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PECULIARITIES OF TRUCK TRANSPORTATION IN WARTIME CONDITIONS

Purpose. To identify the peculiarities and problems of automobile transport (AT) in the war conditions (WC) in Ukraine. To propose ways to solve the mentioned problems, to eliminate reasons that lead to an increase in the risks for AT. To develop a mathematical model for optimization of transportation by AT under unclear military risks.

Methodology. The method of abstract-logical analysis made it possible to establish peculiarities and problems of AT in WC and propose ways to solve these problems, to eliminate the causes that lead to increase in risks of AT. The method of analysis and synthesis is used to determine the circumstances of the narrowing of the influence of institutional approaches on the optimization of AT and to propose a combination of direct and indirect institutional influence. The method of comparative analysis finds that the unevenness of risks on transport routes leads to the imbalance of transportation and proposes measures to reduce the level of imbalance, to approach optimal results as well as proposes the formation of multi-stage transportation, which will ensure the variability of transport chains due to fragmentation and an increase in the level of organization of transport networks. Mathematical methods were applied to develop a model for optimization of AT in WC.

Findings. The key tasks of building a strategy of a highly adaptive transport system were formulated and its peculiarities were indicated. Circumstances of narrowing the influence of institutional approaches to AT in WC were established and a combination of direct and indirect institutional influence was proposed, which will be based on the developed mathematical model. It is established that unevenness of risks on transport routes leads to imbalance of transportation and measures to reduce the imbalance are proposed. The formation of multi-stage transportation is proposed for variability of transport chains, organization of transport networks and ensuring the reliability of AT.

Originality. To take into account risks with a significant level of uncertainty, a strategy for building a highly adaptive transport system was proposed, and a mathematical model for optimization of AT in the presence of uncertain military risks was developed.

Practical values. The peculiarities and problems of AT in the conditions of the war in Ukraine are given. Ways to solve the mentioned problems, to eliminate the causes that lead to increase in risks for AT are proposed.

Keywords: *mathematical modeling, optimization, undefined parameters, road cargo transportation, war conditions*

Introduction. Full-scale hostilities radically changed the cargo transportation system of Ukraine in all its aspects: the structure of cargo, cargo transportation by types of transport, the complex of tasks and problems faced by carriers.

The first thing that led to this was the uneven growth of war risks for the transportation of goods by various modes of transport. In particular, the blockade of sea ports led to an increase in the share of rail and road transport in the total volume of transportation. Further airstrikes on the railway infrastructure led to a decrease in the volume of freight transportation by railway transport, as a result of which the special importance of road transport for the supply of vital goods, first of all to the population of the affected areas, increased.

Road freight transportation continued to be carried out even under the conditions of a lack of vehicles, deterioration of transportation conditions due to the destruction of highways, bridges, infrastructure facilities, the need for rapid reorganization of receptions and methods to ensure the reliability of several strategic tasks at the same time: military cargo, humanitarian cargo, and cargo transportation for economic and social tasks, functioning of state and commercial enterprises of Ukraine in war conditions. But even with the reorganization, nowadays there is inefficient use of resources in the field of road transportation of goods. For example, the average mileage of a freight transport vehicle for cross-border transportation in Ukraine is ~4,000 km per month. For comparison, this indicator for Poland is more than 15,000–17,000 km per month. Only the minimization of queues at the border crossing for trucks will make it possible to reach values of 10,000–12,000 km per month. The average speed of traffic on highways in Ukraine is three times lower than in the countries of the European Union [1], which also reduces the efficiency of freight transportation.

The above indicates that at present the task of optimizing road freight transportation complicated by military actions, increasing the quality of transportation management under the drastic changes in logistics and the dynamic nature of the distribution of supply chains, and the conditions of uneven growth of transportation risks on certain sections of routes is becoming especially important. Solving this problem required both the development of proposals for improving the transportation process and the development of relevant models that could serve in the systems of preparation and maintenance of decisions in the management of road transportation of goods.

Literature review. A number of scientific works are devoted to the problems of logistics during the war. Shults, et al. [1] pointed out the significant uncertainty of logistics processes and named the primary vectors of the development of road freight transportation. Kulakova, et al. [2] pointed to the trends of moving the warehouse infrastructure to the West of Ukraine, even after the liberation of Kyiv Oblast, and the influence of this process on the organization of road transportation of goods. Lysis and others [3] indicated the problem of imbalance in the transportation system. This problem is considered in more detail in the presented article. Lysis and others [3] also indicated the problems of customs checkpoints. Hudimov, et al. [4] investigated the problems of ensuring the continuity of transport operations in conditions of constant destruction of transport infrastructure objects. Ozarko and oth-

ers [5] proposed a "concept of rapid response" to threats and "neutralization of the influence of problem areas on logistics processes in wartime". This approach is developed in the presented article. Optimization of logistics is often based on economic and mathematical models, in particular Lesnikova, et al. [6] presented a two-stage transport problem. Due to the dynamic conditions of military operations and uncertain risks, it is not possible to apply such models. A more rational approach is the model proposed by Kotenko, et al. [7] because dynamic changes in cargo transportation risks are taken into account. But the peculiarities of this model, due to the task of optimizing sea transportation, make it difficult to adapt it for automobile transportation of goods.

