., Bazhynova, T.O., & Kravtsov, M.M. (2018). *Fundamentals of effective use of environmentally friendly vehicles*. Kharkiv: Panov A.M. Publishing House.

[4] Dvadnenko, V., Dziubenko, O., & Pushkar, O. (2022). Asynchronous motor in a mild hybrid vehicle. *Vehicle and Electronics. Innovative Technologies*, 22, 47-53. doi: 10.30977/veit.2022.22.0.6.

[5] ISO 15550:2016. (2016). *Internal combustion engines – determination and method for the measurement of engine power – general requirements*. Retrieved from https://www.iso.org/standard/70030.html.

[6] Kumbar, P. (2020). Impact of hybrid vehicles on fuel economy and emissions: A comprehensive analysis. *World Journal of Advanced Research and Reviews*, 8(1), 307-319. doi: 10.30574/wjarr.2020.8.1.0347.

[7] Maush, Kh. (2017). *Increase of the energy efficiency of vehicles by the use of hybrid technologies*. (Doctoral dissertation, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine).

[8] Mustafi, N.N. (2021). An overview of hybrid electric vehicle technology. In G. Kalghatgi, A.K. Agarwal, F. Leach & K. Senecal (Eds.), *Engines and fuels for future transport. Energy, environment, and sustainability.* Singapore: Springer. doi: 10.1007/978-981-16-8717-4_5.
[9] Pan, Y., Zhong, K., Xie, Y., Pan, M., Guan, W., Li, L., Liu, C., Man, X., Zhang, Z., & Li, M. (2025). A review of hybrid vehicles classification and their energy management strategies: An exploration of the advantages of genetic algorithms. *Algorithms*, 18(6), article number 354. doi: 10.3390/a18060354.
[10] Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 “Setting CO_2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011”. (2019, April). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631.
[11] Regulation No 83 of the Economic Commission for Europe of the United Nations (UNECE) – Uniform Provisions Concerning the Approval of Vehicles with Regard to The Emission of Pollutants According to Engine Fuel Requirements [2015/1038]. (2015, January). Retrieved from https://eur-lex.europa.eu/eli/reg/2015/83/oj/eng.
[12] Rimpas, D., Barkas, D.E., Orfanos, V.A., & Christakis, I. (2025). Decarbonizing the transportation sector: A review on the role of electric vehicles towards the European green deal for the new emission standards. *Air*, 3(2), article number 10. doi: 10.3390/air3020010.
[13] Rojas-Reinoso, E.V., Anacleto-Fernández, M., Utreras-Alomoto, J., Carranco-Quiñonez, C., & Mata, C. (2024). Comparative study of fuel and greenhouse gas consumption of a hybrid vehicle compared to spark ignition vehicles. *World Electric Vehicle Journal*, 16(1), article number 4. doi: 10.3390/wevj16010004.
[14] Saju, C., Michael, P.A., & Jarin, T. (2022). Modeling and control of a hybrid electric vehicle to optimize system performance for fuel efficiency. *Sustainable Energy Technologies and Assessments*, 52, article number 102087. doi: 10.1016/j.seta.2022.102087.
[15] Sakhno, V.P., Bezborodova, H.B., Maiak, M.M., & Sharai, S.M. (2004). *Automobiles: Traction-speed characteristics and fuel economy*. Kyiv: KVITS Publishing House.
[16] Šarkan, B., Gnap, J., & Kiktová, M. (2019). The importance of hybrid vehicles in urban traffic in terms of environmental impact. *The Archives of Automotive Engineering – Archiwum Motoryzacji*, 85(3), 115-122. doi: 10.14669/am.vol85.art8.
[17] Sergienko, N., Pavlova, N., Sergienko, A., Lyubarsky, B., Borysenko, A., Kalinin, P., Gubskyi, S., & Dreval, O. (2023). Results of modeling of components and working processes of a hybrid car with an asynchronous motor. *Bulletin of the National Technical University «KhPI». Series: Automobile and Tractor Construction*, 2, 31-47. doi: 10.20998/2078-6840.2022.2.04.
[18] Smyrnov, O.P. (2016). *Scientific and technical basis of increasing the operational efficiency of hybrid vehicles*. (Doctoral dissertation, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine).
[19] Sosida, S.V. (2023). *Improvement of the fuel economy of the engine with spark ignition when using an alcohol-containing additive to gasoline*. (Doctoral dissertation, National Transport University, Kyiv, Ukraine).
[20] Staunton, R.H., Ayers, C.W., Marlino, L.D., Chiasson, J.N., & Burress, B.A. (2006). *Evaluation of 2004 Toyota Prius hybrid electric drive system.* Oak Ridge, TN: Office of Scientific and Technical Information. doi: 10.2172/890029.
[21] Taymaz, I., & Benli, M. (2014). Emissions and fuel economy for a hybrid vehicle. *Fuel*, 115, 812-817. doi: 10.1016/j.fuel.2013.04.045.
[22] Tomita, M., Shibata, R., Mizuno, Y., Maeda, H., Murasato, K., Shimura, A., Takayama, T., Nakado, T., & Tomita, Y. (2024). Development of new 2.0-liter plug-in hybrid system for the Toyota Prius. *SAE Technical Paper Series*, 1, article number 2169. doi: 10.4271/2024-01-2169.
[23] Toyota Motor Europe. (n.d.). Retrieved from https://www.techdoc-toyota.com.
[24] Toyota Motor Sales. (2004). *04 Prius*. Retrieved from https://www.auto-brochures.com/makes/Toyota/Prius/Toyota_US%20Prius_2004.pdf.
[25] Wang, Y., Wang, Y., & Ren, G. (2021). A brief introduction to a novel high-efficiency hybrid power system for hybrid electric urban light commercial vehicles. *SAE International Journal of Commercial Vehicles*, 14(2), 185-191. doi: 10.4271/02-14-02-0014.

Дослідження показників енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням

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Анотація. У статті наведено результати експериментального дослідження показників енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням. Метою роботи було здійснення комплексної оцінки енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням. Методика дослідження передбачала проведення експериментальних стендових випробувань гібридної електричної автомобільної силової установки у визначених режимах роботи для встановлення закономірностей зміни керувальних параметрів двигуна внутрішнього згоряння, електричних підсистем, показників паливної економічності та екологічних характеристик. У ході експериментального дослідження встановлено закономірності зміни показників енергоефективності та характеристик робочого процесу залежно від частоти обертання та потужності вихідного вала. Виявлено зміни швидкісних і навантажувальних режимів двигуна внутрішнього згоряння, мотор-генератора 1 і мотор-генератора 2, а також витрати палива, коефіцієнта надлишку повітря та кута випередження запалювання двигуна внутрішнього згоряння. Проаналізовано ступінь заряду тягової акумуляторної батареї, параметри теплового режиму систем впуску повітря, змащування, охолодження та випуску двигуна внутрішнього згоряння, мотор-генератора 1, мотор-генератора 2, інвертора й акумуляторної батареї, а також концентрації шкідливих речовин у відпрацьованих газах і ефективність їх нейтралізації. Встановлено майже прямий зв'язок між частотою обертання та навантаженням двигуна внутрішнього згоряння і загальним навантажувальним режимом силової установки. Керування складом паливно-повітряної суміші та кутом випередження запалювання в усіх режимах забезпечило високу паливну економічність і низький рівень викидів шкідливих речовин. Високі показники енергоефективності за різних умов експлуатації досягнуті завдяки електричній підсистемі силової установки, яка забезпечувала оптимальне керування швидкісним і навантажувальним режимами двигуна внутрішнього згоряння

Ключові слова: потужність; крутний момент; гібридна трансмісія; режим роботи; ступінь заряду тягової акумуляторної батареї; паливна економічність; екологічні показники

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Anti-crisis strategies and modern technologies in sustainable project management

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Abstract. The increasing frequency and complexity of economic, infrastructural, and geopolitical crises has significantly increased the need for effective crisis management in project-oriented enterprises. This is particularly true in the transport sector, which is sensitive to external changes. In conditions of increased uncertainty, traditional management approaches often prove insufficient, requiring the use of innovative and flexible solutions. The purpose of this study was to justify modern approaches to anti-crisis management based on the use of digital technologies within the framework of sustainable project management. The research methodology was based on systematic and comparative analysis, synthesis, statistical analysis, data visualisation, and scenario modelling, which together provide a comprehensive assessment of anti-crisis management processes. It has been established that the use of data analytics, artificial intelligence, cloud computing, and digital platforms contributes to early crisis detection, risk assessment, and rapid response. These technologies enable enterprises to process large amounts of data in real time, improve forecasting accuracy, accelerate management decision-making, and optimise the allocation of limited resources. An analysis of statistical data for Ukraine's transport sector for 2022-2024 showed the growing adaptive potential of companies undergoing digital transformation, particularly in response to the challenges of wartime and the post-crisis period. The results of the study confirmed that the integration of digital technologies into anti-crisis management systems increases organisational potential, ensures the continuity of project implementation, and contributes to the achievement of sustainable development goals. The practical significance of the study lies in the possibility of applying the results in the activities of transport enterprise managers, government authorities, and other

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stakeholders involved in infrastructure and investment projects, which will contribute to the development of more sustainable and stable transport systems

Keywords: digital technologies; prevention; decision making; business analytics; stakeholders; risks

Introduction

Companies operating in unstable economic conditions face increased uncertainty and risks and need to develop effective anti-crisis strategies. In the transport industry, these challenges are exacerbated by damage to infrastructure, logistics disruptions, and financial constraints. Scholarly research, in particular T. Balanovska *et al.* (2020), O.M. Girzheva *et al.* (2024) and V. Huriev (2024), highlighted the growing role of digital technologies in strengthening organisational resilience. Nevertheless, their application to sustainable project management in Ukrainian transport companies remains underexplored. Anti-crisis management of an enterprise's economic sustainability should be conceptualised as an integrated system encompassing both internal and external dimensions. In order to develop and implement innovative projects while ensuring their stable functioning, Ukrainian enterprises are adopting adaptive strategies, including market diversification, reduced import dependence, innovation and technological advancement, the integration of digital technologies within broader digitalisation processes, and the strengthening of corporate social responsibility practices. Under such conditions, the implementation of effective anti-crisis strategies becomes imperative to anticipate potential risks, prevent crisis situations, mitigate their adverse effects, and ensure the rapid recovery and continuity of enterprise operations. Enterprises operating within a market environment inherently face conditions of uncertainty and risk. In the context of economic instability, the intensity of these factors increases, potentially leading to a decline in organisational efficiency and the emergence of crisis situations. Such crises may arise both in interactions with stakeholders and in the framework of public-private partnerships, particularly in the field of transport infrastructure. Commercial enterprises interact with other organisations, suppliers, consumers, banks, tax authorities and stakeholders, each of which has its own potential and development cycles that may not coincide with the general economic cycles.

The evolution of a company is determined by changes in its activities, technologies, personnel, products, services, etc. These changes are dual in nature, as they can be both positive and negative. Positive changes are reflected in the improvement of the quality of goods and services, which enhances the stability and harmony in the company's operations through increased productivity, the introduction of new technologies, and increased staff motivation. As noted by K. Ivanchenko & O. Bilovodska (2024), adverse changes can cause instability within a company, manifested in a misalignment between its current operational interests and long-term development objectives, ineffective management practices, or the persistence of obsolete technologies. Such negative transformations serve as indicators of an emerging organisational crisis. Accordingly, it is essential to examine the evolution of anti-crisis strategies and the integration of digital technologies into sustainable project management under conditions of ongoing change. T.I. Balanovska *et al.* (2020) focused on the importance of employees' digital competencies in increasing the flexibility of enterprises during crises and spreading the latest technologies among society. Full use of their capabilities is impossible without the constant growth of digital competence, and the formation and development of digital competence among potential and current employees requires their approximation and adaptation to global practices. O.M. Girzheva *et al.* (2024) argued that the main goal of crisis management at the stage of crisis development is to restore the financial stability and solvency of the enterprise, as well as to minimise possible losses. The study by V. Huriev (2024) examined the integration of digital technologies as a component of the anti-crisis management mechanism to ensure regional stability and development. It investigated the impact of digitalisation on enhancing the efficiency of management processes, accelerating decision-making, and implementing measures aimed at mitigating crisis phenomena.

The use of digital technologies to optimise business development management is the subject of a study by O.S. Druhova (2024). The study described the main digital technologies that influence business development management and project management sustainability. This optimises existing business processes and increases employee motivation to implement new technologies and processes. K. Voloschuk *et al.* (2021) explored the theoretical aspects and practical specific tools for resolving crisis situations in the system of anti-crisis management of an enterprise. The integration of digitalisation into the business processes of anti-crisis management of an enterprise contributes to the timely prevention of financial, operational (production), personnel, and marketing crises. I. Plikus (2021) substantiated the role of AI (artificial intelligence), Big Data, and machine learning in the formation of digital tools for crisis management in business processes. This allows companies to significantly reduce operating costs for their business and become customer-oriented by creating personalised services and products. O.Yu. Sokhatskyi & O.D. Zakharov (2025) considered the risks for international business in the context of military conflicts, which necessitates the implementation of effective crisis management strategies. Effective crisis management helps minimise negative consequences, but also helps maintain business reputation and partner trust even in the most difficult conditions. Scientists I.V. Tokmakova *et al.* (2022) considered anti-crisis strategies that use digital technologies, which subsequently change both management processes and the business model of the enterprise itself, with the aim of ensuring the sustainability of project management.

One of the current areas of research is the study of the peculiarities of the implementation of digital technologies in the activities of Ukrainian enterprises. Given the specific nature of the impact of various types of risks that lead to crises, it is necessary to develop effective anti-crisis management strategies. In addition, it is necessary to take into account the importance of public-private partnerships, as they play an important role in the restoration and reconstruction of Ukraine's infrastructure, help minimise risks, and ensure the sustainable development of enterprises in the context of digital transformation. The results of such research can be useful for developing effective business strategies in the context of digitalisation and project management in the transport industry.

The purpose of this study was to theoretically substantiate and develop a comprehensive mechanism for digital anti-crisis management of transport enterprises of Ukraine. Research objectives included:

1. To conduct a comprehensive theoretical analysis of contemporary approaches to anti-crisis management and to substantiate directions for their improvement under modern economic challenges, including the development of an integrated crisis management mechanism for enterprises.

2. To investigate the potential of public–private partnerships as an effective instrument for ensuring business resilience in crisis conditions and to justify their role within sustainable economic development frameworks.

3. To substantiate the role of digital technologies in strengthening anti-crisis response strategies and to develop a conceptual framework for strategic crisis information and analytical centres aimed at enhancing managerial decision-making, ensuring flexible risk response, and restoring enterprise stability.

Materials and Methods

The object of the study was the process of anti-crisis management at transport enterprises in conditions of economic instability and military risks. The subject of the study was the use of digital technologies to ensure the sustainability of project management at transport enterprises, including tools of business analytics, big data analytics, AI, cloud computing and digital financial diagnostics. The study was based on a systemic and risk-oriented approach, according to which anti-crisis management is considered as a cyclical and adaptive process that integrates risk identification, analysis, strategic decision-making, their implementation, monitoring and feedback correction. The study included theoretical generalisation and empirical analysis of transport sector indicators for 2022-2024. The analysis was based on the following regulatory documents: Law of Ukraine No. 1351-r (2025) and Law of Ukraine No. 4510-IX (2025). A combination of quantitative and qualitative methods was employed to ensure methodological validity, and statistical techniques were applied to assess the dynamics of passenger and freight transport over the specified period. Time series analysis made it possible to identify trends, patterns, and fluctuations in transport performance indicators: phases of decline caused by infrastructure destruction and logistical disruptions; recovery trends associated with the development of alternative routes and digital logistics solutions; structural shifts in transport efficiency indicators. Descriptive statistics and year-on-year comparative assessment were used to determine growth rates and deviations.

Comparative analysis was employed to evaluate traditional and digital approaches to crisis management, compare financial diagnostic models such as the modified Altman and Springate models, and examine the distinctions between reactive and proactive crisis management systems. This approach enabled the identification of the advantages associated with integrating digital technologies into crisis response mechanisms. To assess the risks of financial stability, bankruptcy prediction models were considered, in particular the modified Altman model and the Springate model. These models were analysed as components of digital information and analytical centres for crisis prevention and liquidity forecasting. The study uses the classification of data analysis methods: descriptive analytics (analysis of past transport dynamics); diagnostic analytics (determination of cause-and-effect relationships); predictive analytics (forecasting risk scenarios); prescriptive analytics (selection of optimal response strategies). Methods such as regression modelling, simulation modelling, time series forecasting were considered as tools used in transport enterprises. Scenario modelling was employed to explore alternative development trajectories under conditions including the risks of military escalation, infrastructure disruptions, fluctuations in export logistics, and variability in investment inflows within the framework of public-private partnerships. This approach allowed for the assessment of potential outcomes and the identification of strategies to enhance enterprise resilience in uncertain and dynamic environments. A cyclical risk management model was applied, encompassing risk identification, probability assessment using elements of probability theory, impact evaluation, the development of mitigation strategies, and feedback-based performance assessment. In addition, data visualisation tools were employed to interpret transportation trends and to illustrate structural changes in passenger and freight volumes.

Results and Discussion

Anti-crisis management technologies are a set of measures aimed at implementing a mechanism of influence on the system in order to prevent, mitigate, or overcome various types of crisis situations and ensure effective management of transport enterprises, prevention, and assessment of risk consequences. The main areas of anti-crisis management at the organisational level are constant monitoring of its condition, development of new management, financial, and marketing strategies, as well as strengthening work with personnel. Anti-crisis management uses a set of methods from various fields of management: social technologies, economic analysis, forecasting, development of investment projects, anti-crisis programmes, etc. Anti-crisis management is based on scientific knowledge, innovative solutions for employee interaction, rights and responsibilities at all levels of the enterprise hierarchy, as well as analysis of practical experience in optimising system regulation mechanisms and identifying hidden opportunities for potential development. It requires making complex management decisions in conditions of limited financial resources, high uncertainty, and risk. In such conditions, there is a growing need to act quickly, timely, competently, and responsibly. (Kompanets *et al.*, 2022; Porfirenko *et al.*, 2025). The process of anti-crisis management in transport companies is complex and systematic, aimed at preventing and eliminating adverse events, ensuring a gradual recovery from the crisis, and maintaining the ability to function effectively in a market economy. This process involves making complex management decisions at every stage, from data collection to the implementation of the final decision (Fig. 1). Therefore, there is a need to introduce modern information technologies to ensure the effectiveness and soundness of decisions, especially in forecasting and overcoming crises at enterprises. This also contributes to the comprehensive use of simulation modelling, intelligence, and the experience of decision-makers.

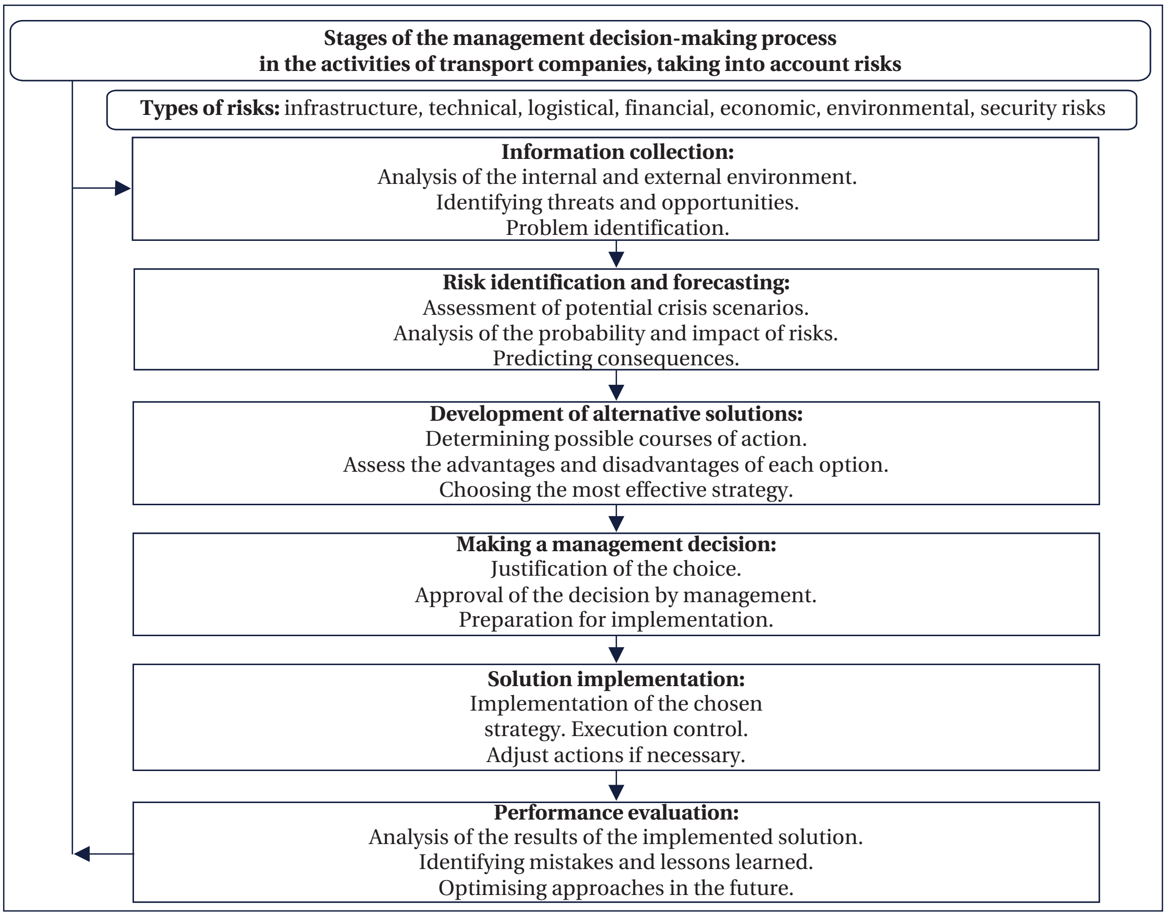

Figure 1. The procedure for making managerial decisions in the context of anti-crisis management
Source: developed by the authors according to K. Kompanets *et al.* (2022), V.I. Porfirenko *et al.* (2025)

Digital technologies are actively being implemented in various sectors of the economy, in public-private partnerships, and in interactions between stakeholders. This evolution necessitates the adaptation of management approaches, the development of new business models, and the implementation of innovative strategies to increase competitiveness. According to McKinsey research, about 89% of companies have initiated digital transformation processes, but only a small proportion of them have fully achieved their planned results (Zaika & Zaika, 2024). Law of Ukraine No. 1351-r (2025) defines priority tasks within the framework of the National Economic Strategy until 2030. In particular, it aims to ensure access for small and medium-sized businesses to modern technologies such as broadband Internet, the Internet of Things, and big data. The strategy outlines the main directions of the country's digital transformation, focusing on supporting innovation, cooperation with business and international partners, developing digital infrastructure, and encouraging the use of information technologies in public and economic life. This document is a strategic policy at the government level, where digitalisation acts as a driving force for development, directly linked to potential public-private partners in the digital sphere. According to the Law of Ukraine No. 4510-IX (2025), public-private partnerships can be used in various areas, including transportation and transportation infrastructure, electronic communications network infrastructure, education, scientific and scientific-technical activities, tourism, etc. The law provides a regulatory framework for the legal consolidation of digital solutions in the management of public-private partnerships (including electronic tendering, record keeping, data publication, etc.). In the field of public-private partnerships, digital technologies play a key role in streamlining processes, improving project financing and monitoring mechanisms, and strengthening trust between the parties involved. Through cooperation with stakeholders, digital transformation improves access to information, expands opportunities for attracting investors, and strengthens interaction between all participants (stakeholders). Digitalisation processes have become indispensable factors in ensuring the sustainability of project management and business development. They mitigate the negative effects of crises, open up new dimensions of strategic management, and promote innovative growth. In addition, they help optimise operational procedures, improve communication between partners, and increase the transparency and efficiency of decision-making.

The model of risk-based management of transport companies presented in the figure reflects a logically consistent and cyclical process of management decision-making based on systematic risk analysis, development of alternatives, and performance evaluation. The presence of a feedback mechanism ensures the adaptability of the management system to changes in the external environment and increases its stability. The challenges caused by the COVID-19 pandemic in 2019-2020 and the full-scale war in Ukraine since 2022 have significantly changed the established dynamics of business operations and business processes. These crises have led to a transformation of approaches to management, logistics, digitalisation, and strategic planning in such areas of the economy as public-private partnerships, trade, transport and road infrastructure, services, and education, which have also suffered significant economic losses. At the same time, these events have become a catalyst for active digital development in these industries. These transformations have significantly affected the activities of companies of various sizes and geographical locations. In today's environment, the use of digital technologies and modern management tools is seen by businesses as a necessary prerequisite for ensuring effective and uninterrupted operations.

Ukraine's digital transformations in the context of full-scale war are focused on increasing inclusiveness, developing digital literacy, and strengthening cybersecurity at all levels (Table 1). Technology plays a crucial role in enhancing citizens' quality of life, optimising management processes, and stimulating economic growth. Digital tools, including AI, cyber defence, and data analysis, are increasingly being integrated into the country's defence capabilities. Such transformations are a key mechanism for achieving economic stability, strengthening defence capabilities, expanding international cooperation, and establishing Ukraine's digital sovereignty. Thus, 2019-2021 marks a fundamental stage in the launch of state-level digital services. In 2022-2023, the war became a catalyst for the active implementation of digital solutions in government processes and business operations. 2024-2025 saw significant achievements in the implementation of digital infrastructure, international recognition, and the creation of national strategies.

Table 1. Development of digital processes in Ukraine in 2019-2025

Year	Key events/initiatives	Digital transformation trends
2019	Active launch of the "state in a smartphone" idea and announcement of the creation of mobile services	Initial phase of digitalisation, formation of basic strategies
2020	COVID-19 accelerates demand for digital services, remote work, and online business processes	A push for digital solutions in the public and private sectors
2021-2022	Government services, registries, and e-services begin to be more widely used by citizens and businesses	Increased availability of e-services; institutional implementation of digital platforms
2023	Transformation of digital services in wartime: adaptation of actions and online solutions for economic resilience	Active integration of digital tools into critical processes
2024	Development of digital skills, modernisation of registries and data exchange; improvement of cybersecurity	Deepening of digital competencies in the public sector
2025	Approval of the Digital Innovation Development Strategy (WinWin) until 2030	–
	Focus on AI strategy and the development of innovative technologies	Significant strengthening of the digital ecosystem; transition to global standards and international indicators; active partnership

Source: Digital transformation of Ukraine's economy… (2026)

Thus, 2019-2021 marks a fundamental stage in the launch of state-level digital services. In 2022-2023, the war became a catalyst for the active implementation of digital solutions in government processes and business operations. 2024-2025 saw significant achievements in the implementation of digital infrastructure, international recognition, and the creation of national strategies. Among the key state digital initiatives implemented in Ukraine prior to the full-scale war, particular attention is given to their objectives and areas of application. The Diia application was created as a unified digital platform providing citizens with access to public services in electronic form. Its scope includes the use of electronic documents (digital passport and driver's license), access to government services, and direct communication with public authorities. The eSupport Programme was introduced to provide targeted financial assistance to citizens in digital form, including subsidies and other types of social payments. Its scope covers social assistance, support for low-income households, and the automation of payment processes. Diia.Education was launched to facilitate distance learning and enhance citizens' digital literacy. The platform provides access to educational services, professional development courses, and online training programmes. Diia.Open Data ensures transparent public access to government data for citizens and businesses. Its scope includes open public datasets, analytical tools, and the development of applications based on open data. Diia. Business aims to simplify administrative procedures for entrepreneurs through electronic services. The platform supports business registration, tax services, licensing procedures, and electronic reporting. The eHealth system was developed to digitise healthcare services and introduce electronic medical records. Its scope includes medical information management, electronic prescriptions, patient records, and telemedicine services. The eVeteran platform provides digital services tailored to veterans, taking into account their benefits and social guarantees. It facilitates access to social support measures and state benefits. The eDeclaration system introduced an electronic mechanism for submitting income and asset declarations by public officials. Its scope relates to anti-corruption policy, transparency, and income control. The eRegistration system enables the digital registration of legal entities, real estate, and other types of property. It supports registration services and the automation of state registries. The Ukrainian Railways e-Portal provides electronic services for purchasing tickets, planning trips, and managing train traffic. Its scope includes transport services, logistics, and communication with passengers. The eTicket system was introduced to implement electronic ticketing in public transport. It facilitates fare payment, automated control, and improved convenience for passengers. The ProZorro electronic procurement system ensures transparency and efficiency in public procurement. Its scope includes state tenders, procurement procedures, and monitoring of public expenditures.

The Paperless initiative promotes the transition to electronic document management within public institutions. It aims to optimise administrative processes, improve document circulation, and enhance overall management efficiency. Other electronic documents in the process of digitisation – conversion of a wide range of state services and documents into digital format. Scope of application: all areas of public administration, communication, social security. These initiatives are government projects aimed at creating a modern, transparent, and convenient system of electronic services for citizens, businesses, and government agencies. They cover key areas of public life – from education and health to the economy, social protection, and infrastructure – and contribute to Ukraine's digital transformation. Companies are faced with the task of developing a comprehensive strategy for transforming their activities in order to effectively prevent and manage crises in conditions of instability. The use of digital tools in business contributes to increasing the resilience of enterprises, helping to prevent crises or quickly overcome them in various industries (Voloschuk *et al.*, 2021). The implementation of anti-crisis measures in organisations requires a comprehensive approach that includes an analysis of project implementation experience, particularly in the field of public-private partnerships. This takes into account the impact of risks, sustainable development, digitalisation, and big data analysis to adapt strategies to current business conditions. The interrelationship between the elements of the crisis management process is shown in Figure 2.

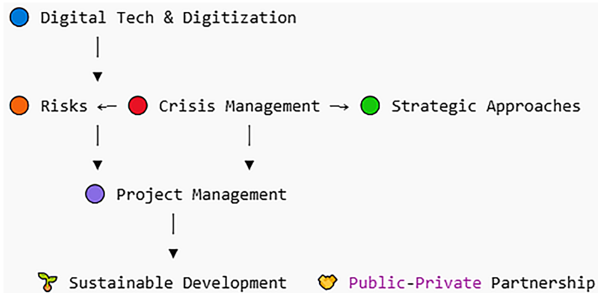

Figure 2. Diagram of the relationship between key concepts of crisis management
Source: developed by the authors

An analysis of Figure 2 indicates that crisis management functions as the central element coordinating the other components of the system. Digital technologies and digitalisation are tools that facilitate effective risk, project, and strategy management. Risks are challenges that need to be identified and minimised with the help of digital solutions. Strategy defines long-term approaches to crisis management and sustainable development. Project management is a system for coordinating crisis management activities using digital technologies. Sustainable development is the ultimate goal, achieved through effective crisis management, digitalisation, and public-private partnerships. Public-private partnerships are a mechanism that facilitates the implementation of digital crisis management strategies. The goal of sustainable development is achieved through effective crisis management, digital integration, and public-private partnerships, which act as catalysts in the implementation of digital crisis management methodologies. In a world where there is an abundance of information, it is extremely important to be able to quickly find, analyse, and apply the most relevant data. The excessive flow of information creates both new opportunities and challenges: the need for effective filtering, accuracy verification, and strategic use of the knowledge gained. Therefore, governments and companies can model different scenarios, identify potential threats, and respond to them in a timely manner using big data analysis. The application of probability theory in the management of business processes of transport companies facilitates the selection of transport routes, time planning, and risk assessment in finance, insurance, and other areas; assessment of the practical limitations of probability theory, especially in conditions of high uncertainty or unreliable information (Khobta *et al.*, 2025). AI automates complex processes, allowing for faster and more accurate analysis of information, while cloud technologies provide accessibility and flexibility in data storage and processing. The speed and accuracy of decision-making are becoming critical factors for success, and the integration of these technologies not only reduces the negative effects of crises but also builds more resilient and adaptive management systems. In this context, modern technologies such as data analytics, AI, and cloud computing are moving beyond their traditional role as simple tools for optimising business or improving everyday life. Instead, they serve as fundamental mechanisms for addressing and mitigating global crises in the economic, social, political, environmental, medical, and transportation spheres.

Under conditions of instability, organisations increasingly rely on advanced technological solutions to strengthen adaptive capacity, improve responsiveness to dynamic changes, and support evidence-based decision-making. Data analytics, in this context, functions as a key instrument for retrospective assessment and predictive modelling of future trends. As noted by O.M. Veres & R.M. Olyvko (2017), Big Data Analytics is applied to large and complex datasets; Discovery Analytics focuses on identifying patterns and hidden relationships within data; and Exploratory Analytics is aimed at explaining and interpreting data and analytical models. Data analytics is the process of collecting, processing, and interpreting large volumes of data to identify patterns, trends, and correlations that can inform evidence-based decision-making. In the context of crisis management, data analytics enables to:

1) understand the past, as data analytics allows organisations to examine historical data, identify trends and patterns, which helps to understand how past decisions have affected outcomes;

2) identify early warning signs: by analysing data from various sources (social media, financial reports, sensors, etc.), it is possible to detect the first signs of potential crises, such as epidemics, natural disasters, economic downturns;

3) predict the development of the situation: using statistical models and machine learning, it is possible to predict how the crisis will develop, what its consequences will be, and what measures should be taken. It will be much easier to predict future events, allowing them to be more proactive in their strategy;

4) optimise resources: data analysis can help identify inefficient processes and find ways to improve them, allocate resources more efficiently, focusing on the highest priority tasks (Davenport, 2017; Kompanets & Ilchenko, 2025).

The volumes of passenger and freight transportation to Ukraine in 2022, 2023, and 2024 across all modes of transport were analysed (Fig. 3).

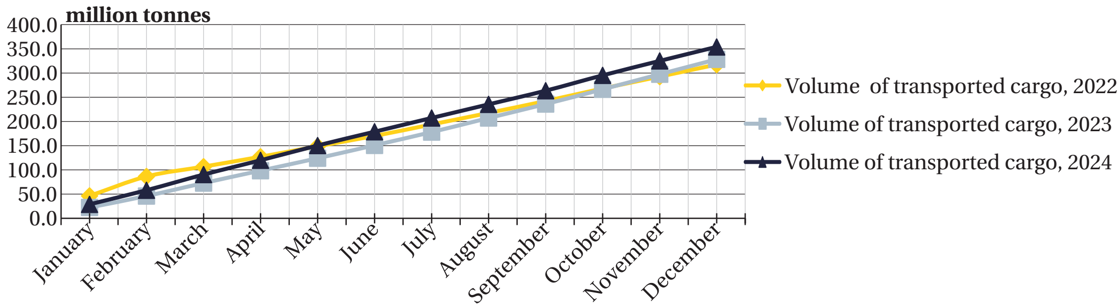

Figure 3. Dynamics of cargo transportation volumes in Ukraine for 2022-2024
Source: developed by the authors according to State Statistics Service of Ukraine (2025a; 2025b; 2025c)

The study findings indicate that in 2022 there was a significant decline in the volume of freight transportation due to the destruction of logistics routes and infrastructure, as well as the blockade of seaports. In 2023, transportation volumes partially recovered due to the creation of alternative delivery routes (rail and road) and the development of the grain corridor. The growth in transportation in 2024 is attributed to the restoration of infrastructure, growth in humanitarian cargo, agricultural exports, and the expansion of partnerships with European countries. Figure 4 shows that the number of passengers transported in 2022-2024 is 209.4 million passengers at the beginning of 2022, and at the beginning of 2023 there is an increase to 1,600.6 million passengers. The annual increase amounted to 1,391.2 million passengers, with the highest growth rates observed during the period from July to December 2022. Analysis of statistical data shows that the transportation system continues to improve. 2023 showed further improvement, but started from a lower level. At the end of the year, the indicators exceeded the level of 2022. Therefore, in the context of military operations, detailed analysis of large amounts of data and the use of business intelligence in transportation services has become a key tool for optimising logistics processes, allowing to assess the efficiency of routes, forecast costs and profitability. Figure 5 shows the methods of big data analysis, which are classified according to the functional relationships and the formal model of this information technology:

1) descriptive analytics provides information about what happened in the past. Statistical methods are used to describe the data;

2) diagnostic analytics – this method helps to understand why something happened by studying cause and effect relationships;

3) predictive analytics uses historical data to predict future events; various models are used, such as regression and machine learning;

4) prescriptive analytics – this method not only predicts, but also offers solutions to optimise the results (Fedorov, 2025; A marketer's guide to descriptive…, 2025; Singh, 2026).

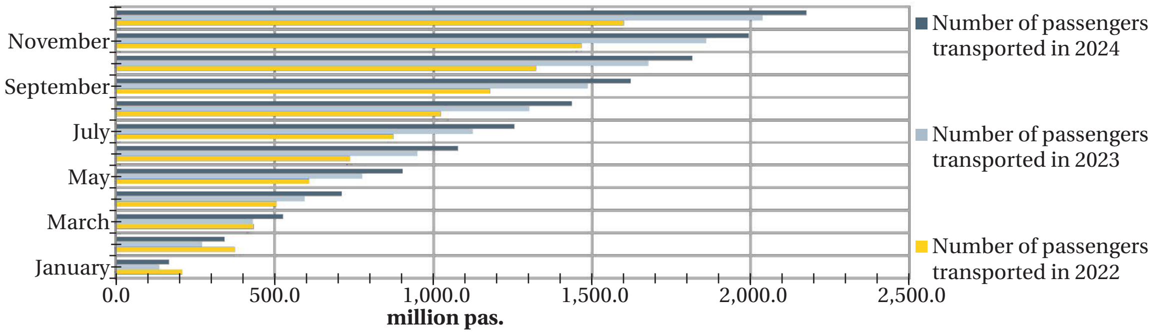

Figure 4. Dynamics of passenger transportation volumes in Ukraine for 2022-2024
Source: developed by the authors according to State Statistics Service of Ukraine (2025b; 2025c)

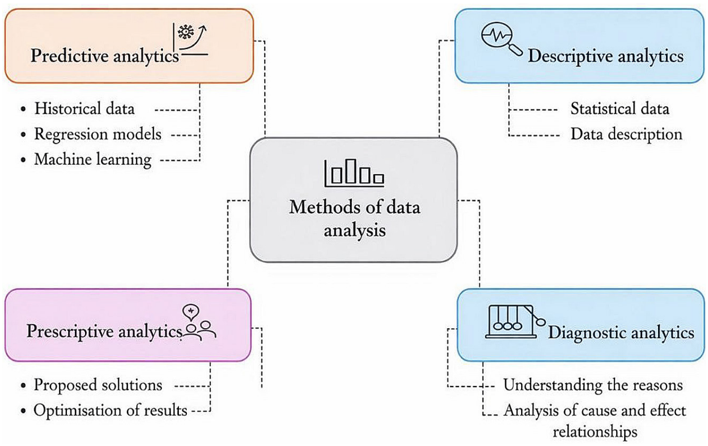

Figure 5. Methods of data analysis
Source: developed by the authors according to T.H. Davenport (2017)

Descriptive analytics provides information about what happened in the past using statistical methods that are used to characterise information. Diagnostic analytics helps to understand why something happened by studying the cause and effect. Different models are used for different purposes, including regression and machine learning, which allows, according to the dogma of descriptive analytics, not only to predict but also to choose the right solutions to improve results. The following analysis methods are used in various fields of activity, including the transportation industry: crowdsourcing, data consolidation and integration, machine learning, neural networks, network analysis, optimisation, including genetic algorithms, pattern recognition, analytics, forecasting, modelling, spatial analysis, statistical analysis, and analytical data visualisation. A variety of tools are available for data analysis. Microsoft Excel is widely used due to its accessibility and user-friendly interface, which enables efficient processing and visualisation of datasets. Tableau serves as a reliable platform for advanced data visualisation and interactive presentation of analytical results. Programming languages such as Python and R are extensively applied in data analysis and machine learning, offering powerful capabilities for statistical modelling and predictive analytics. In addition, SQL is utilised to interact with relational databases, allowing efficient data retrieval, management, and manipulation. Within this framework, business intelligence metrics play a crucial role in supporting informed decision-making during periods of crisis, as well as in assessing economic challenges and identifying potential development opportunities. Business intelligence plays a crucial role in the innovative management of transportation companies. It enables the introduction of advanced digital technologies. Developing strategies for transportation companies allows them to strengthen their ability to focus on the challenges posed by the global market. This ensures effective risk management, optimal resource allocation, and long-term competitiveness of the company in the market (Lozhachevska *et al.*, 2023). Business intelligence is also used to assess the onset of a financial crisis and prevent a company's bankruptcy using the following methods: decision tree, time series analysis, and simulation modelling. Ukrainian companies can apply the modified Altman model (ZAM), which was proposed by Altman in 1983:

$$Z_A\text{м}=0.717A_1+0.847A_2+3.107A_3+0.42A_4+0.995A_5, \quad (1)$$

where X4 – is the book value of equity/debt, with a threshold value of 1.23.

The Springate model (ZC) is also used to estimate the probability of bankruptcy:

$$Z_C=1.03C_1+3.07C_2+0.66C_3+0.4C_4, \quad (2)$$

where *C*1 – working capital/amount of assets; *C*2 – profit before taxes and interest/amount of assets; *C*3 – profit before taxes/short-term debt; *C*4 – revenue from the sale of products, goods, services/amount of assets. It is believed that the accuracy of predicting bankruptcy by this model is quite high and amounts to 92%, but this indicator decreases over time, and if $Zc < 0.862$, the company is a potential bankrupt.

Thus, the problem is to determine how the methods of formation of enterprise finances within the framework of information and analytical centres can effectively prevent or overcome the financial crisis in the enterprise. The solution to these problems necessitates the development of a mechanism for managing enterprises in crisis and determining the set of information and analytical centres for strategic crisis. This will make it possible to effectively manage financial flows with the use of digital technologies, in particular through the introduction of flexible models of control over current assets. The proposed mechanism for managing enterprises in crisis and determining the set of information and analytical centres of strategic crisis is presented in Figure 6.

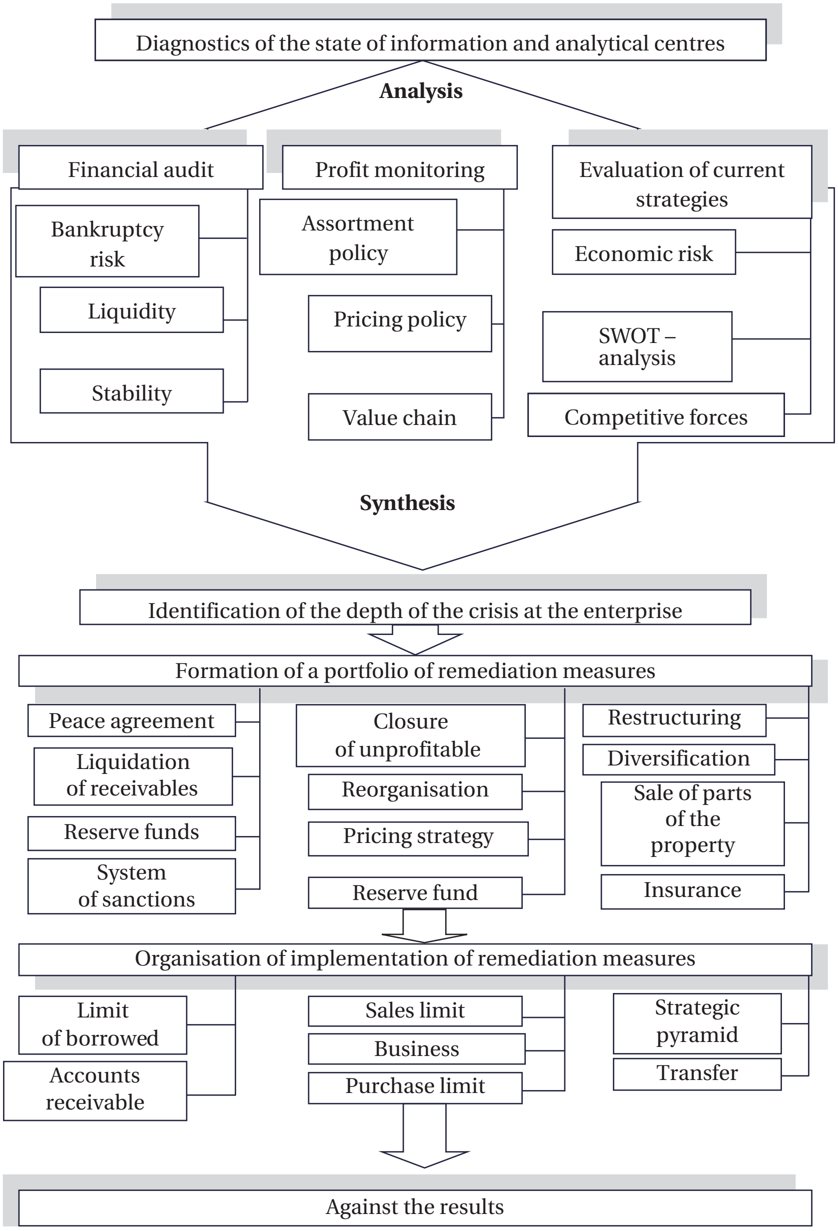

Figure 6. The mechanism of management of enterprises in crisis and the set of information and analytical centres of strategic crisis

Source: developed by the authors according to O.M. Lozhachevska *et al.* (2023), M.O. Khobta *et al.* (2025)

Within the subsystem of information and analytical centres, it is advisable to implement digital liquidity forecasting platforms integrated with risk management, which will allow for the prompt identification of destabilising factors. Such an approach will provide the company with flexibility in financial planning, minimise cash gaps and increase resilience to external risks. Thus, the crisis management mechanism includes the analysis of a large database, the use of digital technologies, and the consistent performance of management functions, which allows achieving a certain economic effect. Based on business analytics, it is possible to determine the effectiveness of attracting investments and innovations to cities and regions of Ukraine based on the public-private partnership mechanism, which allows ensuring the development of regional transport infrastructure in the context of European integration. As for sustainable development in the transport sector, it is based on: innovative digital technologies that improve the efficiency of transport systems; resource optimisation that minimises environmental impact and costs; social responsibility that provides for safe, affordable and comfortable transport. O.M. Lozhachevska *et al.* (2023) emphasised that the continuous analysis and understanding of a situation, along with the dynamics of its change, constitutes an ongoing and dynamic process. One-time analysis and diagnostics cannot serve as a reliable basis for this process, as they provide only limited information. Consequently, the development of strategic decisions cannot be long-term, given the rapidly changing environment in which an innovation-oriented enterprise operates. Modern technologies, including AI, offer powerful tools for predicting, preventing, and overcoming crisis situations in the enterprise. AI plays an important role in modern crisis management, helping organisations to anticipate, analyse risks and respond quickly to crisis situations. The main areas of AI application in crisis management are as follows:

1) predicting and forecasting crises, as AI uses big data analytics to predict possible crises. By analysing historical data, social media, market trends, and other sources of information, algorithms can predict certain threats, such as financial risks, natural disasters, or reputational crises. For example, AI-based systems can detect abnormal patterns in data that may indicate impending crises;

2) rapid data analysis. In crisis situations, it is critical to quickly process a large amount of information to make decisions. AI allows automating data analysis, reducing the time spent on finding the causes of the crisis and the best ways to solve it. This can be useful for tracking competitors' market activity, changes in supply, and social reactions to the crisis;

3) optimising response processes. AI enables the automation of selected crisis response processes, thereby increasing the speed and overall efficiency of decision-making and operational implementation. For example, AI systems can run algorithms to automatically activate contingency plans. This can include supply chain management, resource allocation, or customer and stakeholder interaction. Such solutions help reduce human errors and significantly increase the effectiveness of actions during a crisis;

4) scenario modelling and decision-making. AI allows to adapt models in real time. AI systems can quickly recalculate forecasts depending on changes in the external environment. This allows managers to make informed decisions faster in the face of uncertainty;

5) reputation management. AI plays an important role in monitoring and managing the reputation of companies, especially in times of crisis. Thanks to its ability to analyse large amounts of data in real time, AI allows companies to respond quickly to changes in public opinion and take measures to mitigate negative consequences;

6) post-crisis analysis. AI can also help automate the creation of reports on crisis events, which will save time and allow for a detailed understanding of the causes and consequences of the crisis. These reports can be used to improve crisis response plans and avoid similar problems in the future.

