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## IMPROVEMENT OF METHODOLOGY OF JUSTIFICATION OF SAFE ROUTES FOR TRANSPORTATION OF DANGEROUS SUBSTANCES AND CARGO

**Purpose.** To improve existing methods for safe routing when transporting hazardous materials as well as waste products.

**Methodology.** Methods of mathematical modeling, methods of statistics, methods for predicting risks and long-term environmental consequences are used. Taking into account time factors, the distribution of population into different sections of highways is considered.

**Findings.** Parameters of the transport network and their influence on the magnitude of the risk of an emergency situation and possible accidents in the transportation of hazardous waste (THW) are established in the work. An analysis is conducted of dangerous effects that can be caused by THW taking into account the parameters of road, transport network, type and modes of transport, and others. In order to minimize the risk of accidents during THW, it is proposed to use appropriate approaches and criteria  $K_1$  and  $K_2$ , which take into account the lowest values of dangerous effects on the person during the transportation time, which allow evaluating the safety of the transportation system and the selected route, whereas their product takes into account all the possible main factors of the transportation system. Typical road and rail transport schemes have been identified to ensure a minimum number of accidents and reduce environmental and human hazards.

**Originality.** Approaches are improved to transportation of dangerous goods by motorway and railroad, in particular, the parameters of curvature and inclination of the road, availability of settlements and bridges, meteorological conditions and traffic congestions, which improves the efficiency and safety of transportation of dangerous substances and materials.

**Practical value.** The original mathematical models of mapping the route for transporting dangerous substances are offered while the existing ones are improved. The results of the research can be used by transport companies, public authorities in the transportation of hazardous substances and logistics and non-hazardous industries.

**Keywords:** *environmental safety, transportation of hazardous waste, safe transportation routes, risks of accidents*

**Introduction.** As large volumes of hazardous substances, such as pesticides or radioactive materials, are imported and used inside the country, their transportation by various means of transport, especially without strict adherence to the relevant rules and regulations, can lead to major emergencies with possible negative consequences and possible long-term consequences, including even victims among the population. Therefore, planning and justification of safe routes for transportation of hazardous waste, as well as the management of relevant risks is a pressing scientific and practical problem [1].

**Literature review.** The analysis of relevant scientific works on the peculiarities of transportation of dangerous goods, in particular, pesticides, radioactive drugs, explosives, and others shows that the methodology, although sufficiently developed, still needs improvement and modification in the implementation of safe routes, taking into account important parameters of the relationship with the characteristics of the road. This applies to the specifics of vehicles, as well as the qualifications of staff. In addition, the peculiarities of risks and relevant safety criteria for such dangerous transport remain unexplored [1–16].

**Unsolved aspects of the problem.** As you know, the general scientific and applied problem is the need to strictly ensure the safe transportation of dangerous goods along the entire laid or planned route, as well as the unquestionable exclusion of any harmful and dangerous effects on people and the environment. At the same time, the general theoretical basis for forecasting risks and laying safe routes is quite adequate, but, especially for pesticide-containing wastes of different physical state, the safety criterion  $\bar{R}$  requires consideration in addition to partial criteria  $K_1$  and  $K_2$ , additional criteria  $K_n$  describing other hazardous factors of possible accidents on the transportation route.

**Results.** The transport network can be considered as a series of arcs and nodes [2]. When analyzing the degree of trans-

port risk, each segment of the potential route must be characterized by certain properties and parameters of danger, and the risks are numerically assessed. In carrying out the analysis of the degree of transportation risk, each link must be characterized by some properties [3]. So let us mark it  $N_{link}$  as a series of highway network connections  $l$ . In doing so, we consider the following connection options:

1. Geographic location in the impact area; to do this, we apply the Cartesian structure  $X/Y$ ;  $O_{X/Y}$  should be arbitrarily blocked in the affected area.

2. Transport network topology (in this case, taking into account the parameters of the road network, including the presence of water bodies along the route).

3. The number of annual shipments  $N_{ship}(l, v)$  moving on each link  $l$  of freeways.

4. Incidence rate  $\lambda_{inc}(l)$ , expressed at events/(km of road), for each road; this variable is a function of the peculiarities of the route, traffic conditions, environment, and status of the driver. Frequency of movement  $\lambda_{rel}(l)$  of a motor vehicle can be estimated as the frequency of the incident and the likelihood of an accident from a car following this route.