Many works have been devoted to the problems of modeling freight road transport under risk conditions. This is evidenced, for example, by the review work of Tubis [8], the conclusions of which are that modeling should not "focus on the business goals of companies", but should also consider other target functions and move to multi-objective models. Such an approach based on risk analysis was proposed by Shevchenko, et al. [9]. The mathematical model developed by them is based on the analysis of the distribution function of transportation parameters and random risk variables. Unfortunately, due to the significant uncertainties of the war and the dynamics of changes in transportation risks, the use of this model during military operations is limited on the territory of the country. The model developed by Waller, et al. [10] makes it possible to determine the distribution of road transport network traffic using statistical methods developed by other scientists for estimating the variability of transportation time and choosing a route based on reliability estimates. Unfortunately, the specified model does not take into account the significant level of uncertainty of the main parameters in wartime conditions.

A significant number of scientific articles are devoted to the search for optimal solutions for ensuring cargo transportation by road transport. Thus, in the article by Oglih, et al. [11] it is proposed to use a mathematical tool based on the "matrix of decisions" and expert assessments of the main parameters for the implementation of effective decisions regarding road transportation of goods under conditions of uncertainty. The proposed approach will be effective for a specific enterprise under stable conditions. Under highly dynamic conditions, the ability of this toolkit to ensure adequate reliability of results is questionable. Juman and Nawarathne [12] compare different cost minimization methods in road freight transportation using an iterative approach. The advantages and disadvantages of the methods compared with those under changes in external conditions are indicated. Khalipova, et al. [13] proposed a cluster approach – one of the neural network algorithms for modeling transport and logistics networks of enterprises. This approach is useful, but under the dynamic conditions of the war, the possibility of its implementation on a large scale is doubtful, how quickly everything changes in road transportation today – routes, types of cargo, their industry affiliation, etc., which will significantly lengthen the time of data preparation for this model.

In general, the review of the literature showed that with a significant number of methods and mathematical models for the optimization of road transportation, their use in war conditions is limited due to the significant dynamics of transportation conditions, the variability of cargo transportation risks, and the uncertainty of parameters.

Purpose. To identify the peculiarities and problems of truck transportation in the conditions of war in Ukraine. To propose ways to solve the mentioned problems, to eliminate the reasons that lead to an increase in the risks for truck transportation. To develop a mathematical model for the optimization of transportation by road transport under unclear military risks.

Methods. General and special cognitive methods were used to obtain research results.

The implementation of the method of abstract logical analysis made it possible to identify the peculiarities and problems of truck transportation in the war in Ukraine and to propose ways to solve the mentioned problems, to eliminate the reasons that lead to an increase in the risks of truck transportation.

The method of analysis and synthesis made it possible to establish the circumstances of the narrowing of the influence of institutional approaches on the optimization of road freight transportation in times of war and to propose a way with the introduction of a combination of direct and indirect institutional influence, which will be based on the proposed mathematical model.

The method of comparative analysis is to establish that the uneven growth of risks on transportation routes leads to an imbalance of transportation and to propose measures both to reduce the imbalance, approach optimal values, and neutralize risks differentiated by transportation zones. The method of comparative analysis also made it possible to propose the formation of options for multi-stage transportation, which will ensure the variability of transport chains due to fragmentation and increase the level of organization of transport networks. This approach will also increase the reliability of cargo transportation.

Mathematical methods have been applied to develop a model for the optimization of road transport in the conditions of wartime (military) risks.

Results. First of all, the concept of "wartime (military) risks" needs to be defined. The concept of wartime (military) risks has entered the practice of economic activity of Ukrainian enterprises. Thus, insurance companies identify wartime (military) risks as category D insurance and refer to them the risks of loss/damage of motor vehicles, loss/damage of cargo, harm to health or death of employees of motor vehicle enterprises as a result of military operations [14]. But the military risks of road freight transportation are not limited to insurable events. Therefore, the following definition is proposed. Military risks of road freight transportation are primary threats of loss/damage of vehicles, loss/damage of cargo, injury to health or death of employees of motor vehicle enterprises as a result of military operations and secondary risks due to the indirect impact of primary threats on the activities of enterprises, for example, increased time and expenditure of resources for transportation, increased risks of accidents of vehicles on bypass roads due to the deteriorated state of their covering, etc.

During the full-scale war, the share of road transport in the total volume of transport services increased significantly, primarily due to the blockade of seaports, increased bombing and missile damage to railway and river transport hubs, the need in wartime to carry out transports, the implementation of which is extremely difficult by other types of transport, or at all, impossible, in particular, due to the destruction of railway tracks, or a dynamic change of destinations, for example, due to their destruction, already in the process of transportation. This is confirmed by the data [15] on the results of the transport industry in 2022, according to which in monetary terms, export deliveries were: road transport – $1,123 million, railway – $677 million, water – $435 million. In commodity terms, by road transport – 1.1 million tons, by rail – 2.8 million tons, by water – 435 million tons. Import deliveries in monetary terms were: by road transport – $3,275 million, by rail – $517 million, by water – $332 million. Import deliveries in commodity terms by road transport – 1.11 million tons, by rail – 0.5 million tons, by water – 0.3 million tons. This testifies both to the increase in the significance of the automobile mode of transport, especially for ensuring the transportation of imports, and to the diversification of commodity flows by the nomenclature of goods – more valuable and, therefore, more important goods were transported by automobile transport.