AI can free professionals from routine work, allowing them to focus on more complex tasks that require a creative approach; speed up big data analysis and decision-making several times faster; and create special systems that can learn and adapt to changing conditions. Cloud technologies enable organisations to quickly adapt to changing conditions, reducing costs and increasing productivity. This is especially important in situations where it is necessary to respond quickly to challenges and make informed decisions based on the analysis of large amounts of data. According to V.M. Andriievska & N.V. Olefirenko (2015), cloud service providers enable users to rent computing power and storage via the Internet. This approach offers significant advantages, including cost-effectiveness, as users pay only for the resources they require, and flexible scalability. Furthermore, clients are relieved from the necessity of creating and maintaining their own computing infrastructure. When using cloud technologies, software and hardware are provided to the user as an Internet service. The user has access to their own data, but cannot manage and should not take care of the infrastructure, operating system and software they work with. The "cloud" is the Internet that hides all technical details. Cloud services fundamentally transform the processes of accessing and utilising information and software by enabling remote interaction with data and server infrastructures from any location worldwide, thereby eliminating dependence on stationary hardware and enhancing collaborative engagement among geographically dispersed users. O.O. Hudzovata (2013) emphasised that Amazon was the first company to fully realise the commercial potential of virtualisation technologies, concentrating its efforts on the development and scaling of the Amazon Web Services cloud platform. This approach enabled virtualisation to become an effective business service accessible to a wide range of users. As defined by I. Chernikov (2024), the main models of cloud computing for data processing include the following:

1) IaaS (Infrastructure as a Service): provision of virtual servers, networks, and storage systems. Suitable for companies that want to have full control over their infrastructure;

2) PaaS (Platform as a Service): providing a platform for developing and running applications. Ideal for developers who want to focus on creating software;

3) SaaS (Software as a Service): providing ready-made software solutions over the internet. Popular examples: Google Workspace, Microsoft 365.

Cloud computing allows organisations to quickly analyse large amounts of data, which is critical in crisis situations. Thanks to the powerful computing resources available in the cloud, companies can receive results in real time, allowing them to quickly respond to changes in the market or in internal business processes. Using cloud technologies can reduce IT infrastructure costs. Organisations do not need to invest in expensive hardware because all the necessary resources are provided in the cloud. This is especially important for small and medium-sized enterprises, which may not have the capacity for significant capital expenditures. Cloud computing makes it easy to scale computing resources to meet business needs. When workloads increase or additional data needs to be processed, companies can quickly adapt their resources without significant delays or costs. This allows organisations to remain flexible and ready for any challenge. Therefore, using modern digital technologies, such as Big Data, machine learning, analytical platforms, for a comprehensive and in-depth analysis of the activities of transport enterprises or by studying stakeholder groups, the manager forms an information base for each criterion, which is the basis for developing an anti-crisis strategy, taking into account risks, as noted by I.V. Kravchuk (2024). Thus, the study confirmed that crisis management of transport enterprises in conditions of a wartime economy and global instability has become systemic and multidisciplinary. Its effectiveness is determined not by isolated financial stabilisation measures, but by the integration of a risk-oriented approach, digital technologies, public-private partnership mechanisms, and sustainable development instruments.

Conclusions

Analysis of transportation dynamics showed the industry's deep dependence on external crises, including military risks and logistical constraints. At the same time, the gradual recovery of transportation volumes in 2023-2024 indicated the system's adaptability under conditions of active use of digital solutions, development of alternative routes, and expansion of international cooperation. This confirmed the feasibility of implementing business analytics and Big Data tools to support strategic decisions in the transport sector. It was substantiated that the use of descriptive, diagnostic, predictive, and prescriptive analytics ensured a logical sequence of the management cycle, from identifying problems to selecting optimal solutions. The combination of these methods with financial instability forecasting models, in particular the modified Altman model and the Springate model, improved the quality of risk assessment and contributed to a timely response to crisis phenomena. A key element of digital transformation involved the development of strategic crisis information and analytical centres designed to consolidate data resources, perform scenario modelling, and ensure continuous feedback within governance and management systems. The proposed mechanism involved the integration of digital liquidity forecasting platforms, risk management tools, and cloud infrastructure, which increased the flexibility of financial planning and reduced the likelihood of cash gaps. Public-private partnerships were shown to be a catalyst for implementing digital anti-crisis strategies. Regulatory consolidation of electronic procedures, transparency of tenders, and open data contributed to increased trust between stakeholders and attracted investments in transport infrastructure. However, the study showed that digital transformation was accompanied by several limitations, including uneven digital maturity of enterprises, shortage of data analytics specialists, cyber threats, and limited financial resources. This necessitated further scientific understanding of mechanisms for increasing the effectiveness of digital anti-crisis solutions. Promising directions for further research included empirical testing of the proposed mechanism based on specific transport enterprises with quantitative measurement of the economic effect of implementing digital tools, development of an integral index of digital maturity of transport enterprises and establishing its connection with the sustainability of project management, and modelling of transport infrastructure restoration scenarios using simulation modelling and AI.

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Conflict of Interest

None.

References

[1] A marketer's guide to descriptive, predictive, diagnostic, and prescriptive analytics. (2025). Retrieved from https://business.adobe.com/blog/basics/descriptive-predictive-prescriptive-analytics-explained.

[2] Andriievska, V.M., & Olefirenko, N.V. (2015). The use of cloud technologies in the training of future teachers. *CTE Workshop Proceedings*, 3, 78-87. doi: 10.55056/cte.248.

[3] Balanovska, T.I., Havrysh, O.M., & Vyrzhykovska, B. (2020). Formation and development of employees' digital competence as a component of anti-crisis management of the organization. *Economics. Management. Business*, 1(31), 97-106. doi: 10.31673/2415-8089.2020.019716.

[4] Chernikov, I. (2024). *Cloud service models: Difference between IaaS, SaaS, PaaS and examples*. Retrieved from https://www.sim-networks.com/ukr/blog/cloud-computing-service-models.
[5] Davenport, T.H. (2017). Competing on analytics. *Harvard Business Review*, 84(1), 98-134.
[6] Digital transformation of Ukraine's economy. December 2025. (2026). Retrieved from https://surl.lu/gyeonp.
[7] Druhova, O.S. (2024). Use of digital technologies to optimise business development management. *Digital Economy and Economic Security*, 3(12), 85-90. doi: 10.32782/dees.12-15.
[8] Fedorov, M. (2025). *Types of data analytics: Descriptive, diagnostic, predictive, prescriptive*. Retrieved from https://skillsup.ua/blog/2025/03/introduction-to-data-analysis/.
[9] Girzheva, O.M., Nahaiev, V.M., & Solopun, N.M. (2024). Anti-crisis management: Formation of an industrial enterprise program in the context of modern communications. *Problems and Prospects for the Development of Entrepreneurship*, 33, 140-153. doi: 10.30977/PPB.2226-8820.2024.33.140.
[10] Hudzovata, O.O. (2013). Information security of cloud services. *Scientific Bulletin of the Lviv State University of Internal Affairs. Economic Series*, 2, 228-239.
[11] Huriev, V. (2024). Digital technologies as a component of the anti-crisis management mechanism of regional development. *Innovation and Sustainability*, 3, 151-159. doi: 10.31649/ins.2024.3.151.159.
[12] Ivanchenko, K., & Bilovodska, O. (2024). Conceptual approaches to defining and classifying crises in business activities. *Bulletin of Taras Shevchenko National University of Kyiv. Economics*, 1(224), 28-36. doi: 10.17721/1728-2667.2024/224-1/4.
[13] Khobta, M.O., Malakhova, Yu.A., & Sukmaniuk, V.M. (2025). Application of probability theory in managing business processes of transport enterprises. *Herald of Khmelnytskyi National University. Economic Sciences*, 342(3(2)), 229-236. doi: 10.31891/2307-5740-2025-342-3(2)-36.
[14] Kompanets, K., Lytvyshko, L., Fedoriak, R., & Krasnoshtan, O. (2022). Simulation modeling of rights distribution and management system of innovative personnel development under the influence of COVID-19 pandemic factors. *AIP Conference Proceedings*, 2413, article number 040003. doi: 10.1063/5.0079789.
[15] Kompanets, K.A., & Ilchenko, V.Yu. (2025). Marketing innovative technologies and business analytics of foreign economic activity in risk management of transport enterprises. *Current Issues in Economic Sciences*, 7. doi: 10.5281/zenodo.14760573.
[16] Kravchuk, I.V. (2024). Modern approaches to stakeholder management of transport enterprise projects. *Managing the Development of Complex Systems*, 60, 79-86. doi: 10.32347/2412-9933.2024.60.79-86.
[17] Law of Ukraine No. 1351-r "On the Approval of the Strategy for Digital Development of Innovative Activity in Ukraine for the Period up to 2030 and the Approval of the Operational Plan of Measures for its Implementation in 2025-2027". (2025, July). Retrieved from https://zakon.rada.gov.ua/laws/show/1351-2024-%D1%80#Text.
[18] Law of Ukraine No. 4510-IX "On Public-Private Partnership". (2025, October). Retrieved from https://zakon.rada.gov.ua/laws/show/4510-20.
[19] Lozhachevska, O.M., Pidvalna, O.H., & Mokhonko, H.A. (2023). Business administration of the anti-crisis financial management mechanism of innovation-oriented enterprises in the context of digitalization and public administration development. *Investments: Practice and Experience*, 24, 30-34. doi: 10.32702/2306-6814.2023.24.30.
[20] Plikus, I.Y. (2021). Anti-crisis business management in the digital economy. *Social Economy*, 62, 88-97.
[21] Porfirenko, V.I., Kompanets, K.A., & Mytrokhin, L.D. (2025). Managerial decisions in administrative and communicative management of business processes in enterprise planning. *Current Issues in Economic Sciences*, 11. doi: 10.5281/zenodo.15564838.
[22] Singh, D. (2026). *Types of analytics explained: Descriptive, diagnostic, predictive & prescriptive*. Retrieved from https://supaboard.ai/blog/types-of-analytics.
[23] Sokhatskyi, O.Yu., & Zakharov, O.D. (2025). Anti-crisis management as a tool for ensuring economic sustainability of international business in wartime conditions. *Economy and Society*, 80. doi: 10.32782/2524-0072/2025-80-124.
[24] State Statistics Service of Ukraine. (2025a). *Transport of Ukraine, 2022*. Retrieved from https://stat.gov.ua/en/publications/transport-ukraine-2022.
[25] State Statistics Service of Ukraine. (2025b). *Transport of Ukraine, 2023*. Retrieved from https://stat.gov.ua/en/publications/transport-ukraine-2023.
[26] State Statistics Service of Ukraine. (2025c). *Transport of Ukraine, 2024*. Retrieved from https://stat.gov.ua/en/publications/transport-ukraine-2024.
[27] Tokmakova, I.V., Panchenko, N.H., & Kurhuzova, M.Yu. (2022). Development of an anti-crisis enterprise strategy in the context of digital transformation. *Bulletin of Transport and Industry Economics*, 76-77, 70-80. doi: 10.18664/btie.76-77.282040.
[28] Veres, O.M., & Olyvko, R.M. (2017). Classification of big data analysis methods. *Bulletin of the National University "Lviv Polytechnic". Series: Information Systems and Networks*, 872, 84-92.
[29] Voloschuk, K., Ivanyshyn, O., & Savchuk, O. (2021). Traditional and innovative tools of anti-crisis management of agro-industrial enterprises. *Innovative Economy*, 5-6, 92-98. doi: 10.37332/2309-1533.2021.5-6.13.

[30] Zaika, Yu., & Zaika, O. (2024). Business transformation under the influence of digital technologies. *Young Scientist*, 6(130), 185-188. doi: 10.32839/2304-5809/2024-6-130-7.

Антикризові стратегії та сучасні технології в стійкому управлінні проєктами

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Анотація. Зростаюча частота та складність економічних, інфраструктурних та геополітичних криз значно підвищила потребу в ефективному антикризовому управлінні на проєктно-орієнтованих підприємствах. Це особливо актуально для транспортного сектору, який чутливий до зовнішніх змін. В умовах підвищеної невизначеності традиційні підходи до управління часто виявляються недостатніми, що потребує застосування інноваційних та гнучких рішень. Метою цього дослідження було обґрунтування сучасних підходів до антикризового управління на основі використання цифрових технологій у рамках сталого управління проєктами. Методологія дослідження базувалася на системному та порівняльному аналізі, синтезі, статистичному аналізі, візуалізації даних та сценарному моделюванні, які разом забезпечують комплексну оцінку процесів антикризового управління. Встановлено, що використання аналітики даних, штучного інтелекту, хмарних обчислень та цифрових платформ сприяє ранньому виявленню криз, оцінці ризиків та швидкому реагуванню. Ці технології дозволяють підприємствам обробляти великі обсяги даних у режимі реального часу, підвищувати точність прогнозування, прискорювати прийняття управлінських рішень та оптимізувати розподіл обмежених ресурсів. Аналіз статистичних даних транспортного сектору України за 2022-2024 роки показав зростання адаптивного потенціалу компаній, що проходять цифрову трансформацію, особливо у відповідь на виклики воєнного та посткризового періоду. Результати дослідження підтвердили, що інтеграція цифрових технологій у системи антикризового управління підвищує організаційний потенціал, забезпечує безперервність реалізації проєктів та сприяє досягненню цілей сталого розвитку. Практичне значення дослідження полягає у можливості застосування його результатів у діяльності менеджерів транспортних підприємств, органів державної влади та інших зацікавлених сторін, залучених до інфраструктурних та інвестиційних проєктів, що сприятиме розвитку більш сталих і стабільних транспортних систем

Ключові слова: цифрові технології; профілактика; прийняття рішень; бізнес-аналітика; зацікавлені сторони; ризики

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Reconciliation of economic interests of participants in concession projects for the development of transport infrastructure

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Abstract. This study aimed to identify the key aspects of vertical and horizontal coordination of economic interests among participants in concession projects for the development of transport infrastructure. The research methods included a critical review of existing literature, alongside analysis, comparison, systematisation, and generalisation of information. The study defined the circle of participants in concession projects and examined the crucial elements of their vertical coordination (state-concessionaire) and horizontal coordination (concessionaire – shareholders – creditors – project organisation – subcontractors – service companies). For each participant in a transport infrastructure development project based on a concession model, a set of interests and target indicators was formulated. These indicators were designed to ensure the stability of the implementation coalition. The primary issues underlying the coordination of economic interests related to the distribution of income, profits, responsibilities, and risks. The coordination of these interests relied on selecting mutually agreed-upon values for the following management parameters: 1) for the public partner – the economic benefit (profit) derived from transferring the asset to the concession; 2) for the private partner – income and profit from constructing the motorway and its subsequent operation; 3) for investors/creditors – the required funds to meet contractual obligations and project implementation, along with their cost; 4) for the designer – the scope and price of design work; 5) for contractors (subcontractors) – the scope and cost of construction and installation work; 6) for operators (road maintenance organisations) – the volume and cost of management services. The practical significance of the results lay in the fact that attention to these indicators during the establishment of the concessionaire organisation and its subsequent operation would have incentivised participants to pursue successful project implementation

Keywords: economic effect; public-private partnership; coordination of interests; profit; distribution

Introduction

Concessions are increasingly being recognised by authorities and businesses in Ukraine as an effective tool for the restoration and development of transport infrastructure in the post-war period. This approach is increasingly recognised by authorities and businesses in Ukraine as an effective tool for the restoration and development of transport infrastructure in the post-war period. In response to the growing relevance, the Law of

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Ukraine No. 4510-IX (2025). The objective complexity of such projects is due not only to significant investments, long construction periods, and high risks, but also to the large number of participants. They consist of partners from the public and private sectors. The public sector is interested in the rapid implementation of socially significant capital-intensive transport infrastructure development projects that boost the socio-economic development of territories, strengthen interregional economic ties, and contribute to an increase in international trade. The private sector is interested not only in participating in a state-supported project, but also in obtaining certain benefits that would satisfy its minimum required rate of return. In addition, the concession project provider company is formed from representatives of various business structures, and sometimes representatives of the public sector. Their participation may take the form of co-financing, direct construction works, further operation of the transport infrastructure facility, maintenance of transport infrastructure facilities, provision of land plots for use, permits for use of adjacent plots, etc. In other words, each of the participants, by contributing certain resources (financial, material, labour, information) to the project, faces certain risks and seeks to receive appropriate remuneration. Violation of the interests of private or public sector partners will inevitably lead to the termination of the project and significant losses for the development of a particular region and all project participants. This makes it important to study the fundamental principles of reconciling the interests of participants in concession projects for the development of transport infrastructure.

The issue of aligning the interests of stakeholders is very important. Thus, J. Węgrzyn & A. Wojewnik-Filipkowska (2022) pointed out that compliance with the conditions for ensuring the interests of stakeholders should be at the centre of the state strategy of public-private partnership (PPP). The need to motivate private investors to come to socially important projects is also emphasised by A. Kopańska *et al.* (2024). Reconciling the interests of stakeholders requires a preliminary assessment of the potential for sustainable development, as infrastructure projects directly impact the environment, as highlighted by V.S. Tytykalo (2021), and consequently influence public support and the anticipated socio-economic development prospects of the region. At the same time, T. Tropeano *et al.* (2025) proposed to evaluate the PPP infrastructure project based on its social value, which reflects the expected social welfare of a certain territory. M. Tavana *et al.* (2022) considered the rationale for choosing a private sustainable partner within the PPP as the most important step in the partnership. The private partner should provide the highest value, and its selection is a complex task divided into manageable steps with numerous and complex, interdependent, quantitative and qualitative indicators of economic, environmental and social criteria. B.J. Dykes & I. Uzuegbunam (2022) argued the rationale for choosing a foreign partner to participate in an infrastructure PPP project. Thus, in cross-border infrastructure projects, the decision to choose a partner is more complex due to the participation of a foreign partner and the long-term nature of the contract. Such projects, by their very nature, must protect the public interest in the local environment and share some of the benefits with the foreign partner. The decision to choose a foreign partner is proposed in terms of the trade-offs of partnership between a local and a foreign partner and the nuances of their use. According to the results of research by B.B. Anderson & C. Ratiu (2019), for the development of an effective PPP, the goals and behaviour of both parties must be recognised, considered and addressed. At the same time, the goals and priorities of all these actors are not always well aligned with sustainable development goals. When choosing partners, NGOs will benefit from recognising the different objectives of stakeholders and a common basis for action. In view of the above, it is of interest to determine the fundamental approaches to reconciling the economic interests of participants in transport infrastructure development projects, in particular on the basis of concessions, which will ensure the success of the project. The aim of the study was to explore the main aspects of vertical and horizontal coordination of economic interests among stakeholders in transport infrastructure development projects under concession agreements.

Materials and Methods

The study was qualitative in nature and based on a descriptive research methodology. The object of the study was the relationships that arise between stakeholders during the implementation of transport infrastructure development projects under concession arrangements. The subject of the study was theoretical and practical approaches to reconciling the economic interests of such stakeholders. Due to Russia's military aggression against Ukraine, the implementation of several concession agreements, particularly those related to the development of seaports, has been suspended. This explains the limited practical experience in implementing projects for the development of Ukrainian transport infrastructure based on concessions and the absence of corresponding empirical data. The sources of information were the results of studies on stakeholder interactions during the implementation of PPP and concession-based projects, including works by Z.I. Halushka (2020), A.C. Toochukwu (2025) and V.O. Ovchinnikova & M.I. Diakov (2025). The analysis included selected research results regarding interaction within partnerships and studies focusing on the economic interests of business entities, published over the past 10 years. Publications primarily presented in journals indexed in international scientometric databases such as Scopus and Web of Science were considered.

As this article was of a conceptual nature, a critical review of the literature and logical methods of cognition were employed during its preparation: analysis, comparison, abstraction, synthesis and generalisation. The study of methods for reconciling the economic interests of the parties to a concession agreement was conducted based on a classification of the nature of their interaction: vertical (public partner – private partner) and horizontal (direct participants in the project implementation). A systematic approach was used when justifying management parameters that take into account the interests of the concession participants. In particular, the objects that will fall within the sphere of economic interests of individual concession participants, and their connection with the enterprise's cash flows, were identified. The latter are usually taken as a basis when determining the economic efficiency of projects as a whole. The conceptual approach proposed in this article involved taking into account both the qualitative and quantitative characteristics of the transport infrastructure development project. This ensured the reliability of the proposed conceptual model for reconciling the interests of concession participants.

Results and Discussion

Modern scientific approaches consider the economic phenomenon of "alignment of economic interests" as a mechanism, principle and process aimed at eliminating contradictions, imbalances and reaching agreement between the participants of a particular socio-economic system in the context of constant changes and creating prerequisites for further successful activity of the subjects within the framework of a particular system (Halushka, 2020; Osipova, 2025). At the same time, the coordination of economic interests should to some extent resolve the main contradiction of the economic system, which is the contradiction between significant needs and limited resources (Tytykalo, 2021; Klymchuk *et al.*, 2022) The dialectical interaction of two aspects of economic interest – objective and subjective – is the reason why economic interests are both the cause and the condition of interaction between project participants. According to V.O. Ovchinnikova & M.I. Diakov (2025), the object of economic interests is a certain result of operating activities that serves the purpose of satisfying a need and for which relationships with other entities are formed. The structure of the project and the system of relationships between the concession project participants is determined by the subject matter of the concession agreement. U. Elraaid *et al.* (2024) argued that the result of the interaction of economic interests should be a completed infrastructure project, provided that in the process of project implementation, the interests should generate an increase in utility.

Aligning the interests of project participants is a component of ensuring the realisation of economic interests and lies in the area of project management in general and the activities of business entities – participants in particular, in order to offset the combined effects of economic, social, political, and legal risks on the expected result of the project. In other words, the coordination of economic interests of project participants must meet the conditions of economic security of each project participant separately as a business entity (Dzhereleiko, 2022; Andrusiv & Kulik, 2025). The ability to reconcile interests, or at least to find a compromise, is a measure of the ability to stay safe. The difference in the goals and interests of project participants should be correctly reflected in the system of criteria (indicators), which will be different at the macro and micro levels due to the difference in the goals and interests of the relevant entities. Reconciliation of the interests of the concession project participants, based on the difference in goals and interests from their participation in the project, should be based on a system of criteria (indicators) as the results of interaction under the same understanding of their measurement and evaluation. Thus, throughout the entire project implementation cycle from planning to completion, the criteria, the reasons for their occurrence and the impact on the activities of each participant should be identified. The formation of a system of concepts, indicators and a unified measurement system is an important task in the information support of the interaction of project participants, which is an integral part of the project monitoring and control system for both the public partner and the private partner (Anderson & Ratiu, 2019; Elraaid *et al.*, 2024). In a concession transport infrastructure project, the definition of effectiveness is preceded by performance indicators, which will depend on the form of presentation of the expected result or the identified areas of effectiveness (social, economic, environmental, operational, etc.). The performance indicators of the private partner's participation in the concession project should be consistent with the performance indicators of the business entity as a whole and comply with its strategy, which is determined by its statutory goals and objectives. Guaranteeing the expected financial results of business entities lies in a three-dimensional plane: "income – expenses – profit". Accordingly, management should focus on maximising revenues and minimising costs (Anderson & Ratiu, 2019). To assess the state of the partnership, it is not the indicators themselves that are of fundamental importance, but their critical (threshold) values that reflect the acceptable limits of the partnership. For example, the threshold indicators that will characterise the effectiveness of the partnership may be:

- the break-even point – as the amount of income at which the partnership reimburses only its conditionally fixed costs;
- break-even point – as the amount of income at which the partnership will reimburse its fixed and variable costs, but will not make a profit;
- minimum level of profitability – the amount of income at which the partnership reimburses its fixed and variable costs and receives a profit in an acceptable amount based on the minimum expected return on invested capital; resource-assured profit point – the amount of income at which the partnership reimburses its fixed and variable costs and achieves key performance indicators in the areas of labour productivity, use of fixed assets (capital efficiency) and current assets (asset turnover) (Tytykalo, 2021; Tavana *et al.*, 2022; Mahame *et al.*, 2024).

The components of income, expenses, capital, current and non-current assets will be included in the vector of managing the activities of any participant in the system as a separate system. To assess the expected effectiveness of the public partner's participation in the project, an integral indicator of the sum of social effects can be used, aimed at maximising social welfare and reflecting the reduction of losses due to the expected reduction in the number of road accidents, creation of jobs for the period of works and operation of the road, increase in tax revenues, etc. Thus, in order to assess the prospects of a private participant's participation in the project, the impact of the project implementation status on the performance results, and to find a set of partnership strategies and their consequences, the area of economic interests coordination will cover the amount of resources and their thresholds that exist and/or are expected in the activities of such a partnership. When using the mathematical apparatus to formulate the conditions of the tasks, these thresholds will serve as boundary indicators. Therefore, approaches to aligning interests will take into account forecasting, planning and modelling tools. A condition for reconciling the economic interests of the concession project participants will be that the parties receive income from participation in the project in an amount that is acceptable to them. At the same time, this amount of income will be a satisfactory optimum based on the subjective considerations of decision makers. For the purpose of comprehensive involvement of concession project participants in the process of reconciliation of their interests, it is proposed to consider the interaction of participants in terms of the hierarchy of their actions in fulfilling the terms of the concession agreement. It is proposed to distinguish between vertical and horizontal hierarchy of interests. When considering the vertical hierarchy, the relations between the state and private business are taken into account. The hierarchy of vertical interaction will reflect the levels of business entities whose actions will relate to the conceptual areas of the agreement and whose responsibility for the implementation or organisation will be solely that of the state or the concessionaire (special project company (SPV)) (Fig. 1).

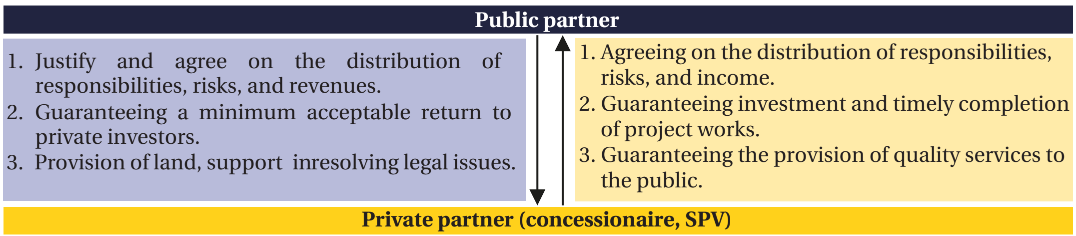

Figure 1. Participants in the vertical alignment of interests and interaction between public and private partners under a concession agreement

Source: developed by the authors

When establishing economic relations between public and private partners, it is necessary to jointly decide on and agree the distribution of responsibilities, risks and revenues between them. The public partner must guarantee the private investor a minimum acceptable return. Support in resolving legal issues and, if necessary for the implementation of a concession project, the provision of land is also necessary. The private partner also has an obligation to agree and comply with the arrangements for the distribution of responsibilities, risks and revenues. The private partner must guarantee the implementation of investments and the timely execution of project works provided for in the concession agreement. The private partner is also obliged to provide quality services to the public. Thus, joint decisions and commitments made by public and private partners minimise the risks of failure to implement concession projects. Breaches of commitments must have significant administrative and financial consequences for the parties (persons) that committed them. In this case, the parties will be interested in fulfilling their commitments. Horizontal coordination will be carried out at the level of the participants involved in the SPV. In this case, such participants may be shareholders of the SPV, as well as contractors whose relations are governed by commercial agreements and who are not parties to the concession agreement, as well as financial and credit institutions whose relations are governed by loan agreements, which may be guaranteed by the state. To formulate the task of horizontal coordination of interests, it is necessary to consider the structure of organisations involved in the implementation of the concession project, analyse vertical or horizontal interactions determined by the objectives of participation in the project, as well as the permissible thresholds for performance indicators that will reflect the area of interest of the project participants (Fig. 2). Organisations participating in a concession project may be direct contractors (design, construction and/or operational organisations), financial and credit institutions (investment funds, banking institutions, private pension funds, etc.), or insurance organisations. All of them may be co-owners (shareholders) of a special project organisation – a private partner that is a party to the concession agreement – or cooperate with this company on contractual terms. Shareholders of a special project company may be either legal entities or private individuals. The interests of the shareholders are represented by the joint-stock company's governing body – the general meeting of shareholders. The area of coordination of the interests of participants covers the cash flows necessary for the implementation of the project, the volume of work performed (design or construction) or the volume of services provided (for the maintenance of the concession road) as stipulated in the agreement. On the other hand, cash flows expected during the concession facility's operation stage are also of interest. Accordingly, the management parameters will be the amount of financing, works and services, as well as tariffs and income distribution. Therefore, the coordination of interests is based on the selection of agreed values of the following management parameters:

- for the public partner – the economic effect (profit) from the transfer of the facility to the concession;
- for the private partner – profit from the construction of the road and its further operation;
- for investors/creditors – the amount of funds required to fulfil obligations under the contract and implement the project, as well as their cost;
- for the designer – the scope of design works and their price;
- for contractors (subcontractors) – the scope and cost of construction and installation works;
- for operators (road maintenance organisations) – the scope of management services and their cost.

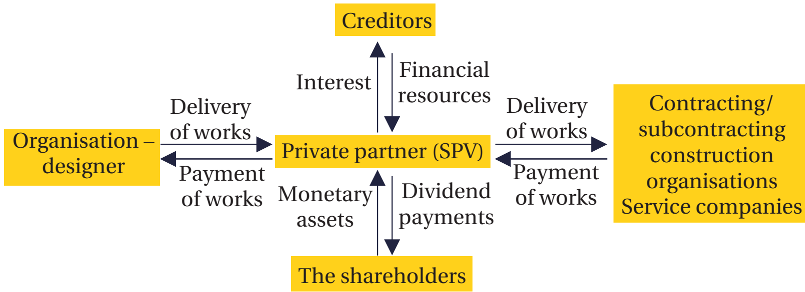

Figure 2. Participants in the horizontal alignment of interests and interaction between public and private partners under a concession agreement

Source: developed by the authors

In order to coordinate interests between the participants of a transport infrastructure project, it is assumed that each subject of interaction has a decision-making centre (or a decision-maker) in its structure, which determines the purpose of interaction with other subjects of the relevant interaction focus and influences the management of such a subject. The objectives of interaction of each entity should be subordinated to the objectives of the project (or certain aspects of its implementation) and the functioning of such entity as a whole. The interaction of vertical stakeholders concerns the conceptual framework for organising and implementing a concession project, establishing key qualitative and quantitative characteristics of the project, which serve as the boundaries for the participation of horizontal stakeholders in the project (Osipova, 2025). Interaction of horizontal interaction subjects concerns the implementation of certain, formally defined, mandatory aspects of the concession project under the restrictions (cost, resource, time, etc.) set by vertical interaction subjects. The horizontal actors influence each other through information interaction, and the coherence of their actions should mean that the activities of such actors meet the goals, objectives, and expectations set by the vertical actors. If coordination is not achieved by the horizontal interaction actors, it is considered that the achievement of goals (objectives) is under threat and the issue is within the scope of the vertical interaction actors. In this case, the task of horizontal coordination moves to the plane of actors of a different hierarchy and concerns their interests. Changes in project characteristics by vertical interaction actors affect the state of the system of horizontal interaction actors by changing the boundaries and conditions of its operation.

Thus, the coordination of interests should take place simultaneously at all levels of interaction. In this way, the synthesis of the coherence of interests of vertical and horizontal interaction actors will be achieved with the unity of achieving goals by all actors. Modern approaches, such as those proposed by S. Dzhereleiko (2022) and L. He *et al.* (2022), to the coordination of economic interests within economic relations, provide a basis for formulating the following principles for the coordination of interests of participants in a concession project. These principles take into account the specific characteristics of project implementation and include planning, limitation, systematicity, awareness, efficiency, competence, and complementarity. The content of these principles is shaped by the specific nature of a concession project as a form of PPP. A concession project for the construction of a road is a complex infrastructure undertaking with the potential to significantly impact society. It plays a crucial role in addressing important social and economic issues, helping to prevent social contradictions, and contributing to the overarching goal of creating an innovative society. According to K.J. Aladayleh & M.J. Aladaileh (2024) and T. Tropeano *et al.* (2025), the resolution of these challenges lies in the interaction of several key components: the theoretical foundations of economic theory, scientific research in project management, the practical implementation of innovations, and the effective professional and intellectual development of individuals involved. S. Jayasuriya *et al.* (2024) argued that poor stakeholder management is one of the main reasons for failure in PPP projects, and therefore specialised strategies must be developed specifically for projects in the economic infrastructure sector.

As noted by G. Sun *et al.* (2023), since the coordination of interests among concession project participants is considered with a focus on the economic aspect of their interactions, the definition of coordination methods, tools, and the structure of the coordination process will draw upon an interdisciplinary arsenal, including economic analysis, project analysis, project management, and systems analysis. This approach is required because the coordination of interests of project participants is closely linked to the subjects of study in these disciplines.

Conclusions

The study showed, that the success of PPP projects, including concession-based projects, depends on how well the interests of its participants are aligned. These participants include authorities at various levels of government, private investors – shareholders of a special project organisation, construction, installation and operating organisations, residents of local communities, insurance organisations, and financial and credit institutions. The group of participants in a concession project and the relationships between them can be viewed as a specific economic system. Relationships within it are formed: 1) at the vertical level (public and private partners) and must take into account the vertical hierarchy of the state-private partner; 2) and at the horizontal level (design organisation, special project company, creditors, contractors, service and operating companies, shareholders). This system must have quantitative and qualitative characteristics of functioning. The conditions and results of its functioning may be subject to threshold levels of indicators and areas of agreement between the participants. The questions underlying the coordination of their economic interests concern the distribution of income, profits, responsibilities and risks. The coordination of interests among participants in a concession project is based on the selection of agreed values for the following management parameters: 1) for the public partner – the economic effect (profit) from transferring the facility to concession; 2) for the private partner – income and profit from the construction of the motorway and its subsequent operation; 3) for investors/creditors – the amount of funds required to fulfil the obligations under the contract and implement the project, as well as their cost; 4) for the designer – the scope of design work and its price; 5) for contractors (subcontractors) – the volume and cost of construction and installation work; 6) for operators (road maintenance organisations) – the volume of management services and their cost. In order to reconcile the interests of the participants in a transport infrastructure project, it is assumed that each entity involved in the interaction has a decision-making centre (or decision-maker) within its structure, which determines the purpose of interaction with other entities involved in the relevant area of interaction and influences the management of such entities. The tasks of each entity involved in the interaction must be subordinate to the objectives of the project (or specific aspects of its implementation) and the functioning of such an entity as a whole. The professionalism and competence of persons involved in project management play a significant role in the possibility and quality of reconciliation of interests as a process, principle and result. It is advisable to conduct further research in the area of studying methods and tools for reconciling the interests of participants in concession projects for the development of transport infrastructure.

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Conflict of Interest

None.

References

[1] Aladayleh, K.J., & Aladaileh, M.J. (2024). Applying analytical hierarchy process (AHP) to BIM-based risk management for optimal performance in construction projects. *Buildings*, 14(11), article number 3632. doi: 10.3390/buildings14113632.

[2] Anderson, B.B., & Ratiu, C. (2019). Stakeholder considerations in public-private partnerships. *World Journal of Entrepreneurship, Management and Sustainable Development*, 15(3), 212-221. doi: 10.1108/WJEMSD-04-2018-0046.

[3] Andrusiv, U.Ya., & Kulik, T.P. (2025). Conceptual principles for the formation of a comprehensive system of financial and economic security for economic entities. *Current Issues in Economic Science*. doi: 10.5281/zenodo.14957432.

[4] Dykes, B.J., & Uzuegbunam, I. (2022). Foreign partner choice in the public interest: Experience and risk in infrastructure public-private partnerships. *Journal of International Business Policy*, 6(1), 47-66. doi: 10.1057/s42214-022-00134-z.

[5] Dzhereleiko, S. (2022). Instruments for improving financial results in the system of strengthening the economic security of the enterprise. *Bulletin of Khmelnytsky National University*, 6(l), 67-74. doi: 10.31891/2307-5740-2022-312-6(1)-10.

[6] Elraaid, U., Badi, I., & Bouraima, M.B. (2024). Identifying and addressing obstacles to project management office success in construction projects: An AHP approach. *Spectrum of Decision Making and Applications*, 1(1), 33-45. doi: 10.31181/sdmap1120242.

[7] Halushka, Z.I. (2020). Strategic stakeholder – management: Theoretical concept and features of application. *Scientific Bulletin of the University of Chernivtsi*, 829, 52-58. doi: 10.31861/ecovis/2020-829-1.

[8] He, L., Wang, B., Xu, W., Cui, Q., & Chen, H. (2022). Could China's long-term low-carbon energy transformation achieve the double dividend effect for the economy and environment? *Environmental Science and Pollution Research*, 29, 20128-20144. doi: 10.1007/s11356-021-14195-9.

[9] Jayasuriya, S., Zhang, G., & Yang, R.J. (2024). Towards successful economic infrastructure partnership project delivery through effective stakeholder management. *Transportation Research Interdisciplinary Perspectives*, 26, article number 101173. doi: 10.1016/j.trip.2024.101173.

[10] Klymchuk, M., Kukharuk, A., Ivanova, T., & Redko, K. (2022). Content and principles of economic harmonization of interests of industrial enterprises. *Economic Bulletin of NTUU "KPI"*, 24, 7-11. doi: 10.20535/2307-5651.22.2022.259832.

[11] Kopańska, A., Osinski, R., & Korbus, B. (2024). Private entities motivations to participate in public-private partnerships. *Socio-Economic Planning Sciences*, 92, article number 101841. doi: 10.1016/j.seps.2024.101841.

[12] Law of Ukraine No. 4510-IX "On Public-Private Partnerships". (2025, October). Retrieved from https://zakon.rada.gov.ua/laws/show/4510-20#Text.

[13] Mahame, C., Kikwasi, G.J., & Baruti, M.M. (2024). Barriers to the effective selection of sustainable materials for residential building projects: A qualitative study. *Sustainability,* 16(21), article number 9526. doi: 10.3390/su16219526.

[14] Osipova, L. (2025). Theoretical aspects of the process of harmonising economic interests in economic systems. *Economic Space*, 198, 209-214. doi: 10.30838/EP.198.209-214.

[15] Ovchinnikova, V.O., & Diakov, M.I. (2025). Formation of a mechanism for interaction between the enterprise and stakeholders. *Bulletin of Transport and Industry Economics*, 90, 274-281. doi: 10.18664/btie.90.337702.

[16] Sun, G., Zhang, W., Dong, J., Wan, S., & Feng, J. (2023). Behavioral decision-making of key stakeholders in public-private partnerships: A hybrid method and benefit distribution study. *CMES – Computer Modeling in Engineering and Sciences*, 136(3), 2895-2934. doi: 10.32604/cmes.2023.025652.

[17] Tavana, M., Nasr, A.Kh., Mina, H., & Michnik, J. (2022). A private sustainable partner selection model for green public-private partnerships and regional economic development. *Socio-Economic Planning Sciences*, 83, article number 101189. doi: 10.1016/j.seps.2021.101189.

[18] Toochukwu, A.C. (2025). Sustainable construction practices: Balancing cost efficiency, environmental impact, and stakeholder collaboration. *International Research Journal of Modernization in Engineering Technology and Science*, 7(1), 4118-4140. doi: 10.56726/IRJMETS66703.

[19] Tropeano, T., Bellazzecca, E., & Bengo, I. (2025). Exploring the functions and role of social impact measurement in enhancing the social value of public-private partnerships: A systematic literature review. *Public Policy and Administration*, 40(4), 535-560. doi: 10.1177/0952076724123864.

[20] Tytykalo, V.S. (2021). Determinants of state regulation of economic interests of enterprises. *Business Inform*, 5, 96-102. doi: 10.32983/2222-4459-2021-5-96-102.

[21] Węgrzyn, J., & Wojewnik-Filipkowska, A. (2022). Stakeholder analysis and their attitude towards PPP success. *Sustainability*, 14(3), article number 1570. doi: 10.3390/su14031570.

Узгодження економічних інтересів учасників концесійних проєктів розвитку транспортної інфраструктури

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Анотація. Метою цього дослідження було виявлення ключових аспектів вертикальної та горизонтальної координації економічних інтересів учасників концесійних проєктів у розвитку транспортної інфраструктури. Методи дослідження включали критичний огляд існуючої літератури, а також аналіз, порівняння, систематизацію та узагальнення інформації. У дослідженні було визначено коло учасників концесійних проєктів і проаналізовано основні елементи їх вертикальної координації (держава-концесіонер) та горизонтальної координації (концесіонер – акціонери – кредитори – проєктна організація – підрядники – сервісні компанії). Для кожного учасника проєкту розвитку транспортної інфраструктури на основі концесійної моделі було сформульовано набір інтересів і цільових показників, які забезпечують стабільність коаліції, що реалізує проєкт. Основні питання, що лежать в основі координації економічних інтересів, стосуються розподілу доходів, прибутків, відповідальностей і ризиків. Координація цих інтересів здійснювалась через вибір взаємно погоджених значень таких управлінських параметрів: 1) для публічного партнера – економічна вигода (прибуток), отримана від передачі активу в концесію; 2) для приватного партнера – доходи та прибуток від будівництва автостради та її подальшої експлуатації; 3) для інвесторів/кредиторів – необхідні кошти для виконання контрактних зобов'язань та реалізації проєкту, а також їх вартість; 4) для проєктувальника – обсяг і вартість проєктних робіт; 5) для підрядників (субпідрядників) – обсяг і вартість будівельних та монтажних робіт; 6) для операторів (організацій з утримання доріг) – обсяг і вартість управлінських послуг. Практична значущість результатів полягає в тому, що увага до цих показників під час створення концесіонерської організації та її подальшої роботи стимулювала б учасників до успішної реалізації проєкту

Ключові слова: економічний ефект; публічно-приватне партнерство; координація інтересів; прибуток; розподіл

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A new approach to increasing the lifecycle of energy storage for electric vehicle

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Abstract. The article identified the most promising aspects for achieving a significant level of development in lithium battery technology. The purpose of this work was to analyse a new approach to increasing the life cycle of lithium batteries by replacing cobalt with organic electrode material, to demonstrate the operational competitiveness of stable organic electrode materials in lithium-ion batteries, and to determine the advantages of such application. The object of the study was the physicochemical foundations of organic materials that dissolved in the electrolyte of a lithium-ion battery and their transfer to the opposite side of the battery. The research method involved an analysis of the optimal properties of the physicochemical basis of organic materials and cathodes of lithium-ion batteries on an inorganic basis at the electrode level. The article analysed the results of scientific studies devoted to the development of high-performance lithium-ion batteries, mainly using organic electrode materials, namely bis-tetraaminobenzoquinone, composed of carbon, nitrogen, oxygen and hydrogen. It was found that tetraaminobenzoquinone, owing to hydrogen bonds, formed nearly flat sheets, which allowed effective layering and storage of lithium ions and provided a tenfold increase in gravimetric energy density. The article identified the advantages of organic electrode materials in comparison with leading contemporary lithium-ion integrated batteries cathode technologies. The results of the research based on the new organic battery technology made it possible to suggest the potential for a breakthrough in the field of large-capacity batteries and the development of batteries with high charge storage density and rapid charging capability. The article is recommended for specialists in electric transport and manufacturers of electric vehicles, as well as for specialists of operating enterprises carrying out conversions, in particular of trolleybuses with autonomous propulsion

Keywords: battery; cobalt-free cathodes; charging; hydrogen bonding; organic material

Introduction

The issue of saving fuel and energy resources and the use of energy-efficient methods is the most important and acts as a priority direction in the economic policy of the state. The need to develop the road and transport complex is due to the improvement of the technical characteristics of vehicles and the introduction of energy-efficient and resource-saving technologies. This is influenced by the increase in the price of fuels and lubricants for motor vehicles and road machinery; the energy intensity of the country's gross product is almost twice as high as the European one. Therefore, the strategic direction of the state policy for the development of the economic and social sphere is to strengthen energy saving, which ensures high economic efficiency. According to S.V. Voitkiv (2023), a key measure in the implementation of resource-saving structural optimisation is the use of resources, which is based on the implementation of new technological solutions using non-traditional materials and energy sources. Solving energy saving issues when operating electric vehicles requires a special method of energy saving and, accordingly, increasing the service life of energy storage devices for electric vehicles. Scientific discourse focuses on the prospects for improving batteries for electric vehicles.