On the freeway, each section is characterized by a substantially straight line. As a consequence, it is possible to consider access to freeway endpoints, as there may be significant changes over the year. The calculation procedure can be divided into smaller periods ( $N_{seas}$ ), which we will call “seasonal situations” ( $j = 1, N_{seas}$ ) and assign different weight to the bonds during the season [3]. For example, transportation processes may be limited by the day period, the frequency of the incident on the route, and the time of year.

In this way  $\lambda_{inc}(l)$ ,  $\lambda_{rel}(l)$  and  $N_{ship}(l, v)$  become a function of the seasonal situation  $j$  as well:  $\lambda_{inc}(l)$  – the probability of an accident;  $\lambda_{rel}(l)$  – the probability of emission;  $N_{ship}(l, v)$  – the number of annual shipments;  $p_{wind}(l, k, \vartheta)$  – probability density of wind direction.

**Impact of output route parameters on the magnitude of the risk.** The transportation route can be considered as a linear

source of risk because the emission of harmful substances can occur at each of its points [4]. This means that each object can be considered as a source of risk, or, in other words, the vehicle must be considered as a source of risk on the route [5]. Therefore, in the analysis of the degree of transport risk, the second step is to analyze the vehicle parameters or the initial route parameters, indicating the sources of risk. The transport inherent parameters characterize different typologies  $\mathcal{Q}$  and  $N_{ver}(l)$ , which are considered at each connection  $l$ .

For each route there is a risk that there is a probability of emission  $p_{rel}(l, v)$  for each road "route typology" and the probability of one incident ( $p(R|A)$ ). The designs of vehicles differ for different methods of transportation, and strongly depend on the peculiarities of the substance being transported. In addition, it may also depend on the transport network  $l$ , that is, there is a greater likelihood of high speed areas.

It is worth noting that determining the characteristics of the road transport conditions with proper emission probabilities makes it possible to calculate each  $f_{rel}(l, v, j)$ , that is, the frequency of emission from the specified transport typology  $v$  in the specified area ( $l$ ) in the specified season ( $j$ ). In fact, this leads to the expression

$$f_{rel}(l, v, j) = N_{ship}(l, v, j) \cdot \lambda_{inc}(l, j) \cdot p_{rel}(l, v).$$

To identify and determine the number of random scenarios, we summarize the sources of risk along the route:

1. Transportation conditions for each type of waste may vary.

2. The dimensions of the equivalent openings that have been selected to describe all possible releases (substance leaks) from each "transport typology". For each mode of transport and for each gap, measure the physical aspect of the result and the rate of leakage, or the amount of release in the event of an immediate outflow. Each type of transportation can lead to  $N_{out}(v)$  of the end results ( $i$ ).

3. The end results to which each value of a different mode of transport may lead must take into account the circumstances if: there arises a poisonous cloud; explosive (liquid explosion with poisonous vapors or unlimited explosion with a cloud of steam); flame; jet fire, and so on.

4. The likelihood of the end result if one leak,  $P_{out}(i)$ , that is, the result of the likelihood of a leak when it occurred. Here, examples of definitions of the device's characteristics can be found in [1] and in the Advisory Committee on Dangerous Substances.

**Analysis of hazardous effects caused by emergencies during THW: models and simulation parameters.** As noted earlier [6], to calculate the number of people involved in an accident caused by the transport of dangerous goods, it is necessary to know, or at least estimate the scale of the area affected by the accident. Accidents that can occur during the transportation of dangerous goods are classified into three categories [7]: emissions of substances that are toxic to health and the environment; thermal energy release; pressure release [8]. The consequences depend on the type of transport, the substance being transported and how the event took place, and so on.

At the same time, the most convenient representation of risk during THW is the  $F-N$  curve. This curve, expressed in real time, and characterized by a monotonous rise, represents the frequency ( $F$ ) of accidents and the number ( $N$ ) of potential victims, ranging from 1 to the maximum possible number.  $N$  is determined by population density maps along a potential freight route. There are two general methods for representing the  $F-N$  curve: first, you need to calculate the  $F-N$  curve directly from the empirical frequency of accidents; second, they must develop and use a probabilistic model to estimate the frequency ( $F$ ) [9].