Road transportation in the structure of exports in terms of monetary value by the end of 2022 accounted for 49 %, and at the same time, rail transportation accounted for 29 %, and transportation by water transport – 19 %. In the structure of imports in monetary terms, automobile transportation ac-

counted for 74 %, rail transportation accounted for 12 %, and water transportation accounted for 8 %. The data indicate an increase in the importance of road transport for the country's economy and defense during the war.

This also led to increasing needs for rolling stock, caused the need to change the structure of motor vehicles in terms of carrying capacity, in particular, led to an increase in the share of heavy vehicles, overloading of motor vehicles due to their shortage when entering routes. This resulted in an increase in the destruction of the road surface, that is, the deterioration of transportation conditions.

This problem was significantly related to the beginning of full-scale actions, because at that time foreign logistics companies completely suspended their activities in Ukraine. That is why the delivery of even goods critical for ensuring the livelihood of citizens, humanitarian goods, was carried out with a long delay.

The conditions of the war exacerbated the troubles characteristic of road transport before the start of the war: the lack of qualified personnel, the problems of planning and organization of transport under dynamically changing conditions. A significant disproportion was felt in the structure of vehicles – Ukraine lacked means of transportation that would meet Euro-5 and Euro-6 standards, specialized vehicles for transporting fuel, etc. The negative effects of the war on the number of qualified drivers were also revealed, both through conscription into the ranks of the Armed Forces of Ukraine, and through the outflow of personnel to transport companies of other countries, primarily Poland, due to the reluctance of individual drivers to run routes to dangerous regions.

The road network already in pre-war times as well as its condition (road wear was 90 % [16]) did not meet the tasks of economic development and defense of the country.

The structure of Ukraine's highways by coverage (Fig. 1) also indicates the inability to ensure the proper efficiency of transportation. Only 165,800 km of Ukrainian roads is paved. Overloading of motor vehicles in the conditions of war quickly destroys roads, which reduces the efficiency of their movement, and increases the risks for transport and cargo.

Institutional decisions of 2019–2020 regarding the solution to the problem of road surface, construction of new roads, introduction of mechanisms for adapting road transport to the conditions of local military operations on the territory of Ukraine, as indicated by the full-scale war, were insufficient.

Under conditions of the war, the structure of cargo in road transport changed significantly. So, if in 2020 the first place was occupied by the service of the extractive industry (33 % of the total volume of cargo), followed by the agricultural sector (14 % of the total volume of cargo) and the food industry (13 %), then due to the destruction of Ukrainian consumers of mining products, the occupation of the territories where mining enterprises are located and the obstruction of the export of agricultural products by sea transport, the first place in road transport, except for military cargo, for which the statistics are closed, was occupied by agricultural and food products.

This, in turn, led to an increase in the directions of road transport and the spread of the geography of transport in one vehicle trip ("door to door"), which also led to an increase in the use by freight transport of those roads on which traffic was previously insignificant and, accordingly, until the wear of their coating. By the beginning of 2023, the aggressor had damaged 25,000 km of paved highways and 315 bridges [16]. Together, this led to the need for a flexible response of the management of the automobile type of freight transportation to the choice and dynamic change of transportation routes.

The formation of traffic jams at border checkpoints with the beginning of large-scale military operations also required considerable flexibility. The length of car queues at the border crossing, even after the first shock period, sometimes exceeds ten kilometers.

The introduction of institutional measures after the start of full-scale hostilities, first of all, the adoption of the Agreement between Ukraine and the EU on freight transportation by road, simplification of obtaining a carrier's license, overcoming fuel shortages, reduction of customs procedures, introduction of "preferential" shipments to some extent simplified cross-border road transportation. In particular, the use of the eQueue mechanism contributed to the dynamic redistribution of traffic flows between border checkpoints. But, as can be seen from Fig. 2 [17], these measures did not lead to a radical solution to the problem, but increased the troubles, for example, provoked the overloading of vehicles. As can be seen from Fig. 2, there is an increase in the number of border crossings in 2022 relative to the index of 2020–2021, but this increase only in some checkpoints reached the value of 2018–2019, which does not solve the problem.

This leads not only to loss of time and resources, inefficient use of vehicles, but also to increased risks. This requires the adoption of appropriate institutional decisions, both regarding the reorganization of the pass procedure and the increase in the number of specified points. Also, as the data presented in the Table show, this leads to an increase in the cost of transporting goods by highways, the impact of secondary military risks on this indicator is much greater than in the border regions of the European Union countries [18].

During the war, the location, working hours, and even the presence of senders and receivers of goods: warehouses, enterprises, distributors are changing dynamically. Before the active phase of hostilities, the indicator of the use of transport in the logistics process reached 90 %, and by the end of 2022 this indicator was ~30 %. This determines the need to ensure the flexibility and efficiency of management decision-making. The condition for the implementation of the stated thesis is the formation of a highly adaptive system of road freight transportation and, for this, the implementation of an information system that provides feedback to ensure the reliability of the transport process. Therefore, the implementation of the proposed mathematical model can contribute to the fulfillment of the specified task.