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Lithium-ion batteries (LIBs) play a crucial role in the decarbonisation of electric transport and energy networks. N.V. Martyushev *et al.* (2023) determined that LIBs depend on expensive, earth-scarce cobalt in the widely used high-energy layered cathodes. Authors revealed the role of lithium deficiency in suppressing the phase transformation of rock salt into a layered structure and crystal growth using multi-scale correlated experimental characterisation and computer simulation of the calcination process. The study resulted in small-sized composites with desirable low anisotropic lattice expansion/contraction during charging and discharging. This provided significant first-cycle coulombic efficiency, 90% capacity retention, and near-zero voltage drop over 100 deep cycles, demonstrating its potential as a trackless cathode for stable LIBs. Using stoichiometry, N.V. Martyushev *et al.* (2023) demonstrated an effective route to structural and morphological tuning of lithium batteries to stabilise cobalt-free cathodes. Moreover, the desired cost-effectiveness was obtained, which was achieved by eliminating additional coating/doping steps, and a promising and cost-effective alternative to cobalt-dependent cathodes was proposed. Therefore, the study addressed the critical need for the development of stable and commercially viable LIBs. M. Mądziel & T. Campisi (2023) highlighted the importance of addressing the scaling and manufacturing challenges associated with cobalt-free cathode materials to enable widespread adoption in commercial batteries. The study summarised the scientific and technical gaps and potential of a variety of cobalt-free lithium-ion cathodes, including layered, spinel, olivine, and disordered rock salt systems. It also predicted the enormous potential of cobalt-free LIBs for sustainable electric vehicle production in the coming decades.

The study by R.V. Bagach (2021) identified the critical design parameters of high-nickel layered oxide cathodes intended for implementation in electric vehicles over the coming decade. It is noted that nickel is of great interest for the production of layered oxide cathodes due to its lower cost, wider availability and lower toxicity than other constituent elements. The study outlined various intrinsic limitations to maximising their energy output. Furthermore, current/new development roadmaps approaching low-cobalt/zero-cobalt chemistries were compared. Attention was paid to the production of materials related to cost reduction and solving practical problems of high-nickel layered oxides for electric vehicles. As a result, a series of stabilisation methods were evaluated for their prospects for achieving aggressive vehicle electrification goals. V. Haydamaka & L. Ivanov (2022) analysed in detail the scientific basis of the synthesis of single-crystal materials and comparative studies between single-crystal and polycrystalline materials. Single-crystal materials have great potential to solve the problems that hinder their polycrystalline counterparts. Industrial methods and equipment have been identified, which are considered in combination with some experience in single-crystal research. As a result, it has been found that future development should focus on simplified production with strict control of particle size and distribution, structural defects and impurities, in order to fully exploit the advantages of single-crystal materials. In this context, the following prospects for single-crystal technology have been considered:

1. Development direction. The favourable properties of single-crystal materials were taken into account and the need to develop a route to single-crystal cathodes for layered oxides with an ultra-high nickel content was emphasised.

2. Synthesis problems. To solve this problem, the molten salt method was recently applied, which included comparative studies of different salts instead of the high-temperature method. According to the results of the study, it was found that the growth of crystal faces can improve the transport of lithium ions in the presence of any type of salt.

3. Further technologies. During the study, it was determined that additional processing procedures, including grinding, sieving and washing, have a significant impact on the electrochemical characteristics of single-crystal materials, as two important steps for obtaining single-crystal materials with well-distributed sizes. It was found that single-crystal materials can take advantage of particle size tuning to maximise volumetric energy density.

4. Electrochemical properties. In order to gain insight into the rational design of cathode materials with thermal and cyclic stability, it is necessary to investigate the relationship between the properties and characteristics of single-crystal materials.

Ensuring that single-crystal materials exhibit optimal properties is crucial, which highlights the necessity of developing reliable strategies for synthesising single-crystal cathodes based on layered oxides with ultra-high nickel content. According to V. Haydamaka & L. Ivanov (2022), the strategies for modifying single-crystal cathodes are at an early stage and require further research. Issues of operational characteristics and resource efficiency, in particular, of traction batteries, are considered in works by W. Li *et al.* (2020) and S. Lee & A. Manthiram (2022). The advantages of replacing inorganic cathodes with organic electrode materials (OEMs) were investigated by P. Poizot *et al.* (2020) and J. Kim *et al.* (2023). The implementation of such technologies is expected to play an important role in achieving global decarbonisation goals and supporting the broader adoption of electric vehicles. The purpose of this work was to evaluate a new method for extending the service life of LIBs by replacing cobalt with organic electrode materials, to illustrate the functional competitiveness of durable OEMs in real batteries, and to determine the advantages of this application.

Materials and Methods

The study had a theoretical nature and was conducted within the framework of a qualitative analytical design. The object of analysis was the process of solving the issues of fast charging and longevity of LIBs, while the subject was the properties of OEMs. A literature review was conducted with a focus on cobalt-free cathode materials for LIBs and alternative technologies for replacing cobalt in LIB cathodes. The selection of sources included works by Y. Wang *et al.* (2008), S.W.D. Gourley *et al.* (2020) and A. Zeng *et al.* (2022). Emphasis was placed on the approaches of R. Zhang & L. Ma (2023), who demonstrated that organic materials composed of abundant elements provide high specific capacity due to the dense arrangement of redox centres and low molar mass. Literature was searched through scientific databases such as Scopus, Web of Science, and Google Scholar using keywords such as "cobalt-free cathode", "organic electrode material TAQ", "bis-tetraaminobenzoquinone", "redox-active organic cathode", and "lithium-ion battery cobalt replacement".

The methodology included a systematic critical literature review to identify and assess relevant publications. A content analysis of scientific texts was used for in-depth analysis, employing categorical coding that covered chemical structure, redox-reaction mechanisms, molecular packing, solubility in electrolytes, Li^+ ion diffusion, electronic conductivity, cyclic stability, and energy density at the electrode level. A comparative method was used to contrast the characteristics of TAQ with traditional cathodes Mn (e.g., $LiCoO_2$ (LCO) and $LiNi_{1-x-y}MnxCoyO_2$ (NMC), $LiFePO_4$ (LFP)), particularly in terms of electrochemical efficiency and operational stability. A synthetic analysis combined results from various studies to create a conceptual model of the advantages of TAQ as a cobalt-free cathode material. Special attention was given to the analysis of graphical materials, including diagrams, spectroscopic data (^1H and ^{13}C NMR), and structural schemes presented in the source base of the article. The critical evaluation method allowed for the identification of the limitations of existing organic materials, such as solubility, low conductivity, and the need for large additives, and justified the innovative potential of TAQ due to its properties: virtually zero solubility, high electronic conductivity due to intermolecular interactions, and rapid Li^+ diffusion in the two dimensions (2D)-layered structure. The study was based on an interdisciplinary approach combining elements of materials science, electrochemistry, and environmental chemistry. The methodology used enabled the generalisation of the current state of research and the formulation of conclusions regarding the practical prospects of using TAQ in LIBs for electric transportation.

Results and Discussion

A key avenue for advancing energy-efficient technologies in the transportation sector is the deployment of lithium-ion batteries in electric vehicles. Batteries are designed to store and use electricity that is not used during generation, increasing energy self-sufficiency and independence. It should be noted that LIBs are the predominant energy storage solutions for energy efficiency in electric vehicles. It is modern LIBs that provide high energy density, which ensures sufficient range. Energy density is a crucial indicator for electric vehicles, as it determines the range. Conventional cathodes for LIBs are made of inorganic oxides, particularly Co, Ni, and Mn (LCO, NMC, LFP). Among these, cobalt presents serious limitations due to its rarity and significant social costs (e.g., child labour). The complete elimination of cobalt has been difficult because cobalt-free oxide cathodes experience insufficient cycling or capacity (Wang *et al.*, 2008). In fact, electric vehicles currently use mainly cobalt-based batteries. But the growth of the global electric vehicle fleet is virtually impossible without the development of cobalt-free technologies, as noted by A. Zeng *et al.* (2022). Articles by J.-M. Tarascon (2010), D. Larcher & J.-M. Tarascon (2015) and B.M. Spears *et al.* (2022) identified an organic substance that could replace the environmentally harmful cobalt currently widely used in LIBs. Redox organic materials derived entirely from earth-based elements represent just such an opportunity. TAQ is a distinct organic compound, or TAQ, composed of carbon, nitrogen, oxygen, and hydrogen. Its structure, a sequence of three connected hexagons, is similar to graphite, which is often used in battery anodes. TAQ is characterised by the fact that it forms nearly flat sheets through hydrogen bonding, which allows it to efficiently layer and store lithium ions (Mishchenko, 2024). From a design perspective, small organic molecules offer high specific capacity due to the compact arrangement of redox centres and their low molar mass compared to redox polymers or framework materials. However, discrete molecules typically have low bulk conductivity and are often soluble in battery electrolytes, leading to poor utilisation of redox sites, low charge-discharge rates, and poor cycling stability (Lu *et al.*, 2018; Lu & Chen, 2020). These problems are routinely addressed by the addition of conductive and/or stabilising polymer additives, often exceeding 50 wt%, which significantly reduces the effective capacitance, making the electrodes impractical (Luo *et al.*, 2017). Consequently, there remains considerable enthusiasm for the fabrication of inherently insoluble and conductive OEMs. The goal is to achieve high specific capacitances at appropriate cathode potentials exceeding 2.0 V for LIBs, as shown in Figure 1.

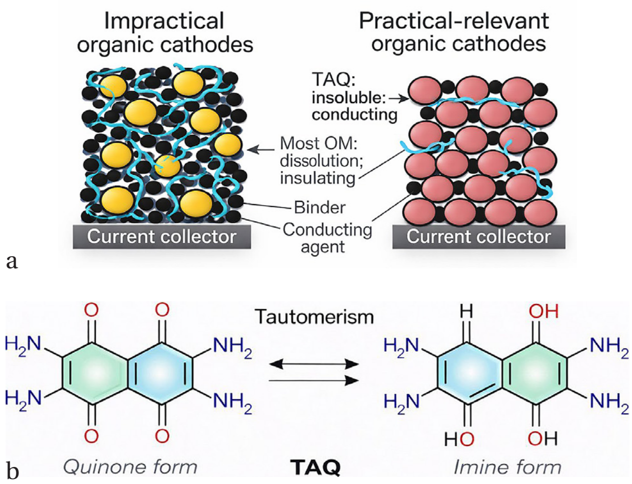

Figure 1. Characteristics of TAQ
Source: R. Zhang & L. Ma (2023)

Poly(acetylene), poly(pyrrole), poly(thiophene) and poly(aniline) are omitted because they function through anion incorporation rather than Li^+ incorporation. Asterisks indicate a rapid capacity decline during the first few cycles, mainly as a result of dissolution. TAQ, a molecule consisting of fused conjugated elements with a rigid layered arrangement in the solid state, has been found to be an effective component for OEMs used in LIB cathodes, exhibiting properties such as fast charging, high energy density, and extended cycle life (MIT team develops…, 2024). The defining feature of TAQ is its tightly packed structure, which includes a conjugated framework filled with redox-active carbonyl (C=O) and imine (C=N) groups. These are the active sites. The TAQ molecule exhibits strong intermolecular hydrogen bonds and donor-acceptor ϖ–ϖ interactions, which render it insoluble in standard battery electrolytes. At the same time, these interactions contribute to the extended electron delocalisation within the molecule, leading to high bulk conductivity, as shown in reference (Zhang & Ma, 2023). Due to its small solid-state packing, TAQ exhibits very low solubility in common organic solvents and battery electrolytes. A notable observation is that when TAQ is heated in deuterated N,N-dimethylformamide at 120°C for extended periods of time, including overnight, it becomes virtually insoluble. This conclusion is supported by the fact that the 1H and 13C spectra of the supernatant show no detectable signals corresponding to TAQ. Due to its small solid-state packing, TAQ exhibits very low solubility in common organic solvents and battery electrolytes. The minimal solubility of TAQ, which is maintained even at elevated temperatures, is strikingly different from that of other OEMs used in lithium-ion batteries (LIBs). This characteristic is crucial for achieving extended battery life in these batteries (Zhang & Ma, 2023). Due to these specific characteristics, electrodes containing a minimum of 90 wt% TAQ are able to store charge reversibly and operate safely for more than two thousand cycles. This is a notable improvement, especially when compared to the persistent electrode dissolution problems often observed in established OEMs (Fig. 1). The layered structure characteristic of TAQ molecules in two dimensions 2D facilitates the easy movement of Li^+-ions – both input and extraction – within the layers. Thus, extraordinary capabilities are achieved with full charging in just three minutes. In addition, the optimised electrodes demonstrate excellent performance. They maintain this quality even when operating with significant planar loads, reaching 16 mg/cm^2. The resulting capacity area, up to 3.52 mAh cm^{-2}, rivals that observed in commonly used LIBs. This fully demonstrates the potential of TAQ for practical applications in the field of LIBs (Zhang & Ma, 2023). This metal-free, layered organic material, designed for use as a cathode in Li-ion batteries, offers superior performance. It facilitates the intercalation of Li^+ ions and achieves a higher energy storage capacity within a significantly reduced charging duration, compared to the established inorganic battery technologies. AQ electrodes, when composed of a pure substance, demonstrate commendable durability, enduring no fewer than 50 cycles. These cycles are executed under a constant-current constant-voltage (CCCV) regime, set at a rate of 0.2 C for charging and 0.125 C for discharging. The experiments conducted by R. Zhang & L. Ma (2023) involved a complete depletion of capacity, reaching a 100% depth of discharge (DOD). After this rigorous testing, the electrodes retained 75% of their original capacity, with an average coulombic efficiency (CE) exceeding 98% (Fig. 2).

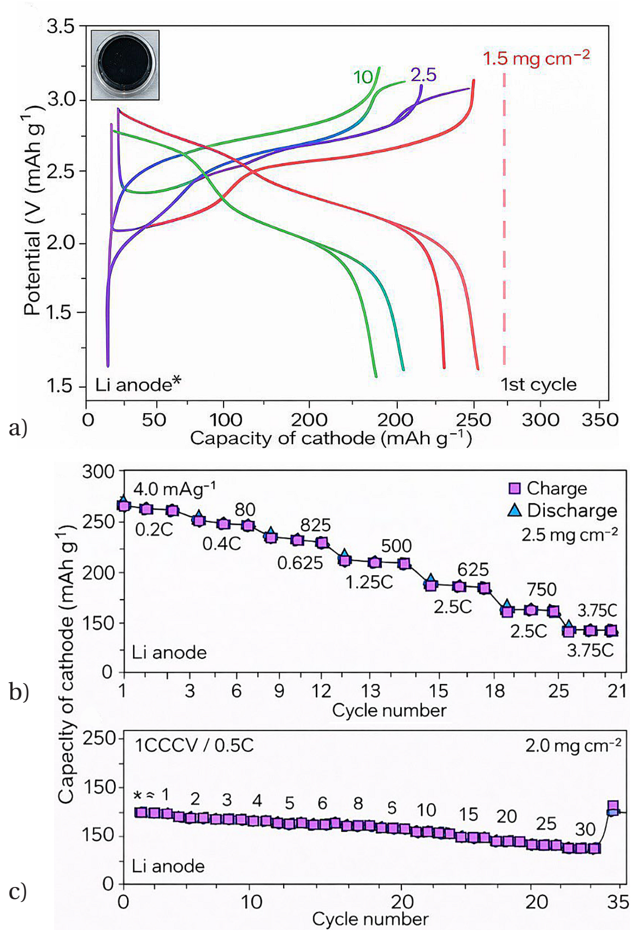

Figure 2. Characterisation of clean TAQ electrodes
Source: R. Zhang & L. Ma (2023)

The cycling behaviour demonstrated by these pristine factory standard electrodes surpasses all previous records. This remarkable performance is indicative of the efficient ion diffusion and charge transfer characteristics of TAQ, as well as its almost complete resistance to dissolution in standard battery electrolyte solutions. In fact, although the claimed voltage of TAQ is lower than that of traditional inorganic cathodes, the gravimetric specific energies observed in the electrode itself in the C range exceed those of even the most advanced inorganic cathodes. The energy density achieved at the electrode level with TAQ cathodes exceeds that of many alternative composite cathodes. These include single crystal NMC811 (NMC811-sc), as well as the conventional polycrystalline variants NMC811 and NMC111. Furthermore, TAQ cathodes outperform even advanced cobalt-free oxides. This advantage, which provides an increase of at least 20-30%, is maintained over a wide range of charge/discharge rates, extending from approximately 0.1 C to 10 C (Zhang & Ma, 2023). Moreover, TAQ outperforms LiFePO4 graphite-coated cathodes (LFP-GC) in terms of gravimetric energy density, achieving this at a charging rate that is at least ten times faster (MIT team develops…, 2024; Chen *et al.*, 2024). It should be noted that although the nominal voltage of TAQ is lower than that of conventional inorganic cathodes, the gravimetric specific energies at the electrode level for TAQ cathodes in the range of C values exceed even those of optimised inorganic cathodes. As the analysis showed, cobalt, a critical metal used in LIBs, is predominantly obtained from low-concentration by-products of nickel and copper mining, making it the most valuable metal in this context. Given this, the necessity and feasibility of developing cobalt-free materials and substituting them with organic materials for LIBs have been carefully evaluated. Therefore, increasing efforts to develop cobalt-free cathode materials, particularly through the use of layered organic electrodes with advantageous properties, presents a promising solution to the issue of cobalt scarcity. This approach could significantly enhance the performance of LIBs and contribute to their widespread adoption, especially in electric vehicles.

Based on a comparison of results reported by various authors and the present study, several trends were identified. First, it was evident that cobalt-free cathode materials, particularly organic alternatives, show promising potential for replacing cobalt in LIBs, as highlighted in the studies by S. Lee & A. Manthiram (2022). Depending on the cathode composition, 80-200 g of cobalt per kWh is added to commercial LIBs. Cobalt has long been an important element in the layered oxide cathode family, from the parent LCO composition to the NMC family with various Ni/Mn/Co ratios. The paper also considered the possibility of replacing Co with Ni and Mn as a viable way to increase the usable specific capacitance by utilising $Ni^{2+}/^{3+}$ and $Ni^{3+}/^{4+}$ redox centres while maintaining the advantages of Co, such as good electronic conductivity and low Li/Ni miscibility for easy ionic conductivity. Therefore, layered oxides with increasing Ni content are gradually being introduced. At the limit of Ni content is the archetypal high-energy material LiNiO2 (LNO), which provides an average voltage of ~3.8 VLi (V vs Li/Li) and a specific capacity of up to ~240-250 mAh^{+}. However, increasing the Ni content in layered oxides also increases surface, structural and thermal instabilities, which negatively affects battery life and safety. At higher lithium extraction rates at high state of charge (SoC), layered oxides with high Ni content undergo a phase transformation (H2 → H3), which causes large anisotropic compression and collapse of the layered structure. It was found that during thermal retreat, layered oxides with high Ni content experienced a larger exothermic energy release at a lower initial temperature, which compromised battery safety. Rational compositional designs and material engineering strategies on high-Ni oxides, such as surface coatings and electrolyte modifications, have achieved some success in overcoming these instability issues. Thus, high-layer oxide cathodes remain an ideal choice for electric vehicles due to their high energy density, sufficient cycle life and rate performance, and long-standing large-scale synthesis infrastructure (Lee & Manthiram, 2022). Although Fe- and Mn-based cathodes have lower energy densities, they are attractive alternatives to Co- and Ni-based cathodes for electric vehicles due to the abundance of raw materials. LFP is the most ideal Fe-based compound, providing decent energy density at the material level (~3.4 V Li, ~160 mAh g^{-1}). Combined with the facile phase transformation kinetics with nanoparticles and low charge cut-off voltage (~3.6 V), LFP has demonstrated exceptional cycle life and rate capability, as well as robust resistance to extreme operating conditions. As a result, a low-Ni cathode, HE-N50, was successfully developed to remove Co from a commercial ternary layered cathode based on a sophisticated concentrated doping strategy This strategy provided outstanding structural and thermal stability, leading to improved cycling performance both at room temperature and under thermal stress conditions. Furthermore, the reduced use of Ni and zero use of Co can reduce the cost of the cathode compared to the basic NMC materials while maintaining high energy density. This work also opened up opportunities for optimising low-NiMn cathodes, including Li-excess cathodes, through controlled combinations of several elemental components.

The article by S.W.D. Gourley *et al.* (2020) raised the need to develop cobalt-free cathode materials for LIBs. LIBs are a straightforward solution for recovering cobalt, but the technical challenges of disassembling the battery pack and the mixed metal components limit its use. A more efficient and long-term solution for a sustainable future for LIBs is the development of cobalt-free cathode materials. To achieve a significant increase in energy density, the cathode must be combined with a high-capacity anode, specifically silicon or lithium metal. Engineering innovation is needed to optimise cell production for these new technologies. As noted in the article, LIB technology for electric vehicles is currently dominated by two main cathode compositions – layered $LiNi_{1-x-y}KoxElO_2$, $x + y < 0.2$ (NCA) and $LiNixMinnesotayKozO_2$, $x + y + z = 1$ (NMC). Among NMC-type compositions, LiNi1/3Minnesota1/3Ko1/3O2 (NMC111) is the best known, characterised by its stability and safety. Taking into account the increase in power (at 4.3 V versus the upper limit of Li/Li) and low cobalt content, a replacement for NMC111 (~160 mAh g^{-1}, 20.4 wt% Co) was developed with LiNi0.6Minnesota0.2Ko0.2O2 (NMC622, ~180 mAh g^{-1}, 12.2 wt% Co) and LiNi0.8Minnesota0.1Ko0.1O2 (NMC811, ~200 mAh g^{-1}, 6.1 wt% Co) (Myung Ni-rich cathodes also suffer from increased sensitivity to moisture. These cathodes exhibit Li/Ni^{+2+} cationic mixing and electrolyte side reactions (solvent oxidation from Ni^{4+}). They are also characterised by phase transitions to spinel and rock salt structures. Furthermore, they exhibit oxygen evolution at elevated temperatures and stresses (Gourley *et al.*, 2020). This study also proposed a promising approach to addressing these issues: synthesising NMCs in the form of micron-sized single-crystal particles. The single-crystal morphology has a minimal number of grain boundaries and, therefore, is capable of mitigating particle cracks and side reactions with the electrolyte. It was found that one of the most promising approaches to developing cathodes for LIBs with less cobalt dependence was the improvement of multilayer LiNi with Ni-xMxO$_2$ (M = Mn, Al, and/or Co) materials. Accordingly, the main barriers hindering the further adoption of cobalt-free layered cathodes over existing materials in modern lithium-ion batteries (LIBs) are thermal instability. This study confirms the feasibility of replacing cobalt with nickel in NMC and NCA-type compositions, which has proven to be an effective method for stabilising Ni^{2+} ions in the transition metal layer, thereby reducing the degree of cation mixing. High-temperature performance (≥50°C) can improve the rate for cobalt-free formulations; however, operating above 30°C may accelerate structural failure.

Therefore, the use of modern low-cobalt materials (e.g., NMC622, NMC811, NCA) is not a sufficient mitigation strategy, as cobalt supply shortages may arise in the near future depending on the sales situation of electric vehicles. S.W.D. Gourley *et al.* (2020) noted that, due to their high energy density, layered transition metal oxides based on $LiNiO_2$ have attracted significant research efforts. A cation doping strategy was considered, which can be combined with morphology control (e.g., individual crystals to suppress cracks). Moreover, the doping strategy can also be combined with coatings that improve interparticle conductivity, provide a protective barrier against electrolyte side reactions, suppress oxygen production, and adjust the oxide packing structure to suppress phase changes. Research in this area has provided the most practical and immediate path to the use of cobalt-free cathodes. On the other hand, cationically disordered rock salt cathodes represent a new class of materials with high energy density (up to ~1,000 Wh kg^2). The results of J. Song *et al.* (2016) demonstrated that applying an ultrathin, highly graphitic carbon coating to LiFePO4 significantly enhances electronic conductivity and reduces the Li^+ diffusion path, enabling excellent rate performance and cycling stability even at high currents and low temperatures. In the present study, TAQ also outperforms traditional LFP-GC in energy density, with at least ten times faster charging speed, without requiring additional conductive additives due to its own high electronic conductivity, attributed to hydrogen bonding and ϖ–ϖ interactions. Thus, while both approaches aim to overcome the low conductivity of LFP, TAQ offers a more radical solution – a complete shift away from inorganic cathodes and cobalt, providing higher capacity with minimal additives and a significantly longer lifespan. In the work of C. Barchasz *et al.* (2013), the focus was on ether-based electrolytes for lithium-sulphur batteries, where the key issue is the dissolution of polysulfides, leading to the "shuttle effect" and rapid capacity degradation during cycling. In contrast, the key achievement of TAQ in this study is its virtually zero solubility in standard lithium-ion battery electrolytes, due to strong intermolecular hydrogen bonds and dense packing, which completely prevents material migration and short circuits, allowing for over 2,000 stable cycles.

Based on the conducted analysis, it has been determined that the potential for replacing cobalt with other organic materials or avoiding reliance on cobalt in LIBs is both feasible and promising. Fe- and Mn-based cathodes, although having lower energy densities, present an attractive alternative to Co- and Ni-based cathodes. Therefore, replacing Co with Ni and Mn has been proposed as a viable way to increase the specific capacity of LIBs. Furthermore, as an alternative to substituting Co with Ni, an ideal mixture of LiFePO4 (LFP) has been proposed, which provides a respectable energy density at the material level (~3.4 V Li, ~160 mAh g^{-1}). LFP remains a viable and cobalt-free alternative as long as the energy density at the cell level is adequate. It is noteworthy that the electrical conductivity of TAQ is comparable to that of LCO and modern NMC, and approximately five orders of magnitude higher than that of LFP. These favourable properties of TAQ enable the production of electrodes with minimal or no additives. Equally important is that TAQ provides a higher gravimetric energy density than graphite-coated LiFePO4 (LFP-GC) cathodes, with a charge rate at least ten times higher. In terms of energy density, TAQ offers at least 20-30% higher energy density at the electrode level compared to most monocrystalline oxide composite cathodes, commercial polycrystalline cathodes, and even modern cobalt-free oxides. The proposed method may reduce or even eliminate the need for cobalt, leading to the development of a new generation of LIBs.

Conclusions

The research has thus identified a cobalt replacement: a layered organic electrode. This material has properties that are important for excellent battery performance. Its excellent electrical conductivity, significant storage capacity, and absolute insolubility contribute to the smooth intercalation of Li^+ ions. It rivals the capabilities of traditional inorganic lithium-ion battery cathodes, matching them in all key performance indicators at the electrode level. It is worth noting that the results demonstrate the practical viability of stable organic electrode materials in the field of LIBs, highlighting their functional advantages. TAQ electrodes also have the significant advantage of offering a higher volumetric energy density compared to similar LFP electrodes. The author notes that TAQ offers significant advantages over the common cathode technologies for LIBs currently available. The primary pathway for organic materials to degrade is through their dissolution in the battery electrolyte. The dissolved material then migrates to the opposite side of the battery, ultimately leading to a short circuit. The author believes that by making the material completely impermeable to dissolution, this phenomenon is prevented, allowing for over 2,000 charge cycles with little degradation. It should be noted that the material cost of assembling these organic batteries can be approximately one-third to one-half the cost of cobalt batteries. Overall, the findings indicate that the development of cobalt-free organic cathodes, particularly with TAQ, could revolutionise LIB technology, offering enhanced performance and sustainability for future energy storage solutions. Further research should focus on optimising manufacturing processes for the production of cobalt-free organic cathodes, enhancing their stability at high temperatures, improving their durability and ensuring the cost-effectiveness of large-scale production, as well as on refining electrolytes to maximise their compatibility with new materials.

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Conflict of Interest

None.

References

[1] Bagach, R.V. (2021). Prospects for further improvement of batteries for electric vehicles. In *The latest technologies in automotive engineering, transport and specialist training: Scientific papers from the international scientific and practical conference* (pp. 346-349). Kharkiv: Kharkiv National Automobile and Highway University.

[2] Barchasz, C., Leprêtre, J.-C., Patoux, S., & Alloin, F. (2013). Electrochemical properties of ether-based electrolytes for lithium/sulfur rechargeable batteries. *Electrochimica Acta*, 89, 737-743. doi: 10.1016/j.electacta.2012.11.001.

[3] Chen, T., Banda, H., Wang, J., Oppenheim, J.J., Franceschi, A., & Dincă, M. (2024). A layered organic cathode for high-energy, fast-charging, and long-lasting Li-ion batteries. *ACS Central Science*, 10(3), 569-578. doi: 10.1021/acscentsci.3c01478.

[4] Gourley, S.W.D., Or, T., & Chen, Z. (2020). Breaking free from cobalt reliance in lithium-ion batteries. *iScience*, 23(9), article number 101505. doi: 10.1016/j.isci.2020.101505.

[5] Haydamaka, V., & Ivanov, L. (2022). Accumulator batteries. Impact on the life cycle of the battery. In I.Sh. Nevlyudov (Ed.), *M&MS 2022: Proceedings of the international scientific conference*. Kharkiv: Kharkiv National University of Radioelectronics.

[6] Kim, J., Kim, Y., Yoo, J., Kwon, G., Ko, Y., & Kang, K. (2023). Organic batteries for a greener rechargeable world. *Nature Reviews Materials*, 8, 54-70. doi: 10.1038/s41578-022-00478-1.

[7] Larcher, D., & Tarascon, J.-M. (2015). Towards greener and more sustainable batteries for electrical energy storage. *Nature Chemistry*, 7, 19-29. doi: 10.1038/nchem.2085.

[8] Lee, S., & Manthiram, A. (2022). Can cobalt be eliminated from lithium-ion batteries? *ACS Energy Letters*, 7, 3058-3063. doi: 10.1021/acsenergylett.2c01553.

[9] Li, W., Erickson, E.M., & Manthiram, A. (2020). High-nickel layered oxide cathodes for lithium-based automotive batteries. *Nature Energy*, 5, 26-34. doi: 10.1038/s41560-019-0513-0.

[10] Lu, Y., & Chen, J. (2020). Prospects of organic electrode materials for practical lithium batteries. *Nature Reviews Chemistry*, 4, 127-142. doi: 10.1038/s41570-020-0160-9.

[11] Lu, Y., Zhang, Q., Li, L., Niu, Z., & Chen, J. (2018). Design strategies toward enhancing the performance of organic electrode materials in metal-ion batteries. *Chem*, 4, 2786-2813. doi: 10.1016/j.chempr.2018.09.005.

[12] Luo, Z., Liu, L., Zhao, Q., Li, F., & Chen, J. (2017). An insoluble benzoquinone-based organic cathode for use in rechargeable lithium-ion batteries. *Angewandte Chemie International Edition*, 56, 12561-12565. doi: 10.1002/anie.201706604.

[13] Mądziel, M., & Campisi, T. (2023). Energy consumption of electric vehicles: Analysis of selected parameters based on created database. *Energies*, 16(3), article number 1437. doi: 10.3390/en16031437.

[14] Martyushev, N.V., Malozyomov, B.V., Sorokova, S.N., Efremenkov, E.A., & Qi, M. (2023). Mathematical modeling of the state of the battery of cargo electric vehicles. *Mathematics*, 11(3), article number 536. doi: 10.3390/math11030536.

[15] Mishchenko, T. (2024). *Lamborghini licenses new high-capacity organic battery technology developed at MIT*. Retrieved from https://mezha.media/2024/01/22/lamborghini-tekhnolohiia-akumuliatoriv/.

[16] MIT team develops organic alternative to cobalt cathodes. (2024). Retrieved from https://www.theengineer.co.uk/content/news/mit-team-develops-organic-alternative-to-cobalt-cathodes.

[17] Poizot, P., Gaubicher, J., Renault, S., Dubois, L., Liang, Y., & Yao, Y. (2020). Opportunities and challenges for organic electrodes in electrochemical energy storage. *Chemical Reviews*, 120, 6490-6557. doi: 10.1021/acs.chemrev.9b00482.

[18] Song, J., Sun, B., Liu, H., Ma, Z., Chen, Z., Shao, G., & Wang, G. (2016). Enhancement of the rate capability of LiFePO4 by a new highly graphitic carbon-coating method. *ACS Applied Materials & Interfaces*, 8, 15225-15231. doi: 10.1021/acsami.6b02567.

[19] Spears, B.M., Brownlie, W.J., Cordell, D., Hermann, L., & Mogollón, J.M. (2022). Concerns about global phosphorus demand for lithium-iron-phosphate batteries in the light electric vehicle sector. *Communications Materials*, 3, article number 14. doi: 10.1038/s43246-022-00236-4.

[20] Tarascon, J.-M. (2010). Key challenges in future Li-battery research. *Philosophical Transactions of the Royal Society A*, 368, 3227-3241. doi: 10.1098/rsta.2010.0112.

[21] Voitkiv, S.V. (2023). Directions of energy saving in urban electric bus transport. In V.H. Daleka, N.I. Kulbashna & A.V. Kovalenko (Eds.), *Proceedings of the all-Ukrainian scientific and practical conference* (pp. 128-130). Kharkiv: Kharkiv National University of Municipal Economy named after O.M. Beketov.

[22] Wang, Y., Wang, Y., Hosono, E., Wang, K., & Zhou, H. (2008). The design of a LiFePO4/carbon nanocomposite with a core-shell structure and its synthesis by an in situ polymerization restriction method. *Angewandte Chemie International Edition*, 47(39), 7461-7465. doi: 10.1002/anie.200802539.

[23] Zeng, A., *et al.* (2022). Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nature Communications*, 13, article number 1341. doi: 10.1038/s41467-022-29022-z.

[24] Zhang, R., & Ma, L. (2023). Long-life lithium-ion batteries realized by low-Ni, Co-free cathode chemistry. *Nature Energy*, 8(7), 695-702. doi: 10.1038/s41560-023-01267-y.

Новітній підхід щодо збільшення життєвого циклу енергонакопичувача для електричного транспортного засобу

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Анотація. У статті визначено найбільш перспективні аспекти для досягнення значного рівня розвитку технології літієвих батарей. Метою роботи було проаналізувати новий підхід до збільшення терміну служби літієвих батарей шляхом заміни кобальту на органічний електродний матеріал, продемонструвати експлуатаційну конкурентоспроможність стабільних органічних електродних матеріалів у літій-іонних батареях, а також визначити переваги такого застосування. Об'єктом дослідження стали фізико-хімічні основи органічних матеріалів, які розчиняються в електроліті літій-іонної батареї та їх перенесення на протилежний бік батареї. Метод дослідження полягав в аналізі оптимальних властивостей фізико-хімічної основи органічних матеріалів і катодів літій-іонних батарей на неорганічній основі на рівні електродів. У статті проаналізовано результати наукових досліджень, присвячених розробці високопродуктивних літій-іонних батарей, переважно з використанням органічних електродних матеріалів, а саме біс-тетраамінобензохінону, що складається з вуглецю, азоту, кисню та водню. Було встановлено, що тетраамінобензохінон завдяки водневим зв'язкам утворює майже пласкі листи, які дозволяють ефективно шарувати та зберігати іони літію, забезпечуючи десятикратне збільшення гравіметричної густини енергії. У статті визначено переваги органічних електродних матеріалів порівняно з провідними сучасними технологіями катодів інтегрованих літій-іонних батарей. Результати дослідження на основі нової органічної технології батарей дали змогу запропонувати потенціал для прориву в галузі великоємкісних батарей та розробки акумуляторів із високою густиною зберігання заряду та можливістю швидкого заряджання. Статтю рекомендовано для спеціалістів електричного транспорту та виробників електромобілів, а також для фахівців експлуатаційних підприємств, які здійснюють переобладнання, зокрема тролейбусів з автономним ходом

Ключові слова: акумулятор; катоди без кобальту; заряджання; водневі зв'язки; органічний матеріал

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Prospects of the National Transport Strategy of Ukraine

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Abstract. The relevance of this study stems from the need to reassess the directions of Ukraine's transport system development in the context of military challenges, the restoration of damaged infrastructure, and deeper integration into the European transport area. Of particular importance is the formulation of an effective, sustainable and environmentally oriented transport policy capable of ensuring economic recovery and improving the quality of transport services. The aim of the study was to analyse the objectives of the National Transport Strategy of Ukraine up to 2030, assess the status of its implementation under current conditions, and justify the priority directions for the further development of the transport system, taking into account European standards and the principles of sustainable development. The study utilised methods of analysis and synthesis of scientific sources, comparative analysis of strategic and regulatory documents, as well as a systematic approach to assessing the state of transport infrastructure and the prospects for the development of electric transport. The information base comprised state programmes, scientific publications and analytical materials in the field of transport. The study analysed the key provisions of the National Transport Strategy of Ukraine up to 2030, in particular the directions for infrastructure modernisation, integration into the Trans-European Transport Network (TEN-T), the development of multimodal transport, and the introduction of environmentally friendly modes of transport. It has been established that the implementation of a significant portion of the measures is being hindered in part by financial constraints, institutional problems and the impact of military operations. The main challenges facing the development of public transport have been identified, including the ageing of the rolling stock, insufficient funding and the underdevelopment of the charging infrastructure for electric transport. Based on the analysis, promising directions for formulating an updated transport strategy have been substantiated, including the development of electric buses, the expansion of the charging station network, the introduction of intelligent transport systems, and increased state support for the modernisation of the transport fleet. The practical value of the results lies in their potential application in the development of national and regional transport infrastructure programmes, as well as in the formulation of an effective transport policy for Ukraine in the context of post-war reconstruction

Keywords: public transport; recovery of Ukraine; development strategy; transport issues; electric bus

Introduction

The development of Ukraine's transport system under current conditions is becoming critically important for ensuring economic stability, population mobility, and integration into the European transport space. Transformational processes in the sector are accompanied by the need for simultaneous infrastructure restoration, modernisation of public transport, and the introduction of environmentally safe technologies. Electric transport plays a particularly important role in this context as a tool for improving energy efficiency and reducing negative environmental impact. An important direction is also the renewal of transport systems, which involves the digitalisation of management, increasing the efficiency of transport services, and integrating different modes of transport into a single functional network. Consequently, there is a need to rethink current strategic approaches and

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formulate an updated transport policy capable of ensuring the sector's sustainable development and the modernisation of transport systems.

Research into the implementation of the strategy reveals a number of systemic issues affecting both scientific and practical tasks: the modernisation of public transport, the development of charging infrastructure, and the optimisation of investments (Olishevska & Olishevskiy, 2022; Vnukova & Pozdnyakova, 2023; Markiv & Ryshkovets, 2024). One of the priority areas of modern transport policy is the development of electric transport and the reduction in the use of traditional fuels. The expansion of electric transport is seen as a key tool for reducing the negative impact of transport on the environment, improving energy efficiency and decreasing dependence on fossil fuels. At the same time, the development of electric transport requires comprehensive changes to the transport system, including infrastructure modernisation, the development of charging stations, improvements to the regulatory framework, and the attraction of investment. Contemporary challenges, both local ones facing Ukraine and global ones, demand rapid adaptation by the country and a comprehensive resolution of transport issues. Issues such as climate change, rising fuel prices, the obligation to comply with international agreements on reducing greenhouse gas emissions, and the introduction of environmentally friendly transport technologies. Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018) was aimed at creating a foundation for addressing key challenges. However, these are compounded by contemporary unforeseen challenges – an increase in the number of passengers entitled to concessions and disabled passengers, insufficient modernisation and maintenance of public transport, and a funding shortfall in the passenger transport sector.

In contemporary research, the development of the transport system is increasingly viewed not merely as a technical or organisational task, but as part of a broader transformation linked to the modernisation of outdated infrastructure, the greening of transport, energy efficiency and alignment with European standards. It is precisely this approach that best aligns with the focus of this study, which analyses not a single element of transport policy, but the need for a comprehensive review of the current transport development strategy in Ukraine. N. Ivanenko (2023) examined the introduction of electric transport in relation to the operation of Ukraine's integrated power system and argues that the development of electric transport must be planned with due regard to energy loads, charging regimes and grid stability. As a result, electric transport emerges not merely as an environmentally friendly alternative, but as an element of a new transport-energy model. This position aligns with the findings of a study in which the modernisation of the transport system is viewed as a combination of infrastructural, technological and energy solutions.

B. Verbrugge *et al.* (2022), N. Brinkel *et al.* (2023) and P. Jarvis *et al.* (2024) investigated various aspects of electric bus operations: charging strategies, energy consumption forecasting, timetable optimisation, and the coordination of transport solutions with energy infrastructure. Taken together, these works demonstrate that the modernisation of the transport system can no longer be limited to simply replacing the rolling stock. Standardised approaches to charging infrastructure, precise route planning, digital monitoring and the integration of transport with energy systems are required, as noted by R. Lacombe *et al.* (2024) and N. Kulbashna *et al.* (2025a). This directly echoes research emphasising the need to move from piecemeal modernisation to a comprehensive transport renewal strategy. Y. Khodova (2020) and M. Mytko *et al.* (2025) further demonstrated that improving the efficiency of urban transport is possible through a combination of various technological solutions, in particular overhead contact lines and autonomous driving. At the same time, materials on the environmental and economic benefits of electric transport for Ukrainian communities emphasise that the key focus of modernisation should be on reducing emissions, energy efficiency and compliance with environmental requirements, which is particularly important in the context of the European direction of transport policy development. In conclusion, the analysed works confirm that the renewal of outdated infrastructure, the development of electric transport, the greening of transport, and alignment with European standards should be viewed as interrelated components of a new transport strategy for Ukraine.

The results of the analysis of scientific works indicate that contemporary research focuses on interrelated issues in the development of the transport sector: the modernisation of outdated infrastructure, the expansion of the charging network, the improvement of energy efficiency, the reduction of environmental impact, and the alignment of the transport system with European norms and standards. At the same time, in most of the works examined, these issues are addressed primarily in separate areas, without integrating them within a holistic strategic approach. This suggests that the further development of the transport system in Ukraine requires the formulation of a new transport strategy, in which these issues must be addressed comprehensively, taking into account contemporary infrastructural, environmental, economic and technological challenges. The aim of this study was to analyse the current problems in the development of the transport system of Ukraine and to identify promising directions for the formulation of a new transport strategy, taking into account contemporary economic, environmental and technological challenges. The study had the following objectives: to analyse the initial goals of the current strategy and the status of its implementation by 2025; formulating tasks for a new transport strategy; to draw the attention of researchers to transport issues and to encourage the development of academic work that addresses transport-related issues in economic, environmental, socio-political and other spheres.

Materials and Methods

The study employed a combination of analytical, comparative and descriptive-predictive methods, which made it possible to examine Ukraine's National Transport Strategy not merely as a regulatory document, but as a comprehensive system of interrelated objectives, instruments and outcomes implemented within specific economic, infrastructural and institutional contexts. The methodological framework comprised the analysis and synthesis of academic sources, a comparative analysis of strategic documents, a content analysis of regulatory and legal acts, as well as a systematic approach to assessing the state and development of transport infrastructure. The information base for the study was formed on the basis of specific official and academic sources. First and foremost, Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018) was analysed, the action plan for its implementation, approved in 2021, as well as the updated version of the strategy, adopted at the end of 2024 together with the operational plan for 2025-2027 (Resolution of the Cabinet of Ministers of Ukraine No. 1550, 2024). This made it possible to compare the initial strategic guidelines with the current conditions of the transport system's operation and to identify changes in state policy priorities in accordance with the approved resolution. In addition, statistical data from Ukraine's state statistical bodies were utilised, covering indicators of transport network development, passenger transport volumes and passenger turnover, as well as data on the operation of urban electric transport. Furthermore, analytical materials from relevant state bodies were taken into account, reflecting the state of road infrastructure, the scale of its restoration and modernisation, as well as the dynamics of electric transport implementation and the development of charging infrastructure. The use of these sources made it possible to track changes in the functioning of the transport system and to compare the regulatory targets with statistically recorded results, as confirmed by statistical data (State Statistics Service of Ukraine, n.d.).

The implementation of the Strategy was assessed using a system of qualitative and quantitative criteria. Qualitative criteria included the alignment of strategic objectives with current challenges in the transport sector, the level of alignment with European development trends, and the presence of mechanisms for digitalisation, decarbonisation, inclusivity and integration into the TEN-T. Quantitative criteria were formulated on the basis of statistical indicators characterising the pace of restoration and modernisation of transport infrastructure, trends in passenger transport and passenger turnover, changes in the use of urban electric transport, the scale of public transport renewal, in particular the electric bus segment, the development of charging infrastructure, as well as the promotion of integration processes towards TEN-T.

Conceptual modelling was used to construct a generalised logical framework for updating the transport strategy. Within this framework, the following components are sequentially linked: "challenges", "strategic objectives", "implementation tools", "coordinating bodies" and "expected outcomes". The "challenges" block includes the consequences of hostilities, financial constraints, the need for European integration, environmental requirements and the technological limitations of the existing infrastructure. Implementation tools included regulatory updates, funding mechanisms, the development of charging infrastructure, the standardisation of technical requirements for electric buses and the introduction of monitoring systems. A separate component of the model was the coordination unit in the form of an inter-agency mechanism, which assesses the readiness of cities and routes for the introduction of electric transport, analyses infrastructure provision, and monitors the effectiveness of investments. This enabled the formation of a comprehensive understanding of the interrelationship between strategic objectives, the instruments for their implementation, and the expected outcomes of transport system development.

This study employed a range of scientific analysis methods, enabling a systematic assessment of the current state and development prospects of Ukraine's transport system. The main methods included the analysis and synthesis of scientific sources, a comparative analysis of strategic documents, a systematic approach to assessing transport infrastructure, and content analysis of regulatory acts and state programmes in the fields of transport and ecology. In addition, elements of forecasting and conceptual modelling were used to assess potential scenarios for the development of the National Transport Strategy and the integration of electric transport into urban and inter-city transport. The subject of the analysis was Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018), the status of its implementation, current issues in public transport and electric transport, charging station infrastructure, financial support for the sector, as well as issues of inclusivity and modernisation of public transport. In addition, practical and scientific developments by Ukrainian and foreign researchers in the field of electric transport and the sustainable development of transport systems were examined.

The research database included official statistics from the Ministry of Infrastructure of Ukraine and the State Statistics Service, regulatory and legal acts and state programmes, as well as contemporary scientific sources, conference materials and academic publications. To assess the infrastructural and technological aspects of electric transport development, the results of research by Lviv Polytechnic National University on optimising the placement of charging stations using Big Data were utilised, as confirmed in the relevant studies by O. Markiv & Y. Ryshkovets (2024) and in the regulatory document Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018). During the study, forecasting techniques were applied to assess the economic efficiency of electric transport implementation, identify optimal infrastructure development models, and develop scenarios for integrating the latest technologies into the national transport system. Conceptual modelling enabled the assessment of various pathways for implementing the future transport strategy, taking into account the economic, environmental and social challenges facing Ukraine.

