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MODELING THE RAILWAY AND AUTOMOBILE SUPPLY CHAIN ON THE BASIS OF «GREEN» LOGISTICS

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МОДЕЛЮВАННЯ ЗАЛІЗНИЧНО-АВТОМОБІЛЬНОГО ЛАНЦЮГА ПОСТАЧАННЯ ВАНТАЖІВ НА ОСНОВІ «ЗЕЛЕНОЇ» ЛОГІСТИКИ

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Abstract. *Considering the prospects for the formation of a supply chain of goods based on the application of the concept of «green» logistics in multimodal transportation of goods with the participation of railway transport.*

Studies have found that the introduction of green multimodal technologies is possible by reducing the share of road transport over a distance of 300 km or more. Proposing the direction of savings from environmental taxes on investments in logistics infrastructure. Under these conditions, proposing an economic and mathematical model of a two-stage transport problem of integer programming with fuzzy criteria for optimizing the distribution of container flows between suppliers and consumers, taking into account the environmental criterion.

Keywords: *railway, road transport, supply chain, «green» logistics, multimodal transportation, environmental impact, carbon air pollution.*

Анотація. *Розглянуто перспективи формування ланцюга постачання вантажів на основі застосування концепції «зеленої» логістики при мультимодальних перевезеннях вантажів за участю залізничного транспорту. Доведено, що мультимодальні технології порівняно з доставкою вантажу одним видом транспорту мають менший негативний вплив на навколишнє середовище та повітря. Розглянуто традиційний підхід до визначення екологічного критерію на основі розрахування ряду окремих показників.*

Дослідженнями встановлено, що впровадження «зелених» мультимодальних технологій можливе за рахунок зменшення частки автомобільних перевезень на відстань 300 км і більше. Запропоновано спрямування економії від екологічних податків на інвестиції в логістичну інфраструктуру. За наведених умов запропоновано економіко-математичну модель двоетапної транспортної задачі цілочисельного програмування з нечіткими критеріями оптимізації розподілу контейнеропотоків між постачальниками та споживачами з урахуванням екологічного критерію. Формування значення екологічного критерію здійснюється за допомогою логіко-лінгвістичних методів опису систем у термінах лінгвістичних змінних і розглядається як сукупність лінгвістичних висловлень. Нечітка база знань, що відображує функціональний взаємозв'язок вхідних і вихідних нечітких змінних, є основою побудови узагальненого нечіткого відношення, заданого на універсальній множині для вхідних і вихідних змінних. Нечіткий висновок значення *екологічного критерію здійснюється в чотири етапи: фаззифікація, безпосередній нечіткій висновок, акумуляція результатів, дефаззифікація за методом «центра ваги». Побудовано функцію приналежності нечіткій множині. Оцінено значення нечіткого екологічного критерію при відстані перевезень 200 і 300 км. Встановлено, що розвиток мультимодальних перевезень в Україні потребує вирішення низки внутрішніх організаційно-правових питань, насамперед здійснення гармонізації національного транспортного законодавства з нормами ЄС.*

Тарифи на перевезення контейнерів залізничним і автомобільним транспортом взято відповідно до даних відкритих джерел та апроксимовано за лінійною функцією.

Ключові слова: *залізниця, автотранспорт, логістичний ланцюг, «зелена» логістика, мультимодальне перевезення, вплив на довкілля, вуглецеве забруднення повітря.*

Introduction. Modern trends in freight traffic under the influence of martial law in Ukraine are determined by a decrease in the level and significant fluctuations in loading volumes, as well as significant queues towards interstate transitions. This means that the technology of transporting goods with the participation of railways must be updated using logistics principles. Any cargo owner carries out trade interaction with all open markets, therefore, efficient, fast and, if possible, cheap delivery of goods is a key factor in ensuring a carrier's stable profit. In particular, if in the past, due to the lack of a flexible approach to organizing the transportation of goods, the railway gradually lost traffic volumes and income from them, now «Ukrzaliznytsia» is the main domestic carrier, which should ensure the stability of the country's economy. In addition, the use of resource-saving transportation technology and environmentally friendly approaches will contribute to the correct decision-making on the integration of the domestic transport system into the transport network of the EU countries.

Analysis of recent research and publications. Multimodal, in particular, container and piggyback transportation, is defined by many authors as a promising way to deliver goods [1, 2]. The development of combined and multimodal transport in Ukraine involves the creation of a unified system for the functioning of the transport system, in particular, rail, water and road transport.

According to experts [3], transport accounts for 8 % of all carbon dioxide emissions on the planet. Therefore, the introduction of «green» technologies in logistics activities will make it possible to take certain steps towards preserving the climate on the planet suitable for human life. Therefore, «green» logistics, which appeared in the early 90s of the last century, refers to the concept of sustainable economic development [4].