In order to calculate the  $F-N$  curve, one actually needs to know the following information: the number of trips annually, accident rates ( $F$ ), probability of a single accident occurring, the magnitude of the area potentially involved in the accident,

and population density in the study area, and so on. The innovative approach proposed by [10] is that the frequency of an accident during the  $i$ -time can be expressed by the following equations

$$f_i = y_j \cdot L_j \cdot n_j;$$

$$y_j = y_0 \cdot \prod_{j=1}^n k_j,$$

where  $y_j$  is the frequency expected at the  $i^{\text{th}}$  section of the road;  $L_j$  is road length (km);  $n_j$  is event number;  $y_0$  = fundamental frequency (km l accident per event);  $k_j$  is parameters (Table 1). They can be divided into 6 categories;  $k_1$  and  $k_2$  – parameters that characterize the geometric features of the road;  $k_3$  – type of highway;  $k_4$  – atmospheric conditions;  $k_5$  – type and intensity of movement;  $k_6$  – the presence of tunnels and bridges.

As already suggested in [11], combining the defined values of the frequency of accidents, the calculated use of the Fabiano et al. approach [10] with the population indicators involved was made in [4], where a complete definition of the risk associated with road traffic was obtained in the decision illustrated in Fig. 1.

The following approaches are based on modeling the effects caused by an accident on the road. They indicate that it is important to take these considerations into account for safety and crisis management purposes.

**Analysis of the "target tree" of the THW system.** Fig. 2 shows a scheme for the transportation of dangerous goods, for example, by rail, as an illustration of the purpose tree. This scheme should be applied when planning the organization of transportation of dangerous substances and materials [12].

At the same time, minimizing the risk of causing harm to people, the environment, property should be an absolute priority of the THW system, the global goal of the whole system of transportation (transit through a certain territory) of dangerous goods, for example, by rail [13]. Achieving this goal requires some local goals to be achieved. The mentioned local goals may conflict with each other (some goals exclude others). For example, the goals of routing and reducing the mass of a train, minimizing the transit distance and taking into account the population of the danger zone (which may be the most populated in the shortest distance) may be opposite [14]. The existence of such contradictions requires the alignment of goals under certain conditions, in other words setting and solving optimization problems according to certain criteria [15]. Therefore, a "comprehensive security criterion  $\bar{R}$ " was proposed below including partial criteria  $K_1$  and  $K_2, K_n$ .

This study focuses on the following:

1) improvement of technology and organization of transportation of dangerous goods;

2) rationalization of routes of transportation of dangerous goods taking into account the location of the means of response and elimination of the consequences of possible transport events with dangerous goods;

3) rationalization of the means of response and elimination of the consequences of possible transport events with dangerous goods.

The task of optimizing transportation support is also important. It applies to rolling stock, infrastructure, station equipment and the like.

**Criteria and approaches to improving the efficiency of the THW system.** Consider the scheme shown in Fig. 3. Suppose that at a point located approximately in the middle of an AU railway station, because of a vehicle accident, accident or for other reasons, damage or destruction of the rolling stock occurred resulting in the contact of the dangerous substance being transported with the environment in the air, soil (soil) water), reservoirs or in all three environments at the same time. Let us call this contact a dangerous event. The location of the event is shown in the diagram by an appropriate sign, as well as the wind direction, location and conditional sizes of the two settlements,