The study's timeframe covered the period 2018-2025, which allowed for the consideration of current trends in the transport sector, changes in financial and regulatory frameworks, as well as the impact of war damage on transport infrastructure. The combination of these methods and the use of a comprehensive information base ensured the scientific reliability and practical value of the study's findings and enabled the identification of promising directions for the development of the national transport system.

Results and Discussion

Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018) sets out the country's plan to modernise transport infrastructure, improve safety, ensure environmental sustainability, integrate transport systems, attract investment and implement regulatory reforms. The strategy's objectives were to develop multimodal transport and integrate into the Trans-European Transport Network (TEN-T) by establishing logistics centres and reforming and upgrading transport infrastructure to improve international transport, aligning legislation with EU standards, digitising processes, introducing new environmental standards, encouraging the use of public transport, and increasing the proportion of electric transport. Electric transport, particularly electric buses, is one of the key elements of the decarbonisation strategy, which will help reduce the impact of fossil fuels and improve the environmental situation. In its efforts to integrate into the transport system, Ukraine has developed Resolution of the Cabinet of Ministers of Ukraine No. 430 (2018), which aims to modernise infrastructure and develop environmentally friendly modes of transport. The strategy's plans focus on the development of transport infrastructure, with particular attention paid to the development of international transport routes that will ensure integration with the EU transport system, as well as a gradual transition to European standards in the manufacture and operation of electric transport (NULES, 2019; INSAT, 2021).

Key objectives in the road transport sector: improving safety, reducing harmful emissions from internal combustion engines, increasing the proportion of electric vehicles, modernising outdated public transport, improving the quality of public transport services, and preparing for a gradual increase in fares to bring them into line with EU levels (EBRD, n.d.). The results obtained are consistent with current research on the development of electric transport and the introduction of electric buses into urban transport systems. Many authors note that the electrification of transport is one of the key areas for improving the environmental sustainability of the urban environment and reducing the negative impact of transport on the environment. In particular, the work by O. Shostal (2025) examines the trends in Ukrainian cities' transition to the use of electric buses and the gradual reduction in the number of route taxis. The author notes that active procurement of electric buses could lead to a significant transformation of the urban transport structure as early as 2030. The results obtained in this study generally confirm these conclusions, as they also indicate the potential for the introduction of electric transport within the context of the development of modern transport infrastructure. At the same time, the study focuses more on the general environmental and energy aspects of such transport's operation.

Similar conclusions regarding the positive impact of electric vehicles on the environment are presented in the study by N. Vnukova & O. Pozdnyakova (2023), which emphasises the importance of transitioning to environmentally friendly modes of transport to reduce emissions of harmful substances. The study also notes the environmental benefits of developing electric transport, but additionally emphasises the need for a comprehensive approach to introducing such technologies into the urban environment. The prospects for the development of electric mobility in Ukraine are also examined by L. Nikiforova & R. Lukian (2019), who note that the spread of electric transport depends on infrastructure development, state support and the economic viability of using such vehicles. Similar aspects are highlighted in the study, which emphasises the importance of creating the right conditions for the effective operation of electric transport. The studies by S. Würtz *et al.* (2024) and O. Markiv & Y. Ryshkovets (2024) are devoted to analysing the electric transport infrastructure in Ukraine. The authors draw attention to the need to develop a network of charging stations and improve transport infrastructure to ensure the stable operation of electric transport. The results obtained also confirm the importance of these factors, as the effective operation of electric buses depends to a large extent on the availability of charging infrastructure and the proper organisation of the transport system.

A separate area of research concerns the optimisation of electric bus charging processes and the improvement of their energy efficiency. In particular, L. Caustur *et al.* (2025) examine the issue of planning electric bus charging schedules, taking into account the use of renewable energy sources. Similar issues are also investigated in the work of N. Kulbashna *et al.* (2025b), where the authors analyse the energy aspects of charging schedule formulation and propose approaches to improving the energy efficiency of transport systems. In this study, these issues are examined in a more generalised manner; however, the results obtained confirm the relevance of rational planning of electric bus energy consumption. Furthermore, the study by N. Kulbashna *et al.* (2025b), dedicated to improving the energy efficiency of electric buses using modern photovoltaic technologies, highlights the potential for utilising alternative energy sources to reduce electricity consumption and enhance the efficiency of transport systems. The results are also consistent with these approaches, as they confirm the feasibility of using innovative technologies to improve the efficiency of electric transport. Thus, a comparative analysis shows that the study's findings are generally consistent with international trends: the effective development of electric transport requires the integration of route planning, energy management and financial support mechanisms. At the same time, the Ukrainian context is characterised by a high level of underfunding of public transport and the need for state incentives, which makes the introduction of electric buses a more complex task than in countries with developed transport infrastructure.

An analysis of electric transport infrastructure in Ukraine by O. Markiv & Y. Ryshkovets (2024) demonstrates the effectiveness of modelling the placement of charging stations and their integration into urban transport and energy systems, confirming the validity of conclusions regarding the need for strategic planning of charging infrastructure development. In their work, L. Zhang *et al.* (2025) emphasise the economic rationale for a gradual increase in the number of electric vehicles in Ukraine and highlight the main stages of electric transport implementation, which partly echoes the findings, particularly regarding the planning of the transition from conventional to electric transport, taking into account financial and organisational aspects.

An important part of the environmental sustainability strategy is the integration of renewable energy sources, such as solar and wind power, into the process of generating electricity for the needs of electric transport. This approach ensures a full cycle of environmental efficiency, reducing dependence on fossil fuels and cutting CO_2 emissions not only during transport operation but also in the production of energy for it. The development of infrastructure for electric transport is a key element of the strategy. Plans were in place to install charging stations across the country, particularly in major cities and along major motorways. It was projected that the share of electric vehicles in the total fleet would increase to 5% and that up to 30% of the urban public transport fleet in major cities would be replaced by modern electric transport, through the expansion of trolleybus networks and the creation of new routes (Resolution of the Cabinet of Ministers of Ukraine No. 430, 2018).

The strategy envisages the development of multimodal transport, which will ensure cooperation between different modes of transport (road, rail, water and air). Plans were in place to establish logistics centres to ensure the smooth movement of goods and passengers between EU countries and other neighbours. Integration with the Trans-European Transport Network (TEN-T) is a key priority for improving international transport. To implement the strategy, the plan was to attract foreign investment in transport infrastructure through public-private partnerships and optimise the use of public funds. Securing international grants and loans is a vital element of project financing. Regulatory reforms include aligning Ukrainian legislation with EU standards, simplifying procedures for businesses, and improving the efficiency of public administration in the transport sector. Plans were made to digitise processes and introduce new standards for safety and the environment. To encourage the use of electric transport, the plan provides for the introduction of tax incentives and subsidies for electric vehicle users, the adoption of European standards for the production and use of electric transport, and regular monitoring of compliance with environmental standards.

Subsidising public transport in Ukraine is a pressing issue in both large and small towns and villages, where the problem of air pollution is far from being the main concern. In towns with a population of no more than 70,000, there remain issues regarding the modernisation of public transport (where public transport services are usually provided by private operators). In other words, around 80% of towns have the potential to develop their transport systems, particularly public transport, but due to chronic underfunding, the age of the vehicles is unsatisfactory and they require replacement (Palant *et al.*, 2023; Pryimak, 2024). At the same time, the criteria for replacing vehicles are low purchase cost, fuel economy, maintainability and durability. If the Ukrainian market for electric buses can be developed, with vehicles made affordable for city budgets through subsidies and state loans, then the construction of component factories and electric bus production could reach a new level in Ukraine. All this meets the needs of cities: an electric bus means electricity, and therefore fuel savings, durability and reliability, as electric motors and batteries have a much longer service life. With state interest and subsidies for the purchase of Ukrainian electric buses, the cost of vehicles could be significantly reduced, which would help to renew the fleet and assist private operators in smaller towns.

In the coming years, the number of alternatives for key electric transport components will increase, which will lower the price of the end product. Another issue is the development of infrastructure for electric transport, its universality and standardisation, particularly as regards public transport. The speed of decision-making after the war ends must be taken into account, as the priority tasks will be the restoration of road infrastructure and the rehabilitation of public transport companies (PTCs). It is necessary to introduce standardisation of processes, which will help avoid waste; for example, the restoration of public transport will be more effective if it is brought into line with EU standards from the outset. Such an approach can contribute to the efficient use of resources and ensure the long-term sustainability of the transport system.

To regulate and monitor the expansion of electric transport, the future development strategy must include the establishment of a commission capable of providing support for the integration of public electric transport in urban areas. It will help analyse the increase in the number of electric vehicles, the population size, route lengths, the number of regular public transport users, the complexity of transport routes, the cost of electricity in the region, and calculate the prospects for transport development in this city, payback periods, etc. It should ensure coordination and facilitate development, taking into account the technical, financial and infrastructural aspects of monitoring for each route or PTCs as a whole. The commission should assess the need to introduce electric buses for each specific city, which will allow for the rational and effective planning of fleet renewal, following the example of EBRD commissions (n.d.). The commission must ensure: the standardisation of technical requirements for electric buses, including specifications regarding maximum range, charging time, energy efficiency and safety; financial support, which will analyse opportunities to attract additional funds for the renewal of the city's transport fleet; verification of the readiness of the charging infrastructure, including the installation of charging stations on routes, at car parks and other locations; monitoring and evaluation of the introduction of electric transport in cities, analysing effectiveness and making the necessary adjustments to optimise the process.

Strategy targets have been met. Ukraine's National Transport Strategy for the period up to 2030 was launched in 2018, and significant progress has been made since then. One of the main achievements has been the modernisation of transport infrastructure, which has included the construction and reconstruction of roads, bridges and railways. The President of Ukraine's "Great Construction" initiative has played a key role in these achievements. Since 2018, over 10,000 km of roads have been repaired, including motorways and regional roads. Over 560 bridges have also been repaired, as stated in the materials from the plenary session (Verkhovna Rada of Ukraine, 2021). In the context of electric transport, Kyiv and other major cities have taken significant steps towards the introduction of electric buses. Around 50 new electric buses were introduced in Kyiv, and the total number across the country reached 200. Over 10,000 charging stations for electric vehicles were installed, which contributed to the growth in demand for electric transport among the population. As a result, according to expert estimates, 35-40% of the strategy was implemented during the 2018-2022 period.

Assessment of uncompleted projects. The National Transport Strategy envisaged the further expansion and modernisation of transport infrastructure by 2030. However, it can be accurately concluded that the plans concerning the expansion of electric transport routes, safety measures, and the reconstruction of the urban road network (provision of charging stations, improved road markings, widening of roads in problem areas, etc.) could not be fully implemented. As of 2025, work on projects for which funding had already been allocated up to 2022 but which had not yet been completed is continuing. The pace of completion of such projects has slowed. Those projects for which funding was planned have been frozen or cancelled (those 90% complete remain unfinished) and may not be completed by the end of hostilities. Since 2022, the condition of the infrastructure has deteriorated; parts of the road surface used by military vehicles once again require assessment and repair. The infrastructure situation in the south and east of the country is critical in certain areas.

The war in Ukraine has significantly impacted the ability to fully implement the National Transport Strategy up to 2030. Many infrastructure facilities have been damaged or destroyed as a result of military operations, complicating the process of restoration and modernisation. Despite these challenges, Ukraine continues to work on implementing the strategy. Given the circumstances, around 30% of the planned measures have been implemented by 2025, which is a significant achievement in wartime conditions. However, full implementation of the strategy by 2030 appears unlikely (Resolution of the Cabinet of Ministers of Ukraine No. 430, 2018).

The analysis conducted indicates that the current transport development strategy no longer fully corresponds to the current conditions of the sector's operation. Large-scale changes resulting from hostilities have necessitated a thorough investigation of the state of transport infrastructure, an assessment of existing losses, and the identification of priority areas for its restoration. In this regard, particular importance is attached to the systematisation of statistical data, the clarification of strategic objectives, the formulation of relevant tasks, and the development of comprehensive plans for the development of the transport system. Further strategic planning must be based on a clear breakdown of general directions into specific practical measures, which will ensure a more informed formulation of a new transport development strategy. At this stage, Ukraine is facing numerous problems arising from the war. Large-scale damage to infrastructure, roads, bridges and other transport network facilities requires urgent restoration. Current conditions demand that the strategy be adapted to the new realities. The new transport development strategy must take these challenges into account and adapt to changing conditions.

An important part of the new strategy should be the incorporation of European standards and legislative requirements. This includes the introduction of environmentally friendly technologies and approaches to road construction and maintenance, the specifications of charging stations, and electric transport itself (including its end-of-life management). The development of electric transport will reduce dependence on diesel fuel and enhance the environmental sustainability of the transport system. Additional incentives are needed for citizens and businesses to switch to electric transport. Subsidies, reduced taxes on the import of spare parts and the charging of electric vehicles, as well as the development of charging station infrastructure, must be key elements of the new strategy.

Battery technologies used in electric transport also overlap with modern unmanned aerial vehicles (UAVs). Ukraine has significant potential for technological development, particularly in the field of UAV components, which have seen rapid development since 2022. Unmanned technologies themselves can be integrated into electric transport, which will enhance its efficiency, cost-effectiveness and safety. The production of sensors, gyroscopes, GPS systems, lidars, cameras and other components for electric vehicles could be a logical next step in the industry's development. There remains significant potential for investment in Ukraine's industry. Given that the development of innovative technologies has slowed considerably due to the crisis in the region, Ukraine is capable of establishing a leading position in the production of affordable electric buses on the market, meeting both domestic and external demand. Its unique location at the heart of Europe and its aspiration to join the EU will serve as a major incentive for partnership with many countries.

Effective investment management and cooperation with international partners will help Ukraine restore and develop its transport system. Ukraine also possesses significant reserves of lithium, a strategic resource that is key to battery production. The development of the metallurgical industry and the production of lithium-ion batteries could become a key element of the strategy, providing the country with the necessary materials for the production of electric transport. All of this is prompting the Ukrainian government to choose the most promising market for the coming years – the development of electric transport, which will make it possible to: increase Ukraine's energy independence from fuel prices; promote the export of technologies and components for electric transport, thereby boosting the country's economic potential; expand the use of electric transport; modernise standards and accelerate European integration; improve the outdated transport system; and develop the industrial sector, creating new jobs in the production and maintenance of electric transport.

Conclusions

The study involved a comprehensive analysis of the provisions of the National Transport Strategy of Ukraine up to 2030, which was approved by the government in 2018. The assessment revealed that certain provisions of this strategic document have become partially outdated due to changes in the economic, social and infrastructural conditions affecting the development of the country's transport system. Current challenges related to economic instability, war-related damage to infrastructure, rising energy costs and the need to fulfil international environmental commitments have significantly impacted the feasibility of achieving certain objectives of the strategy. Consequently, it has been established that even under favourable conditions, the full implementation of the envisaged measures by 2030 is unlikely; thus, this document should be regarded primarily as a general guideline for the further development of the transport sector. In the process of analysing the strategy's initial objectives and the status of their implementation, a number of pressing issues regarding the development of public transport in Ukraine were identified. Among the main challenges are the high cost of implementing modern transport technologies, the insufficient level of infrastructure development to support electric transport – in particular, charging stations for electric buses – as well as financial difficulties in the area of passenger transport subsidies. A separate issue remains ensuring the accessibility of public transport for people with reduced mobility, which requires a comprehensive approach to the modernisation of vehicles and transport infrastructure.

Prospects for further research in this area involve studying modern technological solutions that could help improve the effectiveness of implementing Ukraine's future transport strategy. In particular, research aimed at reducing the production costs of public electric transport, improving its energy efficiency and operational reliability is of particular relevance. Another important area is the development of approaches to standardisation and the optimal placement of charging infrastructure, which will ensure the effective integration of electric transport into the transport systems of Ukraine's cities and regions. The implementation of such research could form the basis for the development of an updated national transport policy and contribute to the sustainable development of the transport sector. The prospect for further development lies in researching modern technologies that will help accelerate the implementation of the future strategy. Specifically, this involves reducing the cost of manufacturing public electric transport, making it more economical and efficient, and enabling the standardisation of charging stations for electric transport.

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References

[1] Brinkel, N., Zijlstra, M., van Bezu, R., van Twuijver, T., Lampropoulos, I., & van Sark, W. (2023). A comparative analysis of charging strategies for battery electric buses in wholesale electricity and ancillary services markets. *Transportation Research Part E: Logistics and Transportation Review*, 172, article number 103085. doi: 10.1016/j.tre.2023.103085.

[2] Caustur, L., Hertoghe, P., Ma, T.-Y., & Vandebroek, M. (2025). An integrated optimization framework for smart charging of electric bus fleets under dynamic electricity prices with on-site solar generation, energy storage, and V2G operations. *arXiv*. doi: 10.48550/arXiv.2509.05940.

[3] European Bank for Reconstruction and Development (EBRD). (n.d.). Retrieved from https://www.ebrd.com.
[4] INSAT. (2021). *Prospects for the development of automotive transport and infrastructure*. Kyiv: Ministry of Infrastructure of Ukraine.
[5] Ivanenko, N. (2023). The impact of the implementation of electric transportation on the Ukraine's integrated power system functioning. *System Research in Energy*, 1(72), 4-11. doi: 10.15407/srenergy2023.01.004.
[6] Jarvis, P., Climent, L., & Arbelaez, A. (2024). Smart and sustainable scheduling of charging events for electric buses. *TOP*, 32, 22-56. doi: 10.1007/s11750-023-00657-5.
[7] Khodova, Y.O. (2020). Intelligent transport system as an innovative concept for the development of the transport and logistics complex of Ukraine. In *Proceedings of the scientific conference on transport development* (pp. 48-50). Kharkiv: Kharkiv National Automobile and Highway University.
[8] Kulbashna, N., Daleka, V., Lukashova, N., & Furtat, S. (2025a). Energy aspects of forming electric bus charging schedules. *Lighting Engineering & Power Engineering*, 64(2), 65-74. doi: 10.33042/2079-424X.2025.64.2.03.
[9] Kulbashna, N.I., Lukashova, N.P., Daleka, V.H., & Skurikhin, V.I. (2025b). Ways to improve energy efficiency of electric buses using modern photovoltaic technologies. *Municipal Economy of Cities*, 1(89), 52-60. doi: 10.33042/2522-1809-2025-1-189-52-60.
[10] Lacombe, R., Murgovski, N., Gros, S., & Kulcsár, B. (2024). Integrated charging scheduling and operational control for an electric bus network. *Transportation Research Part E: Logistics and Transportation Review*, 186, article number 103549. doi: 10.1016/j.tre.2024.103549.
[11] Markiv, O., & Ryshkovets, Y. (2024). The use of big data technologies in the electric transport sector. *Information Systems and Networks*, 15, 419-429. doi: 10.23939/sisn2024.15.419.
[12] Mytko, M., Burlaka, S., Halushchak, O., Halushchak, D., & Zelinskyi, V. (2025). Integration of contact network and autonomous trolleybuses for improving the city's transport system. *Technology Audit and Production Reserves*, 5(1(85)), 49-57. doi: 10.15587/2706-5448.2025.340517.
[13] Nikiforova, L.O., & Lukian, R.R. (2019). *Prospects for the use of electric vehicles in Ukraine*. (Doctoral thesis, Vinnytsia National Technical University, Vinnytsia, Ukraine).
[14] NULES. (2019). *Automotive transport and infrastructure*. Kyiv: National University of Life and Environmental Sciences of Ukraine.
[15] Olishevska, V.Y., & Olishevskiy, H.C. (2022). Concept for the development of electric vehicles and related infrastructure in Ukraine. In *Problems and prospects of automotive transport development* (pp. 225-228). Dnipro: National Mining University.
[16] Palant, O., Zakharov, D., & Pryimak, V. (2023). Perspectives of the development of public transport in the context of the creation smart infrastructures of the cities of Ukraine. *Black Sea Economic Studies*, 84, 85-89. doi: 10.32782/bses.84-14.
[17] Pryimak, V. (2024). Development of public transport in Ukraine in the context of the National Transport Strategy. *Economy and Society*, 68, 1-6. doi: 10.32782/2524-0072/2024-68-25.
[18] Resolution of the Cabinet of Ministers of Ukraine No. 1550 "On the Approval of the National Transport Strategy of Ukraine until 2030 and the Adoption of the Operational Action Plan for Its Implementation in 2025-2027". (2024, December). Retrieved from https://zakon.rada.gov.ua/laws/show/1550-2024-%D0%BF#Text.
[19] Resolution of the Cabinet of Ministers of Ukraine No. 430 "On the National Transport Strategy of Ukraine until 2030". (2018, May). Retrieved from https://zakon.rada.gov.ua/laws/show/430-2018-%D1%80.
[20] Shostal, O. (2025). *Ukraine transitions to electric buses: What will happen to minibuses by 2030*. Retrieved from https://112.ua/en/mista-masovo-zakupaut-elektrobusi-koli-zniknut-marsrutki-109141.
[21] State Statistics Service of Ukraine. (n.d.). Retrieved from https://stat.gov.ua/uk/topics/transport?page=1.
[22] Verbrugge, B., Rauf, A.M., Rasool, H., Abdel-Monem, M., Geury, T., Baghdadi, M.E., & Hegazy, O. (2022). Real-time charging scheduling and optimization of electric buses in a depot. *Energies*, 15(14), article number 5023. doi: 10.3390/en15145023.
[23] Verkhovna Rada of Ukraine. (2021). *Session 32*. Retrieved from https://www.rada.gov.ua/meeting/stenogr/show/7928.html.
[24] Vnukova, N., & Pozdnyakova, O. (2023). Comprehensive assessment of the impact of electric vehicles on the biosphere. *Grail of Science*, 26, 208-214. doi: 10.36074/grail-of-science.14.04.2023.038.
[25] Würtz, S., Bogenberger, K., Göhner, U., & Rupp, A. (2024). Towards efficient battery electric bus operations: A novel energy forecasting framework. *World Electric Vehicle Journal*, 15(1), article number 27. doi: 10.3390/wevj15010027.
[26] Zhang, L., Guo, W., Wang, Y., Hu, Q., & Han, Y. (2025). Optimal charger deployment for electric buses: Incorporating en-route charging and battery management. *Transportation Research Part D: Transport and Environment*, 140, article number 104603. doi: 10.1016/j.trd.2025.104603.

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Анотація. Актуальність дослідження зумовлена необхідністю переоцінки напрямів розвитку транспортної системи України в умовах воєнних викликів, відновлення пошкодженої інфраструктури та поглиблення інтеграції до європейського транспортного простору. Особливого значення набуває формування ефективної, стійкої та екологічно орієнтованої транспортної політики, здатної забезпечити відновлення економіки та підвищення якості транспортного обслуговування. Метою роботи був аналіз цілей Національної транспортної стратегії України до 2030 року, оцінка стану її реалізації в сучасних умовах та обґрунтування пріоритетних напрямів подальшого розвитку транспортної системи з урахуванням європейських стандартів і принципів сталого розвитку. У дослідженні використано методи аналізу та узагальнення наукових джерел, порівняльного аналізу стратегічних і нормативних документів, а також системний підхід до оцінювання стану транспортної інфраструктури та перспектив розвитку електротранспорту. Інформаційну базу становили державні програми, наукові публікації та аналітичні матеріали у сфері транспорту. В роботі проаналізовано ключові положення Національної транспортної стратегії України до 2030 року, зокрема напрями модернізації інфраструктури, інтеграції до транс'європейської транспортної мережі (TEN-T), розвитку мультимодальних перевезень та впровадження екологічно чистих видів транспорту. Встановлено, що реалізація значної частини заходів відбувається частково через фінансові обмеження, інституційні проблеми та вплив воєнних дій. Виявлено основні проблеми розвитку громадського транспорту, зокрема зношеність рухомого складу, недостатній рівень фінансування та нерозвиненість зарядної інфраструктури для електротранспорту. На основі проведеного аналізу обґрунтовано перспективні напрями формування оновленої транспортної стратегії, серед яких розвиток електробусів, розширення мережі зарядних станцій, впровадження інтелектуальних транспортних систем та посилення державної підтримки модернізації транспортного парку. Практична цінність отриманих результатів полягає в можливості їх використання при розробленні державних і регіональних програм розвитку транспортної інфраструктури, а також при формуванні ефективної транспортної політики України в умовах післявоєнного відновлення

Ключові слова: громадський транспорт; відновлення України; стратегія розвитку; проблеми транспорту; електробус

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Implementation of world experience in constructing civil defence shelters

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Abstract. The intensification of contemporary military threats in Ukraine has necessitated a reassessment of approaches to civil protection and the integration of protective shelters into residential and civil infrastructure. The study aimed to analyse Ukrainian legislation alongside selected international practices in order to identify effective models for incorporating protective spaces into buildings and to substantiate directions for expanding the classification of protective structures. The methodological framework was based on a comprehensive analysis of national regulatory documents, a comparative evaluation of international experience, and the generalisation and systematisation of best practices. Particular attention was given to the legislative and technical approaches implemented in Israel and Singapore, especially regarding the integration of shelters into buildings, rapid accessibility, and functional efficiency. The research also considered economic feasibility and the practical aspects of implementing such solutions within existing and newly constructed facilities. The findings demonstrated that international practice consistently emphasised the critical importance of minimising the time required for citizens to access shelters, which was achieved through the integration of protected spaces directly into residential and industrial buildings or through the deployment of modular shelter systems. The analysed cases revealed that such approaches ensured a higher level of population safety, particularly under conditions of frequent and unpredictable threats. It was established that both Israel and Singapore had successfully embedded these solutions within their legislative frameworks, supported by clearly defined technical standards. The study substantiated the feasibility of gradually introducing integrated and modular protective structures in Ukraine, both in the process of post-war reconstruction and in new construction projects. The practical significance of the research lay in the formulation of recommendations for adapting Ukrainian legislation and improving the accessibility, efficiency, and resilience of civil protection infrastructure

Keywords: protected space; dual-purpose structures; urban resilience; subsurface spaces; Mamads

Introduction

Modern security challenges have necessitated the implementation of new protective solutions alongside the modernisation of existing civil defence infrastructure. In Ukraine, this process has gained renewed momentum following the introduction of updated state standards governing the construction of protective structures. These regulatory changes have established new directions for development; however, they have also revealed significant limitations, as not all solutions formally covered by existing standards provide an adequate level of real

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protection under contemporary conditions. Therefore, it is essential to consider and adapt the experience of countries that have long operated under conditions of persistent military or terrorist threats, particularly Israel and Singapore, as noted by S.M. Anas *et al.* (2023). In the current conditions faced by Ukraine, characterised by ongoing warfare and continuous shelling involving various types of weaponry, the time required to reach a shelter has become a critical factor in ensuring civilian safety. The effectiveness of civil protection systems is increasingly determined not only by the structural reliability of shelters but also by their accessibility and proximity to users. The development and implementation of new types of temporary protective structures have enabled rapid access to safe spaces for the population. At the same time, A.I. Almulhim (2025) demonstrated that in high-density urban environments, effective civil protection is based on the integration of shelters into existing infrastructure, particularly transport nodes and underground spaces. It was emphasised that minimising the time required to access shelters directly correlates with increased survival rates. The main regulatory document in Ukraine governing the construction of shelters and bomb shelters is DBN V.2.2-5:2023 (2023). Compared with previous editions, this standard introduced a new category of shelters – rapidly deployable protective structures – alongside existing types such as anti-radiation shelters and the simplest shelters, with specific requirements defined for each category. All of these structures belong to collective protection facilities. However, the continuously evolving nature of military threats, including the changing characteristics of air attacks, necessitates a fundamental rethinking of existing approaches to shelter design and deployment.

Initial steps towards implementing new approaches have already been observed. The first modular underground shelter, constructed by the State Agency for Restoration and Infrastructure Development, was installed in the Kyiv region, indicating the beginning of the state-level introduction of rapidly deployable shelter solutions capable of providing a basic level of protection for the population (Ministry for Communities and Territories Development of Ukraine, n.d.). These structures are characterised by short installation times and immediate operational readiness. Rapidly deployable modular protective structures represent one of the most promising approaches to enhancing civil protection, although their practical implementation remains limited. Their requirements are defined in DSTU 9195:2022 (2022), which regulates their design and operation. A further promising direction involves the integration of protective spaces into transport and urban infrastructure, including tunnels, service galleries, and subsurface areas beneath road structures. This approach enables the expansion of shelter capacity within existing urban environments without the need for extensive new construction. The operational suitability of protective structures is assessed in accordance with DSTU 9329:2025 (2025), which establishes procedures for verifying the protective properties of enclosing structures prior to commissioning. In addition, with the development of modular shelters, national methodologies for testing such structures for blast resistance have begun to emerge, drawing on international experience, including that of the Singapore Civil Defence Force (n.d.). As emphasised by S. Surkes (2025) and Y. Wu *et al.* (2025), effective national protection systems rely not only on dedicated shelters but also on the utilisation of existing housing stock, including household shelters, residential shelters, protected rooms, and communal protected spaces. In parallel, the study by M. Zohourian *et al.* (2025) examined modular construction as an innovative approach within the construction industry, highlighting its advantages over traditional methods. The results indicated that modular construction could reduce construction time by up to 50%, lower costs by approximately 20%, and decrease material waste by up to 83%. At the same time, several limitations were identified, including transportation complexity, limited design flexibility, and high initial costs. These findings are particularly relevant for the implementation of modular shelters in emergency conditions. Despite these developments, Ukraine currently lacks clearly defined technical requirements for so-called "protected spaces" integrated into buildings, which prevents their formal recognition as a distinct category of protective structures. Nevertheless, initial steps have already been taken at the regional level, where local authorities have developed recommendations concerning underground shelter premises, protected spaces within residential and office buildings, and requirements for engineering systems and spatial planning. Therefore, addressing this problem requires the development of a modern approach to shelter design based on the concept of integrated protected spaces ("safe spaces"), capable of providing effective protection under contemporary military conditions. The purpose of this article was to investigate best practices in civil and residential construction regarding the availability and accessibility of protective structures and to identify potential directions for adapting Ukrainian civil engineering legislation in order to introduce new types of shelters that correspond to current threats and post-war recovery needs.

Materials and Methods

The study was theoretical and analytical in nature and was conducted within an interdisciplinary framework at the intersection of civil engineering, urban planning, and civil protection systems. The object of the research was the process of formation and development of civil protection shelter systems under contemporary military threats. The subject of the research comprised the principles of integrating protective spaces into residential, public, and engineering infrastructure, as well as the regulatory and technical mechanisms for their implementation. The theoretical and regulatory framework of the study was based on current Ukrainian building codes and standards (in particular, DBN V.2.2-5:2023 (2023), DSTU 9195:2022 (2022) and DSTU 9329:2025 (2025)), international regulatory acts and technical standards (including civil protection regulations of Israel and Singapore), as well as contemporary scholarly publications addressing shelter design, modular construction, and urban resilience. A set of interrelated scientific approaches was employed in the study. The systems approach enabled protective structures to be considered as elements of a unified civil protection infrastructure. The comparative approach was used to analyse international experience and to identify differences in design approaches and regulatory frameworks for shelters. The institutional approach provided an assessment of the role of state regulation in shaping an effective system for population protection. The principal research methods included the analysis of regulatory and legal documents governing the design and operation of protective structures; a comparative analysis of international experience (Israel and Singapore); the method of generalisation for systematising identified practices; and the method of scientific interpretation to formulate conclusions regarding their potential adaptation in Ukraine. The selection of countries for comparative analysis was determined by their practical experience in operating civil protection systems under constant or potential threats. Israel was selected as an example of a state with extensive experience in integrating protected spaces into residential development and with stringent regulatory frameworks. Singapore was considered an example of a highly developed urban system in which shelters were integrated into urban infrastructure and regulated at the legislative level. Such a selection made it possible to establish a representative basis for comparison and to identify directions for adapting international experience to the Ukrainian context.

Results and Discussion

Considering the experience of Israel, which has built a new construction concept based on a set of principles for creating so-called "residential protected rooms", the legislation and technical standards of this country provided for the creation of specific types of reinforced rooms. According to State comptroller of Israel (2024), the main state principles could be divided into 4 points:

Principle 1. Everyone needs protection. Wherever a person is, they must have access to any shelter. For example: mobile shelters at bus stops, underground shopping centres, subway stations, hotel parking lots, educational centres, gyms – anything that can be considered as a shelter should be an open refuge 24/7 for everyone, supplied with water, lighting, and ventilation. A situation like in Ukraine, where public buildings close during an alarm, public transport stops, and people are turned out onto the street, is unacceptable. On the contrary, everything that can provide protection must be open. And everyone must know where to go in case of danger.

Principle 2. Capsule security. In Israel, in addition to conventional bomb shelters, a numerous of other types of shelters are used. Mamad – (an abbreviation for merhav mugan dirati – "protected apartment space"). This kind of room with massive, usually 30-centimeter, reinforced concrete walls, thickened ceilings, metal airtight doors that withstand blast waves, and shutters made of two-centimetre steel sheets. Mamads began to be created so that people would not have to run outside to reach a bomb shelter but could literally go into an adjacent protected room. The capsule must have its own ventilation with an air filter for chemical protection and special doors.

Mamak – a fortified room in public buildings, located on each floor where people are present. In office buildings, these can serve as internal conference rooms. In apartment buildings, they are created within the volume of the staircase and are located on each floor for use by several families. The size of a Mamak was calculated based on the number of people on the floor. Such fortified rooms were built one above the other to increase structural stability. They could protect occupants from missile and shell fragments, as well as from chemical threats and earthquakes. Without their presence, city authorities would not grant a building permit or commission the building. The construction of buildings with protected spaces began only after 1993. For older buildings, the government launched a renovation programme called TAMA-38. The aim was to reinforce buildings that did not have Mamads. With the consent of 75% of the building's residents, a developer could add Mamads, as well as two or three additional floors of apartments for sale. In some cases, developers also added a lift and reinforced the building's façade. Since 1992, all new residential buildings in Israel have been required to include a reinforced room for protection during rocket and missile attacks. A reinforced room in a house or apartment had to measure at least nine square metres (96 square feet) (Zatulsky, 2023).

Figure 1. Fortified room Mamad during and after construction
Source: A. Zatulsky (2023)

Figure 1 depicts the process of modular construction of Mamad fortified structures – from the manufacture and installation of reinforced concrete blocks to their integration into residential developments. It visually demonstrates the principle of vertical stacking of these modules and their standardisation as components of a civil defence system. Despite the fact that such shelters did not provide a one hundred per cent guarantee of safety, they significantly reduced the time required to reach cover and, consequently, decreased the likelihood of injury from building debris or shrapnel. Temporary or mobile fortification structures were also used. Migunit was a cuboid, box-shaped, dome-shaped, or tent-shaped shelter made of high-quality reinforced concrete and placed in open areas. It had two open exits, allowing people to enter quickly, wait out an attack, and then exit safely. These structures were located at bus stops, along highways, and on streets, enabling people to take cover during shelling while waiting for transport. Children's centres, playgrounds, and hospitals were equipped with additional arched canopies over roofs to provide protected spaces for children's activities, as well as concrete play tunnels painted and shaped like caterpillars for aesthetic appeal. All of this created additional protection and allowed for rapid shelter in the event of sudden danger (State comptroller of Israel, 2024).

Principle 3. Continuous review of building standards towards strengthening. The certification and attestation of new or reconstructed buildings mandatory involves the Ministry of Home Front. This ministry developing requirements, without the fulfilment of which, a developer cannot approve a project or commission a building. The Ministry of Home Front checks the implementation of requirements regarding the shelters compliance to national and local legislation. Each city, regularly, checks how well the infrastructure meets requirements, how quickly people can use it and reach a shelter. Ensuring security is not just a code of requirements for building supplies or work methods. It is a complex set of measures whose ultimate goal is to create a safe environment (Israel's bomb shelters…, 2023; de Yong *et al.*, 2024).

Principle 4. Architectural planning was based on the concept of the "wind rose of war". In border areas, consideration was given to how people could safely reach their homes after entering the yard and parking their vehicles. The building complex was designed taking into account the "wind rose of war", meaning that walls were reinforced and positioned depending on the direction from which a threat might arise. An illustrative example was a school in the city of Sderot, located 4 km from the Gaza Strip. This distance corresponded to approximately a 3-second rocket flight. Therefore, the building was constructed as a complete bomb shelter, with windows oriented away from the Gaza Strip. Another example was a hospital located 25 km from the border, where almost all departments, including maternity wards and facilities for people with disabilities, formed a single large bunker. At the sound of sirens, it was sufficient to close the shutters, after which up to 60% of the hospital became encapsulated; even surgical operations did not stop. During periods of intense shelling, protective doors were also used. Buildings included a fortified room on each floor, and the overall structure was designed so that external walls or specific parts of the building absorbed the main impact, thereby protecting the internal "capsule" where people were located, while only the blast wave affected the capsule itself (Shadan *et al.*, 2024).

Despite the fact that Singapore was a country that had not participated in any armed conflict and had not conducted hostilities on its territory, after the Second World War it became concerned with how to protect its population from potential threats. Singaporean legislation established several types of shelters mandatory for urban planning: household shelters, storey shelters, public shelters, and improvised shelters (Singapore Civil Defence Force, n.d.). People could use any of the more than 595 public shelters listed in the List of Civil Defence Public Shelters (2025) simply by reaching the nearest one. Civil buildings, such as metro stations, schools, and office centres, were designed to be used as improvised shelters if necessary. In particular, in underground metro stations, blast doors separated the underground level from the concourse level, thereby protecting people inside from potential external explosions. All metro stations were equipped with generators and their own air filtration systems, ensuring a continuous supply of electricity, drinking water, and clean air. Since 1997, it became mandatory for every apartment in a residential building to include a built-in shelter. Located one above the other, these individual household shelters were constructed from thick reinforced concrete and were strong enough to withstand bombardment. However, in the event of a direct hit and the collapse of the entire structure, it was unlikely that only a vertical column of fortified rooms would remain intact. In accordance with the Civil Defence Shelter Act 1997 (2020), the primary purpose of such shelters was to protect residents from fragments during explosions, as flying glass, concrete debris, and shrapnel typically caused most injuries. It should be noted that in the aforementioned countries, technical requirements for such shelters were strictly regulated and mandatory.

Ukraine was undergoing processes similar to those experienced by Israel 50 years earlier: with still weak protection, but a strong understanding of the need to adapt everyday life to the conditions of war. Over nearly three years of war, Ukrainian infrastructure, business processes, and society had already begun this transformation (Reznikova & Korniievskyi, 2024). The main regulatory document in Ukraine governing the construction of shelters and bomb shelters was the building code DBN V.2.2-5:2023 (2023). It replaced DBN V.2.2.5-97 (1998), which had originally been a translation of the Soviet SNiP II-11-77 "Civil Defence Protective Structures". The new standard eliminated most Soviet terminology, such as "civil defence", replacing it with "civil protection", updated references to regulatory documents, and removed references to Soviet-era products for specific types of equipment. This allowed Ukrainian manufacturers and suppliers to offer their products freely (provided they did not originate from Russia or Belarus). DBN V.2.2-5:2023 (2023) also introduced a new type of shelter – rapidly deployable protective structures – and defined specific requirements for each type of shelter (Fig. 2).

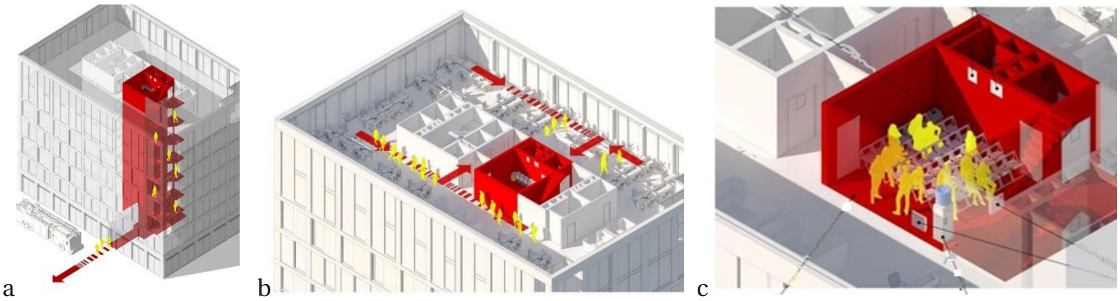
Figure 2. Categories of civil defence protective structures

Note: a – anti-radiation shelters; b – dual-purpose structures; c, d, e – varieties of simplest shelters

Source: Organising the sheltering of the population… (n.d.)

These types of defensive structures have of strategic importance for ensuring the protection of the population and belong to collective protection purpose. However, they do not cover all the protection needs of the population, considering the latest experience of living in wartime conditions (Fig. 1). Critical infrastructure, public buildings, and residential buildings suffer daily from air attacks by various ammunition, which continuously change while a war conditions. The main injuries in urban areas are shrapnel wounds from ammunition and fragments of destroyed building structures, as well as blast waves during the shelling of populated areas. The threats of air attacks that exist during the war will also remain in the post-war period. Therefore, the solution to the problem are in creating a modern, safe spaces for people. The Verkhovna Rada of Ukraine adopted the Civil Protection Code of Ukraine (2018), which stipulated that new housing constructed in Ukraine had to include its own bomb shelter or provide access to a nearby shelter. It also required that urban planning documentation at the local level include a section on engineering and technical measures for civil protection. According to the Civil Protection Code of Ukraine (2018) and Law of Ukraine No. 2486-IX (2022), the deployment of a network of bomb shelters in Ukraine was envisaged, including in all new buildings. Urban planning documentation had to include information on engineering and technical measures for civil protection; otherwise, it was not subject to approval. The law also stipulated that the state architectural and construction control authority could refuse to issue a certificate of readiness for operation if the developer failed to fulfil the required conditions for equipping bomb shelters. At the regional level, initial steps in this direction were already being taken. The Standards for High-Quality Housing… (2022) provided an example of recommendations developed and approved by local urban planning authorities regarding underground shelters, protected spaces in apartments and office buildings, features of engineering communications, life-support systems, and spatial planning. A new type of shelter was planned to be constructed for the first time in Lviv. Safe rooms based on the Israeli model were expected to be introduced in an office centre, following the Israeli example (In Lviv, a property developer…, 2023). This represented a positive practice, but only the beginning of the process of modernising legislation at the state level.

When discussing protective structures, it was important to understand that state standards (such as DBN V.2.2-5:2023 (2023)) did not cover all possible solutions for ensuring protection under real conditions. It was therefore necessary to consider and implement the best practices of countries such as Israel, Singapore, and others. For this reason, particular attention was given to those approaches that were directly relevant to the needs of Ukraine. Based on the above, the key question was what Ukraine should adopt from international experience. First and foremost, the implementation of a comprehensive range of small, yet equally important, shelters installed directly within public or residential buildings should have been regulated at the state level. Such premises could be collectively defined by the general term “protected space” – a type of shelter that could always be quickly accessed and provided rapid protection from most threats when reaching a “traditional shelter” was not possible.



a b c

Figure 3. Principle of placing protected rooms in a building

Note: a – location within the building's rigid core, stacked one above the other; b – location deep within the building; c – functionality of the premises, providing amenities and everything necessary

Source: In Lviv, a property developer… (2023)

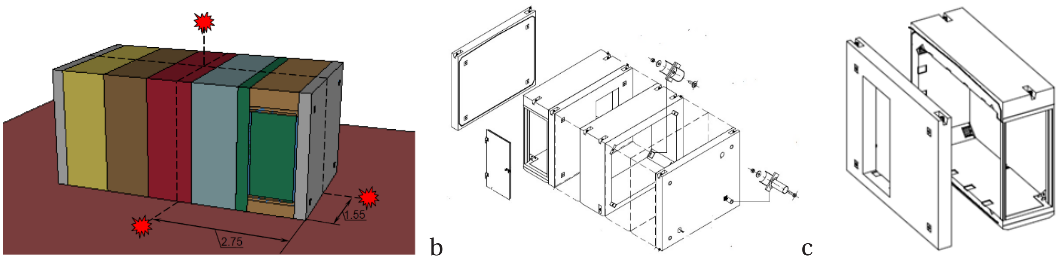
For example, if building has protected space within rooms or under the building, there no need to go outside to looking for official shelter, risking wounds or injuries from debris. The correct concept is not moving to a bomb shelter several blocks away or descend from the 25th floor to a basement under the building, but to have premises built as a protected armoured structure directly where people are located. And ensuring the presence of an elevator that will operate during power outages, and generator – as one of the requirements, without which the building will not be commissioned. For this purpose, legislation must be urgently adapted towards creating population protection. First, there must be types of protective constructions, like as temporary shelters, to allow people quickly find protection. Since there is no regulatory framework for designing protected spaces yet, the fastest and most practical option is to build shelters from prefabricated reinforced concrete structures. Figure 4 shows one such facility in the process and after construction.

The technical requirements for protected spaces in Ukraine are absent. They will not replace full-fledged civil defence protective structures, but as a supplement to them, or for organising people protection at the initial stage of danger, they will be extremely relevant. Figure 5 shows the principle of design-stage calculating a prefabricated explosion shelter, as well as a schematic diagram of how to assemble such a shelter. Regarding placement, it can be at ground level, buried, or semi-buried.

a b c

Figure 4. The simplest type of precast reinforced concrete shelter built at a factory in the Kyiv region

Source: Ruslan Kravchenko: Another modern shelter... (2024)



a b c

Figure 5. Prefabricated reinforced concrete shelters

Note: a – diagram of explosion points; b and c – structural elements of the construction

Source: I.M. Neklonsky (2017)

For industrial facilities, especially critical infrastructure sites where staff cannot leave their workplaces to take shelter in civil defence protective structures – even during threats – the situation is particularly challenging.

Although Ukrainian standards provide for anti-radiation shelters or dual-purpose structures at industrial sites, these requirements are not mandatory for most industrial enterprises, unlike in many other countries. Currently, shelters are actively being built for state-owned critical infrastructure enterprises using state funding (Hasenko *et al.*, 2025; Filonenko & Nikolaienko, 2025). However, in the private sector, this remains a rare exception. Such shelters are usually incorporated only when new facilities are designed in line with best international practices and current state requirements. When comparing a standalone shelter with a built-in dual-purpose structure, the latter is clearly preferable from a safety perspective (Fig. 6).