During the war, road transport increased the geographical area of movement of material flows and the number of directions of cargo transportation, the radius of cargo transportation by road transport increased significantly. So, if before the start

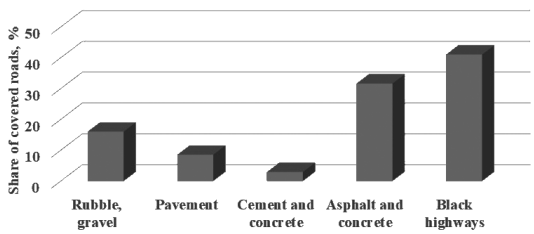

Fig. 1. Structure of roads 2019–2020 by coverage, %

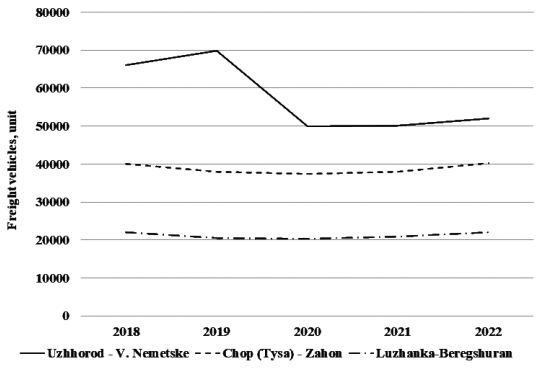

Fig. 2. The number of freight vehicles that crossed the border at border checkpoints, units

Table

An increase in the cost of transporting goods by highways due to the impact of risks

Risk factor	Heavy Trucks Cost (US $) per Vehicle, km	
	EU countries	Ukraine
Traffic jams	0.0005	0.02
Accidents	0.0750	0.10
Road surface	0.0135	0.10

of the large-scale aggression this radius was ~400 km, after the start of the large-scale aggression – more than 1,000 km.

Also, changing the "centers of gravity" of road freight transportation became a significant problem. For example, before the beginning of the large-scale aggression, the largest hub of ~70–80 % of warehouse space (1,800–2,200 thousand square meters) was located in Kyiv region. The destruction of ~400,000 square meters of warehouse space near Kyiv, which is ~20 % of the area of all professional high-tech warehouses in Ukraine, had a significant negative impact.

After the start of large-scale aggression, companies were forced to change the location of warehouses. Warehouses were relocated to the western regions of Ukraine. Warehouse leftovers and goods were also moved. But at the new location, it was not possible to fully develop a professional warehouse infrastructure, carry out IT integration, install security systems, etc.

Under such conditions, it was impossible to wait for the restoration of the full efficiency of loading and unloading operations, warehouse logistics, etc. This had a corresponding effect on the speed of the transport process and its efficiency. After the liberation of Kyiv region, the process of returning logistics began. But the pace of this process still is not significant. There is a change in locational preferences for the southern areas of Kyiv region and the South-Western region of Ukraine. This dynamically and radically changes the transport process.

The war also revealed significant systemic deficiencies in the field of road freight transportation, which significantly increased under the conditions of high-intensity military operations, in particular: a shortage of transit storage facilities; the lack of transport hubs is aggravated by changes in priorities in transport routes; significant variability in the importance of transporting individual cargoes; dynamic changes in the level of risks and the level of damage to roads and infrastructure.

Centralized institutional approaches to the optimization of road freight transportation are complicated by the following circumstances. Road transportation of goods was carried out by a large number of commercial carriers before the start of full-scale hostilities. These were mostly small and medium-sized companies. Thus, the functioning of ~74 % of carrier companies was implemented by teams whose number did not exceed nine employees, ~95 % of carrier companies had an annual turnover that did not exceed €1000 thousand. The vehicle fleet of these companies consisted of ~70 % of cars whose carrying capacity did not exceed 10 tons, and 75 % of the vehicles had a service life of more than ten years [1]. According to expert assessments, a significant share of the cargo transportation market was carried out in a shadowy manner. The result was low transportation efficiency.

The way to optimize in these conditions is to introduce a combination of direct and indirect institutional influence. Direct influence is realized through the use of regulatory, tax and other institutional tools. Examples of its effective use include: simplifying the procedure for obtaining a driver's license (Resolution of the Cabinet of Ministers of Ukraine (hereinafter – the CMU) No. 584-2022-p); simplification of vehicle registration (CMU Resolutions Nos. 1019 and 1299); licensing of the transportation of dangerous goods by road transport during the period of martial law (CMU Resolution No. 297); permission for drivers whose driver's license is issued for the first time and expires, to continue driving vehicles (CMU Resolution No. 360), etc.

At the same time, the impact of direct institutional measures on road transport is felt with a time lag greater than the impact of other factors, especially during wartime. This narrows the use of direct centralized institutional approaches to optimize road freight transport.

Indirect influence allows other adaptation mechanisms to be implemented, and its implementation is recommended for the use of an information system for preparation and decision-making diversified by the tasks of freight transportation, which will be based on the proposed mathematical model. The aforementioned diversification of freight transportation tasks consists in separating military transportation and cargo of state importance, humanitarian cargo and transportation that ensure the activity of commercial organizations and the functioning of the country's economy as a whole. Diversification is a forced step in view of the need to implement measures to hide cargo transportation data from the aggressor, as the level of access to information will be variable based on cargo transportation tasks.

The uneven growth of direct and indirect military risks on transport routes leads to the imbalance of transportation, which, in particular, can cause additional changes in routes in real time, local excess or lack of warehouse capacity, etc. These are additional secondary risks of the transport process. The imbalance of transportation makes it impossible to achieve an optimal result a priori. Therefore, measures to eliminate the imbalance contribute to getting closer to optimal results.