The parameters of the relationship with the features of the road

Traffic conditions	Features of traffic conditions	$k_1$	$k_2$	$k_3$	$k_4$	$k_5$	$k_6$	$k_7$	$k_8$
Features of road parameters	Straight road	1							
	Curve road (distance >200 m)	1.3							
	Curve road (distance <200 m)	2.2							
	Flat road		1						
	Growing road (gradient <5 %)		1.1						
	Steep ascent road (gradient >5 %)		1.2						
	Descent road (gradient <5 %)		1.3						
	Steep descent road (gradient >5 %)		1.5						
	Two lanes for each highway			1.8					
	Two lanes plus an emergency lane for each highway			1.2					
	Three lanes plus an emergency lane for each highway			0.8					
	Tunnel						0.8		
	Bridge						1.2		
Atmospheric conditions	Good weather (no precipitation, warm weather)				1				
	Rain/fog				1.5				
	Snow/ice				2.5				
Intensity of traffic	Low intensity <500 car/hour					0.8			
	Average intensity <1250 car/hour with heavy traffic <125 freight cars a day					1			
	High intensity >1250 car/hour					1.4			
	High intensity <1250 car/hour with heavy traffic >250 freight cars a day					2.4			
Features of the vehicle	Without a trailer							1	
	With a trailer							1.3	
Driver qualification	Average, without experience in transporting dangerous goods								1.2
	High, with experience in transporting dangerous goods								0.8

and their population is considered proportional to these sizes [16]. We analyze the consequences of a dangerous event, taking into account only the air pool. In this case, the gaseous hazardous substance will propagate in the direction of the wind, forming zones with different concentrations of it in the air, and some substances may create explosive mixtures with the air.

Obviously, the concentration will be higher in the settlement, but if the substance is very dangerous even at scant concentrations, more people may be affected in a city farther from the scene because the population is larger. Considering the scheme in Fig. 3 further, it can be noted that if the cargo was transported not along the line (section) of the AU but along the line ABC, then with the same wind direction, the settlement population would not have been affected at all (the rail-

way “bypasses” it), whereas the population of the city would have suffered more.

Thus, the risks and negative consequences of THW may vary depending on many factors. For further analysis, let us try to reduce their number to several important ones, which can be quantified and, preferably, those that can be influenced in the organization of transportation.

Given the relative nature of the hazard, we propose for its evaluation a quantitative indicator – “hazard index (section, direction, line)”, which we denote  $R_D$ , depending on the values below.

1. The relative hazard of dangerous goods is a dimensionless value, and we have proposed a relative expert hazard rating on a scale from 0 to 1 (the assessment criteria are given below).

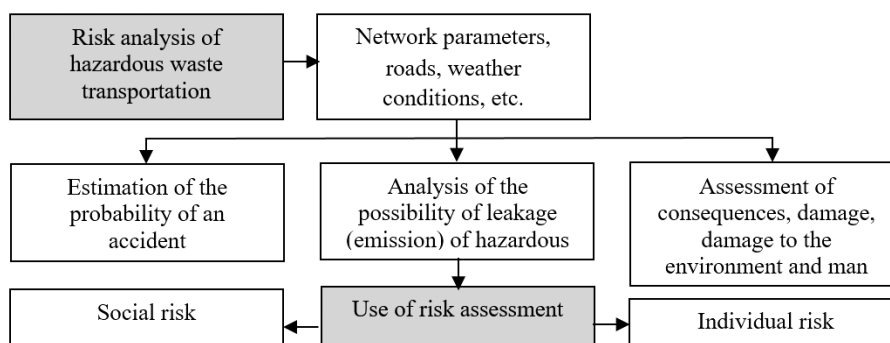


Fig. 1. Summary chart for determining the risk of an accident, taking into account the parameters  $k_n$