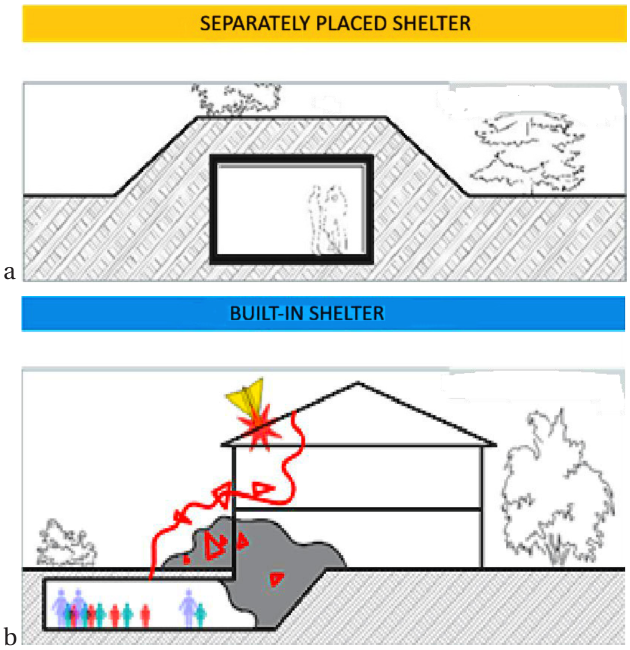


Figure 6. Types of shelters by location

Note: a – separately placed shelter; b – built-in-shelter

Source: S. Malliiani & O. Slietsov (2025)

For example, a built-in canteen, changing room, meeting room, or operator's room at the basement floor, that meets all the standards of shelter is significantly safer and more convenient, as personnel do not need to leave the building to take detached shelter. It reduces the risk of being exposed to shelling while moving from the workplace to an outdoor shelter. In the case of staff, this also means additional time for changing clothes, since, in winter, personnel must leave work change sanitary clothing with warm clothes before heading to the shelter (State comptroller of Israel, 2024). Also to be added that crowds of people need to change clothes simultaneously. Therefore, a shelter within an industrial building is not only safer but also more convenient, considering that dual-purpose structures already have the necessary comfort and amenities for extended stays. The economic aspect is important for industry. On the one hand, a dual-purpose structure seems to be a profitable solution for business, as there is no need to build a separate shelter, and one premise covers both current operational needs and shelter. On the other hand, the cost of such a premise might be higher than, as detached one. Because of the cost for additional equipment, emergency power supply, ventilation, strengthening of walls and ceilings, an additional exits arrangement – can make this option less attractive. An entrepreneur will choose a cheaper option, despite all the safety and convenience advantages. Ukraine's housing stock was quite diverse in terms of implementing the necessary reconstruction. For instance, in the case of monolithic-frame buildings, the required changes were not significant. Protected spaces were located inside the building next to elevators, where they were enclosed from all sides and did not face the façades. This corresponded to the "two-wall rule", whereby the first wall could be hit by a missile, while the second would protect against fragments. Ideally, such a room was designed in the middle of the apartment. According to Ukrainian standards (DBN V.2.2-5:2023 (2023)), "blind room" layouts were not yet provided. The protected room had to be properly organised, including the provision of ventilation, water and food supplies, and an emergency lighting system. In non-frame or existing buildings, such as inexpensive panel and brick structures, the implementation of monolithic-frame protected rooms could require an additional 10-20% investment relative to the property value (Recommendations from the State Emergency Service…, 2022). It should be noted that a safe space was more than just walls. It included the comfort of stay and the ability to remain there for an extended period. For example, the arrangement of shelters in educational and children's institutions involved spaces with bright designs and engaging themes to support children's psychological well-being. At the same time, any strengthening requirements increased costs. For the construction industry, this meant reduced profitability, while for residential construction it led to higher property prices and a potential risk of decreased demand. If a developer invested more in construction, they either earned less or increased the cost of the property. Therefore, the experience of other countries demonstrated the necessity of strengthening state standards for proper construction. It should also be noted that the implementation of new requirements needed to be supported by both state programmes and non-governmental funds aimed at facilitating the transition to functioning under military threats and adapting infrastructure accordingly (State comptroller of Israel, 2024). It is essential to develop a material, technical, legal, and financial framework that would ensure compliance with existing requirements and the adoption of new ones in line with current challenges.

During the study by S. Malliiani & O. Slietsov (2025), a phased analysis of civilian casualties caused by missile and drone attacks was conducted, and three most critical damage scenarios were identified: residential buildings, open spaces, and public facilities with mass gatherings. Based on these scenarios, a comparative analysis of the regulatory framework, spatial and functional parameters, and typology of protective structures in Ukraine, Finland, and Israel was carried out. The study resulted in the identification of the strengths and weaknesses of each model and in the formulation of potential directions for modernising the Ukrainian system of protective structures. The current nomenclature of protective structures in Ukraine did not include solutions capable of effectively protecting the population under the first scenario – attacks on residential buildings. Unlike Ukraine, Israel had a deeply integrated model of Mamad and Mamak shelters, which formed part of the structural system of residential buildings and had regulated parameters of blast resistance, airtightness, and immediate accessibility. Given the similarity of threats, the implementation of adapted individual or floor-level shelters in Ukraine represented an appropriate and potentially life-saving solution. Under the second scenario – protection in open spaces – the Ukrainian system did not include regulated types of structures capable of providing effective protection in such conditions. In addition, relatively large regulatory accessibility radii (300-500 m) created additional risks when attempting to reach a shelter. In this context, fortified ground shelters of the S2 type (Mamak) were particularly relevant – mobile and spatially accessible modules placed in close proximity to public areas (50-100 m). In Ukraine, it would be advisable to develop a national model of ground shelters with an emphasis on modularity, mobility, and blast resistance. Under the third scenario – the presence of large numbers of people in public buildings (schools, theatres, shopping centres) – the current nomenclature of PRU and shelters in Ukraine provided a basic level of protection (Malliiani & Slietsov, 2025). However, it did not eliminate the fundamental risk associated with a high concentration of people within a single large space, which increased the likelihood of mass casualties in the event of a direct hit.

In contrast, the analysis of recent conflicts presented in The resilience of Israel safe rooms… (2025) showed that the wars in Ukraine, the October 7th War, and the 12-day war in Israel demonstrated that the residential protected room, while groundbreaking at the time of its introduction, was no longer adequate for evolving security challenges. Recent conflicts in Gaza, Ukraine, and Israeli urban centres indicated that concrete alone could not ensure safety. The collapse of surrounding structures could turn Mamads into sealed spaces with no escape routes. The lack of proper ventilation and emergency exits also made them potentially dangerous during fires or chemical incidents. O. Sliepstov & S. Malliani (2025) further argued that this type of shelter had become outdated and did not address new scenarios such as urban combat, combined threats, or earthquakes. A. Chudzińska *et al.* (2025) indicated that the most effective integration with the urban environment was achieved by shelters adapted within existing buildings or infrastructure, such as basements of sports halls, shopping centres, or transport tunnels. These solutions enabled the integration of civil protection functions with the maintenance of public order. In contrast, conventional shelters constructed from scratch outside urban centres required significant financial and infrastructural investment, making them difficult to replicate on a large scale in European conditions. Moreover, the ratio of costs to potential benefits, given population density, was often unfavourable. Large-scale protective facilities, such as the Sonnenberg shelter and the AT&T skyscraper, were designed to be fully autonomous and were equipped with electricity generators, air filtration systems, and long-term supplies of water and food. While they represented a high level of technical resilience, this was achieved at the cost of extremely high expenditures. From a historical perspective, the social function of shelters (criterion D) evolved from an exclusive to an inclusive model. The most advanced Cold War shelters were typically intended for elites, such as political and military leadership, and were not accessible to the general population. In contrast, contemporary approaches emphasised universality: in Finland, underground concrete shelters were accessible to the entire population, and legislation required their integration beneath large public buildings (Malliiani & Slietsov, 2025). The evolving dual-use concept of shelters raised the question of how new civic and recreational functions aligned with their primary life-saving purpose. S.H. Jore *et al.* (2025) examined the roles and perceptions of security guards in Norway, demonstrating that security and safety should not be reduced to traditional preventive measures (e.g., physical barriers and armed protection), but are instead constructed through a broader set of practices. The authors emphasised that contemporary safety is co-produced through diverse professional functions, including situational vigilance, inter-agency collaboration, elements of social support, and service-oriented activities, thereby framing security work as an integrated component of societal safety production. While everyday use improved maintenance and public acceptance, it should not have compromised emergency readiness. Maintaining this balance required regular system testing, personnel training, and public awareness to ensure that accessibility in daily use did not reduce effectiveness in emergency situations, as noted by L. Zhao *et al.* (2017). Thus, the emerging concept should promote inclusivity – shelters designed "for all, not the select few". In addition, the time required to reach a safe space remained a critical factor in ensuring effective protection.

Conclusions

The experience of air attacks, particularly in frontline areas in 2025, confirmed that even where technical evacuation measures were available, factors such as time, orientation, and route accessibility determined the success of self-evacuation. This further emphasised the importance of creating local shelters directly within residential buildings, providing immediate access to protected spaces without the need for complex navigation. The integration of residential protected rooms into existing buildings or civil infrastructure not only met the requirements of adaptive responses to contemporary risks, but also compensated for the limitations of traditional shelter systems. Thus, the results of the study indicated that the Ukrainian civil protection system had real potential for development, but required updating, increased spatial accessibility, and a reconsideration of the principles governing the placement and organisation of protective structures in the context of residential development, open spaces, and public facilities. Taking into account behavioural factors in emergency situations, such solutions could become an effective complement to the existing network of protective structures. The implementation of pilot solutions within individual buildings or residential complexes would allow the technical feasibility and cost-effectiveness of such shelters to be tested under real conditions. The results of this stage could form the basis for updating building codes and developing practical recommendations in the field of civil protection as an important component of comprehensive population protection. If pilot projects were successfully implemented, the next stage would involve securing funding and creating conditions for the operation of funds dedicated to the construction of new shelters and the renovation of existing ones.

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References

[1] Almulhim, A.I. (2025). Building urban resilience through smart city planning: A systematic literature review. *Smart Cities*, 8(1), article number 22. doi: 10.3390/smartcities8010022.
[2] Anas, S.M., Alam, M., & Umair, M. (2023). Reinforced cement concrete (RCC) shelter and prediction of its blast loads capacity. *Materials Today: Proceedings*, 74, 547-568. doi: 10.1016/j.matpr.2022.09.125.
[3] Chudzińska, A., Achramowicz, R., & Kiełb, P. (2025). Architecture dedicated to civil protection as an element of sustainable urban development. The searching for a "New fallout shelters standard" (NFSS) for European city centres. *Buildings*, 15(21), article number 3989. doi: 10.3390/buildings15213989.
[4] Civil Defence Shelter Act 1997. (2020). Retrieved from https://sso.agc.gov.sg/Act/CDSA1997.
[5] Civil Protection Code of Ukraine. (2018). Retrieved from https://zakon.rada.gov.ua/laws/show/5403-17/ed20180526#Text.
[6] DBN V.2.2.5-97 "Buildings and Structures. Civil Defense Structures". (1997, July). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=4653.
[7] DBN V.2.2-5:2023 "Civil Defense Structures". (2023, August). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=104666.
[8] de Yong, S., Rachmawati, M., & Defiana, I. (2024). Theorizing security-pandemic aspects and variables for post-pandemic architecture. *Building and Environment*, 258, article number 111579. doi: 10.1016/j.buildenv.2024.111579.
[9] DSTU 9195:2022 "Prefabricated Civil Defense Structures of Modular Type. Substantive Provisions". (2022, December). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=99454.
[10] DSTU 9329:2025 "Primary (Mobile) Shelters of Modular Type. Substantive provisions". (2025, June). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=115969.
[11] Filonenko, O., & Nikolaienko, D. (2025). Design of civil defense protective structures in residential multi-story buildings for individual use. *Academic Journal. Industrial Machine Building, Civil Engineering*, 2(65), 77-83. doi: 10.26906/znp.2025.65.4192.
[12] Hasenko, A.V., Hasenko, L.V., Slon, V.V., & Darienko, V.V. (2025). Identifying the need for civil protection shelters in existing residential areas. *Taurida Scientific Herald. Series: Technical Sciences*, 1, 551-559. doi: 10.32782/tnv-tech.2025.1.57.
[13] In Lviv, a property developer is fitting out safe rooms in office buildings, just as they do in Israel. (2023). Retrieved from https://city-adm.lviv.ua/news/architecture-and-historic-heritage/u-lvovi-zabudovnyk-v-ofisakh-zvodyt-bezpechni-kimnaty-iak-tse-robliat-u-izraili/.
[14] Israel's bomb shelters: Is this feasible in Ukraine? (2023). Retrieved from https://defence-ua.com/minds_and_ideas/bomboshovischa_izrajilju_chi_realno_tak_zrobiti_v_ukrajini-11761.html.
[15] Jore, S.H., Størkersen, K.V., Haavik, T.K., & Almklov, P.G. (2025). What constitutes safety? A qualitative interview study of what the work of Norwegian security guards really is about. *Safety Science*, 191, article number 106954. doi: 10.1016/j.ssci.2025.106954.
[16] Law of Ukraine No. 2486-IX "On Amendments to Certain Legislative Acts of Ukraine Regarding Ensuring Civil Protection Requirements During Planning and Development of Territories". (2022, July). Retrieved from https://zakon.rada.gov.ua/laws/show/2486-20#Text.
[17] List of Civil Defence Public Shelter (as of Nov 2025). (2025). Retrieved from https://surl.li/vfvbom.
[18] Malliiani, S., & Slietsov, O. (2025). Comparative analysis of architectural and spatial solutions for civil protective structures: Experience of Ukraine, Finland, and Israel. *Architectural Bulletin of KNUBA*, 33, 121-133. doi: 10.32347/2519-8661.2025.33.121-133.

[19] Ministry for Communities and Territories Development of Ukraine. (n.d.). Retrieved from https://www.kmu.gov.ua/en/news/pershe-modulne-pidzemne-ukryttia-vstanovyly-u-borodiantsi-na-kyivshchyni.

[20] Neklonsky, I.M. (2017). *Tactics for the management of emergencies: A course of lectures*. Kharkiv: National University of Civil Defence.

[21] Organising the sheltering of the population in civil defence shelters. (n.d.). Retrieved from https://nmc.dsns.gov.ua/zt/informaciya-pro-zahisni-sporudi-civilnogo-zahistu.

[22] Recommendations from the State Emergency Service of Ukraine on organising shelters. Civil protection guidelines for educational establishments. Guidelines on civil protection, industrial safety and emergency response. (2022). Retrieved from https://svyatruo.org.ua/blog/2022/06/29/rekomendacziyi-dsns-ukrayiny-shhodo-organizacziyi-ukryttya-instrukcziya-z-czyvilnogo-zahystu-v-zakladi-osvity-instrukcziya-z-czyvilnogo-zahystu-tehnogennoyi-bezpeky-ta-diyi-u-nadzvychajnyh-sytuaczi/.

[23] Reznikova, O., & Korniievskyi, O. (2024). Resilience of the Ukrainian society in wartime: Components and influencing factors. *Eastern Journal of European Studies*, 15(1), 113-133. doi: 10.47743/ejes-2024-0105.

[24] Ruslan Kravchenko: Another modern shelter with capacity for almost 800 people has been built in the town of Ukrainka in the Kyiv region. (2024). Retrieved from https://koda.gov.ua/ruslan-kravchenko-v-misti-ukrayinka-na-kyyivshhyni-pobuduvaly-shhe-odne-suchasne-ukryttya-majzhe-na-800-osib/.

[25] Shadan, P., Sharafi, P., & Saeed, N. (2024). Blast response and protection level of concrete composite wall panels made with recycled tyre fibres in a cement matrix. *Construction and Building Materials*, 451, article number 138866. doi: 10.1016/j.conbuildmat.2024.138866.

[26] Singapore Civil Defence Force. (n.d.). *Types of shelter*. Retrieved from https://www.scdf.gov.sg/home/civil-defence-shelter/types-of-shelter.

[27] Sliepstov, O., & Malliani, S. (2025). Comparative analysis of architectural and spatial solutions for civil protection shelters: The experience of Ukraine, Finland, and Israel. *Architectural Bulletin of KNUCA*, 33, 121-133. doi: 10.32347/2519-8661.2025.33.121-133.

[28] Standards for High-Quality Housing Construction in Lviv. (2022). Retrieved from https://city-adm.lviv.ua/lmrdownloads/2022/05/%D0%A1%D1%82%D0%B0%D0%BD%D0%B4%D0%B0%D1%80%D1%82%D0%B8%20%D0%BF%D1%80%D0%B5%D0%B7%D0%B5%D0%BD%D1%82%D0%B0%D1%86%D1%96%D1%8F_13-05-2022.pdf.

[29] State comptroller of Israel. (2024). *Approval of protected spaces by the home front command and the control institutes as part of the building permit granting process*. Retrieved from https://library.mevaker.gov.il/sites/DigitalLibrary/Documents/2024/2024.01-74A/EN/2024-74A-402-Oref-Taktzir-EN.pdf.

[30] Surkes, S. (2025). *Knesset passes bill allowing Israelis to expand reinforced rooms, add bathrooms*. Retrieved from https://www.timesofisrael.com/knesset-passes-bill-allowing-israelis-to-expand-reinforced-rooms-add-bathrooms/.

[31] The resilience of Israel safe rooms (Mamad) in modern warfare: Critical reassessment and alternative solutions. (2025). Retrieved from https://sheltersecurityproducts.com/2025/07/11/mamad-safety-israel-modern-warfare/.

[32] Wu, Y., Zhao, L., & Sun, J. (2025). Analysis of the emergency shelter function of large-scale international sports event venues. *Transportation Research Interdisciplinary Perspectives*, 34, article number 101680. doi: 10.1016/j.trip.2025.101680.

[33] Zatulsky, A. (2023). *How to continue living and developing during a constant military threat – the experience of Israel*. Retrieved from https://mind.ua/openmind/20252994-yak-prodovzhuvati-zhiti-ta-rozvivatisya-pid-chas-postijnoyi-vijskovoyi-zagrozi-dosvid-izrayilyu.

[34] Zhao, L., Li, H., Sun, Y., Huang, R., Hu, Q., Wang, J., & Gao, F. (2017). Planning emergency shelters for urban disaster resilience: An integrated location-allocation modeling approach. *Sustainability*, 9(11), article number 2098. doi: 10.3390/su9112098.

[35] Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. *Buildings*, 15(12), article number 2020. doi: 10.3390/buildings15122020.

Впровадження світового досвіду будування укриттів цивільного захисту

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Анотація. Загострення сучасних військових загроз в Україні зумовило необхідність перегляду підходів до цивільного захисту та інтеграції захисних споруд у житлову й громадську інфраструктуру. Метою дослідження був аналіз українського законодавства поряд із відібраними міжнародними практиками задля виявлення ефективних моделей інкорпорації захисних просторів у будівлі та обґрунтування напрямів розширення класифікації захисних споруд. Методологічну основу становив комплексний аналіз національних нормативно-правових документів, порівняльна оцінка міжнародного досвіду, а також узагальнення й систематизація найкращих практик. Особливу увагу приділено законодавчим і технічним підходам, запровадженим в Ізраїлі та Сінгапурі, зокрема щодо інтеграції укриттів у будівлі, забезпечення швидкої доступності та функціональної ефективності. Дослідження також враховувало економічну доцільність і практичні аспекти впровадження таких рішень в існуючих та новозбудованих об'єктах. Результати показали, що міжнародна практика послідовно наголошує на критичній важливості мінімізації часу, необхідного громадянам для доступу до укриттів. Це досягається шляхом вбудовування захищених просторів безпосередньо в житлові та промислові будівлі або завдяки розгортанню модульних систем укриттів. Проаналізовані приклади засвідчили, що такі підходи забезпечують вищий рівень безпеки населення, особливо в умовах частих і непередбачуваних загроз. Встановлено, що як Ізраїль, так і Сінгапур успішно закріпили ці рішення у своєму законодавстві, підкріпивши їх чітко визначеними технічними стандартами. Дослідження обґрунтувало доцільність поступового впровадження інтегрованих і модульних захисних споруд в Україні – як у процесі післявоєнної відбудови, так і в нових будівельних проєктах. Практичне значення роботи полягає у розробленні рекомендацій щодо адаптації українського законодавства та підвищення доступності, ефективності й стійкості інфраструктури цивільного захисту

Ключові слова: захищений простір; споруди подвійного призначення; міська стійкість; підземні простори; Мамади

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Innovative approaches to rebuilding the logistics infrastructure of Ukraine

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Abstract. The article was devoted to the analysis of modern innovative approaches to the restoration of the logistics infrastructure of Ukraine in the context of post-war recovery and global changes in the world economy. The object of research was the processes of restoring the transport and logistics infrastructure of Ukraine, taking into account modern technological and organisational solutions. The purpose of the study was to identify key strategies and technologies for the reconstruction of the country's logistics system, taking into account digitalisation, environmental sustainability and integration into the European transport network. The research methods included mathematical modelling of traffic flows, analysis of current logistics trends, the use of multi-agent systems for route optimisation, and an empirical study of international experience. The article discussed the main challenges associated with the restoration of logistics infrastructure and identified ways to overcome them. In particular, it was proposed to use urban microhubs to optimise the delivery of goods in cities, to introduce digital technologies (Internet of Things, artificial intelligence, blockchain) to improve the efficiency of logistics processes, and to develop multimodal transportation. Based on modelling using Simulation of Urban Mobility, the effectiveness of the proposed approaches to reduce traffic load, cut costs, and reduce CO_2 emissions was demonstrated. The results of the article can be used by public authorities, transport companies and logistics operators to develop a strategy for the restoration and modernisation of Ukraine's logistics infrastructure. Forecast assumptions about the development of the research object were related to the further introduction of intelligent transport systems and digital technologies in the field of logistics, the creation of innovative logistics clusters, and the integration of Ukraine into European transport corridors

Keywords: digitalisation; multimodal transportation; urban microhubs; route optimisation; transport technologies

Introduction

Restoration of Ukraine's logistics infrastructure is one of the key conditions for economic growth and stability of the country in the post-war period. The large-scale destruction of transport arteries, warehouses, ports and logistics centres requires not only their reconstruction, but also the introduction of new, innovative approaches that will ensure increased sustainability and efficiency of the logistics system. In the current environment of logistics processes, global trends are focusing on digitalisation, automation, use of environmentally friendly technologies and development of multimodal transportation. Ukraine has a unique opportunity to create a more efficient, safe

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and sustainable logistics infrastructure that meets European and global standards using the latest technologies and innovations. Thus, the problem of restoring Ukraine's logistics infrastructure is complex, multidimensional, and requires the introduction of innovative approaches based on scientific research, advanced technologies, and strategic planning. Its solution will contribute not only to the rapid economic recovery of the country, but also to the creation of a competitive transport network capable of ensuring sustainable development in the future. The restoration of Ukraine's logistics infrastructure requires integrated planning and modern policy approaches, as noted by P.N. Alves Junior *et al.* (2021). The study by S. Aebi *et al.* (2024) argued that experience from post-conflict settings indicates that infrastructure reconstruction should be accompanied by the integration of smart technologies. This is essential for achieving long-term sustainability and economic resilience. Restoration of logistics infrastructure in crisis situations and post-war reconstruction is one of the key areas of modern scientific research. Over the past three years, the world's scientific literature has shown considerable interest in the problems of logistics digitalisation, integration of sustainable transport systems and application of innovative solutions to improve the efficiency of transport infrastructure. According to J. Zaman *et al.* (2025), the use of Internet of Things (IoT) and artificial intelligence (AI) technologies helps optimise logistics processes in crisis-affected regions. Such technologies can significantly improve the monitoring of traffic flows and reduce risks in supply management.

Y. Sultana & S.M. Rawoof (2025) studied the role of blockchain in ensuring the transparency and efficiency of supply chains in the post-war period. Authors concluded that the integration of blockchain into the transport resource management system reduces costs and minimises corruption risks. Sustainable development of transport infrastructure is also a priority of modern research. For example, A. Jugović *et al.* (2025) examined the introduction of "green corridors" and the use of low-carbon technologies in the logistics systems of countries recovering from conflicts. They emphasised that the use of electric vehicles and hydrogen technologies can significantly reduce CO_2 emissions and improve the environmental performance of the transportation network. One of the key approaches to the reconstruction of logistics systems is the development of multimodal transportation. The study by D.A. Kurniawan (2024) showed that the integration of rail and road transport can increase the efficiency of transportation in regions that need rapid recovery. In addition, the S.E. Antos *et al.* (2021) report emphasised the need to introduce modern logistics hubs in urban centres, which will reduce transportation costs and increase the speed of delivery of goods. Thus, the analysis of recent research demonstrated that the reconstruction of Ukraine's logistics infrastructure should be based on the application of advanced digital technologies, the development of multimodal transportation, and environmentally sustainable solutions. The rebuilding of Ukraine's logistics infrastructure in the post-war period is a complex and multidimensional process that requires a systematic approach and the implementation of innovative solutions. Given the large-scale destruction of transport networks, the key tasks are to ensure the effective functioning of the logistics system, its adaptation to new geopolitical conditions and integration into global transport corridors. The purpose of this article was to analyse modern innovative approaches to the restoration of Ukraine's logistics infrastructure in the context of post-war recovery and global changes in the world economy. In particular, the study was aimed at solving the following tasks: (1) assessment of the possibilities of digitalisation of logistics processes – consideration of the prospects for the use of AI, blockchain, the IoT and Big Data to optimise traffic management; (2) development of approaches to increasing the sustainability of the logistics system – analysis of environmental and energy-efficient solutions in the transport infrastructure; (3) substantiation of the role of multimodal transportation – assessment of the effectiveness of integration of different modes of transport to increase the capacity and reliability of logistics chains.

Materials and Methods

This study was based on a comprehensive combination of analytical, mathematical, and simulation approaches to investigate logistics processes in the context of post-war recovery. The research design was applied and descriptive, involving the development of a theoretical model of infrastructure restoration followed by its validation through digital simulation. The object of the study was the processes of restoring the transport and logistics infrastructure of Ukraine, taking into account modern technological and organisational solutions. The subject of the study included key strategies and technologies for the reconstruction of the national logistics system, with particular emphasis on digitalisation, environmental sustainability, and integration into the European transport network. The research was conducted in several successive stages. At the first stage, an analysis of scientific literature was carried out to identify current trends in logistics development, digitalisation of transport processes, and the use of urban microhubs. The analysis was based on international research and reports from organisations such as the World Bank (Antos *et al.*, 2021) and the European Commission (n.d.), as well as scholarly publications indexed in Scopus and Web of Science. The theoretical framework was informed by the studies of M. de Bok *et al.* (2024), J.-P. Rodrigue (2024), and J. Liu *et al.* (2025). At the second stage, mathematical modelling of transport flows was applied to assess logistics performance and determine optimal delivery routes. Route optimisation was conducted using the Greedy algorithm, the Vehicle Routing Problem (VRP), and dynamic routing techniques, which enabled the identification of efficient delivery configurations and the reduction of transport costs under varying constraints. At the final stage, simulation modelling was implemented as the core analytical tool using the

Simulation of Urban Mobility (SUMO) environment. This approach enabled the creation of a digital representation of an urban transport system incorporating different vehicle types, including electric trucks, bicycles, and conventional freight transport, as well as varying traffic conditions and demand patterns.

A multi-agent system (MAS) approach was integrated into the simulation framework to model interactions between vehicles and logistics centres. This allowed the assessment of system adaptability under dynamic traffic conditions and facilitated the evaluation of decentralised decision-making processes in logistics operations. The simulation was conducted using a synthetic urban transport network representing a typical medium-sized European city. The network included arterial roads, secondary streets, and central areas with high delivery demand density, allowing the generalisation of results to similar urban environments. Each simulation covered a 24-hour operational cycle, including peak and off-peak periods. Traffic congestion was modelled through variable vehicle density and speed constraints, while demand dynamics were introduced via time-dependent delivery requests. The modelling scenario incorporated key parameters affecting logistics performance, including delivery intervals to end users, the number and spatial distribution of urban microhubs, route network configurations connecting microhubs with other parts of the city, and technical characteristics of the transport infrastructure and vehicle fleet. Input parameters were defined as follows: traffic intensity ranged from 800 to 1,800 vehicles per hour on main roads and from 200 to 600 vehicles per hour on secondary streets; daily delivery demand varied between 1,200 and 2,500 orders; the freight structure consisted of 65% small parcels, 25% medium shipments, and 10% bulk deliveries; and the average delivery distance ranged from 3 to 8 km. Model performance was evaluated using indicators of average delivery time, operating costs, traffic congestion, and CO_2 emissions. The average delivery time was calculated as the total duration from dispatch to final delivery, including travel time, waiting time at microhubs, and delays caused by congestion. Operating costs were estimated based on vehicle operating time, distance travelled, fuel or energy consumption, and maintenance costs. To ensure the reliability of the results, a total of 30 simulation runs were performed for each scenario. Two scenarios were analysed: a baseline scenario representing a traditional delivery system without microhubs, and an experimental scenario incorporating urban microhubs, optimised routing strategies, and multi-agent coordination. The number of microhubs varied from 3 to 7 units, while delivery time windows ranged from 1 to 4 hours. The model was validated by comparing the obtained results with findings reported in previous studies, particularly regarding delivery time reduction and cost efficiency (de Bok *et al.*, 2024; Ruan *et al.*, 2025). The consistency of the results with established ranges in the literature confirmed the adequacy and reliability of the modelling approach.

Results and Discussion

Restoring Ukraine's transport infrastructure after the hostilities is a critical strategic task for stabilising the country's economic situation. Transport is a key element of economic activity, as it ensures not only the movement of goods and services, but also the continuity of the functioning of enterprises and markets. According to Q. Li & J.S.L. Lam (2025), transport infrastructure is a fundamental component of a country's economic development, and its restoration is critical to ensuring the efficiency of national supply chains. The need for rapid and high-quality infrastructure reconstruction was also emphasised by J. Liu *et al.* (2025), who noted that investment in transport network restoration can significantly accelerate economic recovery following crises. For Ukraine, given the current challenges, the restoration of transport networks should be based on innovative approaches that allow not only to quickly restore physical infrastructure, but also to ensure its sustainability and efficiency in the long term. In the context of global changes and the growing need for environmentally friendly sustainable logistics, an important task is to create a transportation system that combines efficiency and sustainable development. Implementation of innovative solutions is key to addressing road congestion, reducing CO_2 emissions, and improving transportation efficiency. According to B. Gerrits *et al.* (2024), one of the biggest challenges for post-war recovery is adapting transportation systems to new conditions, which include the need to use more environmentally friendly modes of transport and integrate digital technologies into logistics processes. The main requirements for modern transport infrastructure include the introduction of digitalisation, integration of smart transport systems, the use of electric vehicles, and improved route optimisation methods to reduce environmental impact and improve economic efficiency. The restoration of the logistics infrastructure should not only restore the physical flow of goods, but also optimise them with the help of modern information technologies (Ning & Yao, 2023).

One of the most promising solutions for achieving efficient and environmentally sustainable urban delivery is the development of a network of urban microhubs. These facilities represent compact logistics centres located at strategically important points within the city, enabling route optimisation and traffic reduction (de Bok *et al.*, 2024). Their implementation contributes to a decrease in transport load, lower CO_2 emissions, and improved delivery speed. In addition to physical infrastructure, microhubs are part of a digitalisation system that automates the management of logistics processes and increases their efficiency using the latest technologies such as the IoT, AI, and route optimisation algorithms. Such solutions can significantly improve logistics processes and reduce operating costs for companies, which is confirmed by numerous studies on the example of European cities (Rodrigue, 2024). Urban microhubs are compact, well-located logistics centres within the city that provide convenient distribution of goods to the end consumer. They help optimise the last mile of delivery, reducing costs and the burden on urban transport infrastructure. The main goal of microhubs is to reduce the need for large vehicles to deliver goods to city centres by replacing them with smaller, more environmentally friendly vehicles such as electric trucks or bicycles. Since 2022, European countries have implemented initiatives incorporating urban microhubs to reduce traffic congestion and improve the efficiency of urban logistics. For example, in the Netherlands, where this approach has been actively adopted, a 20% reduction in the number of trucks was recorded, leading to a 10% decrease in urban air pollution (European Commission, n.d.). One of the main advantages of urban microhubs is the reduction of traffic congestion, as large freight vehicles are replaced by more compact and flexible modes of transport. This transition can decrease the number of trucks in urban areas by approximately 20-30% (Rodrigue, 2024). Another important advantage is the reduction of CO_2 emissions, as the use of electric transport for last-mile delivery significantly decreases environmental impact. For instance, electric courier services can reduce emissions by up to 40% compared to conventional diesel vehicles (de Bok *et al.*, 2024). Another advantage is the improvement in delivery speed, as decentralised logistics facilities reduce the distance required to reach final destinations. This can increase overall operational efficiency by approximately 30-40% compared to conventional delivery systems. Table 1 presents a comparison of the efficiency of urban microhubs and traditional delivery systems, allowing for an assessment of the advantages of these logistics solutions in urban environments.

Table 1. Comparison of the efficiency of urban microhubs and traditional delivery

Parameter	Traditional delivery	Urban microhubs
Reduced traffic	0%	20-30%
Reduced delivery time	0%	30-40%
Reducing CO_2 emissions	0%	40%
Increase delivery efficiency	0%	30-40%

Source: compiled by the authors based on M. de Bok *et al.* (2024), European Commission (n.d.)

The data presented in Table 1 indicate that the implementation of urban microhubs is associated with improvements in delivery efficiency. Compared to conventional delivery models, their use contributes to reduced traffic congestion and lower environmental impact, primarily due to the replacement of heavy freight vehicles with more sustainable transport solutions. Overall, the findings suggest that decentralised logistics infrastructure can enhance delivery flexibility and support more efficient urban distribution processes, particularly in densely populated areas. Within this study, the digitalisation of logistics processes was considered an integral component of the microhub-based delivery model. The application of digital technologies facilitated coordination between logistics operators, transport systems, and end users. In this context, digital transformation functioned as a supporting technological framework that enhanced the overall efficiency of microhub-based logistics systems, rather than as an independent development direction.

IoT and AI technologies to optimise logistics operations Digitalisation of logistics processes has become a major trend in recent years. The introduction of IoT and AI technologies allows automating the processes of planning, tracking goods and managing vehicles. The IoT allows connecting all elements of the logistics system into a single network, which makes it possible to effectively track the location of goods and predict delivery requests in real time. The use of modern technologies, such as IoT and AI, contributes to the improvement of logistics processes, as evidenced by the data in Table 2. IoT technologies improve logistics efficiency through the use of smart sensors, GPS trackers, automated cargo monitoring systems and digital communication platforms. These technologies enable real-time monitoring of cargo movement, allow predictive maintenance of vehicles and provide accurate delivery scheduling. The integration of IoT platforms ensures continuous data exchange between logistics operators, microhubs and transport infrastructure, significantly improving operational coordination. AI uses machine learning algorithms to predict demand, plan routes, and even manage inventory. It is estimated that the use of AI in logistics can increase transportation efficiency by 15-25% (Ning & Yao, 2023).

Table 2. Impact of IoT and AI technologies on the efficiency of logistics processes

Technology	Impact on efficiency	Notes
IoT	10-15%	Improved cargo tracking
AI	15-25%	Demand forecasting and route optimisation
Combination IoT and AI	20-35%	Integrated traffic flow management

Source: compiled by the authors based on L. Ning & D. Yao (2023), Z. Ruan *et al.* (2025)

The results showed that the integration of IoT technologies improves cargo tracking accuracy and provides real-time monitoring of transportation processes. IoT devices such as GPS sensors, smart trackers and automated monitoring systems allow logistics operators to collect operational data about vehicle movement, cargo conditions and traffic flows. AI complements these technologies by analysing collected data and predicting demand, which significantly improves route planning and resource allocation efficiency. To maximise the efficiency of logistics processes, it is important to use algorithms for route optimisation, such as Greedy Algorithm, VRP, Dynamic Routing, and MAS. The Greedy algorithm is a heuristic approach that constructs a solution by iteratively selecting the locally optimal option at each stage. This enables the rapid identification of feasible delivery routes, particularly in relatively simple or constrained scenarios. VRP is a more complex task that takes into account restrictions on the number of vehicles and their routes, taking into account time and distance. Dynamic routing was applied to enable real-time adaptation of delivery routes in response to changing road and traffic conditions. In addition, MAS were employed to model and optimise logistics processes, wherein individual agents interacted to achieve coordinated system-level performance and global optimisation.

The effectiveness of urban microhub implementation was evaluated through simulation modelling using the SUMO environment, which enabled the creation of digital representations of urban transport systems and the detailed simulation of vehicle movements under varying traffic conditions, cargo distribution patterns, and fleet characteristics. The results demonstrated that, compared to the baseline delivery model, the introduction of urban microhubs led to a reduction in average delivery time by approximately 25-30% and a decrease in operating costs by 15-20%, including savings in fuel consumption and vehicle maintenance. These findings indicate that the microhub-based approach enhances the efficiency of urban logistics systems while reducing pressure on transport infrastructure and mitigating environmental impacts. To further examine alternative delivery configurations, additional simulations were conducted, the results of which are presented in Table 3.

Table 3. Comparison of modelling results of traditional delivery and delivery through microhubs

Parameter	Traditional delivery	Urban microhubs
Average delivery time (hours)	2.5	1.8
Operating expenses (percentage)	100	80
Number of freight vehicles	100	70
Reducing emissions CO_2 (%)	0	25

Source: compiled by the authors based on J.-P. Rodrigue (2024)

The results presented in Table 3 are based on 30 simulation runs for each scenario and represent average values. To assess the stability of the obtained results, minimum and maximum values were also recorded. The modelling results confirmed the effectiveness of microhub-based logistics compared to traditional delivery systems. The reduction in delivery time and vehicle numbers indicates improved traffic flow distribution and more efficient use of transportation resources. The data also demonstrate the environmental benefits of logistics optimisation, particularly through reduced carbon emissions and improved operational performance. For the traditional delivery scenario, the average delivery time ranged from 2.3 to 2.8 hours, with a standard deviation of ±0.2 hours. In the microhub-based scenario, delivery time varied between 1.6 and 2.0 hours, with a standard deviation of ±0.15 hours. Operating costs in the baseline model ranged from 95% to 105% (normalised baseline), while in the experimental model they varied between 75% and 85%, indicating consistent cost reduction. The number of freight vehicles fluctuated within ±5% of the reported values, confirming the stability of the simulation outcomes. The baseline scenario represents a traditional centralised delivery model, where goods are transported directly from distribution centres to final customers using conventional diesel vehicles without route optimisation. The experimental scenario includes:

- integration of 3-7 urban microhubs;
- use of electric vehicles and bicycles for last-mile delivery;
- implementation of dynamic routing algorithms and multi-agent coordination.

The average delivery time includes total time from dispatch to final delivery, including travel time, waiting time at microhubs, and delays caused by traffic congestion. Operating costs were calculated based on total vehicle operating time, distance travelled, fuel or energy consumption, and estimated maintenance costs. The analysis of European initiatives in Germany, France, and the Netherlands demonstrated that the adoption of urban microhubs has been associated with improved delivery efficiency and reduced traffic congestion. Across these countries, multiple projects have been implemented to enhance urban logistics performance through the integration of decentralised distribution solutions. In major German cities such as Berlin and Munich, a network of microhubs has been implemented, which significantly reduces the number of trucks on the roads. According to the results of the projects, it is possible to reduce traffic by 20-25% and reduce delivery time by 15-20% (European Commission, n.d.). Paris (France) is also actively integrating microhubs into its urban logistics. The introduction of the microhub system as part of the Paris Logistic Hub project has increased the speed of delivery of goods by 30%, while reducing CO_2 emissions by 20% compared to traditional delivery methods (Crainic & Montreuil, 2015). Amsterdam

(Netherlands) is an example of successful integration of microhubs into the urban logistics system. Here, the introduction of microhubs has reduced traffic congestion by 15% and reduced emissions of harmful gases by 18% (Rodrigue, 2024). The experience of European cities in implementing urban microhubs is presented in Table 4.

Table 4. Results of microhubs implementation in European cities

Country	Reduced traffic (%)	Increase the speed of delivery (%)	Reducing emissions CO_2 (%)
Germany	20-25	15-20	10-15
France	15-20	30	20
Netherlands	15	25	18

Source: compiled by the authors based on T.G. Crainic & B. Montreuil (2015), European Commission (n.d.)

Table 4 confirmed that the implementation of microhubs has a positive impact on urban logistics performance. European cities demonstrated consistent improvements in delivery speed and environmental indicators. These results highlighted the relevance of coordinated infrastructure planning and integration of sustainable transportation technologies. Studies of European initiatives show that the introduction of urban microhubs helps to reduce traffic and increase delivery efficiency. Given the experience of other countries, Ukraine has the opportunity to effectively use this concept to improve its logistics infrastructure.

Technological solutions to improve efficiency. Intelligent transportation systems (ITS) are an important component for improving the efficiency of logistics and traffic management in modern cities. They use advanced technologies to monitor and control traffic flows, as well as to predict and manage infrastructure loads. Such systems can achieve significant improvements in the following areas:

1. Traffic monitoring. IoT-based systems allow for continuous real-time monitoring of road conditions and congestion, which makes it possible to adjust cargo delivery routes.

2. Traffic flow management. The use of sensors and cameras for vehicle tracking enables effective queue management on congested road sections and the redirection of traffic to less congested routes.

3. Data analysis. Intelligent transportation systems can process large amounts of data to predict congestion and adjust routes in real time. This makes it possible to reduce travel time and increase vehicle efficiency.

Studies by J.-P. Rodrigue (2024) and O.-O. Aderibigbe & T. Gumbo (2024) indicated that the application of ITS can reduce delays by approximately 15-20% and improve transportation efficiency by around 25%. Furthermore, the integration of ITS with modern infrastructure solutions was associated with a reduction in the load on urban transport systems, contributing to more sustainable urban mobility. The impact of ITS on logistics performance is illustrated in Table 5.

Table 5. The impact of intelligent transportation systems on delivery efficiency

Parameter	Before ITS implementation	After the implementation of ITS
Delivery time (hours)	2.5	1.8
Operating expenses (%)	100	80
Average traffic delay time (min)	15	5
Number of vehicles	100	70

Source: compiled by the authors based on J.-P. Rodrigue (2024), O.-O. Aderibigbe & T. Gumbo (2024)

The data illustrated that intelligent transport systems significantly improve traffic flow coordination and reduce delays. The integration of ITS enables predictive traffic management and dynamic route adjustments, which leads to improved delivery reliability and reduced operational costs. These results confirm the strategic importance of ITS implementation in modern logistics systems. MAS are one of the most promising approaches to optimising cargo delivery, as they allow for the automatic management of complex processes involving interaction between numerous agents (in this case, vehicles, couriers, and other logistics elements). MAS were characterised by several key features, including distributed control, interactive route optimisation, and adaptability. Within such systems, individual agents (e.g., vehicles) operated autonomously, making decisions based on current conditions, which contributed to reduced delays and improved delivery efficiency. In addition, agents interacted with one another to optimise delivery routes in real time, enabling dynamic adjustments in response to changing traffic conditions. A further advantage of this approach was its adaptability, allowing the system to respond effectively to variations in traffic, weather, and unforeseen disruptions. Examples of multi-agent logistics applications included automated fleet coordination platforms used in smart city projects and distributed warehouse management systems. In such systems, each vehicle operates as an independent agent capable of dynamically adjusting delivery routes based on traffic data. Similar approaches are implemented in automated parcel delivery services and robotic warehouse logistics systems, where agents coordinate delivery tasks without centralised control. J.-P. Rodrigue (2024) noted that the introduction of MAS can reduce delivery time by 20-30% and increase vehicle utilisation by 25-40%. In addition, when combined with other technologies such as AI and IoT, multi-agents allow for flexible management of routed cargo flows in urban environments. As can be seen from Table 6, MAS can significantly improve logistics processes by optimising routes and traffic flow management.

Table 6. The impact of MAS on logistics efficiency

Parameter	Without MAS	From MAS
Delivery time (hours)	3.0	2.0
Reduced fuel costs (%)	0	15
Route optimisation (%)	0	25
Number of delays in delivery (%)	30	10

Source: compiled by the authors based on T.G. Crainic & B. Montreuil (2015), J.-P. Rodrigue (2024)

MAS are actively used in smart city projects and automated warehouse management platforms. For example, distributed fleet management systems allow vehicles to independently adjust delivery routes based on real-time traffic data. Similar approaches are used in automated parcel delivery networks and robotic warehouse logistics. The presented results confirm that multi-agent coordination improves delivery stability and reduces delays by enabling adaptive decision-making processes. Thus, intelligent transport system technologies and MAS are powerful tools for improving the efficiency of urban logistics, reducing delays, optimising delivery routes, and improving the overall productivity of transport operations.

The obtained results were consistent with recent international studies on sustainable logistics development. Y. Sun *et al.* (2021) emphasised the role of digital technologies in enhancing the resilience of logistics systems, which was supported by the modelling results presented in this study. Similarly, A. Shafiee *et al.* (2026) demonstrated that urban microhubs significantly improved last-mile delivery efficiency, which aligned with the simulation findings indicating reduced delivery times and lower operational costs. In comparison, M. Browne *et al.* (2012) highlighted the importance of intelligent transport systems in optimising traffic flow, whereas the present study further demonstrated their relevance in the context of post-war infrastructure recovery. Furthermore, the integration of multi-agent logistics management, as described by B. Kin *et al.* (2024), supported the findings regarding enhanced delivery adaptability and a reduction in delays. Therefore, the combined use of microhubs, digital technologies and ITS represents a comprehensive approach to rebuilding logistics infrastructure in Ukraine. One of the key areas of development is the wider adoption of digital technologies in urban logistics. This involves the implementation of advanced solutions for the automation and monitoring of transport processes, as well as the refinement of algorithms to optimise delivery operations and traffic management. To manage demand and traffic flows even more efficiently, it is necessary to develop AI systems that can predict changes in demand, determine optimal delivery routes in real time, and adapt logistics strategies to changing road conditions. A fundamental component of development is the creation of infrastructure for microhubs, including their integration with other parts of the urban transportation system. This will facilitate faster adaptation to changes in the urban environment and improve cooperation between different modes of transportation. Prospects for Ukraine's integration into the European transport network. Ukraine's integration into the European transport network opens up new opportunities for the development of international transportation and improved cooperation with other European countries. The creation of efficient and environmentally friendly urban logistics, including micro hubs and digital solutions, will help attract investment in the development of Ukraine's transport infrastructure. Thanks to modern technologies, such as AI and digital platforms, Ukraine will be able to establish closer cooperation with European countries, increase the efficiency of its logistics processes, and integrate into the European transport network. The results obtained in this study, particularly the 25-30% reduction in delivery time, were consistent with the findings of K. Katsela *et al.* (2022) regarding the impact of microhubs on urban logistics efficiency. Furthermore, the simulation model confirmed the global trend towards the digital transformation of city logistics, which has been shown to provide new opportunities for addressing transport challenges (Taniguchi *et al.*, 2016; Ballare & Lin, 2020). Overall, the implementation of innovative solutions, such as urban microhubs and the digitalisation of logistics, will allow Ukraine not only to rebuild its infrastructure but also to become part of the modern European transport system, contributing to sustainable economic and environmental development.