The experience of the EU countries shows that the sources of revenues to national environmental funds are formed from taxes and payments for environmental pollution for further targeted use for environmental protection measures. At the same time, their essential difference from the Ukrainian funds for environmental protection is their legal status and independence from the state budget. Thus, the impact of environmental taxes and fees on operation features of the transport network is significant. The intensification of multimodal transportation with the participation of railways in Ukraine is carried out in the direction of increasing the share of railway transport in transportation [5], in particular, the following measures are envisaged:

- preservation of highways;
- reduction in the number of heavy trucks (container carriers) on long routes over 200 km;
- development of transportation by environmentally friendly modes of transport.

The strategy for the introduction of «green» logistics is one of the main ones in the

White Paper of the European Conference of Ministers of Transport (ECMT) [6], according to which the EU aims to transfer 30 % of road freight transport with a travel distance of more than La = 300 km to other modes of transport by 2030 (rail or water) and over 50 % by 2050. It can be expected that this will lead to a decrease in the competitive advantages of road transport, significantly increasing the tariffs for road freight. The analysis shows that the majority of freight transports with ECMT licenses far exceed the distance La=300 km.

The joint UNECE, ECMT and EU document «Terminology of Combined Transport» [7] notes that multimodal transport is «the carriage of goods by two or more modes of transport», intermodal transportation means «carriage of goods by two or more modes of transport in the same cargo unit or vehicle without reloading the cargo itself when changing the mode of transport», combined transport – «intermodal transport within which the majority of the journey is by rail, inland waterway or sea transport and any initial and / or final segment of the journey on which road transport is used is as short as possible». Thus, the main feature of the supply chain of goods in containers based on «green» logistics is the absence of transshipment operations on the route, that is, the transportation of cargo without reloading it into another cargo unit.

In this context, all participants in freight transportation need to ensure environmental safety and environmental protection. This can be achieved by creating an environmental management system in accordance with the international standard DSTU ISO 14001, which contains a system of measures related to: impact on the atmospheric air; impact of parametric pollution (noise, vibration); impact on soils; impact on water bodies; waste handling.

The assessment of the environmental performance of the railway, as part of the logistics chain, can be made on the basis of the recommendations of the ISO / FDIS 14031:2021 standard [8], which allows determining the structure of the carrier's operating activities and the factors, which influence on its environmental efficiency, waste generation processes and emissions.

Strategies for the implementation of «green» logistics involve the reduction of harmful emissions from mobile sources. However, the growth in demand for freight transport is closely linked to economic growth, so in an era of rapid global economic development, there is a strong correlation between the reduction of carbon dioxide emissions and the demand for freight transport [9]. A number of foreign studies are related to the prospects for reducing CO_2 emissions by reducing and adjusting the demand for transportation using methods such as optimization of planning a manufacturing enterprise [10], rational design of a logistics network [11], optimization of transport routes [12], application in freight transportation of road electric transport [13] and electrification of railways [14].

On the other hand, scientific research within the framework of the global Shift strategies aimed at reducing CO_2 emissions is focused on the analysis of the behavior of shippers in choosing a delivery method. To justify the choice of the method of transportation by the consignor, the study is devoted to the transfer of the flow of goods from roads to railways due to the competitiveness of the railway and its better environmental performance [12].

Thus, the prospect of «green» logistics in the field of rail and other modes of transport can be linked to the requirements of international ISO standards and regulations, which are a recognized tool for creating an effective environmental management system. The development of multimodal transportation of goods contributes to the introduction of «green» logistics technologies in the process of gradually abandoning long-distance (over 300 km) road freight transportation.

Determination of the purpose and task of the research. In modern conditions, important for economic recovery and relevant in the post-war period is the formation of a scientifically based approach to the creation of effective supply chains for containerized cargo in unimodal and multimodal transportation, taking into account the impact of environmental factors. This meets the main objective of «green» logistics – the creation and development of transportation technologies that help reduce the negative impact of transport on the environment. This goal can be achieved through the rational integration of various modes of transport, in particular rail, with their interaction with a minimum participation of road transport.

For achieve this goal, the following tasks are solved:

- assess energy costs and harmful emissions into the environment during the transportation of containers by different modes of transport;
- assess the value of the environmental criterion for unimodal and multimodal transportation;
- make an assessment of the value of the fuzzy environmental criterion depending on the fuzzy terms «distance of transportation» and «size of CO_2 emissions»;
- build an assessment of the effectiveness of the proposed logistics chain;
- build an economic-mathematical model of a two-stage transport problem of goal-numerical programming.

The main part of the study. Studies show that road transport accounts for 72 % of all emissions. Therefore, it is obvious that by combining different modes of transport in a multimodal scheme, the harm from the impact of pollutants will be minimized. In particular, rail transport has the lowest CO_2 emissions compared to road and water transport: according to estimates, transporting 1000 tons of goods by rail requires three times less energy than transporting them by road. The approximate level of specific emissions of waste gases is given in [4, 16]. In particular, it is noted that a truck with a diesel engine has an estimate of CO_2 emissions at the level of 0.171 kg/h, and a shunting diesel locomotive at the level of 6.410 kg/h.