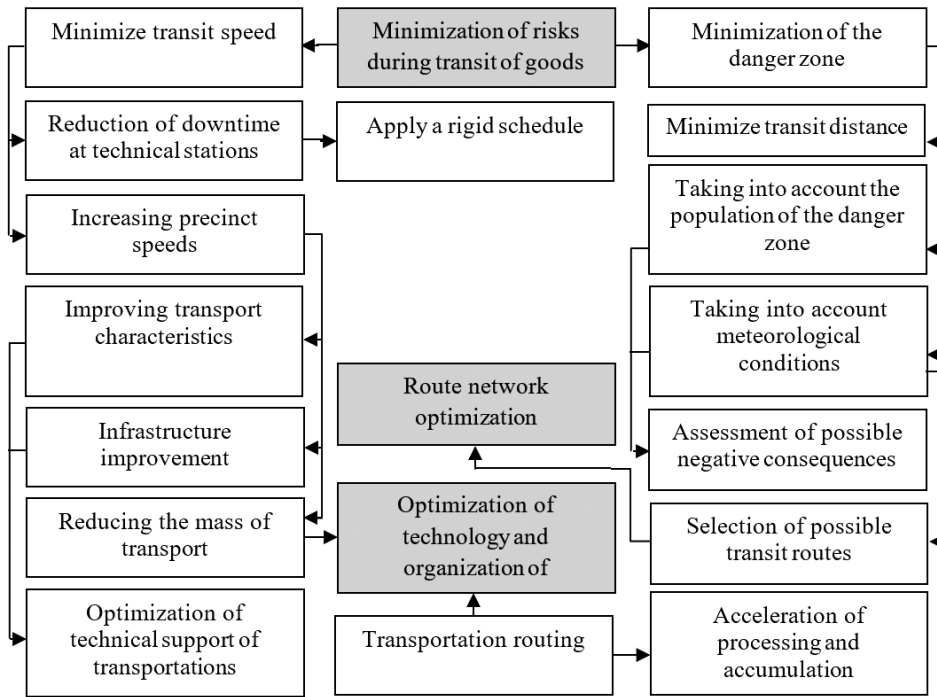


Fig. 2. Tree of risk minimization targets for hazardous waste transportation

2. Intensity of dangerous goods transportation, where  $\Lambda_D$  is the amount of dangerous goods transported at a given site over a period of time (tons per year, month or day).

3. Hazard zone (area,  $\text{km}^2$ ) is the area of the territory within the limits indicated in Fig. 3 below.

4. Population of the danger zone,  $p_{ZD}$  is the maximum number of population that may be within the given risk range (persons/km).

5. Danger distance  $L_D$  – the shortest distance in the direction opposite to the wind from the geographical center of the settlement in the danger zone to the axis of the railway line of the section (if the settlement is not located directly on this line) or the distance from the geographical center of the section (mid-length of the section) to the geographical center of the settlement, which is located directly on the line (Figs. 3, 4). Named geographical centers are determined by rail maps (geographical maps).

6. Maximum permissible concentration of dangerous substance  $C_{gdk}$ ,  $\text{mg}/\text{m}^3$  is determined by the properties of the dangerous substance and the characteristics of its action on the human body, fauna and flora.

7. The proportionality factor  $k$  is calculated by the formula

$$k = \frac{R_D \cdot L_D \cdot S_D \cdot C_{gdk}}{H_D \cdot \Lambda_D \cdot P_{ZD}}$$

An analysis of the dimensions and magnitudes of the measurements included in the previous formula shows that after their substitutions, the proportionality factor, in turn, may have different dimensions.

In Fig. 5, the most “expressive” is the danger zone with respect to the section B-C1-E, bounded by the lines on which the stations B, C, E, B and the geographical centers of the sections are designated as C2 and within which there are

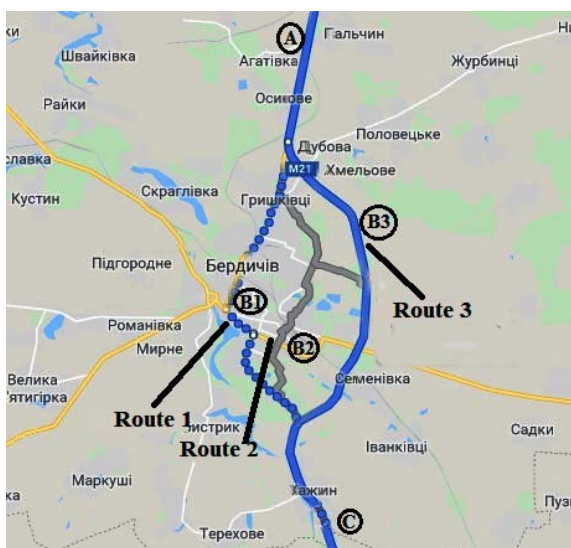


Fig. 3. Scheme of possible road routes of transportation of hazardous waste, taking into account the possible consequences of a transport event