The above said leads to the need to introduce a distributed system of transit and auxiliary warehouses, formed as terminal-warehouse complexes, for processing and temporary storage of goods, a network of logistics hubs of different capacity.

It is also proposed to implement the formation of options for multi-stage transportation, which will ensure the variability of transport chains in the conditions of fragmentation and increase in the level of organization of transport networks. This approach will also increase the reliability of transportation, which is especially important for providing enterprises of a stable production nature with raw materials and components.

A solution to the problem of insurance of vehicles, cargo, and drivers under wartime conditions would significantly improve transportation conditions and the personnel situation in the field of road transport. Today, insurance companies terminate the validity of insurance contracts at a certain distance from the war zone, some foreign insurance companies consider the entire territory of Ukraine to be a zone of unacceptable risks. In this matter, road transport in areas of excessive risks needs state insurance support.

Cross-border transportation has a significant amount of restrictions under the legislation of the European Union, in particular, according to: "European Agreement on International Road Transportation of Dangerous Goods", which Ukraine joined on March 2, 2000; "Agreement on the international transportation of perishable food products and on special means of transport intended for these transportations", the competent authority for the implementation of which was approved by the Cabinet of Ministers of Ukraine on 24.10.2007; TIR Convention, etc. Certain problems also arise in connection with the need to comply with certain clauses of the "Mobility Package" in the EU, in particular with the "Conditions of access to the carrier profession and the market of international road transport" and "Rules for the posting of drivers in international transport". These restrictions should be adjusted at the interstate level to increase the efficiency of transportation in connection with military operations on the territory of Ukraine.

In general, the following can be attributed to the peculiarities and problems of truck transportation in the conditions of war in Ukraine:

- significant changes in the areas of senders and receivers of goods (in particular, due to the relocation of enterprises, migration processes in the country, etc.);
- insufficient provision of the transportation process with rolling stock and qualified personnel, loss of vehicles and personnel as a result of missile and bomb attacks;
- differentiation of needs for drivers and vehicles by routes, increase in the level of their shortage when the location of senders and receivers of goods approaches the war zone;
- change in "centers of gravity" of road freight transportation;
- permanent instability of the road freight transportation process, which causes the uncertainty of cargo delivery reliability;
- significant complication of transport logistics due to the destruction of a part of logistics centers and the need to bypass dangerous sections of routes;
- growth of the average radius of road freight transportation;
- increase in the share of transportation with overloads and empty return mileage of motor vehicles;
- growth of insurance premiums due to military risks;
- the need for a significant change in the client base;
- difficulties with the provision of spare parts, a significant increase in the cost of resources and services, in particular, an increase in costs for maintenance and current repairs of vehicles, fuel, lubricants;
- increasing expectations of salary increase for personnel of transport enterprises due to inflation;
- significantly increasing queues at border crossing points;
- significant increase in the price of credit resources;
- a need to increase the accumulation of goods in transit warehouses to ensure an uninterrupted transport process, which leads to an increase in the volume of frozen working capital and the risk of missile and bomb damage.

These factors significantly complicated truck transportation. The market reacted to this, first of all, with a significant increase in tariffs for cargo transportation [22]. Compared to 2021, tariffs increased by 2.5–3.0 in dollar terms, and at the end of 2022, the cost of transporting one ton of cargo by road transport was $1,088, while the tariff for rail transport was $260 per ton, by water – $344 per ton. The difference in tariffs is also an indication of the demand for road transport services. But the possibility of increasing the efficiency of the transport process only by increasing tariffs is not unlimited and requires the development of a mathematical model.

Using a strategy of building a highly adaptive supply system can help to take into account risks under a significant level of uncertainty. The peculiarity of the implementation of this strategy should be a high level of information integration of senders, receivers of goods and a set of information mechanisms for the implementation of transport processes and dynamic variable supply chains. The key tasks are:
- maximum integration between the main parties of this supply system, in particular in software tools and databases;
- prompt response to challenges and threats;
- forecasting, planning, changes in routes, supply chains should be carried out taking into account the general trends of changes in risks. In particular, forecasting requires an assessment of how operationally selected logistics schemes are able to respond to changes in the supply of goods. In the time before the start of the active phase of hostilities, the inertia of logistics with a ~30 % change in the range of goods amounted to ~40 days. This needs to be taken into account in the mathematical model.

Optimization of road transport should be based on effective coordination between the subjects of the transport process, including institutional structures. The proposed mathematical model is aimed at realizing this problem.

The construction of a mathematical model for the optimization of road transportation in war conditions is significantly complicated by the significant uncertainty of risks, the dynamics of their changes, and the significant variability of the risks of cargo transportation [19, 20]. This requires the expansion of the traditional subject area of the transport problem.

The uncertainty of military threats, for example, air-bombing strikes, is that the specific meaning of the time, the target, the number of attacking means, their power before striking the carriers is unknown. After the vehicle leaves the point of departure, the level of risks for each of the possible route options is also uncertain, as this level can change dynamically [21]. Undefined risks are also present in all important objects of transport infrastructure on transportation routes. The uncertainty of military threats, in particular, increases significantly when approaching the combat zone, therefore the zoning of cargo delivery points in the territories close to this zone is due to a significant differentiation of risks on road transport routes.