By summarizing the data given in works [4, 12, 16, 17] an assessment was made of energy costs and harmful emissions into the environment during the transportation of containers by various modes of transport:

- average specific electricity consumption by an electric locomotive 0.6040…0.6552 kW·h/TEU·km;
- average specific electricity consumption for railway electric traction, taking into account losses in the power supply system 0.6647…0.7208 kW·h/TEU·km;
- average specific emissions of harmful substances in railway electric traction CO_2 η_m = 0.0033…0.0038 g/TEU·km (in mixed mode of electricity generation by fuel oil/coal power plants);
- average specific emissions of harmful substances during shunting work CO_2 $\eta_{sh.loc}$= 320.50 g/TEU·h, (ChME-3 shunting diesel locomotive in engine operation mode Ne = 75 % of full power and shunting train consists of 10 wagons);
- average specific emissions of harmful substances of a truck CO_2 η_{a} = 13.194 g/TEU·km (6-cylinder diesel engine, average speed 60 km/h, full container load).

The assessment of the value of the environmental criterion for unimodal transportation by road can be calculated as the value of the harm from the negative impact of carbon dioxide on the atmospheric air [16, 18].

$$B_{\text{a}} = m_{\text{TEU}}\eta_{\text{a}} \sum_{n=1}^{K}(L_{r\,i}\; c_{\text{en.t}\;i}), \qquad (1)$$

where $L_{r\,i}$ – distance of unimodal transportation on the territory of the i-th state, km;

K – the number of transportation sections on the territory of other states (for domestic traffic K=1);

$c_{\text{en.t}\;i}$ – rate of environmental tax on polluting CO_2 emissions on the territory of the i-th state, UAH/t;

m_{TEU} – mass of cargo transported in a container (TEU), i.e.

Significance of the environmental criterion for multimodal transportation

$$B_{\text{м}} = m_{\text{TEU}} \begin{pmatrix} \eta_m \sum_{n=1}^{K} (2L_{3\,i}\, c_{\text{en.t}\,i} + t_{sh.loc\,i}\, \eta_{sh.loc}) + \\ \eta_{\text{a}} [L_{\text{a}1}\, c_{\text{en.t}\,1} + L_{\text{a}2}\, c_{\text{en.t}\,\text{K}}] \end{pmatrix}, \quad (2)$$

where $L_{m\,i}$– distance of the railway part of the multimodal transportation on the territory of the i-th state, km;

2 - coefficient taking into account the return of the rolling stock to the owner country;

$t_{sh.loc\,i}$ – average duration of shunting operations with a multimodal unit, hour;

$L_{\text{a}1}, L_{\text{a}2}$ – average distance, respectively, import and export of a multimodal unit, km.

In Ukraine, the environmental tax is a nationwide obligatory payment levied on actual volumes of emissions into the atmospheric air. According to Art. 14.1.57 of the Tax Code of Ukraine, the tax rate for carbon dioxide emissions is 30 hryvnia per 1 ton.

Through analysis, it was found that the carbon environmental tax rates vary significantly in different countries. To stimulate «green» technologies in Ukraine, it is planned to gradually increase it to 5 UAH/t every year. At the same time, the carbon environmental tax rates in developed countries range from 1.00 USD/t (Poland) up to 25 EUR/t in some EU countries and up to 139 USD/t (Sweden) [17].

The usual approach proposed above to determine the environmental criterion is determined on the basis of the calculation of a number of individual characteristics, which sufficiently reflects the essence of unimodal transportation. But its use for multimodal transportation does not allow to fully evaluate the effectiveness of this option, since it is necessary to use a generalized assessment of changes in the main indicators of delivery by several modes of transport to the final result. The number of indicators may be different, but they must be significant for the participants in the transportation, and also serve as the basis for substantiating management decisions on the formation of the logistics chain [19].

If we consider this in formal terms, then the value of the environmental criterion for the formation of a supply chain of goods based on «green» logistics is represented as a vector membership function of linguistic variables B.

$$\widehat{B_{\text{м}}} = \left\{ \mu_{b_1}(B),\ \mu_{b_j}(B), \ldots,\ \mu_{b_N}(B) \right\}, \quad (3)$$

where b_i – desired level of performance of the j-th component of the indicator, the total number of which is N;

$\mu_{b_j}(B)$ – membership function of the execution level of the fuzzy set indicator $\widehat{B_{\text{м}}}$.

The values of the linguistic variable B are fuzzy sets, the elements of which are the characteristics of the indicator. Each indicator has a constraint $\forall j \in N\ \exists\ b_j \in \bar{B}_j$, where $\bar{B}_j$ there is a set of valid values for a particular indicator.

The formation of a fuzzy environmental criterion $\widehat{B_{\text{м}}}$ can be used as the basis for a decision support system for choosing parameters and components of a multimodal logistics chain by assessing the impact of the environmental friendliness of each link using linguistic variables and obtaining fuzzy conclusions based on them [20].