Conclusions

The study confirmed that innovative logistics solutions play a key role in rebuilding the transport infrastructure of Ukraine under conditions of post-war recovery and increasing integration into global supply chains. The findings demonstrated that the implementation of urban microhubs contributes to a significant reduction in traffic congestion by decreasing the number of heavy freight vehicles operating in densely populated areas. At the same time, the decentralisation of logistics processes enabled shorter delivery distances and improved time efficiency, resulting in a measurable reduction in average delivery time and operating costs. The results obtained through simulation modelling using the SUMO environment showed that the combined application of microhub-based logistics, route optimisation algorithms, and multi-agent coordination ensures more efficient use of transport resources and enhances the flexibility of logistics systems under dynamic traffic conditions. The integration of digital technologies, including IoT and AI, further strengthens these effects by enabling real-time data exchange, demand forecasting, and adaptive route planning, which improves decision-making and operational coordination. In addition, the study confirmed the environmental benefits of innovative logistics approaches, particularly through reduced CO_2 emissions and more sustainable use of urban transport infrastructure. The comparative analysis of baseline and experimental scenarios indicated that the transition to decentralised and digitally supported logistics models leads to stable improvements across key performance indicators, including delivery time, cost efficiency, and traffic load. Overall, the results highlighted the strategic importance of combining infrastructure modernisation with digital transformation in order to ensure the resilience and long-term sustainability of Ukraine's logistics system. Future research should focus on the practical implementation of these models in real urban environments, including the optimisation of microhub placement, the integration of multimodal transport systems, and the development of advanced AI-driven decision-support tools.

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References

[1] Aebi, S., Hauri, A., & Kamberaj, J. (2024). *Critical infrastructure resilience in Ukraine: Energy, transportation, and communication*. Zürich: Center for Security Studies.

[2] Alves Junior, P.N., Melo, I.C., Branco, J.E.H., Bartholomeu, D.B., & Caixeta-Filho, J.V. (2021). Which green transport corridors (GTC) are efficient? A dual-step approach using Network Equilibrium Model (NEM) and Data Envelopment Analysis (DEA). *Journal of Marine Science and Engineering*, 9(3), article number 247. doi: 10.3390/jmse9030247.

[3] Antos, S.E., Triveno Chan Jan, L.M., Ghesquiere, F., Czapski, R., Syed Shafat Ali, B., Anapolsky, S., Gosling-Goldsmith, J., & Wang, C. (2021). *Detecting urban clues for road safety: Leveraging big data and machine learning*. Washington, DC: World Bank. doi: 10.1596/37029.

[4] Ballare, S., & Lin, J. (2020). Investigating the use of microhubs and crowdshipping for last mile delivery. *Transportation Research Procedia*, 46, 277-284. doi: 10.1016/j.trpro.2020.03.191.

[5] Browne, M., Allen, J., Nemoto, T., Patier, D., & Visser, J. (2012). Reducing social and environmental impacts of urban freight transport: A review of some major cities. *Procedia – Social and Behavioral Sciences*, 39, 19-33. doi: 10.1016/j.sbspro.2012.03.088.

[6] Crainic, T.G., & Montreuil, B. (2015). *Physical Internet enabled interconnected city logistics*. Montreal: CIRRELT.

[7] de Bok, M., Giasoumi, S., Tavasszy, L., Thoen, S., Nadi, A., & Streng, J. (2024). A simulation study of the impacts of micro-hub scenarios for city logistics in Rotterdam. *Research in Transportation Business & Management*, 56, article number 101186. doi: 10.1016/j.rtbm.2024.101186.

[8] European Commission. (n.d.). *Sustainable & smart mobility*. Retrieved from https://ec.europa.eu/transport/themes/mobilitystrategy.

[9] Gerrits, B., van Heeswijk, W., & Mes, M. (2024). Towards self-organizing logistics in transportation: A literature review and typology. *International Transactions in Operational Research*, 31, 1309-1374. doi: 10.1111/itor.13408.

[10] Jugović, A., Sirotić, M., Jugović, T.P., & Žgaljić, D. (2025). Green shipping corridors: A bibliometric analysis of policy, technology, and stakeholder collaboration. *Applied Sciences*, 15(6), article number 3304. doi: 10.3390/app15063304.

[11] Katsela, K., Güneş, Ş., Fried, T., Goodchild, A., & Browne, M. (2022). Defining urban freight microhubs: A case study analysis. *Sustainability*, 14(1), article number 532. doi: 10.3390/su14010532.

[12] Kin, B., Buldeo Rai, H., Dablanc, L., & Quak, H.J. (2024). Integrating logistics into urban planning: Best practices from Paris and Rotterdam. *European Planning Studies*, 32, 24-44. doi: 10.1080/09654313.2023.2242400.

[13] Kurniawan, D.A. (2024). Multimodal logistics for resilient and sustainable global supply chains: Strategic insights from integrated transport systems. *Sinergi International Journal of Logistics*, 2(4), 213-224. doi: 10.61194/sijl.v2i4.731.

[14] Li, Q., & Lam, J.S.L. (2025). Impact factors on level of participation in transport infrastructure technology development: The role of technology capability. *Case Studies on Transport Policy*, 22, article number 101598. doi: 10.1016/j.cstp.2025.101598.

[15] Liu, J., Ling, F.Y.Y., & Chen, C. (2025). The impact of transportation infrastructure on inclusive growth: A cross-national analysis of developed and developing countries. *Research Square*. doi: 10.21203/rs.3.rs-6493861/v1.

[16] Ning, L., & Yao, D. (2023). The impact of digital transformation on supply chain capabilities and supply chain competitive performance. *Sustainability*, 15(13), article number 10107. doi: 10.3390/su151310107.

[17] Aderibigbe, O.-O., & Gumbo, T. (2024). Smart cities and their impact on urban transportation systems and development. In O.-O. Aderibigbe, T. Gumbo & S.O. Fadare (Eds.), *Emerging technologies for smart cities* (pp. 105-129). Cham: Springer. doi: 10.1007/978-3-031-66943-9_5.

[18] Rodrigue, J.-P. (2024). *The geography of transport systems* (6th ed.). New York, NY: Routledge. doi: 10.4324/9781003343196.

[19] Ruan, Z., Min, J., Kim, D.-S., Ghardallou, W., Ben-Salha, O., & Alazzam, F.A.F. (2025). Driving supply chain agility through digitalization. *Journal of Global Information Management*, 33(1). doi: 10.4018/JGIM.395354.

[20] Shafiee, A., Rastegar Moghaddam, H., Ballare, S., & Lin, J. (2026). An alternative last-mile delivery system: Leveraging microhubs and crowdshipping. *Transportation Research Part D: Transport and Environment*, 154, article number 105239. doi: 10.1016/j.trd.2026.105239.

[21] Sultana, Y., & Rawoof, S.M. (2025). Blockchain integration in supply chain logistics: Opportunities and challenges. *International Journal of Research in Finance and Management*, 8(2), 102-106. doi: 10.33545/26175754.2025.v8.i2b.533.

[22] Sun, Y., Chung, S.-H., Wen, X., & Ma, H.-L. (2021). Novel robotic job-shop scheduling models with deadlock and robot movement considerations. *Transportation Research Part E: Logistics and Transportation Review*, 149, article number 102273. doi: 10.1016/j.tre.2021.102273.

[23] Taniguchi, E., Thompson, R.G., & Yamada, T. (2016). New opportunities and challenges for city logistics. *Transportation Research Procedia*, 12, 5-13. doi: 10.1016/j.trpro.2016.02.004.

[24] Zaman, J., Shoomal, A., Jahanbakht, M., & Ozay, D. (2025). Driving supply chain transformation with IoT and AI integration: A dual approach using bibliometric analysis and topic modeling. *IoT*, 6(2), article number 21. doi: 10.3390/iot6020021.

Інноваційні підходи до відновлення логістичної інфраструктури України

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Анотація. Статтю присвячено аналізу сучасних інноваційних підходів до відновлення логістичної інфраструктури України в умовах післявоєнної відбудови та глобальних змін світової економіки. Об'єктом дослідження були процеси відновлення транспортно-логістичної інфраструктури України з урахуванням сучасних технологічних та організаційних рішень. Метою дослідження було визначення ключових стратегій і технологій реконструкції логістичної системи країни з урахуванням цифровізації, екологічної сталості та інтеграції до європейської транспортної мережі. Методи дослідження включали математичне моделювання транспортних потоків, аналіз сучасних тенденцій розвитку логістики, використання мультиагентних систем для оптимізації маршрутів, а також емпіричне дослідження міжнародного досвіду. У статті розглянуто основні виклики, пов'язані з відновленням логістичної інфраструктури, та визначено шляхи їх подолання. Зокрема, запропоновано використання міських мікрохабів для оптимізації доставки товарів у містах, впровадження цифрових технологій (інтернет речей, штучний інтелект, блокчейн) для підвищення ефективності логістичних процесів, а також розвиток мультимодальних перевезень. На основі моделювання із використанням Simulation of Urban Mobility продемонстровано ефективність запропонованих підходів щодо зменшення транспортного навантаження, скорочення витрат та зниження викидів CO_2. Результати дослідження можуть бути використані органами державної влади, транспортними компаніями та логістичними операторами для розроблення стратегій відновлення та модернізації логістичної інфраструктури України. Прогнозні припущення щодо розвитку об'єкта дослідження пов'язані з подальшим впровадженням інтелектуальних транспортних систем і цифрових технологій у сфері логістики, створенням інноваційних логістичних кластерів, а також інтеграцією України до європейських транспортних коридорів

Ключові слова: цифровізація; мультимодальні перевезення; міські мікрохаби; оптимізація маршрутів; транспортні технології

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Effect of aggressive environments and stray currents on the corrosion resistance of corrugated metal pipes

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Abstract. The study aimed to investigate the role of corrosion damage to corrugated metal pipes in determining the durability, technical condition and operational reliability of transport structures. The methodology was based on methods of systematisation, engineering and theoretical analysis, illustrative calculation, and the analysis of practical examples. The study established that the corrosive degradation of metal corrugated pipes is predominantly of an electrochemical nature and is determined by the aggressiveness of the soil and water environments. Localised corrosion poses the greatest danger to such structures, as it reduces the shell's stiffness, local stability and the structure's remaining service life. In underground and water-saturated conditions, corrosion is accelerated by wetting-drying cycles, which destroy the protective coating and increase the metal's vulnerability. Stray currents in the vicinity of electrified transport systems constitute a separate man-made risk factor, causing localised anodic areas and accelerated metal damage. The study demonstrated that the corrosion resistance of metal corrugated pipes should be assessed not only by the aggressiveness of the environment, but also by a system of quantitative indicators reflecting the rate of metal loss, local damage, changes in stiffness and the residual service life of the structure. Quantitative assessment based on Faraday's law has shown that even a relatively small loss of wall thickness is of engineering significance, as it affects the durability, technical condition and operational safety of the transport structure. An engineering approach is proposed for the assessment of the corrosion degradation of corrugated metal pipes based on a corrosion weakening coefficient, which characterises the relative loss of thickness of the metal shell and its approach to a critical state. A simplified relationship linking the initial thickness, critical thickness and corrosion rate is used for the engineering assessment of the remaining service life. The practical significance lies in the possibility of applying the results by designers, operating organisations and diagnostic specialists during the design, operation, inspection and rehabilitation of corrugated metal pipes in transport structures

Keywords: degradation; remaining service life; durability; operation; structures

Introduction

Corrugated metal pipes are used in transport infrastructure as culverts, drainage structures and transition structures; consequently, their technical condition affects the reliability and safety of transport infrastructure. At the same time, such structures are operated in conditions of aggressive soil and water environments, cyclic wetting and drying, and in some cases are also subject to stray currents. The combined effect of these factors requires separate consideration, as this effect determines the intensity of corrosion degradation and must be addressed in the analysis of the durability, technical condition and methods of protection for such structures. This topic has already been extensively explored in academic discourse. The paper by E.M. Farahani *et al.* (2024) summarises the 21st-century definition of corrosion in steel pipelines under cathodic protection when exposed to alternating

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current. The authors emphasised that the influence of alternating current can cause significant corrosion damage to buried metal structures even in the presence of cathodic protection. This indicates the need to account for the influence of alternating stray currents when assessing corrosion risk and the effectiveness of cathodic protection systems. C. Wang *et al.* (2024a) proposed a model for assessing the area of influence of stray currents in the vicinity of a metro depot, which is based on current distribution and surface potential gradient and has been verified by modelling and experimentation. The results obtained can improve accuracy of localisation of areas of increased corrosion risk near electrified transport systems. The study by Y. Li *et al.* (2023) established that in stratified soil, the current corrosion of buried metal is less intense than in a homogeneous medium, decreases with an increase in the soil's specific resistance, and intensifies with a decrease in the distance to the rail. This contributes to the research on the role of the soil environment in the development of corrosion of buried metal under the influence of stray currents.

According to S. Rossi *et al.* (2022), elevated concentrations of chlorides and sulphates accelerate the degradation of the zinc coating on hot-dip galvanised steel, and their combined action has a pronounced synergistic effect. The authors' findings clarified the role of soil chemical composition in reducing the corrosion resistance of galvanised steel. In turn, the study by G.A. Gaber *et al.* (2023) demonstrates that in an aqueous environment, galvanised steel may be subject to pitting, galvanic and uniform corrosion, and the nature of the damage is determined by the concentration of active components, in particular sodium hypochlorite. This clarifies the influence of the composition of the aqueous environment on the corrosion behaviour of galvanised steel under conditions of wetting and water saturation. J.E. Torres *et al.* (2024) found that in simulated seawater, the corrosion behaviour of galvanised steel depends on the ambient temperature and the thickness of the zinc coating: as the thickness of the protective layer increases, the corrosion rate decreases, whilst at lower temperatures the kinetics of the process increase slightly. This approach quantifies the influence of temperature and the condition of the zinc coating on the corrosion resistance of galvanised steel. A study by E. Nakhostin *et al.* (2022) found that the combination of metal corrosion and erosion cavities in the soil alters the mechanical behaviour of buried corrugated steel pipes, and that the location of cavities at or above the spring line increases the risk of reaching critical conditions. This defines corrosion of corrugated metal pipes not merely as a materials science issue, but as a factor in the structural degradation of the "soil-structure" system, affecting the stiffness, load-bearing capacity and durability of the structure.

In Ukrainian academic discourse, Y.Y. Luchko & V.V. Kovalchuk (2021) summarised the challenges of ensuring the reliability and durability of transport structures made of corrugated metal and emphasised the need to assess their actual technical condition under operational conditions. This forms the engineering context for considering corrugated metal pipes as elements of transport infrastructure, the technical condition of which requires systematic monitoring. M.V. Harkusha (2023) noted that corrosion damage to road culverts is one of the causes of their loss of serviceability and the transition of structures to a defective or emergency condition, and attention is drawn to the importance of modern 21st-century repair technologies. The authors' findings highlight the practical need for timely diagnosis of corrosion degradation, assessment of the actual technical condition of the pipes, and the informed selection of methods for the repair and restoration of such structures.

At the same time, existing studies lack a comprehensive analysis in which aggressive environments and stray currents are considered jointly as factors in the corrosion degradation of corrugated metal pipes, affecting their technical condition, service life, operational reliability, remaining service life, and the selection of engineering measures for protection and rehabilitation. Therefore, the study aimed to summarise the factors and mechanisms of corrosion degradation of metal corrugated pipes to determine their impact on the durability and reliability of transport structures. To achieve this aim, the following tasks were set: to characterise the factors and mechanisms of corrosion degradation of metal corrugated pipes in aggressive environments and under the influence of stray currents; to systematise approaches to assessing corrosion resistance, its quantitative indicators and engineering significance for transport structures; to summarise the practical manifestations of corrosion degradation and engineering solutions for reinforcement and rehabilitation to determine approaches to ensuring the durability of corrugated metal pipes at the design, construction, operation and repair stages.

The scientific novelty of the study is determined by the proposal of an engineering approach to assessing the corrosion degradation of corrugated metal pipes, based on the introduction of a corrosion weakening coefficient and its relationship to changes in the shell stiffness and the residual service life of the structure. An approach to assessing corrosion resistance has been developed by combining the electrochemical parameters of the corrosion process with engineering indicators of technical condition – thickness loss, critical thickness and estimated remaining service life. Further development has been made in the engineering interpretation of the impact of metal loss on the structural behaviour of the "soil-structure" system, which provides a basis for the quantitative assessment of the technical condition and the justification of decisions regarding the rehabilitation of the structure.

Materials and Methods

The study was theoretical in nature and was based on a combination of methods, including systematisation, engineering and theoretical analysis, illustrative calculations, and the analysis of practical examples, with a view to comprehensively examining the factors contributing to the corrosion degradation of corrugated metal pipes and their consequences for transport infrastructure. The study's source base includes 32 scientific and scientific-practical sources published between 2015 and 2025, with the majority comprising works from 2021 to 2025. The period 2015-2025 was chosen to cover both contemporary 21st-century scientific approaches to assessing the corrosion degradation of corrugated metal pipes and earlier studies containing representative practical examples of their damage, reinforcement and rehabilitation. Sources were selected based on criteria of thematic relevance to the problem of corrosion degradation of metal corrugated pipes and buried metal structures, the availability of data on the effects of aggressive environments, stray currents, corrosion resistance indicators, technical condition, durability and remaining service life, as well as the engineering suitability of the results for assessing the load-bearing capacity, serviceability, reinforcement, rehabilitation and life-cycle management of transport structures. The analysis also includes studies on the corrosion of buried metal pipelines, as these elucidate the mechanisms of stray current action, the patterns of electrochemical degradation, and approaches to its quantitative assessment, all of which are methodologically relevant to corrugated metal pipes. Practical examples were included based on the representativeness of key scenarios for changes in the technical condition of corrugated metal pipes in transport infrastructure: corrosion damage and loss of serviceability, structural reinforcement, trenchless rehabilitation, and extension of the structure's safe service life. This interpreted the results of the applied methods in the context of assessing the technical condition, durability and remaining service life of corrugated metal pipes in transport infrastructure.

Using a systematic approach, the factors contributing to the corrosion degradation of corrugated metal pipes in aggressive environments – acidic and alkaline environments (Mundra & Provis, 2021), chlorides, sulphates, humidity and water saturation (Ezzeldin *et al.*, 2024a), and wetting-drying cycles (Ezzeldin *et al.*, 2024b). The selection of these specific factors is due to the fact that they are the most representative of the operating conditions for metal corrugated pipes in a soil-water environment and determine the intensity of electrochemical processes, the stability of the protective coating, and the development of general and localised corrosion. The generalisation was conducted according to the following criteria: the nature of the corrosive effect, the consequences for the metal corrugated pipe, and the significance for the transport structure. This approach has made it possible to systematise the main factors of the aggressive environment and form a basis for further assessment of their impact on the technical condition, durability, stiffness, remaining service life and operational reliability of the structure.

Using engineering analysis, this study examines the specific effects of stray currents on the corrosion degradation of corrugated metal pipes and identifies indicators for assessing this degradation in transport infrastructure: the rate of general corrosion (Chen *et al.*, 2025), mm/year, wall thickness loss, mm, depth and location of localised corrosion damage (Zou *et al.*, 2024), condition of the protective coating and the metal's ability to passivate, stray density/presence of anodic zones (Liang *et al.*, 2024), reduction in stiffness and load-bearing capacity of the shell, remaining service life and feasibility of rehabilitation. These indicators were selected as the most representative, as they correlate the intensity of the effect with the localisation of corrosion damage, the degree of structural weakening of the shell, and the consequences for the reliability and serviceability of the transport structure. The analysis was summarised according to the nature of the impact and its engineering significance for the transport structure. An analysis was also conducted to compare changes in the structural performance of the shell with the serviceability of the transport structure. This was done to consider stray currents as a separate engineering risk factor and to establish a basis for assessing the corrosion resistance, technical condition and serviceability of metal pipes.

Theoretical analysis has been used to derive analytical relationships describing the corrosion degradation of corrugated metal pipes. The formulas presented are used to illustrate, from an engineering perspective, the effect of metal loss on changes in the stiffness, load-bearing capacity and remaining service life of the structure. Faraday's law and its derivatives (ASTM International, 2023) have been chosen as the theoretical basis for this analysis, according to which the mass of metal dissolved as a result of an electrochemical process is proportional to the electric charge passing through the system (1):

$$m = \frac{I \times t \times M}{n \times F}, \tag{1}$$

where m – lost material mass; I – magnitude of the anodic or corrosion current; t – current duration; M – molar mass of the metal; n – number of electrons in the anode process; F – Faraday's constant (96,485 C/mol).

For engineering assessment, it is not the mass loss of metal that is most indicative, but the corresponding reduction in wall thickness. The transition to this parameter is described by equation (2):

$$\Delta h = \frac{m}{\rho \times A}, \tag{2}$$

where Δh – loss of thickness; ρ – metal density; A – area of affected surface.

Incorporating the expression for mass loss, the relationship for thickness loss takes the form (3):

$$\Delta h = \frac{I \times t \times M}{n \times F \times \rho \times A}, \tag{3}$$

where Δh – loss of metal thickness; I – magnitude of anodic or corrosion current; t – duration of the current; M – molar mass of the metal; n – number of electrons involved in anode process; F – Faraday's constant (96,485 C/mol); ρ – metal density; A – area of the affected surface.

Using current density , the rate of thickness loss can be expressed as in (4):

$$v_{\Delta h} = \frac{i \times M}{n \times F \times \rho}, \tag{4}$$

where $v_{\Delta h}$ – rate of metal thickness loss; i – current density; M – molar mass of the metal; n – number of electrons involved in anode process; F – Faraday's constant (96,485 C/mol); ρ – metal density.

These relationships make it possible to establish a direct correlation between the electrochemical parameters of the process and the rate of degradation of the metal coating. The equation for determining the corrosion rate from the corrosion current density, as used in electrochemical laboratory studies, is given by (5):

$$CR = \frac{K \times i_{corr} \times M}{n \times \rho}, \tag{5}$$

where K – unit conversion factor; i_{corr} – corrosion current density; M – molar mass of the metal; n – number of electrons in anode process; ρ – metal density.

This established a theoretical basis for further interpretation of the effect of corrosion on the shell stiffness, local stability and remaining service life of corrugated metal pipes. Furthermore, using an illustrative calculation based on Faraday's law and the relationship for wall thickness loss, the influence of the electrochemical parameters of the corrosion process on the rate of metal loss in corrugated metal pipes was quantitatively demonstrated. Conventional values for current intensity, affected surface area and duration of current exposure have been selected as representative examples to illustrate the transition from theoretical relationships to an engineering interpretation of wall thickness loss, changes in shell stiffness and reduction in the remaining service life of the structure (National Corrugated Steel Pipe Association, 2018). To transition from a qualitative assessment of corrosion degradation to an engineering-quantitative one, it is advisable to introduce the corrosion weakening coefficient , which characterises the relative loss of metal shell thickness (6):

$$K_O = \frac{\Delta t}{t_0} = \frac{t_0 - t}{t_0}, \tag{6}$$

where t_0 – initial wall thickness; t – remaining thickness; Δt – thickness loss due to corrosion.

This coefficient can be used to interpret corrosion degradation not merely as a material loss, but as a factor reducing the stiffness, local stability and load-bearing capacity of the corrugated pipe. It is appropriate to consider the attainment of a critical thickness t_{cr}, at which the condition of local stability or the load-bearing capacity of the shell is violated, as a criterion for the risk of corrosion damage. In equivalent form, this corresponds to condition (7):

$$t \le t_{cr} \text{ or } K_O \ge K_{O,cr} = 1 - \frac{t_{cr}}{t_0}, \tag{7}$$

where t_{cr} – critical wall thickness at which the structure reaches the limit state in terms of local stability or load-bearing capacity; K_O – corrosion reduction factor, which characterises the relative loss of thickness; $K_{O,cr}$ – limit value of the corrosion reduction factor corresponding to the attainment of the critical thickness.

Thus, the extent of corrosion degradation can be characterised not only by the rate of metal loss, but also by the structure's proximity to the limit state. The first condition, $t \le t_{cr}$, means that the residual wall thickness has become less than or equal to the critical value. The second condition, $K_O \ge K_{O,cr}$, is an equivalent form of expressing the same limit state in terms of the relative corrosion weakening of the shell. For the engineering assessment of the residual life of corrugated metal pipes, it is advisable to use the simplified relationship (8):

$$T_{rem} = \frac{t - t_{cr}}{v_{cor}}, \tag{8}$$

where T_{rem} – remaining service life of the structure, years; v_{cor} – average corrosion rate, mm/year.

This relationship exceeds the scope of corrosion damage identification to a simplified engineering assessment of the time remaining before a dangerous technical condition is reached, and justifies decisions regarding the monitoring, reinforcement or rehabilitation of the structure. This approach has been used to demonstrate the practical significance of a quantitative assessment of corrosion degradation in the context of evaluating the technical condition, durability and operational reliability of transport infrastructure.

Using a case-study approach, this paper analyses instances of corrosion-induced degradation, rehabilitation and reinforcement of corrugated metal pipes in transport infrastructure. The analysis includes examples of structural failure resulting from a combination of corrosion and soil degradation (Giresini *et al.*, 2015), and structural reinforcement of corrosion-damaged pipes using an internal composite liner (Taha & Murcia, 2021). Trenchless rehabilitation using GeoSpray geopolymer lining (Liao *et al.*, 2022) and the restoration of the load-bearing capacity of damaged structures under conditions of intensive operational loads (Liang *et al.*, 2024) were analysed. These examples were selected because they represent the main practical scenarios of changes in the technical condition of corrugated steel pipes, ranging from loss of serviceability to restoration of capacity and extension of service life. The analysis was conducted based on the following criteria: characteristics of the event, engineering solution and significance for transport infrastructure. This made it possible to demonstrate the practical manifestations of corrosion degradation, justify approaches to the rehabilitation and reinforcement of structures, and formulate practical recommendations for managing the technical condition, durability and life cycle of corrugated metal pipes as elements of transport infrastructure.

Results and Discussion

Assessment of the corrosion resistance of corrugated metal pipes

Corrosion degradation of corrugated metal pipes is predominantly electrochemical in nature and occurs as a result of the metal contacting an electrolyte, which, under operational conditions, is affected by groundwater, moist soil or saline solutions. The intensity of corrosion is determined by the chemical composition of the environment, the pH level, the oxygen content, the concentration of aggressive ions and the condition of the metal surface. In an alkaline environment, steel can become passivated; however, in the presence of chlorides, the protective layer is disrupted, whereas in an acidic environment, corrosion activity increases and localised damage intensifies (Mundra & Provis, 2021; Chenghui *et al.*, 2024). For corrugated metal pipes, localised corrosion is the most dangerous, as these structures function as thin-walled shells within the "soil-structure" system. This results in a reduction in effective wall thickness, leading to a decrease in stiffness, a loss of local stability, and a redistribution of stresses within the shell. Even minor local metal loss can cause the development of local deformations and a reduction in the structure's remaining service life (Alam *et al.*, 2021; Ezzeldin *et al.*, 2024b).

In underground and water-saturated conditions, corrosion is further accelerated by cycles of wetting and drying, which degrade the protective coating and increase the steel's susceptibility to corrosion (Ezzeldin *et al.*, 2024a). The most vulnerable areas of corrugated metal pipes are the lower part of the casing, the side sections and the crown, where corrosion-induced weakening has the greatest impact on the stress-strain state and geometric stability of the structure (Premasuriya *et al.*, 2025). In the presence of stray currents, the current entry and exit zones also become critical, as local anodic areas with accelerated metal degradation form there (Wang *et al.*, 2024b). From an engineering perspective, such degradation leads to a reduction in the structure's load-bearing capacity, an increased risk of roadbed deformation, and the structure entering a defective or emergency state. Consequently, the corrosion resistance of corrugated metal pipes should be regarded as an integral characteristic reflecting the technical condition, load-bearing capacity and operational safety of the transport structure (Table 1).

Table 1. Effect of aggressive environments on the service life of corrugated metal pipes

Environmental factor	Nature of corrosive effect	Consequences for corrugated metal pipes	Significance for a transport structure
Acidic environment	A decrease in pH accelerates anodic dissolution of steel and hinders the formation of stable corrosion protection products; in the presence of chlorides, the risk of localised damage increases	Both overall metal loss and the development of localised defects in the shell are accelerating	Service life of the pipe is reduced, its rigidity decreases, and the risk of the structure losing its operational reliability increases
Alkaline environment	At high pH values, temporary passivation of steel may occur; however, this effect is disrupted in the presence of chlorides, sulphide-containing compounds, moisture and media heterogeneity	When the passive state is disrupted, localised active areas with accelerated corrosion develop	The beneficial effects of an alkaline environment are not guaranteed and must be assessed based on actual operating conditions
Chlorides	They break down protective films and cause localised corrosion, particularly in acidic environments or those with fluctuating pH levels	They cause a disproportionate loss of rigidity in certain areas of the membrane	Increase the risk of localised damage, which determines the remaining service life of the structure
Sulphates and other harsh ingredients	Alter the electrochemical conditions on the steel surface and influence the composition of corrosion products	Contribute to the long-term development of corrosion in the soil environment	Chemical composition of groundwater is becoming one of the key factors determining a structure's durability
Moisture content and water saturation	Increase the electrical conductivity of the medium, enhance ion mass transfer and facilitate the formation of localised corrosion cells	Accelerate the deterioration of the metal and the protective coating	In areas with unstable water conditions, the risk of structural corrosion significantly increases
Moisturising and drying cycles	These cause periodic activation of the metal surface, changes in salt concentration and the depletion of protective corrosion products	Accelerate the deterioration of the coating and the development of localised corrosion sites	Seasonal fluctuations in humidity have a direct impact on the service life and technical condition of transport infrastructure

Source: compiled by the author based on S. Alam *et al.* (2021), S. Mundra & J. Provis (2021), I. Ezzeldin *et al.* (2024a; 2024b), H. Liang *et al.* (2024), Y.I. Chenghui *et al.* (2024), C. Wang *et al.* (2024a; 2024b)

A corrosive environment should be regarded not merely as a set of chemical characteristics of the soil or water, but as one of the key factors determining the durability of corrugated metal pipes in transport infrastructure. The greatest danger to thin-walled shells arises from conditions in which the chemical aggressiveness of the environment is combined with high humidity, cyclic wetting and damage to the protective coating. Under such conditions, corrosion progresses from material wear to structural weakening, as it reduces the rigidity of the shell and shortens the remaining service life of the structure. Stray currents are one of the most dangerous man-made factors contributing to the corrosion of underground metal structures. They most commonly occur in the vicinity of electrified railways, underground railways and other rail transport systems, where part of the return current is dissipated into the ground and may find a path through underground steel elements. For corrugated metal pipes, this risk is particularly relevant within transport corridors, near electrified tracks and urban rail systems (Liang *et al.*, 2024). The corrosion hazard arises because the current enters the metal in some areas and exits into the soil in others. Anode areas form at the points where the current exits, where intensive electrochemical dissolution of the metal occurs. In contrast to uniform corrosion, this process is localised; therefore, even with a small average metal loss, deep defects and wall breaches can rapidly develop in individual zones (Zou *et al.*, 2024).

For corrugated metal pipes, which act as thin-walled shells, this is dangerous, as local damage leads to a reduction in stiffness, a loss of local stability, and an accelerated transition of the structure to a defective or critical state. In transport infrastructure, this means a reduction in the structure's safe service life, even when the initial condition of the metal and coating is relatively satisfactory (Wang *et al.*, 2024b). Therefore, during the design and operation of corrugated metal pipes in the vicinity of electrified lines, stray currents should be considered as a separate engineering risk factor alongside soil and water aggressiveness, providing for the monitoring of potentials, inspection of the coating condition and assessment of areas of potential current influence (Liang *et al.*, 2024). In the context of transport infrastructure construction, it is advisable to assess the corrosion resistance of corrugated metal pipes not only in terms of the aggressiveness of the environment or the presence of stray currents, but also using a system of quantitative indicators reflecting the rate of metal loss, the degree of structural weakening of the casing and the remaining service life of the structure (Table 2).

Table 2. Indicators for assessing the corrosion resistance of corrugated metal pipes in aggressive environments and under the influence of stray currents

Indicator	Characteristic	Engineering significance for a transport structure
Rate of general corrosion, mm/year	The rate of uniform metal loss in a corrosive environment	Determines the rate at which the design wall thickness decreases and the projected service life of the pipe
Loss of wall thickness, mm	The cumulative reduction in the effective thickness of the metal casing during operation	Affects the stiffness of the shell, the load-bearing capacity and the remaining service life of the structure
Depth and location of localised corrosion damage	Uneven metal degradation; the development of localised, pitting or crevice corrosion	Local defects pose a risk to thin-walled corrugated shells, as they can lead to a loss of local stability and accelerated structural damage
Condition of the protective coating and the metal's ability to passivate	Effectiveness of corrosion protection in acidic, alkaline or chloride-containing environments	Damage to the coating or disruption of the passive state accelerates the onset of degradation and shortens the safe service life
Stray current density/ presence of anodic zones	Electrochemical intensity of the current acting on a metal structure	Can be used for the assessment of the risk of accelerated localised metal loss in the vicinity of electrified transport systems
Reduction in the stiffness and load-bearing capacity of the shell	Transition from material degradation to structural weakening of the pipe	Describes the impact of corrosion on the behaviour of the "soil-structure" system, structural deformation and the operational reliability of transport infrastructure
Remaining service life and the feasibility of refurbishment	The possibility of continued safe operation, reinforcement or restoration without the need to completely replace the structure	A basis for decision-making regarding monitoring, repair, rehabilitation using the pipe-in-pipe method, and the application of GeoSpray

Source: compiled by the author based on S. Alam *et al.* (2021), S. Mundra & J. Provis (2021), I. Ezzeldin *et al.* (2024a; 2024b), H. Zou *et al.* (2024), W. Liang *et al.* (2024), C. Wang *et al.* (2024a; 2024b)

The proposed system of indicators suggests that the corrosion resistance of corrugated metal pipes should be assessed not based on individual environmental factors but rather based on their impact on the rate of metal loss, the nature of localised damage, the degree of structural weakening of the pipe wall, and the remaining service life of the structure. This approach makes it possible to move from a description of corrosion factors to an engineering assessment of the technical condition and the justification of decisions regarding the further operation of the structure. The results of the study showed that the corrosion degradation of corrugated metal pipes in transport structures should be regarded not merely as an electrochemical process, but as a factor affecting the technical condition, durability and operational reliability of the structure, which is determined, in particular, by the pH of the environment and the chloride and sulphate content. This is consistent with the findings of N.T. Chung *et al.* (2021) established that the combination of pH, chlorides and sulphates influences the corrosion behaviour of steel in soil, and that chlorides and sulphates are factors that enhance corrosion activity. The aggressiveness of the environment should be considered as one of the basic parameters of the durability of metal corrugated pipes in transport infrastructure. At the same time, the research results indicate that the intensity of corrosion degradation is determined not only by the chemical composition of the environment but also by underground operating conditions, in particular water saturation, soil condition and damage to the protective coating. This correlates with the approach of G.M. Castro *et al.* (2025), who demonstrated that the degree of saturation, mineralogy and the content of the fine-grained fraction significantly influence corrosion processes in buried metal elements. In this context, the current results confirm that the most hazardous conditions for corrugated metal pipes are those in which the aggressiveness of the environment is combined with high humidity, an unstable water regime and degradation of the protective layer.

The study by S. Safari *et al.* (2024) examined a corrugated metal culvert prior to its rehabilitation using a geopolymer spray-applied lining. To assess its actual condition, the authors used installed sensors, visual measurement methods and diagnostic load tests in static and dynamic modes, which determined the maximum deformations, evaluated the actual behaviour of the structure under load and compared the obtained results with the calculated ones. This correlates with the results of the current study, which showed that for metal corrugated pipes as thin-walled shells, even insignificant local metal loss must be assessed not only in terms of metal loss but also in terms of its impact on the stiffness, local stability, deformation state and residual life of the transport structure. Stray currents pose a particular threat to corrugated metal pipes within transport corridors. The study's findings established that, in their presence, the areas where the current enters and exits become particularly hazardous, as local anodic zones form there, leading to accelerated electrochemical dissolution of the metal. C. Wang *et al.* (2024a) identified the influence of dynamic stray currents caused by underground rail infrastructure on the corrosion behaviour of buried metal elements. The authors demonstrated that such current effects intensify non-uniform and localised corrosion, altering the nature of the electrochemical damage to the metal. This conclusion is consistent with the findings of the current study, according to which stray currents should be regarded as a distinct man-made risk factor which, when combined with a corrosive environment, can significantly reduce the safe service life of a structure.

C. Bryden & A. Valsangkar (2025) examined the long-term assessment of the design service life of a corrugated metal pipe following rehabilitation with a geopolymer lining, focusing on how the rehabilitation solution affects the structure's subsequent structural performance. The proposed study presented rehabilitation not merely as a means of repairing existing damage, but as an engineering approach to restoring functional reliability and extending the service life of the structure in the long term. In this context, the authors' findings align with the conclusions of the current study, according to which the corrosion degradation of metal corrugated pipes in transport infrastructure should be considered as a basis for decision-making regarding monitoring, reinforcement, rehabilitation and the extension of the structure's safe service life. Thus, the corrosion degradation of metal corrugated pipes in transport structures should be regarded not merely as an electrochemical process, but as a factor in structural weakening, arising under the influence of an aggressive environment, water saturation, damage to the protective coating and stray currents. In this regard, it is advisable to assess the corrosion resistance of such pipes in terms of the degree of structural weakening of the shell and the remaining service life of the structure.

Engineering assessment of corrosion damage to corrugated metal pipes

For thin-walled corrugated pipes, the quantitative assessment of corrosion degradation is critical, as even a slight loss of wall thickness affects the stiffness of the pipe, its local stability and the performance of the "soil-structure" system. The theoretical basis for such an assessment is Faraday's law and its derivatives (equations 1-4), which link the electrochemical process to mass loss of metal, reduction in wall thickness and the rate of its further decrease. In the case of non-uniform corrosion damage, this can lead to local deformations, stress concentrations and a reduction in the structure's remaining service life. Consequently, these relationships make it possible to interpret the electrochemical parameters of corrosion in terms of engineering-relevant indicators of the technical condition of corrugated metal pipes.

To assess the impact of corrosion processes, it is advisable to move from a qualitative characterisation of the aggressiveness of the environment and the mechanisms of stray current action to a quantitative assessment of the rate of metal degradation. A numerical example based on Faraday's law is illustrative in this context. Assuming that an anode current of $I = 1$ A acts uniformly on an area of $A = 1$ m² over the course of one year, the calculated loss of steel wall thickness will be approximately 1.16 mm/year. For corrugated metal pipes with a typical wall thickness of 3-6 mm, such metal loss is of engineering significance, as even over a relatively short period of operation, it can lead to a reduction in the shell's stiffness and a loss of local stability. Even at a lower current density, for example, 0.25 A/m², the calculated thickness loss is approximately 0.29 mm/year, which is also a significant figure for the long-term operation of a transport structure (Liang *et al.*, 2024). Given the possibility of localised current concentration in certain surface areas, the actual rate of metal loss under real-world conditions may be even higher. Thus, a quantitative assessment of corrosion losses is an essential link between the electrochemical description of the process and the engineering evaluation of the structure's technical condition.

An interpretation of the relationship (equation 5) shows that the corrosion rate is directly related to the corrosion current density, i_{corr}; consequently, as the electrochemical activity of the medium increases, the rate of metal degradation increases. For corrugated metal pipes, this means that in acidic environments, where i_{corr} values are generally higher, the corrosive weakening of the casing occurs more intensively, whereas in an alkaline environment, the corrosion process may slow down. At the same time, the engineering significance of this relationship lies not only in determining the corrosion rate, but also in the ability to assess the degree of structural weakening via the corrosion weakening coefficient K_O (equation 6), to establish the time at which a dangerous state is reached according to the criterion (equation 7), and to perform a simplified assessment of the remaining service life based on the relationship (equation 8). Thus, as i_{corr} increases, not only does the loss of wall thickness accelerate, but the metal shell also approaches the critical thickness t_{cr}, at which the conditions for local stability or load-bearing capacity are violated. This ensures a transition from an electrochemical description of the process to a quantitative assessment of the remaining service life and the justification of decisions regarding the strengthening or rehabilitation of the structure. In practical terms, this approach links laboratory-determined electrochemical parameters with the assessment of the rate of metal loss, the degree of structural weakening of the shell, and the remaining service life of the structure. The practical significance of corrosion-induced degradation of corrugated metal pipes in transport infrastructure is illustrated by the examples given in Table 3.

Table 3. Examples of corrosion damage, rehabilitation and reinforcement of corrugated metal pipes

Event description	Subject of analysis / engineering solution	Engineering value for transport infrastructure
Damage to the corrugated pipe during heavy rainfall; corrosion of the invert, combined with soil erosion and softening	Analysis of the causes of the building's collapse	Localised corrosion, combined with soil degradation, can lead to structural failure and the collapse of the structure
A metal pipe damaged by corrosion that required repair without being completely replaced	Reinforcement by installing an internal fibreglass composite liner, followed by load-bearing tests; the technology was regarded as a way of extending the service life by 50-100 years	Confirms that the service life of the pipe can be extended through structural reinforcement
Corrosion-damaged corrugated metal culverts, for which traditional replacement was too expensive or would have had a significant impact on traffic	The rehabilitation was conducted by applying GeoSpray geopolymer coating to the actual transport infrastructure	The effectiveness of trenchless solutions for restoring a structure's functionality without significantly impacting the operation of the infrastructure
Damaged metal corrugated culverts on sections of heavy-haul railways exhibiting structural damage, reduced load-bearing capacity and durability under heavy axial loads	Technology for reinforcing corrugated plates has been proposed and investigated	The issue of damaged pipes is viewed as a matter of service life, load-bearing capacity and the safety of transport infrastructure

Source: compiled by the author based on L. Giresini *et al.* (2015), M.R. Taha & D.H. Murcia (2021), H. Liao *et al.* (2022), M.V. Harkusha (2023)

The presented examples have shown that the corrosion-induced degradation of corrugated metal pipes is not merely a process of material wear and tear, but also a factor contributing to the loss of serviceability and a reduction in the structural reliability of the structure. In particular, the collapse of a corrugated pipe due to a combination of localised pitting corrosion and degradation of the soil environment demonstrated that such damage could lead to a complete loss of serviceability and the need for immediate engineering intervention (Giresini *et al.*, 2015). At the same time, the use of an internal composite liner confirmed the possibility of restoring the pipe's structural integrity without its complete replacement and extending its service life (Taha & Murcia, 2021). Rehabilitation using GeoSpray geopolymer coating has demonstrated the effectiveness of trenchless restoration in situations where traditional replacement would be prohibitively expensive or would entail significant operational restrictions (Liao *et al.*, 2022). The necessity of reinforcing damaged corrugated structures, especially under intensive operational loads, highlights that corrosion-induced weakening must be considered in the context of restoring load-bearing capacity and ensuring the overall safety of transport infrastructure (Luchko & Kovalchuk, 2021; Harkusha, 2023). Thus, the analysed cases confirm that corrosion damage to metal corrugated pipes provides grounds for decisions regarding the reinforcement, rehabilitation or restriction of a structure's operation. As an example of practical application, a field project is presented involving the rehabilitation of a corrosion-damaged corrugated metal pipe using GeoSpray geopolymer coating (Fig. 1).

Figure 1. A practical example of the restoration of a corrosion-damaged corrugated metal pipe using GeoSpray geopolymer coating

Source: H. Liao *et al.* (2022)

The durability of corrugated metal pipes is determined throughout the entire life cycle of the structure and must be ensured as early as the design stage. At this stage, it is necessary to assess the aggressiveness of soils and water, based on pH, chloride and sulphate content, degree of water saturation, moisture regime and the environment's capacity to support electrochemical processes. For structures located within the influence zone of electrified transport systems, this assessment should additionally include the risk of stray currents. The selection of material, protective coating and design allowance for metal loss must be conducted based on the expected aggressiveness of the environment, the service life and the reliability requirements of the structure (Ezzeldin *et al.*, 2024b).

During the construction phase, the quality of the implementation of design solutions, monitoring of the condition of the protective coating and adherence to installation procedures are crucial. For thin-walled corrugated pipes, even localised damage to the casing or the anti-corrosion layer during transport, assembly, backfilling or soil compaction can become the starting point for subsequent accelerated degradation. Therefore, construction supervision must focus not only on checking geometry and joints, but also on preventing initial defects, on which the actual service life of the structure depends (Ezzeldin *et al.*, 2024a; Rahmaninezhad *et al.*, 2025). During operation, the main task is the timely detection of signs of degradation and the assessment of remaining service life. This requires periodic inspections, instrumental diagnostics of thickness loss and shell deformations, and, for structures near electrified lines, monitoring of potentials and areas of possible current influence. Under these conditions, corrosion damage should be viewed not merely as a loss of material, but as a source of operational risks that may manifest as ballast settlement, deformations of the track bed or track area, and a reduction in the intervals between repairs. This approach makes it possible to move from simply recording damage to predicting the technical condition and justifying decisions regarding repair or rehabilitation.

In the event of corrosion-induced degradation, engineering measures should combine structural repair with the restoration of anti-corrosion protection. In the case of localised damage, it may be advisable to reinforce specific areas of the casing, whereas for more advanced degradation, internal lining and rehabilitation using the liner pipe method are effective, as they can restore the structure's functionality without complete dismantling. For structures within the vicinity of electrified transport systems, rehabilitation must also include measures to counteract stray currents. Consequently, ensuring the longevity of metal corrugated pipes requires systematic risk management during the design, construction, operation and repair phases. For the designer, this means the need to account for the aggressiveness of the environment and the risk of stray currents when selecting materials, protective coatings and design allowances for metal loss (Zou *et al.*, 2024). For the operating organisation, this means the need for risk-oriented monitoring of the structure's technical condition, including checks on wall thickness loss, shell deformations, the condition of the invert and, in the event of potential current influence, potentials and areas of anodic corrosion (Ezzeldin *et al.*, 2024b). When selecting a repair method, a differentiated approach is advisable – ranging from local reinforcement to the use of trenchless rehabilitation technologies, depending on the degree of degradation and the remaining service life of the structure.