Therefore, let us consider this problem as a problem of optimizing the division of sets of transport routes that connect sets of senders and receivers of goods under conditions of uncertainty. Let the finite set of senders N, differentiated by the nomenclature of goods, be located in points τ_i, where $i = 1, 2, 3, ..., N$, that belong to the region ω. For cargo receivers in the amount of x_j ($j = 1, 2, 3, ..., M$) there is a need for cargo, which is given by the function $\rho_j = \rho(n, \vec{V}_{kj})$, where n is the nomenclature of cargo, $k = 1, 2, 3, ..., n$ is the index of the nomenclature, $\vec{V}_{kj}$ is the vector of volumes of the needs of the j^{th} consumer for each item of the nomenclature.

The set of cargo recipients M can be divided into transportation zones from each of the N senders in such a way that

$$\bigcup_{i=1}^{N} \omega_i = \omega, \quad mes\, \omega_{ik} \cap \omega_{jk} = 0,$$

where *mes* is Liebig's measure.

Then the volumes of transportation of each item from the cargo nomenclature

$$V_k = \int_{\omega_i}^{k} \rho(x)dx \le \int_{t_1}^{t_2} b_{jk}dt,$$

where b_{jk} is the rate of consumption by the j^{th} consumer of the k^{th} type of product nomenclature during time $t = t_2 - t_1$.

This makes it possible to estimate the volume of transportation and the number of freight vehicles by zones of both delivery and receipt of goods. The next step is to determine the transportation routes that connect these zones. Route optimization takes place by minimizing the vague risks of transportation a_{ij}, in particular, primary risks for bridges, pontoon crossings, logistics centers, border crossing points, population centers on the road and secondary risks of accidents due to the condition of bypass roads, etc.

Risk assessment is carried out based on warnings issued by the Air Force of the Armed Forces of Ukraine about the directions of movement of groups of missiles, their composition, "red" areas along the transportation routes, statistics of strikes already carried out on transport infrastructure objects on the route, general tactics of the aggressor's latest strikes, etc.

Taking into account the transportation risks described by the function $c_{ij} = c(\tau_i, x_j)$, where τ_i is the route option, the optimization problem will be solved as

$$\vec{\varphi}^{\pm 1} = \varphi\left[\int_{t_1}^{t_2}\left\{\int_{\omega_i}^{k}\left\{\frac{\rho(x)}{c(\tau_i, x_j)}\right\}dx\right\}dt\right] \to opt.$$

Depending on the user's selection of the optimization function ($\vec{\varphi}$) and the optimization goals, the specified problem will be realized as a problem of its minimization or maximization.

The conditions of the war also forced a radical revision of the objective functions of cargo transportation. In peacetime,

the objective functions for the optimization of transportation were chosen according to the principle of the "short arm" of transportation. A shorter distance of transportation results in lower costs of time for transportation, less consumption of resources – fuel, transport maintenance costs, labor costs for drivers, which, accordingly, reduces the cost of transportation.

In the conditions of war, the main objective function of an economic nature is the minimization of the risks of transportation, because the integral risk of transportation is directly proportional to the probability of loss of both the cargo and the means of transportation, and possibly the loss of human lives. Reducing the time and cost of transportation become functions of the second order.

To formalize fuzzy risks, the functional dependence of the output of each fuzzy risk a_{ij} on z inputs is considered according to the identification sample

$$a_{ij} = a(\beta_1, \beta_2, \beta_3, ..., \beta_z).$$

During the step-by-step structural and parametric identification [16], the membership function (μ_{D_h}) for the class D_h, where h is the output class identifier for all rules of this class $p_{hj}(\beta_1, \beta_2, \beta_3, ..., \beta_z)$, where the index of the rule $w = 1, 2, 3, ..., s_h$, and s_h is the number of rules in class h. Then

$$\mu_{D_h}(a_{ij}) = \sum_{w=1}^{s_h} p_{hj} \quad \text{if} \quad \left(\sum_{w=1}^{s_h} p_{hj}\right) \le 11 \quad \text{if} \quad \left(\sum_{w=1}^{s_h} p_{hj}\right) > 1,$$

where the bell-shaped membership function is calculated as

$$\mu_{zjk}(\beta_z) = \left[1 + \left(\frac{\beta_z - v_{zjk}}{\theta_{v_{zjk}}}\right)^2\right]^{-1},$$

where $\theta_{v_{zjk}}$ is the concentration coefficient of the membership function; v_{zjk} is the coordinate of the maximum of the bell function.

As it is known, during the phase of fuzzification during structural identification [23, 24], for each class D_h its center of gravity $d_h \in D_h$ is determined, and then a clear determination of the factor at the phase of defuzzification can occur when using the method of gravity according to the following formula

$$a_{ij} = \frac{\sum_{h=1}^{l} d_h \mu_{D_h}(a_{ij})}{\sum_{h=1}^{l} \mu_{D_h}(a_{ij})}.$$

By determining unclear factors, the task of minimizing transportation risks will be solved by standard methods. For this, the additive principle of forming the function $c_{ij} = c(\tau_i, x_j)$ can be used taking into account the weight of each individual risk A_i on the risk route. The level of danger of road transport is increased by the fact that during the war the share of dangerous goods (explosives, fuel) in the total volume of transport services increases significantly and by the fact that warehouses, transport junctions, traffic congestion become priority targets for the aggressor, therefore a possible approach to the definition is method of expert evaluations. Then

$$c_{ij} = \sum_{i=1}^{M} A_i a_{ij},$$

and further

$$c_{ij} \to \min.$$

The method of dynamic minimization of the c_{ij} function can be not only changing the route during its execution to a less risky option, but also differentiating the implementation of transportation in time by zone (increasing risks in the zone – dynamic reorientation of transportation to other zones).