Formally linguistic variable is defined as a set

$$\text{B}: \langle T,\ \bar{B}_j\ ,\ G,\ W \rangle, \quad (4)$$

where B – denomination of the linguistic variable;

T – base term-set of linguistic variable values B;

$\bar{B}_j$ – universal set of admissible values of the indicator, which is the domain of definition of each term, namely $T \subseteq \bar{B}_j$;

G – syntactic procedure that allows you to operate on the elements of a term set T.

W – semantic procedure (rules) that makes it possible to turn each new value of a linguistic variable created by the procedure G into a fuzzy variable. Thus, it is possible to form the content of the corresponding fuzzy set.

To form a criterion, we introduce the concept of a fuzzy expression - these are constructions of the form $\langle B_j \in B_j^* \rangle$, where B_j^* is the value of a linguistic variable, which corresponds to a fuzzy set on the universal set $\bar{B}_j$.

To obtain fuzzy conclusions, we will use the following semantic procedures W for transforming fuzzy statements. Rule for transforming the conjunctive form.

$$\langle B_1 \in B_1^* \ \wedge \ B_2 \in B_2^* \rangle \Rightarrow \langle (B_1,\ B_2) \in (B_1^* \ \cap B_2^*) \rangle, \quad (5)$$

where $B_1^* \ \cap B_2^*$ value of a linguistic variable $(B_1,\ B_2)$, that corresponds to the original expression $\langle B_1 \in B_1^* \ \wedge \ B_2 \in B_2^* \rangle$ and to which, for linguistic variables, $B_1$and B_2 is assigned a fuzzy set $\hat{B}_1 \ \cap \hat{B}_2$ with a membership function $\mu_{B_1 \cap B_2}(\bar{B}_1\ ,\ \bar{B}_2\ ) = \mu_{B_1}(B_1{}^*) \cap \mu_{B_2}(B_2{}^*)$.

Disjunctive form transformation rule

$$\langle B_1 \in B_1^* \vee B_2 \in B_2^* \rangle \Rightarrow \langle (B_1,\ B_2) \in (B_1^* \ \cup B_2^*) \rangle, \quad (6)$$

where $B_1^* \ \cup B_2^*$ value of a linguistic variable $(B_1,\ B_2)$, that corresponds to the original expression $\langle B_1 \in B_1^* \ \vee \ B_2 \in B_2^* \rangle$ and to which, for linguistic variables, $B_1$and B_2 is assigned a fuzzy set $\hat{B}_1 \ \cup \hat{B}_2$ with a membership function $\mu_{B_1 \cup B_2}(\bar{B}_1\ ,\ \bar{B}_2\ ) = \mu_{B_1}(B_1{}^*) \cup \mu_{B_2}(B_2{}^*)$.

The rule for the transformation of statements of the implicative form

$$\langle B_1 \in B_1^* \ \supset \ B_2 \in B_2^* \rangle \Rightarrow \langle (B_1,\ B_2) \in (B_1^* \ \rightarrow B_2^*) \rangle, \quad (7)$$

where $(B_1^* \ \rightarrow B_2^*)$ value that corresponds to the value of a linguistic variable $(B_1,\ B_2)$.

The formation of the value of the ecological criterion B_m and the formalization of the decision support system will be carried out using logical-linguistic methods for describing systems in terms of linguistic variables and considered as a set of linguistic statements of the following type.

$$\widehat{B_m} = \begin{cases} B_1 : \langle B_{11} \wedge | \vee | \supset B_{12} \ \dots \wedge | \vee | \supset B_{1N} \rangle \Rightarrow \langle B_{11}^* \wedge | \vee | \supset B_{12}^* \ \dots \wedge | \vee | \supset B_{1N}^* \rangle \\ B_2 : \langle B_{21} \wedge | \vee | \supset B_{22} \ \dots \wedge | \vee | \supset B_{2N} \rangle \Rightarrow \langle B_{21}^* \wedge | \vee | \supset B_{22}^* \ \dots \wedge | \vee | \supset B_{2N}^* \rangle \\ \dots \\ B_j : \langle B_{j1} \wedge | \vee | \supset B_{j2} \ \dots \wedge | \vee | \supset B_{jN} \rangle \Rightarrow \langle B_{j1}^* \wedge | \vee | \supset B_{j2}^* \ \dots \wedge | \vee | \supset B_{jN}^* \rangle \end{cases}, \quad (8)$$

where <Bij>, i=1,2,..,N j=1,2,...,k – fuzzy statements on the corresponding values of input linguistic variables;

<B*ij>, i=1,2,..,N j=1,2,...,k – fuzzy statements on the corresponding values of the output linguistic variables.