The results of the study showed that the invert and the lower section of the casing are among the most vulnerable areas of corrugated steel pipes in terms of corrosion degradation, and damage in these specific areas can significantly affect the casing's stiffness, remaining service life and the operational safety of the transport structure. This is consistent with the approach of B. Lassy & A. Hain (2025), who investigated methods for installing invert linings made of ultra-high-strength concrete in corrugated metal pipes and focused on the rehabilitation of the lower part of the structure as the area most vulnerable to moisture accumulation, corrosion products and localised damage. In this context, the authors' results confirm the conclusions of the present study regarding the advisability of considering local repair of the invert as one of the practical engineering solutions in the rehabilitation of corrugated metal pipes.

K. Żakowski *et al.* (2025) summarised methods for assessing the risk of corrosion caused by constant stray currents in underground pipelines, particularly in the vicinity of rail transport systems. The authors demonstrated that the identification of current-affected zones, the assessment of anodic areas, and the organisation of a system for monitoring electrochemical parameters are of key importance. This is consistent with the results of the presented study, where stray currents are considered one of the most dangerous man-made factors in the corrosive degradation of corrugated metal pipes, and the monitoring of potentials, coating condition and areas of possible current influence is identified as an essential component of operational supervision. Consequently, for structures located near electrified transport systems, the corrosion risk must be assessed not only based on the characteristics of the soil environment, but also incorporating external current influence.

The results of the current study have shown that internal lining and rehabilitation using the liner pipe method are effective approaches to the restoration of corrosion-damaged corrugated metal pipes. Their application makes it possible to restore the structure's functionality and extend its safe service life without the need for complete replacement. This is confirmed by Z.K. Kouchesfehani *et al.* (2021), who, based on field data, examined the rehabilitation of culverts using cement-geopolymer sprayed lining and assessed the actual condition of the structure following the rehabilitation. The authors analysed the field characteristics of the structure, the specifics of the lining installation, and the results of the post-repair inspection, which addressed the suitability of this technology for the practical rehabilitation of the culvert without significantly disrupting the structure's operation. The results showed that cement-geopolymer sprayed lining can perform not only a repair function but also a structural restoration function, ensuring an extension of the pipeline structure's service life. It is advisable to transition from the identification of corrosion damage to the justification of decisions regarding the reinforcement, rehabilitation and extension of the structure's service life.

In a study by S. Raut *et al.* (2024), three-dimensional finite-element modelling was conducted on corrugated metal pipes repaired using sprayed linings, with an analysis of their performance under shallow burial conditions. The authors concluded that the use of sprayed pipe linings can alter the pipe's deformation behaviour, reduce deformations and improve the structural performance of the system following damage. This is consistent with the results of the present study, in which rehabilitation without complete pipe replacement is considered substantial for the engineering management of residual life. In cases of significant corrosion degradation, it is advisable to assess not only the extent of metal loss but also the effect of the rehabilitation solution on reducing deformations and extending the structure's safe service life.

The study found that the greatest risk to metal corrugated pipes stems from a combination of a corrosive environment, high humidity, damage to the protective coating and the effects of stray currents; under such conditions, corrosion degradation becomes localised and escalates from material wear to a structural issue. This correlates with the findings of W. Lan *et al.* (2025), who analysed the mechanisms of pipeline corrosion in the presence of coating defects under alternating current conditions and examined in detail the interphase processes developing in the zone of the damaged protective layer. The authors established that the combination of a coating defect and electrical influence creates conditions for the intensification of local electrochemical damage to the metal, altering the nature of the corrosion process and increasing the risk of its accelerated development. Coating degradation should be regarded not as a secondary defect, but as one of the key factors in the reduction of corrosion resistance and operational reliability of corrugated metal pipes.

Thus, the impact of aggressive environments and stray currents should be regarded not only as a cause of corrosive wear of metal, but also as a factor contributing to the structural weakening of transport infrastructure. For corrugated metal pipes, this manifests itself in accelerated metal loss, the development of localised defects, a reduction in the shell's stiffness, and a shortening of the structure's remaining service life. In practical terms, this can deform the carriageway or track structure, result in a reduction in the intervals between repairs, and necessitate operational restrictions. For this reason, the corrosion resistance of such pipes should be assessed in terms of the degree of structural weakening of the shell and the remaining service life of the structure.

Conclusions

The results of the study established that the key factors contributing to the corrosion degradation of corrugated metal pipes are the aggressiveness of the soil-water environment, high humidity, damage to the protective coating, and the effects of stray currents. For thin-walled corrugated casings, localised metal loss is the most dangerous, as it leads to a disproportionate reduction in stiffness, a loss of local stability and a reduction in the structure's remaining service life. The most vulnerable areas are the lower zone of the casing, the invert, the side sections and the crown, where corrosion-induced weakening has the greatest impact on the structural performance of the "soil-structure" system. The assessment of the corrosion resistance of corrugated metal pipes should be conducted not only based on environmental characteristics, but also using a system of engineering-relevant indicators, which include the rate of metal loss, loss of wall thickness, localisation of damage, condition of the coating, presence of anodic zones, change in stiffness and remaining service life.

A theoretical analysis based on Faraday's law has shown that even a relatively small reduction in wall thickness is significant for pipes with a metal thickness of 3-6 mm and must be considered when assessing the technical condition of the structure. This paper proposes an engineering approach to assessing the corrosion degradation of corrugated metal pipes based on the corrosion weakening coefficient and critical wall thickness as criteria for transition to a hazardous technical condition. This approach makes it possible to link the electrochemical characteristics of corrosion with the parameters of stiffness, local stability and the remaining service life of the structure. The practical significance of the proposed approach lies in the ability to assess the technical condition, predict the remaining service life and justify decisions regarding the monitoring, reinforcement and rehabilitation of metal corrugated pipes. A limitation of the study is its theoretical nature, without experimental, field or numerical verification of the influence of corrosive factors on the condition of metal corrugated pipes. Future research should focus on developing predictive models of service life, risk-oriented monitoring systems, and criteria for selecting effective methods of strengthening and trenchless rehabilitation of corrugated metal pipes in real-world transport infrastructure conditions.

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References

[1] Alam, S., Manzur, T., Matthews, J., Bartlett, C., & Allouche, E.N. (2021). Experimental evaluation of deteriorated CMPs retrofitted by different non-invasive approaches. *KSCE Journal of Civil Engineering*, 25(11), 4335-4347. doi: 10.1007/s12205-021-2236-6.

[2] ASTM International. (2023). *Standard practice for calculation of corrosion rates and related information from electrochemical measurements*. Retrieved from https://store.astm.org/g0102-89r15e01.html.

[3] Bryden, C., & Valsangkar, A. (2025). Long-term design life assessment of a corrugated steel pipe culvert rehabilitated with geopolymer liner. *Journal of Structural Design and Construction Practice*, 30(2). doi: 10.1061/JSDCCC.SCENG-1537.

[4] Castro, G.M., Park, J., Cha, W., Sherik, A., & Santamarina, J.C. (2025). Corrosion processes in metals buried in sediments: Effects of fines content, mineralogy, and degree of saturation. *Journal of Geotechnical and Geoenvironmental Engineering*, 151(11), article number 04025134. doi: 10.1061/JGGEFK.GTENG-13610.

[5] Chen, Y., Wang, F., Zou, G., Sun, W., & Li, C. (2025). Study on corrosion behavior of X65 steel of buried pipeline under dynamic stray current interference. *AIP Advances*, 15, article number 065005. doi: 10.1063/5.0276986.

[6] Chenghui, Y.I., Jinshuo, L.I., Qiang, Y.U., Wang, H., Li, B., Wu, J., Chaofang, D., & Xiao, K. (2024). Corrosion behaviour and mechanism of acid-resistant steel in acidic solutions with different Cl^- concentrations. *Journal of Materials Research and Technology*, 30, 7242-7255. doi: 10.1016/j.jmrt.2024.04.239.

[7] Chung, N.T., So, Y.-S., Kim, W.-C., & Kim, J.-G. (2021). Evaluation of the influence of the combination of pH, chloride, and sulfate on the corrosion behavior of pipeline steel in soil using response surface methodology. *Materials*, 14(21), article number 6596. doi: 10.3390/ma14216596.

[8] Ezzeldin, I., El Naggar, H., & Newhook, J. (2024a). Corrosion performance of buried corrugated galvanized steel under accelerated wetting/drying cyclic corrosion test. *Buildings*, 14(4), article number 1079. doi: 10.3390/buildings14041079.

[9] Ezzeldin, I., El Naggar, H., & Newhook, J. (2024b). Performance of buried corrugated metal culverts in intact and deteriorated states under surface static loading utilizing full-scale laboratory tests. *Tunnelling and Underground Space Technology*, 154, article number 106099. doi: 10.1016/j.tust.2024.106099.

[10] Farahani, E.M., Su, Y., Chen, X., Wang, H., Laughorn, T.R., Onesto, F., Zhou, Q., & Huang, Q. (2024). AC corrosion of steel pipeline under cathodic protection: A state-of-the-art review. *Materials and Corrosion*, 75(3), 290-314. doi: 10.1002/maco.202313955.

[11] Gaber, G.A., Mohamed, L.Z., & Abdelfatah, A. (2023). Study the corrosion issues on galvanized steel induced in water tanks. *Chemical Papers*, 2023(12), 7539-7549. doi: 10.1007/s11696-023-03043-4.

[12] Giresini, L., Giresini, G., & Sassu, M. (2015). Collapse of corrugated metal culverts during rainstorms: A case study in northern Sardinia (Italy). In *IFCRASC15 – Forensic engineering, collapses, structural reliability, consolidation* (pp. 285-296.). Rome: Sapienza.

[13] Harkusha, M.V. (2023). The impact of corrosion on the technical condition of road drainage pipes and modern methods of their repair. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 8(39), 57-66. doi: 10.32515/2664-262X.2023.8(39).1.57-66.

[14] Kouchesfehani, Z.K., Darabnoush Tehrani, A., & Najafi, M. (2021). Culvert renewal with cementitious-geopolymer spray-applied pipe lining: Field data collection and assessment. *Journal of Pipeline Systems Engineering and Practice*, 12(3), article number 04021015. doi: 10.1061/(ASCE)PS.1949-1204.0000555.

[15] Lan, W., Wei, B., Li, Q., Feng, B., Wang, F., Bi, W., & Liu, D. (2025). Corrosion mechanisms of pipelines with adjacent coating defects under AC interference: An interfacial process analysis. *Materials & Design*, 256, article number 114295. doi: 10.1016/j.matdes.2025.114295.

[16] Lassy, B., & Hain, A. (2025). Evaluation of construction methods for ultra-high performance concrete invert linings in corrugated metal pipe culverts. *Infrastructures*, 10(12), article number 322. doi: 10.3390/infrastructures10120322.

[17] Li, Y., Zhang, W., Jiao, M., Kang, H., & Zhang, J. (2023). Study on stray current corrosion of buried metal in layered soil. *International Journal of Electrochemical Science*, 18(11), article number 100335. doi: 10.1016/j.ijoes.2023.100335.

[18] Liang, H., Wu, Y., Han, B., Lin, N., Wang, J., Zhang, Z., & Guo, Y. (2024). Corrosion of buried pipelines by stray current in electrified railways: Mechanism, influencing factors, and protection. *Applied Sciences*, 15(1), article number 264. doi: 10.3390/app15010264.

[19] Liao, H., Jin, J., & Ghatrehsamani, S. (2022). GeoSpray case studies for corrugated steel pipe culvert rehabilitation. In *11th international conference on short and medium span bridges* (pp. 1-10). Toronto: Canadian Society for Civil Engineering.

[20] Luchko, Y.Y., & Kovalchuk, V.V. (2021). Technical condition of transportation structures made of corrugated metal constructions. *Bridges and Tunnels: Theory, Research, Practice*, 19, 38-50. doi: 10.15802/bttrp2021/233873.

[21] Mundra, S., & Provis, J.L. (2021). Mechanisms of passivation and chloride-induced corrosion of mild steel in sulfide-containing alkaline solutions. *Journal of Materials Science*, 56, 14783-14802. doi: 10.1007/s10853-021-06237-x.

[22] Nakhostin, E., Kenny, S., & Sivathayalan, S. (2022). A numerical study of erosion void and corrosion effects on the performance of buried corrugated steel culverts. *Engineering Structures*, 260, article number 114217. doi: 10.1016/j.engstruct.2022.114217.

[23] National Corrugated Steel Pipe Association. (2018). *Corrugated steel pipe design manual*. Dallas: NCSPA.

[24] Premasuriya, A., Lokuge, W., Karunasena, W., & Manalo, A.C. (2025). Performance of the corrugated metal pipe sliplining method using FRP pipes. *Tunnelling and Underground Space Technology*, 162, article number 106603. doi: 10.1016/j.tust.2025.106603.

[25] Rahmaninezhad, S.M., Jawad, S., Han, J., Al-Naddaf, M., & Parsons, R.L. (2025). Behavior of buried sliplined corrugated metal pipes subjected to footing loading. *Frontiers in Built Environment*, 11, article number 1532485. doi: 10.3389/fbuil.2025.1532485.

[26] Raut, S., Azizian, M., Chimauriya, H.R., Tehrani, A.D., Najafi, M., & Yu, X. (2024). Three-dimensional finite element modeling of spray-applied pipe liners repaired corrugated metal pipes buried under shallow cover. *Transportation Research Record*, 2678(9), 574-593. doi: 10.1177/03611981241230534.
[27] Rossi, S., Pinamonti, M., & Calovi, M. (2022). Influence of soil chemical characteristics on corrosion behaviour of galvanized steel. *Case Studies in Construction Materials*, 17, article number e01257. doi: 10.1016/j.cscm.2022.e01257.
[28] Safari, S., DuBose, T., Head, M.H., Shenton III, H.W., Tatar, J., Chajes, M.J., Karam, J., & Hastings, J.N. (2024). Diagnostic load testing and assessment of a corroded corrugated metal pipe culvert before rehabilitation. *Structure and Infrastructure Engineering*, 20(7-8), 1149-1158. doi: 10.1080/15732479.2023.2280053.
[29] Taha, M.R., & Murcia, D.H. (2021). *Structural retrofit of corroded metal culverts using GFRP SLIP liner. Phase II*. New Mexico: University of New Mexico.
[30] Torres, J.E., Amador, A.S., Ortiz-Vasquez, L.F., & Peña-Ballesteros, D.Y. (2024). Corrosion film breakdown of galvanized steel in seawater below 25°C. *Emergent Materials*, 7(2), 2035-2043. doi: 10.1007/s42247-024-00628-x.
[31] Wang, C., Wang, Y., Xu, S., Li, W., Wang, Y., & Xing, F. (2024a). Assessment of interference scope induced by stray current in the metro depot for the corrosion risk of buried metal pipeline. *Electrical Engineering*, 106(4), 4277-4296. doi: 10.1007/s00202-023-02223-5.
[32] Wang, C., Xu, S., Li, W., Wang, Y., Shen, G., & Wang, S. (2024b). Multi-physics coupled simulation and experimental investigation of alternating stray current corrosion of buried gas pipeline adjacent to rail transit system. *Materials & Design*, 247, article number 113394. doi: 10.1016/j.matdes.2024.113394.
[33] Żakowski, K., Szociński, M., & Krakowiak, S. (2025). Assessment methods for DC stray current corrosion hazards in underground gas pipelines: A review focused on rail traction systems. *Energies*, 18(21), article number 5570. doi: 10.3390/en18215570.
[34] Zou, H., Fang, X., Wu, J., Liu, X., & Liang, Y. (2024). Patterns and causes of interference by stray currents from subways on buried pipelines. *Journal of Dynamic Disasters*, 1(2), article number 100006. doi: 10.1016/j.jdd.2024.100006.

Вплив агресивних середовищ та блукаючих струмів на корозійну стійкість металевих гофрованих труб

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Анотація. Метою дослідження було з'ясування ролі корозійного пошкодження металевих гофрованих труб у формуванні довговічності, технічного стану й експлуатаційної надійності транспортних споруд. Методологія базувалась на методах систематизації, інженерного, теоретичного аналізу, ілюстративного розрахунку, аналізу практичних прикладів. Встановлено, що корозійна деградація металевих гофрованих труб має переважно електрохімічну природу й визначається агресивністю ґрунтового та водного середовища. Найбільшу небезпеку для таких конструкцій становить локальна корозія, оскільки вона безпосередньо знижує жорсткість оболонки, місцеву стійкість і залишковий ресурс споруди. У підземних і водонасичених умовах корозія прискорюється через цикли зволоження-висушування, які руйнують захисне покриття та підвищують вразливість металу. Блукаючі струми в зоні електрифікованих транспортних систем є окремим техногенним чинником ризику, що викликає локальні анодні ділянки та прискорене ураження металу. Показано, що корозійну стійкість металевих гофрованих труб слід оцінювати не лише за агресивністю середовища, а й за системою кількісних показників, що відображають швидкість металовтрати, локальні пошкодження, зміну жорсткості та залишковий ресурс споруди. Кількісне оцінювання на основі закону Фарадея показало, що навіть відносно невелика втрата товщини стінки є інженерно значущою, оскільки впливає на довговічність, технічний стан і безпеку експлуатації транспортної споруди. Запропоновано інженерний підхід до оцінювання корозійної деградації металевих гофрованих труб на основі коефіцієнта корозійного ослаблення, який характеризує відносну втрату товщини металевої оболонки та її наближення до критичного стану. Для інженерного оцінювання залишкового ресурсу використано спрощену залежність, що пов'язує початкову товщину, критичну товщину та швидкість корозії. Практична значимість полягає у можливості застосування результатів проєктувальниками, експлуатуючими організаціями та фахівцями з діагностики під час проєктування, експлуатації, обстеження та реабілітації металевих гофрованих труб у транспортних спорудах

Ключові слова: деградація; залишковий ресурс; стійкість; експлуатація; споруди

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Concept and structure of an improved risk management system in international transportation

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Abstract. In the conditions of international transportation development, characterised by a high level of uncertainty, increased requirements for customs control, and active digitalisation of logistics processes, the issue of effective risk management is of particular importance. Risks arise at the intersection of transport, logistics, and customs operations, have a complex nature, and are capable of spreading along the entire supply chain, which complicates their timely identification and mitigation. The aim of the study was to develop a concept and structure of an improved risk management system in international transportation, focused on process integration and real-time decision support. The study employed system analysis, methods of structural and functional modelling, risk assessment methods in accordance with ISO 31000 provisions, as well as fuzzy logic methods to formalise decision-making processes under conditions of uncertainty and incomplete information. A hierarchical transport and technological risk management system was proposed, covering all stages of international cargo transportation – from planning to execution control. The composition of key subsystems was defined, including identification, assessment, decision support, implementation of mitigation measures, and monitoring. A methodology for forming an integrated risk map had been developed, enabling the determination of risk criticality levels and the establishment of management priorities. An architecture of an intelligent decision support system was proposed, ensuring the integration of data, expert evaluations, and analytical tools. The results of the study can be used to improve the efficiency of customs control, reduce delays in international transportation, optimise logistics processes, and enhance the reliability of transport system operations

Keywords: customs procedures; logistics processes; digitalisation; integrated risk map; fuzzy logic; decision support system

Introduction

The modern development of international transportation is characterised by a high level of uncertainty, increasing complexity of transport and logistics processes, and stricter requirements for customs control. The conditions of globalisation, digitalisation of the economy, and geopolitical instability lead to the emergence of new types of risks that affect all stages of cargo delivery – from route planning to the completion of customs clearance. Under these conditions, the formation of an effective risk management system becomes particularly important, as it should ensure the adaptability of transport and logistics systems, enhance their resilience, and minimise losses caused by adverse factors. At the same time, traditional approaches to risk management no longer meet current requirements,

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which necessitates the development of new conceptual solutions based on the integration of digital technologies, analytical tools, and modern decision-support methods.

A significant contribution to the study of risk management in transport and logistics systems has been made by both Ukrainian and international researchers. In particular, K. Yereshko *et al.* (2024) demonstrated that the resilience of supply chains directly depends on the ability of the system to adapt to external changes, while effective risk management is a key factor in ensuring such resilience. In turn, Yu. Zhyshchynskyi & O. Sharko (2025) substantiated the need for a risk-oriented approach to logistics management, emphasising the importance of comprehensive consideration of uncertainty factors. The issues of digitalisation of logistics processes and their impact on risk management are addressed in the works of S. Sakhno & Yu. Khrutba (2025), who found that the implementation of digital technologies enhances transparency and efficiency in supply chain management. A similar position is held by D. Bugayko & V. Reznik (2025), who proved that the use of intelligent transport systems significantly reduces risk levels through real-time monitoring and data analysis. An important aspect of the research is related to the application of modern analytical tools and artificial intelligence in risk management. Thus, V. Prokhorova *et al.* (2025), in their systematic review, established that the use of Big Data & AI significantly improves the accuracy of risk assessment and contributes to more informed managerial decision-making. In turn, V. Tyshchenko *et al.* (2022) identified key directions for the application of artificial intelligence in supply chain risk management, emphasising its role in forecasting and mitigating negative impacts.

A separate group of studies focuses on the analysis of risks in the transport system of Ukraine. In particular, A. Dolgui & D. Ivanov (2021) noted that the digitalisation of customs procedures is a key factor in improving the efficiency of risk management in international trade. Yu. Zhyshchynskyi & O. Sharko (2025) proposed approaches to modelling risks in multimodal transportation and substantiated the need for using mathematical models to assess uncertainty. S. Sakhno & Yu. Khrutba (2025) investigated the risks of dangerous goods transportation and found that their management requires consideration of specific safety factors. In turn, A. Dolgui & D. Ivanov (2021) analysed the functioning of the transport market under martial law conditions and identified key threats to international transportation, while S. Hosseini & D. Ivanov (2020) characterised systemic risks affecting the unified transport system of Ukraine. Recent studies also highlight the importance of collaboration and adaptability in supply chains, particularly under crisis conditions, which significantly affects risk mitigation efficiency (Jarašūnienė & Gelžinis, 2025).

Despite the significant number of scientific studies, it should be noted that most existing approaches to risk management are fragmented and do not ensure a comprehensive consideration of the interaction between transport, logistics, and customs processes. In addition, issues related to the integration of digital platforms, monitoring systems, and analytical tools into a unified decision-support system remain insufficiently explored. The lack of a coherent concept that combines traditional risk management methods with modern digital tools limits the possibilities for improving the efficiency of international transportation. The aim of the study was to develop a scientifically grounded concept and structure of an improved risk management system in international transportation, which ensures the integration of transport, logistics, and customs processes, as well as the use of digital technologies and intelligent data analysis methods to enhance the effectiveness of managerial decision-making under conditions of uncertainty.

Literature Review

The issue of risk management in international transportation has become increasingly relevant at the current stage of development of transport and logistics systems. This is due to the rapid digitalisation of economic processes, the growing complexity of customs procedures, and the increasing influence of external uncertainty factors. Globalisation processes, the transformation of international supply chains, and geopolitical instability significantly affect the functioning of transport systems and create new challenges for ensuring their efficiency and reliability. Under such conditions, risks arise at all stages of cargo delivery, including planning, transportation, customs clearance, and final distribution. Therefore, the development of effective approaches to risk management is a key prerequisite for improving the sustainability and competitiveness of international transportation systems.

A significant contribution to the study of risk management in transport and logistics systems has been made by both Ukrainian and foreign researchers. In particular, V. Tyshchenko *et al.* (2022) demonstrated that the resilience of supply chains depends on the ability of logistics systems to adapt to changes in the external environment. The authors emphasised that effective risk management serves as a fundamental mechanism for ensuring stability and continuity of transport processes. In a related study, V. Prokhorova *et al.* (2025) substantiated the importance of applying a risk-oriented approach to logistics management, highlighting the need to consider uncertainty factors in a comprehensive and systematic manner. The impact of digital transformation on logistics processes and risk management has also been widely studied in recent years. A. Dolgui & D. Ivanov (2021) found that the implementation of digital technologies significantly enhances transparency in supply chain operations and contributes to more efficient risk monitoring and control. According to the authors, digital platforms enable real-time data exchange and improve coordination between stakeholders, which is crucial for reducing operational risks. A. Jarašūnienė & M. Gelžinis (2025) demonstrated that intelligent transport systems play an important role in minimising risks by enabling real-time monitoring of transport operations and predictive analysis of potential disruptions.

An important direction of modern research is the application of advanced analytical tools and artificial intelligence in risk management. For instance, T. Wang *et al.* (2022) conducted a comprehensive review and concluded that the use of Big Data analytics and artificial intelligence significantly improves the accuracy of risk assessment and supports more effective decision-making. Their findings indicate that data-driven approaches allow for early identification of potential threats and provide opportunities for proactive risk mitigation. In turn, V. Lebid *et al.* (2021) analysed the role of artificial intelligence in supply chain risk management and identified key areas of its application, including risk prediction, scenario modelling, and optimisation of decision-making processes under uncertainty.

A separate group of studies focuses on risk management in the transport system of Ukraine, particularly in the context of digitalisation and external challenges. K. Yereshko *et al.* (2024) emphasised that the digitalisation of customs procedures is a critical factor in improving the efficiency of risk management in international trade. The authors highlighted the importance of integrating information systems and analytical tools into customs processes to enhance their effectiveness. Yu. Zhyshchynskyi & O. Sharko (2025) proposed approaches to modelling risks in multimodal transportation and demonstrated the necessity of applying mathematical models to assess uncertainty and support decision-making. Furthermore, S. Sakhno & Yu. Khrutba (2025) investigated the risks associated with the transportation of dangerous goods and concluded that their management requires consideration of specific safety-related factors and regulatory requirements. In addition, D. Bugayko & V. Reznik (2025) analysed the functioning of the transport services market under martial law conditions and identified key threats that significantly affect international transportation. The authors pointed out that increased uncertainty and disruption of logistics chains require the development of adaptive risk management strategies. V. Prokhorova *et al.* (2025) examined systemic risks in the unified transport system of Ukraine and concluded that these risks are complex and interconnected, which necessitates a comprehensive and integrated approach to their management. The application of mathematical modelling and fuzzy logic approaches in customs processes has been substantiated in recent studies by G. Prokudin *et al.* (2025).

Despite the considerable number of scientific studies in this field, it should be noted that most existing approaches to risk management are fragmented and focus on individual aspects of the problem. In many cases, researchers concentrate on specific elements such as risk assessment methods, digitalisation of logistics processes, or supply chain resilience, without considering the interaction between transport, logistics, and customs processes within a unified system. This limitation reduces the effectiveness of risk management practices in real-world conditions, where these processes are closely interconnected and mutually dependent. Moreover, issues related to the integration of digital platforms, monitoring systems, and analytical tools into a unified decision-support system remain insufficiently explored. Although modern technologies provide significant opportunities for improving risk management, their practical implementation often faces challenges related to data integration, system compatibility, and organisational readiness. In this context, there is a growing need to develop integrated approaches that combine traditional risk management methods with advanced digital solutions. Thus, the analysis of recent scientific publications confirms the existence of a solid theoretical foundation in the field of risk management in international transportation, while also highlighting the need for further research aimed at developing integrated and adaptive systems. Such systems should be capable of effectively managing risks under conditions of uncertainty and ensuring the resilience of transport and logistics processes.

Materials and Methods

The methodological framework of this study was based on a systems approach to the analysis of risk management processes in international transportation, which enables the consideration of transport, logistics, and customs operations as a unified integrated system. This approach ensured a comprehensive understanding of risk formation mechanisms and supports the development of effective management solutions under conditions of uncertainty. The research was conducted in several sequential stages. At the first stage, an analysis of the current state of risk management in international transportation was performed based on scientific publications, international standards, and regulatory documents, including ISO 31000:2018 (2018), World Customs Organization (n.d.), European Commission (n.d.). This stage made it possible to identify the main categories of risks and determine the limitations of existing approaches.

At the second stage, methods of systems analysis and structural-functional modelling were applied (Prokudin *et al.*, 2025). Within the framework of this approach, the risk management system was considered as a multi-level structure covering all stages of cargo delivery – from transportation planning to execution control. The proposed system includes interconnected functional blocks: data collection, risk identification, risk assessment decision-making, implementation of measures and monitoring (Vijayakumar, 2025). A key methodological element of the study was the formalisation of risk assessment using a quantitative approach based on two main parameters: probability of occurrence and severity of consequences. The integrated risk indicator was calculated using the following expression (1):

$$R = P \times S, \qquad (1)$$

where R – integrated risk indicator; P – probability level of the event; S – level of impact or severity of consequences.

To ensure consistency in evaluation, a five-level scale is used for both probability and severity parameters, ranging from 1 (very low) to 5 (very high). The combination of these values formed a 5×5 risk matrix, which enabled classification of risks according to their criticality level. Based on this matrix, risks were categorised as low, medium, high, or critical, which provided a foundation for prioritising management actions. The methodology also included the construction of an integrated risk map, which served as a visualisation tool for representing the distribution of risks within the system. The development of the risk map was carried out through a sequence of steps: identification of key risk groups (customs, transport, logistics, documentary, and security risks); assessment of probability and severity for each risk; calculation of the integrated risk indicator; placement of risks within the matrix; determination of appropriate management measures.

This approach allowed for the systematisation of risks, identification of critical vulnerabilities, and development of targeted mitigation strategies. An important component of the methodology was the application of fuzzy logic methods to model decision-making processes under conditions of uncertainty. A significant proportion of risk parameters were of a vague, qualitative nature and cannot be adequately described using classical mathematical methods. The applicability of fuzzy logic methods for decision-making in transport systems had been widely discussed in recent research (Pálková & Mašek, 2024). Hybrid approaches combining fuzzy logic and neural networks have also been proposed for risk assessment in international trade (Luo *et al.*, 2023). The integration of digital traceability technologies further enhances risk control capabilities (Kamble *et al.*, 2020). Quantitative methods for supply chain resilience analysis provide a strong foundation for risk assessment models (Dong & Tian, 2025).

The fuzzy logic model was implemented using a standard structure that includes the following stages: fuzzification – transformation of quantitative input parameters into fuzzy linguistic variables using membership functions; rule Base – formation of a system of expert “if-then” rules reflecting knowledge in logistics and customs processes; inference Engine – logical processing of rules using algorithms such as Mamdani or Sugeno; defuzzification – conversion of fuzzy results into a numerical value using the centroid method. The integrated risk level within the fuzzy model is represented as a generalised function (2):

$$R = \mathrm{f}(R_m, R_l, R_i, R_t), \quad (2)$$

where R_m – the customs risk; R_l – the logistics risk; R_i – the infrastructure risk; R_t – the time-related risk.

This representation enabled the incorporation of multiple heterogeneous factors into a unified risk assessment model and allows the consideration of expert judgments and incomplete data. To support the practical implementation of the proposed approach, an architecture of an intelligent decision support system (DSS) was developed. The system integrates data from multiple sources, including Global Positioning System (GPS), customs information systems (such as new computerised transit system (NCTS) and automated risk analysis systems), and analytical platforms. The effectiveness of data-driven customs risk management systems has also been confirmed in recent studies (Vijayakumar, 2025). The DSS architecture includes the following components: data acquisition and preprocessing module; fuzzification module; rule base and inference engine; defuzzification module; risk evaluation module (Risk Score); decision-making module; feedback loop. The presence of a feedback mechanism ensures continuous improvement of the system through accumulation of experience and adjustment of model parameters.

Furthermore, the methodology required the integration of digital technologies into the risk management process. The use of GPS monitoring, customs information systems and analytical platforms makes it possible to automate the risk assessment process, ensure a prompt response to anomalies and improve the effectiveness of management decisions. Thus, the proposed methodology combines classical quantitative approaches, fuzzy logic methods, and digital technologies into a unified framework for risk management in international transportation. This ensures a high level of adaptability, scalability, and practical applicability of the developed system.

Results and Discussion

The results of the study demonstrate the practical implementation of the proposed integrated risk management system for international transportation and confirm its effectiveness under conditions of uncertainty. The developed system is based on a multi-level structure that integrates transport, logistics, and customs processes into a unified information and analytical environment. The application of a systems approach made it possible to form a structured model consisting of interconnected functional blocks, each of which performs a specific role within the overall risk management framework. As a result of the study, a conceptual structure of the risk management system was developed, which includes ten key stages: data collection, risk identification, risk assessment, fuzzification, rule formation, logical inference, defuzzification, decision-making, implementation of measures, and monitoring with feedback. This structure ensures the continuity of the risk management process and enables the integration of analytical and operational components into a single system. The developed digital model of risk management in international transportation consists of 10 blocks (Table 1).

The presented structure reflects a comprehensive approach to risk management, where each stage is logically interconnected and contributes to the formation of a unified analytical system. The integration of digital tools ensures the automation of processes and enhances decision-making efficiency. The practical application of the model made it possible to identify key risk groups characteristic of international transportation. The study of risks in international road transportation made it possible to develop a risk assessment matrix for international road transport (Table 2).

Table 1. Structure of the risk management system for international transportation

Stage / system block	Input data	Process (functions)	Output / result	Tools / technologies
Data	Cargo characteristics, route, customs procedures	Data collection and aggregation	Analytical database	GPS, ERP, customs systems
Risk identification	Transport data	Identification of risks	List of risks	Data analysis, expert evaluation
Risk assessment	Identified risks	Risk evaluation	Risk level	Risk matrix (5 × 5), ISO 31000
Fuzzification	Quantitative parameters	Transformation into fuzzy variables	Linguistic variables	Membership functions
Rule base	Fuzzy variables	Formation of rules	Rule set	Expert knowledge
Inference engine	Rule base	Logical inference	Fuzzy result	Mamdani / Sugeno
Defuzzification	Fuzzy result	Conversion to numerical value	Risk score	Centroid method
Decision making	Risk score	Formation of decisions	Recommendations	DSS
Implementation	Decisions	Execution of measures	Risk mitigation	NCTS, ASARM
Monitoring	Execution data	Monitoring and adjustment	System update	BI systems

Note: GPS – Global Positioning System; ERP – Enterprise Resource Planning; DSS – Decision Support System; NCTS – New Computerised Transit System; ASARM – Automated System for Analysis and Risk Management

Source: developed by the authors

Table 2. Risk assessment matrix for international transportation

Risk type	Probability (P)	Impact (S)	Risk value	Level
Customs risks	3	4	12	High
Transport risks	3	3	9	Medium
Documentary risks	4	3	12	High
Logistics delays	4	2	8	Medium
Security risks	2	5	10	High

Source: developed by the authors

The analysis of risks presented in Table 2 shows that customs and documentary risks have the highest level of criticality, which confirms their significant influence on the efficiency of international transportation. These risks are primarily associated with delays in customs clearance, inconsistencies in documentation, and the activation of automated control systems. Transport risks are related to operational factors such as vehicle condition, infrastructure, and weather conditions. Although their impact is moderate, their frequency makes them an important factor affecting transportation reliability. Logistical risks arise from disruptions in coordination between supply chain participants, including delays at border crossings and terminal congestion. Security risks, despite their lower probability, have severe consequences and therefore require special attention in risk management strategies. Their presence highlights the importance of implementing preventive measures and ensuring cargo protection. The visualisation of risks within the matrix enabled the construction of an integrated risk map, which reflects their relative importance and supports the prioritisation of management actions. This approach ensures the transition from fragmented risk analysis to a systematic and structured risk management process.

The results also demonstrate the effectiveness of integrating digital technologies into the risk management system. The use of GPS monitoring, customs information systems, and analytical platforms ensures real-time tracking of transportation processes and improves the responsiveness of management decisions. The implementation of intelligent decision support systems allows for the processing of large volumes of data and the generation of recommendations based on integrated risk indicators. This significantly reduces decision-making time and enhances the accuracy of risk assessment. Comparison of performance indicators before and after implementation of the risk management system (Table 3).

Table 3. Comparison of performance indicators before and after implementation of the risk management system

Indicator	Before implementation	After implementation	Change (%)	Explanation of improvement
Average customs clearance time (hours)	18-24	10-14	↓ 35-45	Automation of procedures, reduced manual checks
Probability of delays (%)	30-40	15-20	↓ 40-50	Risk prediction and route optimisation
Number of documentary errors (%)	12-15	5-7	↓ 50-60	Digital document verification and standardisation

Table 3, Continued

Indicator	Before implementation	After implementation	Change (%)	Explanation of improvement
Frequency of additional inspections (%)	25-30	12-18	↓ 35-45	Risk-based customs control (ASARM/NCTS)
Logistics costs per shipment (%)	100 (baseline)	85-90	↓ 10-15	Improved coordination and reduced idle time
Risk detection accuracy (%)	60-65	80-85	↑ 25-30	Use of analytics and fuzzy logic
Level of supply chain transparency (%)	50-60	80-90	↑ 40-50	Integration of GPS and digital platforms
Decision-making time (hours)	6-8	2-3	↓ 60-70	DSS implementation and automation

Note: GPS – Global Positioning System; DSS – Decision Support System; NCTS – New Computerised Transit System; ASARM – Automated System for Analysis and Risk Management

Source: developed by the authors based on modelling results

The comparative analysis of performance indicators before and after the implementation of the proposed risk management system demonstrates a significant improvement in the efficiency of international transportation processes. In particular, the average customs clearance time decreased by up to 45%, while the probability of delays was reduced by nearly half. This confirms the effectiveness of integrating digital technologies and analytical tools into logistics and customs operations. A notable reduction in documentary errors and the frequency of additional inspections indicates improved data quality and the successful application of risk-oriented customs control. At the same time, the use of intelligent decision support systems contributed to a substantial decrease in decision-making time and an increase in risk detection accuracy. Overall, the obtained results confirm that the implementation of the proposed system leads to enhanced transparency, reduced operational costs, and improved reliability of international transportation processes. The reduction in customs clearance time and delays indicates improved coordination between logistics and customs processes. The decrease in documentary errors demonstrates the effectiveness of digital document processing and standardisation.

At the same time, the reduction in logistics costs reflects improved route optimisation and reduced downtime. These results confirm that the proposed system enables the transition from reactive to proactive risk management. The developed DSS plays a central role in ensuring these improvements. By integrating analytical tools and digital platforms, the system supports real-time monitoring and adaptive management of transportation processes. Thus, the obtained results confirm the effectiveness of the proposed concept of an integrated risk management system. The developed model ensures improved transparency, reduced risks, increased efficiency, and high adaptability of international transportation systems under conditions of uncertainty.

The obtained research results confirm that effective risk management in international transportation requires a transition from fragmented approaches to integrated system solutions that encompass all stages of the transport and logistics process (Osipchuk, 2024). The proposed hierarchical risk management model, which combines transport, logistics, and customs aspects, is consistent with modern scientific approaches; however, it extends them through comprehensive process integration and the use of intelligent analytical methods by N. Luo *et al.* (2023). In particular, the results correlate with the findings of V. Tyshchenko *et al.* (2022), who substantiate the necessity of ensuring supply chain resilience under conditions of uncertainty. At the same time, this study further develops this idea by detailing risk management mechanisms at the level of international transportation, taking into account the specifics of customs procedures. V. Lebid *et al.* (2021) emphasise a risk-oriented approach to logistics system management; however, their research focuses mainly on organisational and economic aspects, whereas the present study proposes a specific structural and functional model of the system.

An important direction of modern research is the digitalisation of logistics processes. Thus, K. Yereshko *et al.* (2024) consider digital transformation as a key factor in improving the efficiency of logistics systems. In this study, these provisions are further developed through the integration of digital systems (GPS, NCTS, analytical platforms) into the risk management process, enabling real-time decision-making. Among Ukrainian scholars, the work of Yu. Zhyshchynskyi & O. Sharko (2025) should be highlighted, as it examines the digitalisation of customs procedures and the implementation of risk-oriented technologies. The results obtained in this article confirm the importance of this direction but extend it by integrating customs risks with transport and logistics risks. Studies by S. Sakhno & Yu. Khrutba (2025) focus on risk modelling in multimodal transportation and the transportation of dangerous goods, respectively. In contrast to these works, the present study proposes a universal model applicable to various types of transportation.

Particular attention in scientific research is given to the impact of external factors, especially martial law, on the functioning of transport systems. Thus, A. Dolgui & D. Ivanov (2021) analyse risks and transformations of the transport market under crisis conditions. In this study, these aspects are taken into account in the formation of the risk structure, particularly by identifying security risks as a separate category with a high level of impact. A. Jarašūnienė & M. Gelžinis (2025) are focused on enhancing the resilience of logistics systems and the use of intelligent transport technologies. In the present study, these approaches are integrated into a broader concept that includes not only transport and logistics but also customs processes, which is particularly important for international transportation.

A significant distinguishing feature of the obtained results is the application of fuzzy logic methods for modelling decision-making processes. Unlike traditional approaches based on precise data, the proposed model allows for the consideration of uncertainty and incomplete information, which is typical of real-world transport system operations. Similar approaches are discussed in the work of V. Borsa & Yu. Terebeichyk (2024). Thus, the research results confirm and further develop existing scientific approaches to risk management in international transportation by proposing their systemic integration, digitalisation, and the application of intelligent analytical methods. The obtained results provide a more comprehensive understanding of the risk management process and create a foundation for further research aimed at implementing intelligent systems in the practice of international transportation.

Conclusions

The conducted study has established that risk management in international transportation under current conditions is characterised by a high level of complexity, driven by the integration of transport, logistics, and customs processes, as well as the influence of uncertainty factors in the external environment. It has been demonstrated that existing risk management approaches are fragmented and do not ensure an adequate level of efficiency without their integration into a unified system. The article develops a concept of an improved risk management system for international transportation based on a systemic approach, covering all stages of the transport and logistics process – from shipment preparation to execution control. The proposed system structure includes functional subsystems for risk identification, assessment, decision support, implementation of risk mitigation measures, and monitoring with feedback.

The proposed risk management system enables the integration of different transportation stages into a unified decision-making framework. The use of a matrix-based approach and fuzzy logic methods ensures more flexible and well-grounded risk assessment. The methodological approach to risk assessment has been improved through the application of the matrix, which allows for quantitative determination of risk levels, their classification according to criticality, and the development of substantiated management decisions. An integrated risk map for international transportation has been constructed, providing systematisation of risks and determination of their priorities. The feasibility of applying fuzzy logic methods for modelling decision-making processes under uncertainty has been substantiated. An architecture of an intelligent decision support system has been developed, enabling the integration of statistical data, expert evaluations, and digital risk analysis tools. Prospects for future research include the development of mathematical models for risk assessment using machine learning methods, as well as the implementation of the proposed system within real digital platforms for managing international transportation.

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References

[1] Borsa, V., & Terebeichyk, Yu. (2024). Digitalization of customs as a factor in the development of international trade. *European Scientific Journal of Economic and Financial Innovations*, 2(14), 355-367. doi: 10.32750/2024-0232.

[2] Bugayko, D., & Reznik, V. (2025). Comparative analysis of Ukrainian legislation and international norms regulating the formation and management of the logistics system. *International Journal of Transportation Research and Technology*, 2(1), 49-58. doi: 10.71108/transporttech.vm02is01.04.

[3] Dolgui, A., & Ivanov, D. (2021). Ripple effect and supply chain disruption management: New trends and research directions. *International Journal of Production Research*, 59(1), 102-109. doi: 10.1080/00207543.2021.1840148.

[4] Dong, Y., & Tian, Y. (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.

[5] European Commission. (n.d.). Retrieved from https://commission.europa.eu/index_en.

[6] Hosseini, S., & Ivanov, D. (2020). Bayesian networks for supply chain risk, resilience and ripple effect analysis: A literature review. *Expert Systems with Applications*, 161, article number 113649. doi: 10.1016/j.eswa.2020.113649.

[7] ISO 31000:2018. (2018). *Risk management guidelines*. Retrieved from https://www.iso.org/standard/65694.html.

[8] Jarašūnienė, A., & Gelžinis, M. (2025). Risk and crisis management strategies in the logistics sector: Theoretical approaches and practical models. *Future Transportation*, 5(2), article number 74. doi: 10.3390/futuretransp5020074.

[9] Kamble, S.S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. *International Journal of Information Management*, 52, article number 101967. doi: 10.1016/j.ijinfomgt.2019.05.023.

[10] Lebid, V., Anufriyeva, T., Savenko, H., & Skrypnyk, V. (2021). Study of efficiency of simplication of customs formalities on the digitalization basis. *Technology Audit and Production Reserves*, 1(4(57)), 49-53. doi: 10.15587/2706-5448.2021.225627.

[11] 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.

[12] Osipchuk, D.S. (2024). Risk management in customs affairs under martial law conditions. *Economics, Management and Administration*, 2(108), 16-21. doi: 10.26642/ema-2024-2(108)-16-21.

[13] 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.

[14] Prokhorova, V., Kravchenko, O., Shkurenko, O., Babichev, A., & Polivantsev, A. (2025). Study of priority directions of economic recovery of Ukraine based on scenario modelling. *Economics of Development*, 24(1), 26-34. doi: 10.63341/econ/1.2025.26.

[15] Prokudin, G., Chupaylenko, O., Khobotnia, T., Nazarova, A., & Kolesnyk, Y. (2025). Mathematical formalization of the process of improving cargo movement control to the destination customs. In O. Slavinska, V. Danchuk, O. Kunytska & O. Hulchak (Eds.), *Intelligent transport systems: Ecology, safety, quality, comfort* (pp. 3-12). Cham: Springer. doi: 10.1007/978-3-031-87379-9_1.

[16] Sakhno, S., & Khrutba, Yu. (2025). The state of transportation of dangerous goods in Ukraine in modern. *Management of Development of Complex Systems*, 61, 113-120. doi: 10.32347/2412-9933.2025.61.113-120.

[17] Tyshchenko, V., Ostapenko, V., & Karpova, V. (2022). Digitization in the customs risk management. *Economics and Society*, 37, 1-6. doi: 10.32782/2524-0072/2022-37-35.

[18] 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.

[19] Wang, T., Chen, H., Dai, R., & Zhu, D. (2022). Intelligent logistics system design and supply chain management under edge computing and internet of things. *Computational Intelligence and Neuroscience*, 2022, article number 1823762. doi: 10.1155/2022/1823762.

[20] World Customs Organization. (n.d.). *WCO customs risk management compendium*. Retrieved from https://www.wcoomd.org/en/topics/facilitation/instrument-and-tools/tools/risk-management-compendium.aspx.

[21] Yereshko, K., Khoma, O., & Pyslytsia, A. (2024). Digitalization of customs procedures: Current state and prospects. *Journal of Vasyl Stefanyk Precarpathian National University*, 11(2), 103-115. doi: 10.15330/jpnu.11.2.103-115.