Thus, the model provides an opportunity to optimize transportation in the presence of unclear risks, first of all, risks of a military nature, which are significantly greater than the risks of road transportation, characteristic of peacetime, due to an increase in the level of uncertainty during war.

If, for example, the cost of transportation is chosen as $\vec{\varphi}$ for the stochastic representation of the function c_{ij}, then

$$\vec{\varphi}^{-1} = \int_{t_1}^{t_2} \left\{ \int_{\omega_i}^{k} \left\{ \frac{\left[\frac{\rho(x)}{\gamma}\right] L_i}{\left[1 + c(\tau_i, x_j)\right]^{-1}} \right\} dx \right\} dt \to \min,$$

where γ is the carrying capacity of the vehicle; L_i is the length of route options.

The presented model is variable to the change of the objective functions of the optimization of road transportation under war risks and, if necessary, will be implemented as the task of minimizing or maximizing the chosen optimization goal, which is shown in the example below of minimizing the cost of transportation-by-transportation options under dynamic risks.

The impact of military threats and the level of uncertainty of transportation risks can be significantly reduced. Thus, the level of threat due to strikes on border checkpoints can be reduced by increasing the capacity of transport corridors and their infrastructure, multimodal terminals, border checkpoints, etc.; optimization of the location and operation of cargo customs complexes; improving the interaction of different types of transport, especially on the western borders of Ukraine. The level of threat due to the formation of traffic queues due to attacks on infrastructure can be significantly reduced by accelerating the elimination of damage to highways and transport infrastructure, improving the organization and monitoring of logistics flows; formation of an information system for notifying carriers about changes in the operational situation on transport routes, first of all, regarding the increase in the risks of transporting goods and the time when traffic is impossible in certain areas.

This makes it possible to recommend the following measures:

- coordination of business processes of automotive companies, primarily small and medium-sized ones, and logistics service providers;
- implementation of real-time information support for clarifying the conditions of transportation – the so-called "incoterms", which determine the need to change the cost of transportation and review the cost of goods, which significantly affects the transportation process;
- ensuring the diversification of road transport routes;
- introduction of a joint information platform of Ukrainian and European carrier companies for prompt solution of issues of changing transportation routes, supply of components for vehicles, performance of repair work, etc.;
- introduction of coordinated tactical and strategic planning of production activities of manufacturing enterprises and enterprises transporting commodity products, first of all, ensuring joint forecasting of supply chain irregularity, which requires new approaches to inventory management: construction of transport cycles, planning of commodity lot sizes, etc.;
- reconstruction of destroyed logistics hubs and formation of new ones, distribution of transit warehouses and formation of reserve ones in accordance with the risks of destruction;
- diversification of the goals of reconstruction of the transport infrastructure according to the zones of transport operations: restoration of the functioning of transport routes to meet the urgent needs of territories close to the combat zone; restoration of partial damage, ensuring the uninterrupted transportation of goods for regions far from the combat zone and their prompt clarification during the further liberation of Ukrainian territory.

Conclusions. The definition of the concept of "wartime (military) risks" was provided, which made it possible to form the methodological basis of the study. It is indicated that the conditions of the war intensified the troubles characteristic of road transport before the start of full-scale hostilities. For example,

the need for qualified drivers has increased by leaps and bounds both due to conscription into the ranks of the Armed Forces of Ukraine and due to the outflow of personnel to transport companies of other countries. It was significantly complicated by the fact that the pace of the process of restoring roads and road infrastructure, which began before full-scale hostilities, was far from necessary, given the state of roads and infrastructure. It is indicated that large-scale military operations and the destruction of transport infrastructure led to an increase in the share of road transport in the total volume of transport. This also led to increased needs for rolling stock, caused the need to change the structure of motor vehicles in terms of carrying capacity, in particular, resulted in an increase in the share of heavy vehicles, overloading of motor vehicles due to their shortage when entering routes. This led to an increase in the rate of destruction of the road surface, i.e. a deterioration in transportation conditions.

It is indicated that the formation of traffic jams at border checkpoints with the beginning of large-scale military operations also required considerable flexibility. It is noted that the measures involved did not lead to a radical solution to the problem, but intensified the troubles, for example, they provoked the overloading of vehicles. The increase in the number of border crossings by freight vehicles only at some checkpoints in 2022 reached the value of 2018–2019.

The peculiarities and problems of truck transportation in the conditions of war in Ukraine are given. Ways to solve the mentioned problems, to eliminate the reasons that lead to an increase in the risks for truck transportation were proposed. The peculiarity of the implementation of this strategy should be a high level of information integration of senders, receivers of goods and a set of information mechanisms for the implementation of transport processes and dynamic variable supply chains. The key tasks of this strategy are formulated.