Aggregate of rules (8) will be called a fuzzy knowledge base, which reflects the functional relationship between input and output fuzzy variables and is the basis for constructing a fuzzy generalized relation defined on a universal set $\bar{B}_j$ for input and output variables. The relation of the interconnections is built according to the compositional rule of Zadeh [21]

$$\mu_{b_j}(\bar{B}_j\ ) = \cup_{B_j \in B_j^*}[\mu_{b_i}(\bar{B}_j\ ) \cap \mu_b\ (\bar{B}\ )]. \quad (9)$$

Thus, the compositional rule of inference in this case sets the law of functioning of the fuzzy model. The fuzzy conclusion of the value of the environmental criterion B_m can be carried out in four known stages [22, 23]: fuzzification, direct fuzzy inference, accumulation of results, defuzzification using the «center of gravity» method.

To evaluate suggest approach, it is proposed to evaluate the value of the fuzzy environmental criterion depending on the fuzzy terms «distance of transportation» and «size of CO_2 emissions». Obviously, the number of terms can be increased, which will improve the accuracy of the result.

An analysis of the size of emissions (for the railway part of transportation) allows us to establish three stable segments, which can be conditionally divided into «high», «medium» and «small». Thus, the obtained terms of the linguistic variable B_{11}=<high>, B_{21}=<medium> and B_{31}=<low> on the fuzzy set $\bar{B}_1$ =<size of CO_2 emissions>, the membership functions of which are established by the method of expert assessments, and are shown in fig. 1.

The membership functions for the set of terms $\bar{B}_2$ =<transportation distance> and for the set $\bar{B}_m$ =<environmental criterion> are set in a similar way. Thus, a fuzzy set of linguistic statements, which can be used as the basis for a model for evaluating the effectiveness of the logistics chain, will look like:

$$\hat{B}_m = \begin{cases} B_1: \langle B_{11} \wedge B_{12} \rangle \to \langle B_{11}^* \wedge B_{12}^* \rangle \\ B_2: \langle B_{21} \wedge B_{22} \rangle \to \langle B_{21}^* \wedge B_{22}^* \rangle. \\ B_3: \langle B_{31} \wedge B_{32} \rangle \to \langle B_{31}^* \wedge B_{32}^* \rangle \end{cases} \quad (10)$$

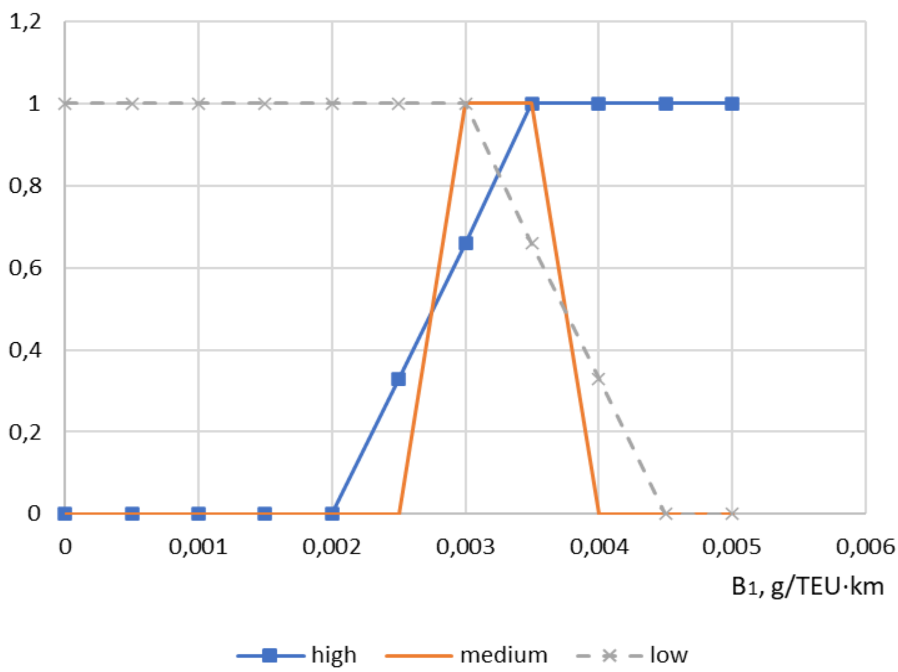

Fig. 1. Fuzzy set membership functions $\bar{B}_1$ =<size of CO_2 emissions>

The results of execution of (9) on (10) at different transportation distances (L=200 km and L=300 km) are shown in fig. 2.

The result obtained indicates that the value of the environmental criterion $\widehat{\mathrm{B}}_\mathrm{m}$ worsens with a decrease in the distance of transportation, and its influence on the total cost of transportation increases. Obviously, the proposed approach is quite universal and can be extended and refined by introducing new terms and statements.

The formation of the supply chain of cargo in containers, taking into account the environmental criterion, is proposed to be solved as a multi-stage transport problem of integer programming with fuzzy criteria. In multi-stage transport tasks, containers from suppliers first arrive at intermediate points (distribution terminals, in our case, these are interstate crossing points), where, if necessary, they are reloaded or stored. That is, products are supplied to end consumers not from suppliers, but from the indicated intermediate points of transport networks (fig. 3).