[22] Zhyshchynskyi, Yu.S., & Sharko, O.V. (2025). Multimodal transportation risk modeling in Ukraine. *Bulletin of the Pryazovskyi State Technical University. Series: Technical Sciences*, 52, 244-254. doi: 10.31498/2225-6733.52.2025.351136.

Концепція та структура вдосконаленої системи управління ризиками у міжнародних перевезеннях

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Анотація. В умовах розвитку міжнародних перевезень, що характеризуються високим рівнем невизначеності, посиленням вимог до митного контролю та активною цифровізацією логістичних процесів, питання ефективного управління ризиками набуває особливої ваги. Ризики формуються на стику транспортних, логістичних і митних операцій, мають комплексний характер і здатні поширюватися вздовж усього ланцюга постачання, що ускладнює їх своєчасне виявлення та мінімізацію. Метою дослідження стало розроблення концепції та структури удосконаленої системи управління ризиками у міжнародних перевезеннях, орієнтованої на інтеграцію процесів і підтримку прийняття рішень у режимі реального часу. У роботі було використано системний аналіз, методи структурно-функціонального моделювання, методи оцінювання ризиків відповідно до положень ISO 31000, а також методи нечіткої логіки для формалізації процесів прийняття рішень в умовах невизначеності та неповноти інформації. Запропоновано ієрархічну транспортно-технологічну систему управління ризиками, що охоплює всі етапи міжнародного перевезення вантажів – від планування до контролю виконання. Визначено склад ключових підсистем (ідентифікації, оцінювання, підтримки прийняття рішень, реалізації заходів мінімізації та моніторингу). Розроблено методику формування інтегрованої карти ризиків, що дозволило визначити рівень їх критичності та встановити пріоритети управління. Запропоновано архітектуру інтелектуальної системи підтримки прийняття рішень, яка забезпечує інтеграцію даних, експертних оцінок та аналітичних інструментів. Результати дослідження можуть бути використані для підвищення ефективності митного контролю, скорочення часу затримок у міжнародних перевезеннях, оптимізації логістичних процесів та підвищення надійності функціонування транспортних систем

Ключові слова: митні процедури; логістичні процеси; цифровізація; інтегрована карта ризиків; нечітка логіка; система підтримки прийняття рішень

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The role of freight forwarding activities in the recovery of Ukraine's economy

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Abstract. The article provided a comprehensive analysis of the role of freight forwarding activities in supporting Ukraine's economic recovery under the conditions of a full-scale war. The primary objective of the study was to analyse the dynamics of Ukraine's trade balance and to develop a forecast for its development in 2025-2026. To achieve this objective, economic and mathematical modelling methods were applied, in particular various types of trend approximation, including exponential, linear, logarithmic, polynomial, and power models. This methodological approach allowed for comparing different functional dependencies and selecting the most suitable models under conditions of high uncertainty. The findings demonstrated a stable negative trade balance (USD -33,390.9 million in 2025 and USD -37,679.1 million in 2026), characterised by a decline in exports and a simultaneous increase in imports. This imbalance is largely driven by the growing need for energy resources, machinery, equipment, and other essential goods required to sustain the economy during wartime and recovery. Given the risks associated with a persistent trade deficit, the article proposed a set of strategic measures aimed at stabilising the economic situation. These included the restoration and modernisation of transport infrastructure, diversification of export markets, promotion of high value-added production, expansion of multimodal transport systems, and the implementation of digital technologies in logistics. Additionally, the study highlighted the strategic importance of Ukraine's integration into the Trans-European Transport Network and the need to attract investment in logistics infrastructure and hubs. Overall, the research confirmed the crucial role of efficient logistics and transport systems in ensuring economic resilience and

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strengthening Ukraine's position in international markets. The results of the study can be used in the development of national logistics strategies, policy-making, and support programmes for exporters

Keywords: foreign trade; logistics; transport infrastructure; TEN-T; export; import; trade balance; forecasting

Introduction

Martial law in Ukraine has created significant challenges for the functioning of the transport and forwarding industry, necessitating the intensification of international cooperation. In wartime conditions, disruptions in logistics chains, port closures, infrastructure destruction, and increased transportation risks have created a demand for new solutions at the international level. Cooperation with European and global partners is crucial for ensuring the stability and efficiency of freight forwarding. Determining the role of freight forwarding in the recovery of Ukraine's economy and developing recommendations for its optimisation is a topical subject for academic research. Numerous studies have explored the challenges of transport and forwarding activities (TFA) in crisis conditions. J. Gnap *et al.* (2021) and A.I. Kiiko (2024) emphasised the crucial role of transport infrastructure for the national economy, stressing the importance of its restoration to facilitate effective freight forwarding operations. K.M. Razumova *et al.* (2023) analysed the impact of globalisation and integration on the development of transport and forwarding enterprises, as well as the challenges faced by the industry in the context of contemporary economic realities. V. Prokhorova *et al.* (2025) identified the key factors influencing the intensity of economic recovery, as well as the construction and evaluation of possible development scenarios for Ukraine after the "hot" phase of the war. For the study of the peculiarities of Ukraine's economic development, they used the tools of non-parametric regression spline functions. The feasibility of using scenario modelling in conditions of high uncertainty about Ukraine's future development was substantiated. R. Subačienė *et al.* (2023) developed organisational and methodological issues related to monitoring the contribution of the corporate sector to achieving sustainable development goals during the post-war reconstruction phase in Ukraine. The work uses methods of analysis and synthesis (to study the consequences of Russia's military aggression on Ukraine's economic development and the achievement of sustainable development goals), comparison (in analysing the requirements of international regulations on the structure, stages of formation, and set of reporting indicators), and a process approach (for developing recommendations on the creation of a repository). Institutional mechanisms to strengthen the harmonisation and comparability of sustainability reporting at the international level in the context of achieving sustainable development goals were substantiated. V. Sanduhei *et al.* (2025) and P. Vesco *et al.* (2025) substantiated the directions and potential for using human capital as a driver of forming the country's competitive advantages in the post-war period. They determined how the quality of human capital in Ukraine aligns with the potential for acquiring competitive advantages, identified factors of positive and negative impact of war and crisis on human capital, and examined trends in changes to the quality of human capital under the influence of these factors.

Despite the availability of research, insufficient attention has been given to integrating TFA into Ukraine's economic recovery process and the impact of this activity on the sustainable development of the national economy. The goal of this article was to assess the role of transport and TFA in Ukraine's economic recovery, identify the main challenges faced by the transport sector, and propose strategies for improving its operational effectiveness. Also, in this context, it is crucial to underscore the development of public-private partnerships in the transport and logistics sector, which will allow for attracting additional investment into the transport industry, improving the quality of logistics services, and ensuring the stability of transport flows in European and global foreign economic markets. In line with the established objective, the following tasks were defined for the research:

- analysis of problems caused by Russia's aggression in the field of TFA in the country;
- development of recommendations to overcome the issues caused by Russia's aggression in the field of TFA in Ukraine to restore its economy.

Materials and Methods

The empirical basis of the research consisted of statistical data on Ukraine's exports and imports of goods for the period 2020-2024, obtained from official sources of the State Statistics Service (n.d.a; n.d.b). The selection of this period was justified by the need to cover both pre-war and wartime stages, which allows identifying structural breaks and transformations in foreign trade dynamics. The object of the study was Ukraine's foreign trade under martial law conditions, while the subject is the dynamics and trends in export and import volumes, as well as the possibilities of their forecasting considering the influence of transport and logistics factors. The least squares method was used to find an approximate solution to the overdetermined system and to estimate the parameters of the linear regression. The application of the least squares method is justified by the following example. Suppose that as a result of some research, four data points (x, y) were obtained: (1, 6), (2, 5), (3, 7), and (4, 10) (shown as dots in Figure 1). The task was to find the line that best fits these points (to determine the values of a and b that approximately solve the system of linear equations):

$$\begin{cases} \beta_1 + 1 \cdot \beta_2 = 6 \\ \beta_1 + 2 \cdot \beta_2 = 5 \\ \beta_1 + 3 \cdot \beta_2 = 7 \\ \beta_1 + 4 \cdot \beta_2 = 10, \end{cases} \quad (1)$$

where β_1 – the intercept; β_2 – the slope coefficient.

The least squares approach to solving this problem was to try to make the sum of the squared errors between the right and left sides of this system as small as possible, that is, it is necessary to find the minimum of the function:

$$S(\beta_1, \beta_2) = [6 - (\beta_1 + 1 \cdot \beta_2)]^2 + [5 - (\beta_1 + 2 \cdot \beta_2)]^2 + \\ + [7 - (\beta_1 + 3 \cdot \beta_2)]^2 + [10 - (\beta_1 + 4 \cdot \beta_2)]^2. \quad (2)$$

The minimum was determined by calculating the partial derivative of $S(\beta_1, \beta_2)$ of β_1, β_2 and setting them to zero:

$$\begin{cases} \frac{\Delta S}{\Delta \beta_1} = 0 = 8 \cdot \beta_1 + 20 \cdot \beta_2 - 56 \\ \frac{\Delta S}{\Delta \beta_2} = 0 = 20 \cdot \beta_1 + 60 \cdot \beta_2 - 154. \end{cases} \quad (3)$$

This resulted in a system of two equations with two unknowns, known as the normal equations. The solution to the system of linear algebraic equations provides the equation of the line that best fits the four given points. The minimum sum of squared errors is:

$$S(3.5, 1.4) = 1.1^2 + (-1.3)^2 - (0.7)^2 + 0.9^2 = 4.2.$$

It should be noted that the form of the linear function obtained analytically coincides exactly with the equation of the linear trend (Fig. 1).

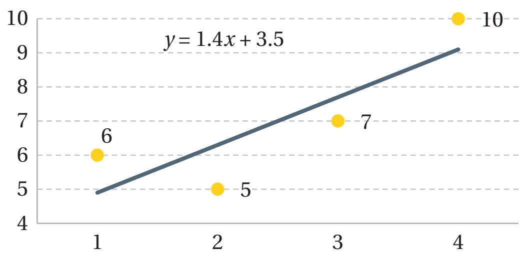

Figure 1. Linear regression example
Source: developed by the authors

Based on Figure 1, it was confirmed that the least squares regression line captured the overall trend of variation in the data, as the obtained linear trend equation closely fit the majority of data points while minimising the deviations from the observed values. This indicated a good fit of the model and supported the appropriateness of using a linear specification for data approximation. At the first stage of the research, general scientific methods of analysis and synthesis were applied to assess the state of freight forwarding activities and their impact on the national economy. At the second stage, economic and mathematical modelling methods were used, in particular trend analysis. Five types of trend models were constructed: linear, exponential, logarithmic, polynomial, and power. This approach was chosen to compare different functional forms and identify the model that best fits the available data under conditions of high uncertainty. The selection of the exponential trend for exports ($R^2 = 0.4092$) and the power trend for imports ($R^2 = 0.2269$) is justified not by the absolute value of the coefficient of determination, but by their relative superiority among the tested models. The relatively low R^2 values are explained by the high volatility of the data caused by exogenous shocks such as war, port blockades, and infrastructure destruction, which disrupt traditional economic patterns. Under such conditions, trend models serve primarily as indicative rather than precise forecasting tools. Preliminary data processing included aggregation and consistency checks; however, no additional smoothing techniques (such as moving averages) were applied, which may have affected the accuracy of approximation. All calculations and model constructions were performed using Microsoft Excel.

Results and Discussion

Following the outbreak of the full-scale war, Ukraine has suffered significant losses in the logistics and transportation sectors. The blockade of seaports, destruction of transport routes, and shifts in international trade have profoundly impacted the economic situation. Under such conditions, TFA are crucial in stabilising economic processes, particularly during post-crisis recovery. TFA facilitates the uninterrupted supply of goods, ensures availability in domestic and international markets, and stimulates investment in infrastructure modernisation. Economic recovery largely depends on the efficient operation of the logistics sector, which supports international trade and helps adapt the transportation system to new challenges (Ivanov *et al.*, 2025). However, the war has led to the destruction of key infrastructure, including bridges, roads, and railway hubs, creating additional obstacles to transporting critically essential goods (Maliuta *et al.*, 2023). Due to the blockade of seaports, businesses have been forced to seek alternative routes, leading to the rapid expansion of railway transportation, the development of land corridors through Ukraine's western borders, and an increase in cargo flows through Danube ports. At the same time, these changes require substantial investments in upgrading the transport network and enhancing its capacity. A separate challenge remains the rising cost of logistics. The war has resulted in increased insurance payments, higher fuel prices, elevated transportation maintenance costs, and rising wages, all of which complicate business operations. Additionally, the shortage of skilled personnel, caused by mobilisation and migration, negatively impacts freight transport efficiency and cargo handling speed (Myskyv *et al.*, 2025). A serious challenge for the economy remains the negative balance of foreign trade, indicating that imports exceed exports, leading to currency risks, increased debt burden, and the devaluation of the hryvnia, as noted by A. Nepran (2025). The war has significantly complicated the sale of Ukrainian products in foreign markets due to the destruction of production facilities, reduced export capabilities, and logistical constraints. At the same time, the demand for imports of energy resources, machinery, and essential goods remains high. Moreover, the significant share of raw material exports makes the economy vulnerable to fluctuations in global prices, further exacerbating the financial system's instability. An attempt was made to forecast the volume of Ukraine's foreign trade in goods for 2025 and 2026 using five trend models – exponential, linear, logarithmic, polynomial, and power. This was achieved through the application of mathematical tools and smoothing functions (Prokudin *et al.*, 2024). The forecast was based on statistical data for the years 2020, 2021, 2022, 2023, and 2024, as presented in Table 1.

Table 1. Volume of Ukraine's foreign trade in goods, 2020-2024

Year	Exports, million USD	Imports, million USD	Trade balance, million USD
2020	49,191.8	54,336.1	-51,44.3
2021	68,072.3	72,843.1	-47,70.8
2022	44,135.6	55,295.7	-11,160.1
2023	36,182.9	63,567.0	-27,384.1
2024	41,733.0	70,709.1	-28,976.1

Source: State Statistics Service of Ukraine (n.d.a; n.d.b)

The data in Table 1 reveals a consistent negative trade balance for Ukraine from 2020 to 2024, with imports consistently exceeding exports. The trade deficit widened significantly from USD 5.14 billion in 2020 to USD 28.98 billion in 2024, reflecting a growing imbalance in foreign trade over the period. Notably, the export value fluctuated, while imports showed a general upward trend, particularly in 2023 and 2024, contributing to the increasing trade deficit. The forecast of foreign trade volume, built on an exponential trend, is presented in Figure 2.

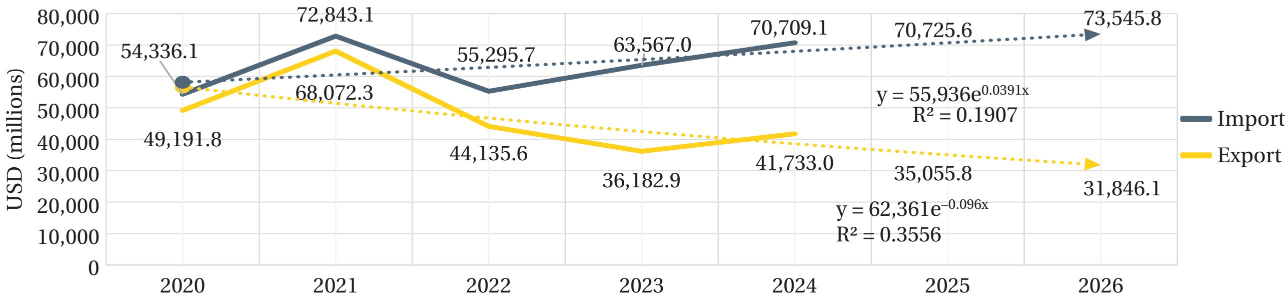

Figure 2. Forecast of foreign trade volume using the exponential trend

Source: developed by the authors

The exponential model indicates a rapid divergence between imports and exports. By the end of the forecast period, the gap reaches roughly USD 40-42 billion, reflecting the compounding nature of exponential growth. Imports expand at an increasing rate, while exports decline proportionally, which amplifies the imbalance over time. From an economic perspective, such dynamics may reflect asymmetric recovery conditions: strong domestic demand and import dependence (e.g., energy, machinery, consumer goods) combined with structural constraints on exports, such as damaged infrastructure, limited production capacity, and restricted access to external markets. Compared to other models, the exponential trend produces one of the most aggressive divergence scenarios, as it assumes constant percentage growth/decline rates. This makes it less conservative than the linear and power trends and more extreme than the logarithmic model, which incorporates deceleration effects. The forecast of foreign trade volume, built on a linear trend, is presented in Figure 3.

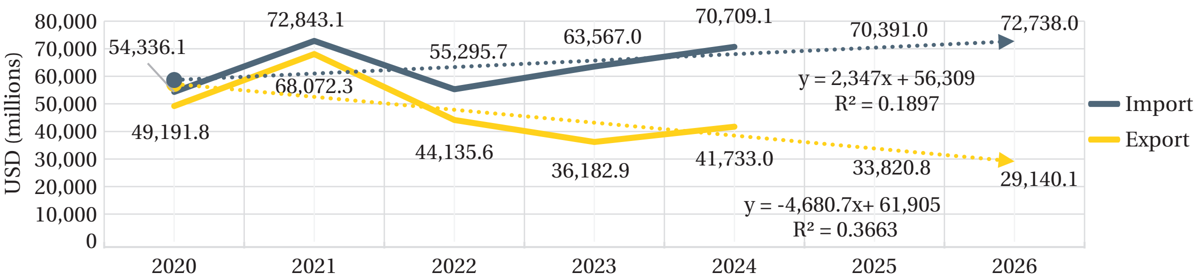

Figure 3. Forecast of foreign trade volume using the linear trend

Source: developed by the authors

The linear model shows a steady and predictable widening of the trade gap, reaching approximately USD 40-43 billion by the final years. The difference grows at a nearly constant absolute rate, reflecting stable but opposing trends in imports and exports. Economically, this suggests a gradual normalisation of trade flows, where imports increase due to recovering consumption and investment, while exports fail to keep pace due to persistent competitiveness issues. The linear assumption implies no major structural shifts, only continuation of current tendencies. In comparison, this model is more conservative than the exponential and polynomial trends, as it avoids acceleration effects. However, it is less nuanced than the logarithmic model, which captures slowing dynamics, and less flexible than the power model, which reflects nonlinear adjustment. The forecast of foreign trade volume, built on a logarithmic trend, is presented in Figure 4.

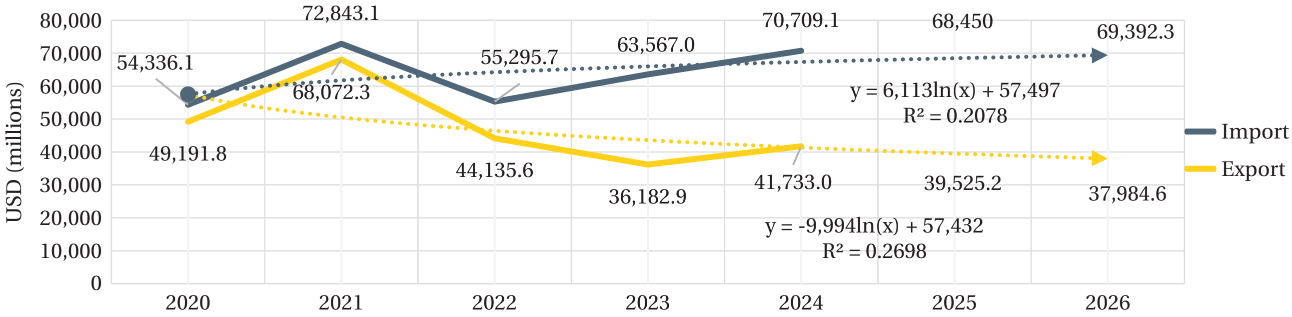

Figure 4. Forecast of foreign trade volume using the logarithmic trend

Source: developed by the authors

The logarithmic model points to a moderate and stabilising gap, estimated at around USD 30-32 billion toward the end of the period. The divergence grows initially but then decelerates, reflecting diminishing marginal changes. This behaviour can be explained by market saturation and adaptive mechanisms. Imports grow more slowly as demand stabilises, while exports, despite declining, begin to adjust to constraints, possibly through market diversification or partial recovery of production. Compared to other models, the logarithmic trend is the most optimistic and balanced scenario. Unlike exponential and polynomial models, it does not imply runaway divergence. It also improves upon the linear model by incorporating nonlinear slowing, making it more realistic in conditions of economic stabilisation. The forecast of foreign trade volume, built on a polynomial trend, is presented in Figure 5.

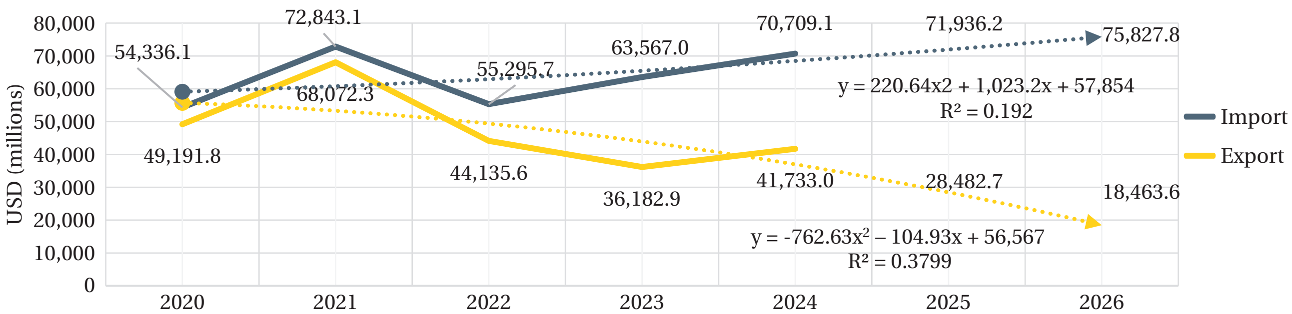

Figure 5. Forecast of foreign trade volume using the polynomial trend

Source: developed by the authors

The polynomial model produces the most pronounced divergence, with the trade gap potentially exceeding USD 55-57 billion by the end of the forecast horizon. Imports accelerate significantly, while exports decline at an increasing rate, creating a sharp imbalance. Economically, this reflects a high-risk scenario characterised by deepening structural asymmetry: strong reliance on imports combined with deteriorating export capacity. This may be linked to prolonged war impacts, deindustrialisation, or loss of key export sectors. Compared to all other models, the polynomial trend is the most pessimistic, as it captures nonlinear acceleration in opposite directions. Unlike the exponential model, which assumes proportional change, the polynomial specification allows for turning points and sharper curvature, leading to more extreme outcomes. The forecast of foreign trade volume, built on a power trend, is presented in Figure 6.

The power model suggests a moderate but persistent gap, reaching approximately USD 30-35 billion. Imports grow steadily but without sharp acceleration, while exports decline gradually, resulting in a smoother divergence. This reflects a scenario of controlled imbalance, where economic agents partially adapt to constraints. Imports remain necessary for recovery and modernisation, while exports face structural but not catastrophic limitations. In comparison, the power trend occupies a middle position between models. It is less extreme than the exponential and polynomial scenarios, but also less optimistic than the logarithmic one. Relative to the linear trend, it better captures non-constant growth rates, making it more flexible and potentially more realistic in transitional economic conditions. The results of the approximation for all five trends are summarised in Table 2.

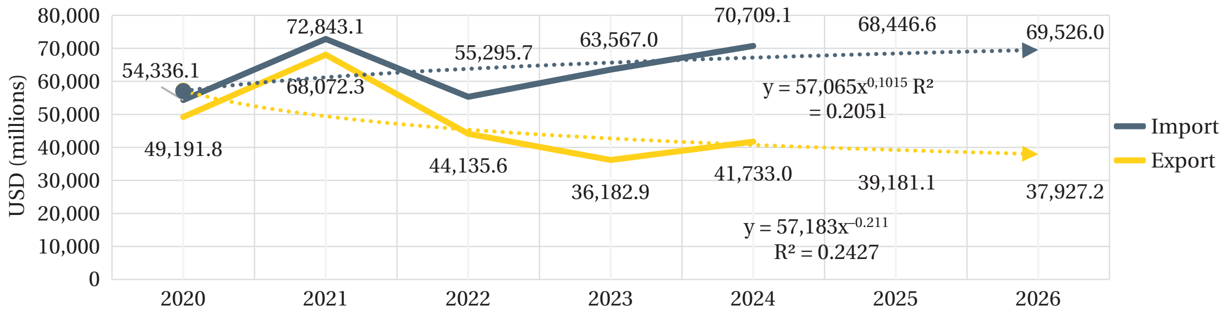

Figure 6. Forecast of foreign trade volume using the power trend

Source: developed by the authors

Table 2. Results of approximation of the volumes of foreign trade in goods of Ukraine for 2020-2024

Type of trend	R^2	
	Export	Import
Exponential	**0.4092**	0.2079
Linear	0.3663	0.1897
Logarithmic	0.2698	0.2078
Polynomial	0.3799	0.192
Power	0.3173	**0.2269**

Source: developed by the authors

For the forecast for 2025-2026, the trends with the highest R^2 values closest to 1 are selected. The exponential trend ($R^2 = 0.4092$) is used for exports, while the power trend ($R^2 = 0.2269$) is applied for imports. The obtained results are presented in Table 3. According to Table 3, the forecast for Ukraine's foreign trade in goods for 2025 and 2026 indicates a further decline in exports and a steady increase in imports. The trade deficit is projected to rise significantly, from USD 28.98 billion in 2024 to USD 33.39 billion in 2025 and USD 37.68 billion in 2026, showing a growing imbalance in foreign trade. The obtained forecasting results are presented in the resulting graph in Figure 7.

Table 3. Forecast of Ukraine's foreign trade volume in goods for 2025-2026

Year	Exports, million USD	Imports, million USD	Trade balance, million USD
2020	49,191.8	54,336.1	-51,44.3
2021	68,072.3	72,843.1	-47,70.8
2022	44,135.6	55,295.7	-11,160.1
2023	36,182.9	63,567.0	-27,384.1
2024	41,733.0	70,709.1	-28,976.1
2025	**35,055.8**	**68,446.6**	**-33,390.9**
2026	**31,846.9**	**69,526.0**	**-37,679.1**

Source: developed by the authors

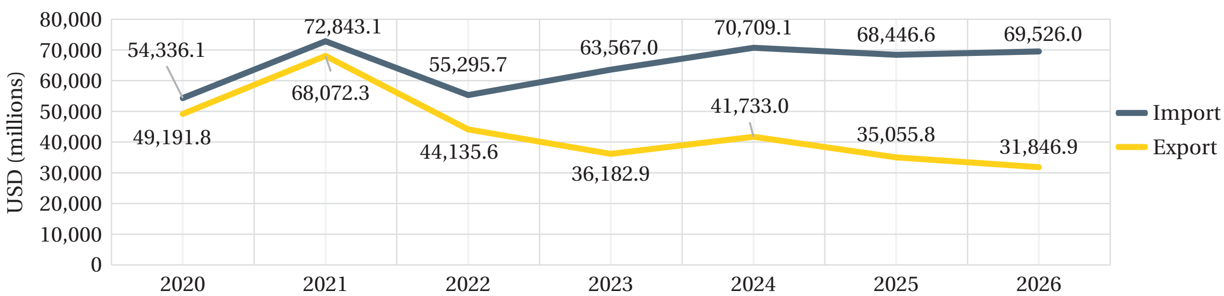

Figure 7. Forecast of Ukraine's trade turnover for 2025-2026

Source: developed by the authors

The results indicate significant fluctuations in export and import volumes and a persistently negative trade balance, which significantly deteriorated between 2022 and 2024. While in 2020-2021, the trade balance remained relatively stable, 2022 witnessed a sharp decline in exports (by 35.2% compared to 2021), leading to an increased deficit of USD -11.16 billion. The situation worsened further in 2023, as exports declined, and the negative balance reached USD -27.38 billion. In 2024, exports partially recovered; imports also increased, further expanding the trade deficit to USD -29.13 billion. The contraction of exports in 2022-2023 was primarily driven by military actions, disruptions in logistics routes, and loss of access to key markets. The slight recovery in 2024 indicates business adaptation and the gradual restoration of economic activity. Despite financial difficulties, the rise in imports during 2023-2024 may be attributed to the necessity of importing critically essential goods, such as energy resources, equipment for production recovery, and military-related supplies. According to the results of the trend analysis, exports are expected to show a declining tendency in 2025-2026, potentially reaching around USD 35.1 billion. Meanwhile, imports are projected to rise, reaching USD 68.4 billion in 2025 and USD 69.5 billion in 2026. This will further exacerbate the trade balance deficit, which is expected to reach USD -33.4 billion in 2025 and USD -37.7 billion in 2026. Despite these challenges, TFA play a key role in economic recovery. Their efficient functioning contributes to maintaining and expanding Ukraine's trade relations with external partners, ensuring the timely delivery of goods and creating new jobs. Given this, it is necessary to implement a series of measures to improve the sector's efficiency. Firstly, priority should be given to restoring transport infrastructure, including reconstructing destroyed facilities and constructing new logistics hubs and freight terminals. Secondly, support for exporters should be provided through state financing programmes for enterprises. Offering long-term preferential loans will enable businesses to invest in expanding production, purchasing equipment, and improving product quality. Thirdly, export diversification is essential through market expansion and enhanced cooperation. Beyond Europe, strengthening trade relations with Asian and Middle Eastern countries is crucial. These regions demonstrate high demand for agricultural products, metallurgy, and engineering goods. Strengthening cooperation with China, India, Saudi Arabia, and Turkey opens up new opportunities for export growth and reduces dependency on European markets. Additionally, the digitalisation of transport and logistics processes is a crucial development direction. This transformation will reduce the time required for processing transport documentation, enhance cargo tracking, and improve overall efficiency in managing material flows. Another key task is the training and retraining of logistics professionals, as a shortage of qualified personnel may hinder the transport sector's growth. Expanding public-private partnerships in transport and logistics is also essential. Cooperation between the state and businesses will help attract additional investments into the transport industry, improve the quality of logistics services, and ensure transport flow stability.

The European Union is developing the Trans-European Transport Network (TEN-T) to connect Europe from west to east and north to south through a network of highways, railways, airports, and waterways. The development of the transport system is planned in two stages: the "core" network is expected to be completed by 2030, while the "comprehensive" network is scheduled for completion by 2050. Ukraine joined TEN-T in 2017. According to Strategy for the EU integration… (2023), projects worth EUR 4.45 billion are planned for implementation in Ukraine by 2030. This represents the most significant investment allocation among all Eastern Partnership countries of the EU. The European Commission for Transport has introduced modifications to the indicative maps of the TEN-T network, incorporating Ukrainian logistics routes. This decision represents a strategic step toward Ukraine's integration into the EU. It will facilitate the implementation of the "Solidarity Lanes" initiative, which aims to support the export of Ukrainian agricultural products and the delivery of humanitarian aid to Ukraine (Hoi *et al.*, 2025). The following changes have been introduced to enhance Ukraine's transportation network: the North-Baltic Corridor has been extended through Lviv and Kyiv to Mariupol, while the Baltic-Black-Aegean Corridor has been expanded through Lviv and Chernivtsi (Romania and Moldova) to Odesa. Furthermore, the Baltic-Adriatic Sea Corridor and the Rhine-Danube Corridor will now pass through Lviv. Additionally, new routes have been designated, including Odesa – Berezyne – Basarabeasca (towards Chișinău and Reni, Republic of Moldova), Zhytomyr – Vinnytsia – Yampil (towards Rîșcani, Republic of Moldova), Chop – Uzhhorod – Sambir – Lviv, and Krasnohrad – Poltava, Krasnohrad – Kharkiv, Krasnohrad – Dnipro. The inclusion of these logistics routes in the TEN-T network brings several significant benefits (Strategy for the EU integration…, 2023). It eliminates existing barriers in logistics operations, improving transportation efficiency and streamlining processes. Additionally, it opens the door for attracting European investments focused on modernising the country's transport infrastructure. Moreover, integration into the TEN-T network grants access to European Union assistance instruments that support the development of Ukraine's segment of the network. It also contributes to the expansion of multimodal transportation capabilities, allowing for more flexible and diversified logistics solutions. Furthermore, this inclusion can lead to a reduction in overall logistics costs while simultaneously improving the quality and reliability of freight transportation services. Additionally, the European Commission has excluded Russian and Belarusian routes from the TEN-T network and downgraded the status of routes within the EU that intersect with these aggressor countries.

The comparison with other publications confirms that the reconstruction of Ukraine's transport infrastructure and the adaptation of logistics systems, including the implementation of European norms, digitalisation, and international partnerships, are crucial for overcoming wartime challenges and ensuring economic recovery (Kiiko, 2024). As emphasised by Y. Korniiko *et al.* (2024), the problems of the transport sector of Ukraine have become more acute as a result of the armed aggression of the Russian Federation. A general assessment of the damage caused to the infrastructure of Ukraine during the war is presented, where the second largest category of damaged assets is precisely the transport infrastructure. It is revealed that despite the existing challenges, there is a positive trend in the restoration of freight traffic volumes and the reconstruction of infrastructure facilities, namely: transshipment complexes, warehouse hubs, car parks, port terminals and private fleets. In the article S. Tkachenko (2024) the role of logistics in the process of post-war economic recovery of Ukraine was investigated, taking into account international experience and the involvement of foreign partners. Strategic directions for the development of logistics infrastructure were identified, which ensure the accelerated recovery of production and trade chains. Modern obstacles and limitations that affect the efficiency of logistics systems in the conditions of reformatting the economic system were considered. Attention was focused on the need to coordinate the actions of state bodies, business and international donors to form an effective supply mechanism, resource allocation and support for the critical infrastructure of the state. The possibilities of implementing foreign logistics approaches and tools in the domestic economy were analysed, taking into account institutional specifics. The conceptual principles of strategic partnership with international structures in the field of logistics were identified in order to strengthen economic stability and ensure the regenerative growth of the national economy of Ukraine. V. Kuranovič *et al.* (2025) stated that the growth of the global freight forwarding market is rapid due to the rapid development of international trade, the expansion of the e-commerce industry worldwide, and the increase in the number of free trade agreements between countries. Enterprises that engage forwarders to organise foreign trade operations in the international trade market can receive a number of advantages in organising cargo delivery and minimising transportation costs. The introduction of information technologies allows forwarders to be prepared for large-scale disruptions and unforeseen risks when organising international freight transportation (Abideen, *et al.*, 2023; Cariou *et al.*, 2025). Even in times of uncertainty, data analytics and automation are becoming the main way to improve the activities of leading freight forwarding companies.

R. Kersys & P.G. Pererva (2025) noted that logistics began to play one of the decisive roles in restoring the economy of Ukraine under martial law. Despite significant losses since the beginning of the war due to such problems as the closure of Ukrainian ports, air traffic, instability of railway transportation, lack of infrastructure and external factors, the Ukrainian transport and logistics system gradually coped with the challenges and began to increase the volume of export-import and domestic supplies. However, a significant part of the logistics infrastructure still needs to be restored and there is a need to accelerate the movement of goods. Therefore, to solve the outlined problems, the spread of digitalisation, which will improve the movement of information and financial flows through the use of reliable technologies and information systems, the restoration of the transport and logistics infrastructure by searching for companies and investors capable of doing this in the shortest possible time, including through privatisation processes, which is no less relevant today than before. Taken together, this will determine the development of logistics in Ukraine in the near future. V. Yanovska *et al.* (2025) and K.M. Prytula *et al.* (2025) examined the transformation of Ukraine's export cargo flows in 2022-2026 amid wartime shocks and structural changes in the transport and logistics system. Authors synthesised theoretical and practical aspects of three key logistics subsystems: the seaports of the Odesa region, the Danube cluster, and land border crossings. The study highlights patterns of flow reorientation during shock periods, institutional turbulence, and the emergence of a new multimodal balance. The trends in sea, rail and road transport rates have been analysed, and their impact on the structure of transport and logistics costs has been assessed. The article further elaborates the mechanism through which changes in logistics costs are transmitted into export price formation under Incoterms (Delivered at Place; Carriage Paid to; Free on Board; Cost, Insurance, and Freight). V. Yanovska *et al.* (2025) also examined how institutional decisions, inspection restrictions, infrastructure congestion, and security risks reshape route configurations. Competitive advantages of alternative export channels are evaluated under capacity constraints and heightened uncertainty. A multicriteria route assessment framework is proposed, incorporating cost, logistics cycle time, reliability, security, and environmental parameters. Finally, key directions for strengthening export logistics resilience are identified based on a multimodal export logistics architecture, and recommendations are offered for transport and technological solutions and infrastructure development under prolonged instability.

Conclusions

The study confirmed that, despite the challenging environment, TFA play a decisive role in sustaining and restoring Ukraine's economy. They help stabilise trade flows, support market diversification, and create conditions for attracting investment into transport and logistics infrastructure. The resilience of foreign trade increasingly depends on the efficiency and adaptability of logistics systems under external shocks. The results indicated a persistent trade deficit (USD 33,390.9 million in 2025 and USD 37,679.1 million in 2026), driven by declining exports and rising imports, largely due to increased demand for energy, machinery, and other essential goods during wartime and recovery. Priority directions for further development should include the modernisation of logistics hubs, deeper integration into the European TEN-T, expansion of multimodal transportation, and comprehensive digitalisation of logistics processes. At the same time, state support for exporters remains essential and should focus on improving access to preferential financing, simplifying customs procedures, and stimulating the development of high-value-added production. Particular attention should also be given to import optimisation through the gradual reduction of dependence on critical goods by strengthening domestic production capacities. In this context, Ukraine's integration into TEN-T opens significant opportunities for removing logistical bottlenecks, enhancing connectivity with European markets, and attracting long-term investment. Overall, the results demonstrate that the future trajectory of Ukraine's foreign trade will largely depend on the effective implementation of TFA-related measures, infrastructure development, and the strategic adaptation of logistics routes to current challenges. The consistent implementation of these priorities will contribute to economic stabilisation, improved competitiveness, and the sustainable long-term development of Ukraine. The econometric modelling of the relationship between logistics costs, supply conditions, and export competitiveness is promising.

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None.

References

[1] Abideen, A.Z., Sorooshian, S., Sundram, V.P.K., & Mohammed, A. (2023). Collaborative insights on horizontal logistics to integrate supply chain planning and transportation logistics planning – a systematic review and thematic mapping. *Journal of Open Innovation: Technology, Market, and Complexity*, 9(2), article number 100066. doi: 10.1016/j.joitmc.2023.100066.

[2] Cariou, P., Jia, H., & Wolff, F.-C. (2025). Price discrimination between freight forwarders and carriers: Evidence from the container shipping industry. *Transport Policy*, 170, 1-11. doi: 10.1016/j.tranpol.2025.05.005.

[3] Gnap, J., Senko, Š., Kostrzewski, M., Brídziková, M., Cződörová, R., & Říha, Z. (2021). Research on the relationship between transport infrastructure and performance in rail and road freight transport – a case study of Japan and selected European countries. *Sustainability*, 13(12), article number 6654. doi: 10.3390/su13126654.

[4] Hoi, N., Zhuk, O., & Nagornyak, M. (2025). The main mechanisms for implementing the state policy of developing rail freight transport in the context of Ukraine's European integration. *Philosophy and Governance*, 7-8(11-12). doi: 10.70651/3041-248X/2025.7-8.08.

[5] Ivanov, Y.V., Nahai, D.R., & Sokhan, T.D. (2025). Logistics in modern conditions of economic development. *Scientific Notes of V.I. Vernadsky Taurida National University. Series: Economics and Management*, 36((75)1), 72-77. doi: 10.32782/2523-4803/75-1-11.

[6] Kersys, R., & Pererva, P.G. (2025). Current trends in the development of logistics in Ukraine. In *Sustainable development: Modern theories and best practices: Materials of the monthly international scientific and practical conference* (pp. 61-65). Tallinn: Teadmus OÜ.

[7] Kiiko, A.I. (2024). Essence and features of transport & forwarding activities of enterprises: Modern aspect. *Herald of Lviv University of Trade and Economics. Economic Sciences*, 79, 106-112. doi: 10.32782/2522-1205-2024-79-14.

[8] Korniiko, Y., Valyavska, N., & Mikheiev, O. (2024). Analysis of the current state of Ukraine's transport industry in the context of freight transportation. *Economics and Society*, 70. doi: 10.32782/2524-0072/2024-70-70.

[9] Kuranovič, V., Ustinovichius, L., Nowak, M., Bazaras, D., & Sokolovskij, E. (2025). Improving the freight transportation system in the context of the country's economic development. *Sustainability*, 17(14), article number 6327. doi: 10.3390/su17146327.

[10] Maliuta, L., Rudan, V., & Balushevskyj, K. (2023). Problems and perspectives of the development of transport logistics in Ukraine under the conditions of martial state. *Economic Analysis*, 33(3), 153-164. doi: 10.35774/econa2023.03.153.

[11] Myskyv, H., & Kladko, A.-I. (2025). International logistics of Ukraine in the context of military aggression. *Economics and Society*, 79. doi: 10.32782/2524-0072/2025-79-107.

[12] Nepran, A. (2025). Statistical analysis of the impact of "terms of trade" on the trade balance of Ukraine. *Bulletin of V.N. Karazin Kharkiv National University Economic Series*, 108, 107-121. doi: 10.26565/2311-2379-2025-108-10.

[13] Prokhorova, V., Kravchenko, O., Shkurenko, O., Babichev, A., & Polivantsev, A. (2025). Study of priority directions of economic recovery of Ukraine based on scenario modelling. *Economics of Development*, 24(1), 26-34. doi: 10.63341/econ/1.2025.26.

[14] Prokudin, G.S., Kapronenko, A.V., Dzuenko, A.O., & Korol, N.P. (2024). Forecasting freight transportation in Ukraine. In *The 9th International scientific and practical conference "Perspectives of contemporary science: Theory and practice"* (pp. 373-379). Lviv: SPC "Sci-conf.com.ua".

[15] Prytula, K.M., Kalat, Y.Y., Tomashyk, L.S., & Kyryk, I.M. (2025). Logistical challenges of realizing Ukraine's export potential in wartime conditions. *Regional Economy*, 117(3), 136-146. doi: 10.36818/1562-0905-2025-3-12.

[16] Razumova, K.M., Novalska, N.I., & Klymenko, V.V. (2023). Features of modern transport forwarding business. *Systems and Technologies*, 65(1), 124-130. doi: 10.32782/2521-6643-2023.1-65.15.
[17] Sanduhei, V., Bila, I., Shevchenko, O., Manzhula, I., & Iliukhina, V. (2025). Human capital as a driver of the formation of Ukraine's competitive advantages in the post-war period. *Scientific Bulletin of the National Mining University*, 1, 157-163. doi: 10.33271/nvngu/2025-1/157.
[18] State Statistics Service of Ukraine. (n.d.a). *Foreign trade in goods by partner country: Archive*. Retrieved from https://ukrstat.gov.ua/operativ/operativ2018/zd/ztt_za_kr_partner/ztt_za_kr_partner_u/Arch_ztt_za_kr_partner_u.htm.
[19] State Statistics Service of Ukraine. (n.d.b). *External trade of goods*. Retrieved from https://stat.gov.ua/en/datasets/external-trade-goods.
[20] Strategy for the EU integration of the Ukrainian and Moldovan rail systems. (2023). Retrieved from https://jaspers.eib.org/files/library/2023/strategy-for-the-eu-integration-of-the-ukrainian-and-moldovan-rail-systems.pdf.
[21] Subačienė, R., Krutova, A., & Nesterenko, O. (2023). Determinants of sustainable development in the post-war recovery of Ukraine. *Economics of Development*, 22(4), 23-33. doi: 10.57111/econ/4.2023.23.
[22] Tkachenko, S. (2024). Post-war recovery of Ukraine's economy: Problems, risks, and solutions. *Economic Horizons*, 2-3(28), 4-13. doi: 10.31499/2616-5236.2(28).2024.300402.
[23] Vesco, P., *et al.* (2025). The impacts of armed conflict on human development: A review of the literature. *World Development*, 187, article number 106806. doi: 10.1016/j.worlddev.2024.106806.
[24] Yanovska, V., Król, M., & Pittman, R. (2025). The logistics of grain exports from wartime Ukraine: What are the highest priority areas to address? *Transportation Research Interdisciplinary Perspectives*, 30, article number 101363. doi: 10.1016/j.trip.2025.101363.

Роль експедиторської діяльності у відновленні економіки України

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Анотація. У статті проведено всебічний аналіз ролі діяльності експедиторських компаній у підтримці економічного відновлення України в умовах повномасштабної війни. Основною метою дослідження було проаналізувати динаміку торгового балансу України та розробити прогноз його розвитку на 2025-2026 роки. Для досягнення цієї мети застосовано методи економіко-математичного моделювання, зокрема різні типи апроксимації трендів, включаючи експоненціальну, лінійну, логарифмічну, поліноміальну та степеневу моделі. Цей методологічний підхід дозволив порівняти різні функціональні залежності та вибирати найбільш підходящі моделі в умовах високої невизначеності. Результати дослідження показали стабільний негативний торговий баланс (-33 390,9 млн дол. у 2025 році та -37 679,1 млн дол. у 2026 році), який характеризується зниженням експорту та одночасним збільшенням імпорту. Такий дисбаланс значною мірою обумовлений зростаючою потребою в енергоресурсах, техніці, обладнанні та інших необхідних товарах для підтримки економіки під час війни та відновлення. Враховуючи ризики, пов’язані з постійним торговим дефіцитом, у статті запропоновано комплекс стратегічних заходів, спрямованих на стабілізацію економічної ситуації. Серед них відновлення та модернізація транспортної інфраструктури, диверсифікація експортних ринків, стимулювання виробництва з високою доданою вартістю, розширення мультимодальних транспортних систем та впровадження цифрових технологій у логістиці. Крім того, дослідження підкреслило стратегічне значення інтеграції України в Trans-European Transport Network та необхідність залучення інвестицій у логістичну інфраструктуру та хаби. Загалом дослідження підтвердило важливу роль ефективних логістичних і транспортних систем у забезпеченні економічної стійкості та зміцненні позицій України на міжнародних ринках. Результати можуть бути використані при розробці національних логістичних стратегій, політики та програм підтримки експортерів

Ключові слова: зовнішня торгівля; логістика; транспортна інфраструктура; TEN-T; експорт; імпорт; торговий баланс; прогнозування

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