It is indicated that forecasting, planning, changes in routes, and supply chains should be carried out taking into account the general trends of changes in risks. In particular, forecasting requires an assessment of how operationally selected logistics schemes are able to respond to changes in the supply of goods. Since before the start of the active phase of hostilities, the inertia of logistics when ~30 % changing the range of goods amounted to ~40 days, this needs to be taken into account in the mathematical model. It is indicated that the optimization of road transport should be based on effective information provision of coordination between subjects of the transport process, including institutional structures. The proposed mathematical model is aimed at realizing this problem. In order to take into account the dynamics of changes in parameters, the growth of their uncertainty in the conditions of war, the apparatus of set theory was used in the development of a mathematical model. The problem was considered as optimization of the division of sets of transport routes that connect sets of senders and receivers of goods under conditions of uncertainty and risks. For the formalization of fuzzy parameters, the functional dependence of the output of each fuzzy parameter on the inputs by sampling was considered and structural and parametric identification was carried out step by step. To clearly define the parameter at the stage of defuzzification, the gravity method was used. As a result, the model provides an opportunity to optimize transportation in the presence of risks, first of all, risks of a military nature, which are significantly greater than the risks of road transportation, typical of peacetime, and uncertain parameters. The conditions of the war also forced a radical revision of the objective functions of cargo transportation. In the conditions of war, the main objective function of an economic nature becomes the minimization of the risks of transportation, because the risk of transportation is directly proportional to the probability of the loss of the cargo, the means of transportation, and, possibly, the loss of human lives. Reducing the time and cost of transportation is becoming a function of the second order. The change in the significance of the objective functions of the optimization of road transport in the conditions of war risks is taken into account in the proposed mathematical model. The circumstances of the narrowing of the influence of institutional approaches to the optimization of road freight transportation are indicated, since it takes much more time to obtain the result of the implementation of institutional measures than the influence of other factors during the war allows. Therefore, a combination of direct and indirect institutional influence is proposed as a way of optimization. It is indicated that mediated regulatory influence forms mechanisms of adaptation to rapid changes in conditions. Indirect regulatory influence is recommended to be implemented through the use of an information system for preparation and decision-making diversified by the tasks of freight transportation, which will be based on the proposed mathematical model. It is noted that the uneven growth of risks on transport routes leads to an imbalance in transportation, which, in particular, can cause dynamic changes in routes, local overcapacity of warehouses, etc. This made it necessary to offer a distributed system of transit and auxiliary warehouses, formed as terminal-warehouse complexes, for processing and temporary storage of goods and a network of logistics hubs of different throughput. It is also proposed to implement the formation of options for multi-stage transportation, which will ensure the variability of transport chains due to fragmentation and increase the level of organization of transport networks. This approach will also increase the reliability of transportation, which is especially important for providing raw materials and components to enterprises with a stable production nature.

Measures to increase the efficiency of road transport, ensure their optimal functioning, taking into account the needs of the country's economy and defense are proposed.

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Особливості вантажних автоперевезень в умовах війни

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Мета. Виявити особливості та проблеми вантажних автоперевезень (ВА) в умовах війни (УВ) в Україні. Запропонувати шляхи вирішення названих проблем, усунення причин, що призводять до збільшення ризиків для ВА. Розробити математичну модель оптимізації перевезень ВА за нечітких військових ризиків.

Методика. Метод абстрактно-логічного аналізу дозволив встановити особливості і проблеми ВА за УВ в Україні й запропонувати шляхи вирішення названих проблем, усунення причин, що призводять до збільшення ризиків ВА. Метод аналізу й синтезу – встановити обставини звуження впливу інституційних підходів на оптимізацію ВА і запропонувати комбінацію прямого та опосередкованого інституційного впливу. Метод порівняльного аналізу – встановити, що нерівномірність ризиків на транспортних маршрутах призводить до незбалансованості перевезень і запропонувати заходи зменшення рівня незбалансованості, наближення до оптимальних результатів. Метод порівняльного аналізу – запропонувати формування багатоетапних перевезень, що забезпечить варіабельність транспортних ланцюгів за фрагментації та збільшення рівня впорядкування транспортних мереж. Це також дозволить збільшити надійність перевезення вантажів. Математичні методи – для розроблення моделі оптимізації автомобільних перевезень в умовах війни.

Результати. Сформульовані ключові задачі стратегії побудови високо адаптивної транспортної системи й вказані її особливості. Установлені обставини звуження впливу інституційних підходів до ВА в УВ і запропонована комбінація прямого та опосередкованого інституційного впливу, що спиратимуться на розроблену математичну модель. Установлено, що нерівномірність ризиків на транспортних маршрутах призводить до незбалансованості перевезень і запропоновані заходи її зменшення. Запропоновано формування багатоетапних перевезень для варіабельності транспортних ланцюгів, упорядкування транспортних мереж і забезпечення надійності ВА.

Наукова новизна. Для врахування ризиків за значного рівня невизначеності запропонована стратегія побудови високо адаптивної транспортної системи та, як її складова, розроблена математична модель для оптимізації ВА за наявності невизначених воєнних ризиків.

Практична значимість. Наведені особливості та проблеми ВА в умовах війни в Україні. Запропоновані шляхи вирішення названих проблем, усунення причин, що призводять до збільшення ризиків для ВА.

Ключові слова: *математичне моделювання, оптимізація, невизначені параметри, автоперевезення вантажів, воєнні умови*

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