In this example, the stocks of products from suppliers, the throughput of intermediate points, the needs of consumers, as well as the tariffs and environmental criteria for the transportation of a container (TEU), as well as the throughput of each of the routes, are considered known. Under these conditions, it is necessary to determine the most economical plan for transporting products from suppliers to consumers.

Denote the number of suppliers as m, and the volume of containers each of them has as $a_i(i = \overline{1,m})$. The number of consumers will be denoted by n, the demand for containers of each consumer - by $b_j(j = \overline{1,n})$. It is assumed that the transportation of products from suppliers to consumers will be carried out in two stages. First, products from suppliers will go to intermediate points, and from intermediate points to consumers (fig. 3). The number of intermediate points will be denoted by p, and the throughput of a separate k-th intermediate point by $c_k(k = \overline{1,p})$.

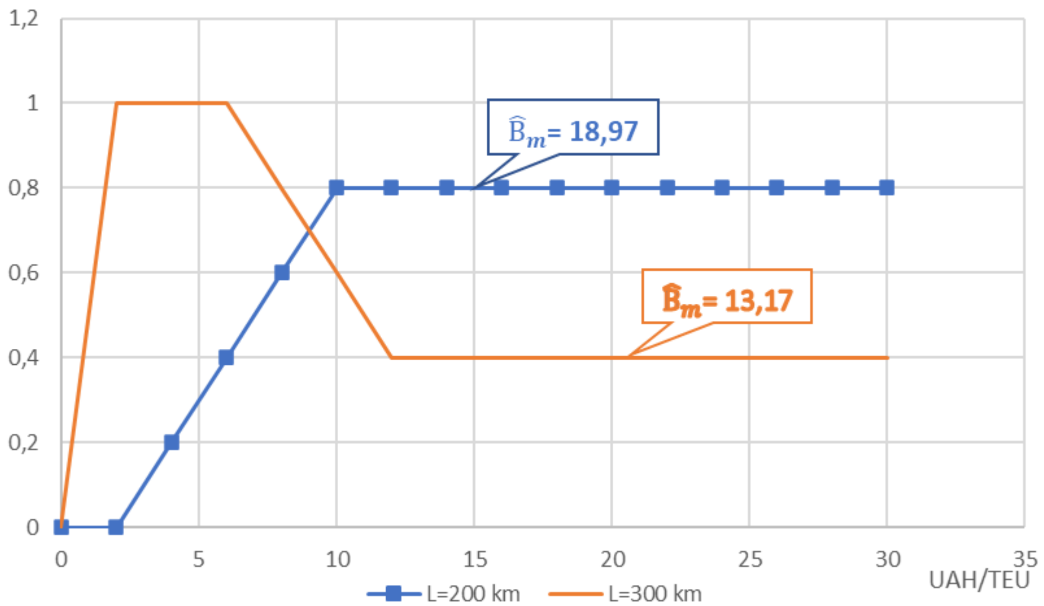

Fig. 2. Estimation of the values of the fuzzy environmental criterion $\widehat{\mathrm{B}}_\mathrm{м}$ for a transportation distance of 200 km and 300 km

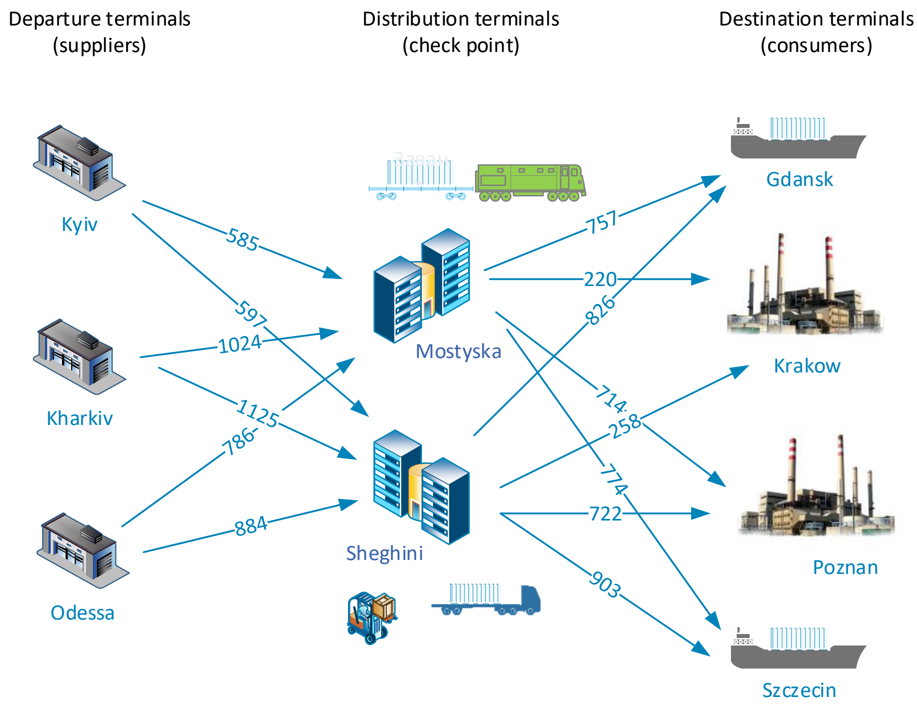

Fig. 3. Diagram of the supply chain of cargo in containers (the arrows show the distance in km)

Cost of transporting a unit of production from the i-th supplier to the k-th intermediate point will be denoted by $s_{ik}\left(i=\overline{1,m};k=\overline{1,p}\right)$, and the cost of transporting a unit of production from the k-th intermediate point to the j-th consumer by $t_{kj}\left(k=\overline{1,p};j=\overline{1,n}\right)$. Necessary to find the volumes x_{ik} of transportation products from suppliers to intermediate points $\left(i=\overline{1,m};k=\overline{1,p}\right)$ and the volumes y_{kj} of transportation of products from intermediate points to consumers $\left(k=\overline{1,p};j=\overline{1,n}\right)$, so that the total cost Ψ of all transportation would be minimal.

Under the given conditions and notation, the economic and mathematical model of a two-stage transport problem of integer programming with fuzzy criteria takes the form.

$$\Omega=\sum_{i=1}^{m}\sum_{k=1}^{p}(s_{ik}+\hat{B}_{mi})x_{ik}+\sum_{k=1}^{p}\sum_{j=1}^{n}(t_{kj}+\hat{B}_{mj})y_{kj}\rightarrow min, \quad (11)$$

$$\sum_{k=1}^{p}x_{ik}\leq a_i,\ i=\overline{1,m}, \quad (12)$$

$$\sum_{k=1}^{p}y_{kj}=b_j,\ j=\overline{1,n}, \quad (13)$$

$$\sum_{i=1}^{m}x_{ik}=\sum_{j=1}^{n}y_{kj}\leq c_k,\ k=\overline{1,p}, \quad (14)$$

$$\begin{aligned}&x_{ik}\geq 0,\quad i=\overline{1,m},\quad k=\overline{1,p},\\&y_{kj}\geq 0,\quad k=\overline{1,p},\quad j=\overline{1,n},\end{aligned} \quad (15)$$

$$L_{akj}\leq \mathrm{La},\quad k=\overline{1,p},\quad j=\overline{1,n}, \quad (16)$$

$$\sum_{j=1}^{n}b_j\leq\sum_{k=1}^{p}c_k. \quad (17)$$

The objective function (11) corresponds to the search for an economic plan for container transportation. Other conditions of the problem mean, respectively:

(12) - the volume of containers taken out from each supplier should not exceed the stock available to him;

(13) - the volume of containers delivered to each consumer must correspond to his demand;

(14) - all containers that will be imported to each intermediate point from suppliers should then be sent to consumers, and the throughput of each waypoint should be taken into account;

(15) - volumes of container traffic on each of the routes should be inalienable;

(16) - the distance of transportation of containers from intermediate points to consumers by road should not exceed themaximum allowable permissible value La from an environmental point of view;

(17) - the capacity of all intermediate points is sufficient to process the total flow of products in the transport network.

Tariffs for the transportation of containers by rail and road are taken in accordance with data from open sources and approximated by a linear function with an error below 1 % (fig. 4). Intermediate points - transitions are accepted, respectively, as multimodal - Mostyska, unimodal (vehicles) - Shegini (fig. 3). The maximum processing capacity of the transshipment points is 180 weights/day.

The solution of the two-stage transport problem of integer programming with fuzzy criterion (11) was carried out by the generalized reduced gradient method. The total minimum costs for ensuring the delivery of containers, taking into account the environmental criterion, amounted to UAH 15,475,223. during the trial month. In the basic version of transportation distribution, the costs amounted to UAH 15,595,678, i.e., savings from optimization amounted to UAH 120,455/month, and the annual savings estimate was UAH 1,445,460/year, or at the level of 7 %.

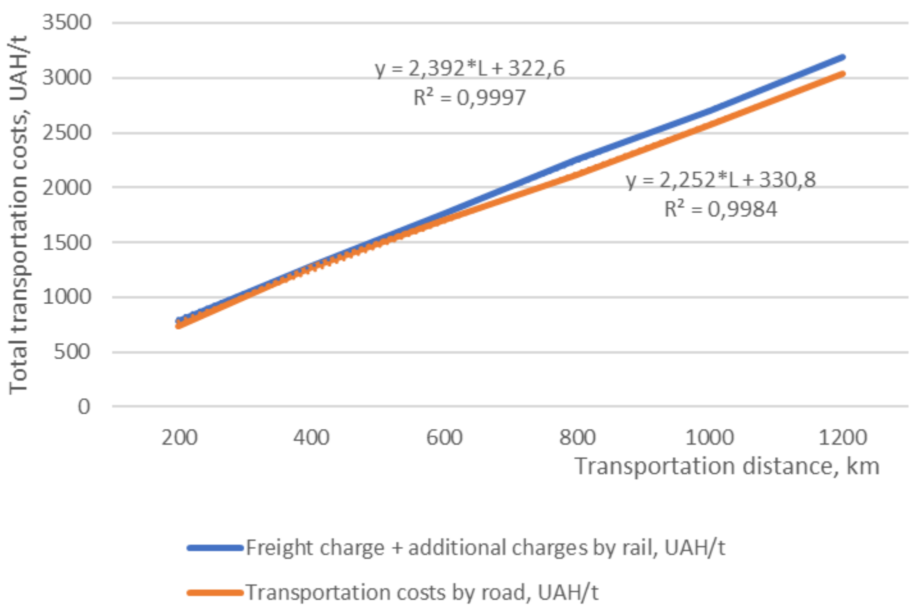

Fig. 4. Determining the level of costs for the transportation of 1 ton of cargo in containers by rail and road

According to the calculated data, the total minimum costs for ensuring the delivery of containers amounted to about UAH 15.5 million during the pilot month. During the simulation, an experiment was carried out to determine the share attributable to the multimodal option for the delivery of containerized cargo, depending on the level of load capacity of the distribution points. It has been established that with an increase in the throughput of automobile distribution points, the container flow is gradually moving to a unimodal automobile transportation method. This can be explained by a certain delay of containers during reloading from 1520 mm gauge cars to 1435 mm gauge cars. But when applying promising environmental conditions and restrictions, the share attributable to the transportation of containers by road does not exceed 15 % (fig. 5), that is, there is an effect of increasing the share of the multimodal method of transporting containers.

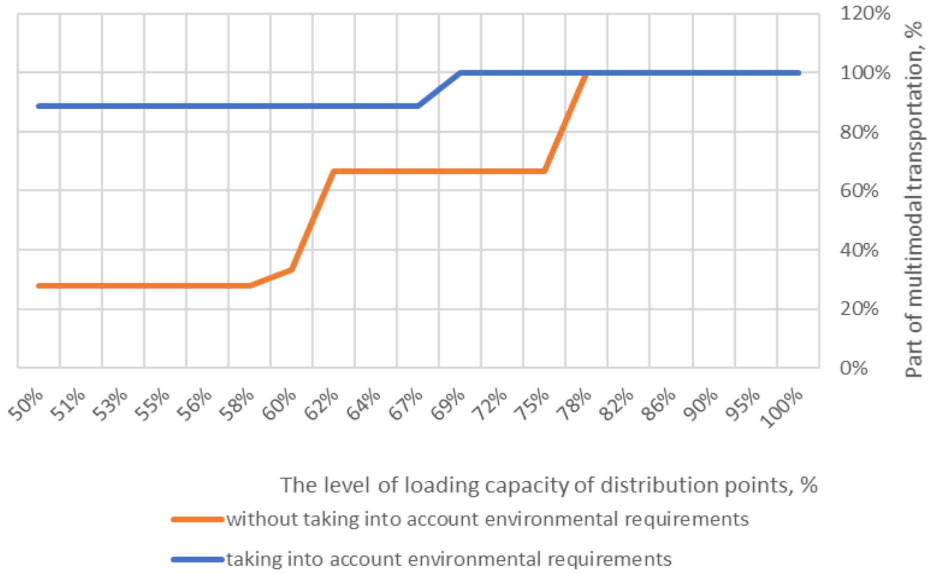

Fig. 5. Determination of the share attributable to the multimodal option for the delivery of containerized cargo

Conclusions. According to the forecast in 2024-2050, the total amount of CO_2 emissions in the cargo transportation sector in Ukraine will increase by 3.9 times. Growth in CO_2 emissions from road and rail transport by 2050 will be 240 % and 600 %, respectively. The introduction of «green» logistics technologies is facilitated by the introduction of multimodal technologies for the transportation of goods. This allows us to identify the following promising areas of activity in this area:

- gradual expansion of the network of logistics and multimodal centers throughout the country, starting with large transport hubs, and the introduction of multimodal technologies will help reduce the level of the integrated air pollution index in most transport hubs by 1-3 %;
- reducing the share of unimodal road transport over a distance of more than 300 km, replacing them with multimodal ones involving rail and water transport will improve environmental performance in the transportation of container cargo, while reducing the number of flights and reducing the harmful environmental impact of the railway roads, the level of emissions of pollutants into the atmosphere can be reduced by almost 200 times, and for CO_2 emissions - by almost 300 times;
- multimodal technology of transportation in domestic transport communications saves 6.1 times on

environmental tax, and 9.8 times in international transport compared to unimodal;

- delimitation of freight and passenger traffic on especially busy railway sections, as well as seasonal use of multimodal technologies for the delivery of goods and passengers in areas with difficult road conditions or in conditions of railway stations with low volumes of work;

- with a view to formalize the supply chain of goods, taking into account the environmental criterion and the requirements of «green» logistics, the economic and mathematical model of a multi-stage transport problem of integer programming with fuzzy criteria has been improved.

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