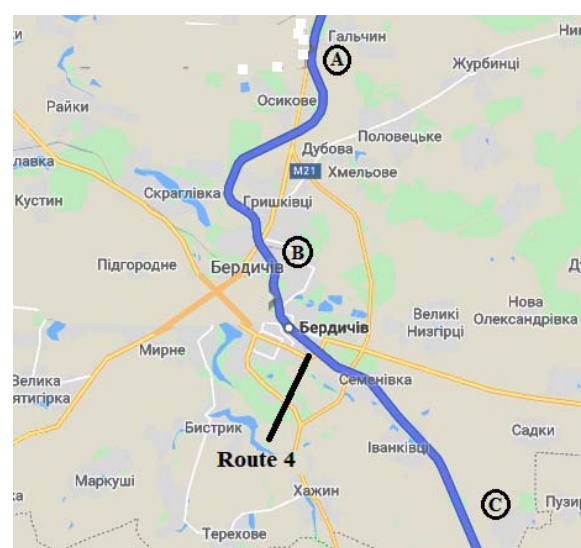


Fig. 4. Scheme of possible rail routes for the transportation of hazardous waste, taking into account the possible consequences of a transport event

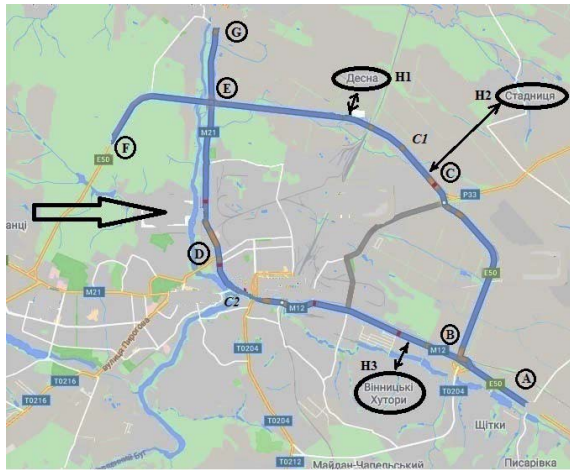


Fig. 5. Scheme of zones and distances when transporting hazardous waste:

– geographical boundaries and center of the settlement;  

 – the prevailing wind direction; – distance hazards

populated items H1 and H2. The settlement H3 is already in another zone of danger, which is formed in relation to another direction of wind and another section B-C2-B-E.

Fig. 4 and its explanations show that the boundaries of the danger zones may be variable depending on the wind direction and the configuration of the railway network. The hazard index is also variable – for this reason and for other reasons, such as different maximum permissible concentrations of dangerous substances being transported.

The analysis and improvement of the dangerous goods transport system, for example, by rail, should be carried out on the basis of a criterion which must take into account the need to minimize the risk of dangerous goods transport events and to eliminate the consequences of accidents involving dangerous goods as quickly and efficiently as possible. At the same time, using the principles of a systematic approach and the application of the specified comprehensive security criterion, it will be possible to correctly and effectively solve the set tasks.

One of the routes is selected where this criterion is  $\sum P_{ij} \rightarrow \min$ . It is proposed to establish as a product of partial criteria  $\bar{R} = K_1 \cdot K_2 \cdot K_n$ , where the partial criterion  $K_1$  is defined as follows:  $K_1$  – a minimum of man-hours of exposure of the population and transport personnel to the potential accident factors (risk criterion). This criterion is explained by an example (Fig. 6).



Fig. 6. Scheme for defining complex and partial security criteria:

– the direction of movement of dangerous goods; – the geographical center and boundaries of the settlement and the location of disaster relief facilities

$$K_{1_1} = \sum P_{i1} = \frac{L_1}{V_1} \cdot \sum_{i=1}^{S=1} P_{ij} \quad \text{– for route 1;}$$

$$K_{1_2} = \sum P_{i2} = \frac{L_2}{V_2} \cdot \sum_{i=1}^{S=2} P_{ij} \quad \text{– for route 2,}$$

where  $L_j$  is the length of the  $j^{\text{th}}$  route, km;  $V_j$  is route speed, km/h;  $S_j$  is the number of settlements on the  $j^{\text{th}}$  route;  $P_{ij}$  is population of the  $i^{\text{th}}$  in the direction of movement of the settlement on the  $j^{\text{th}}$  route;  $K_2$  is a minimum of man-hours of the factors of the accident that occurred before its elimination. By analogy for each route

$$K_2 = \sum_{j=1}^M \left( \frac{d_{ij}}{V_{ij}} + t_{jk} \right) P_{ij} \rightarrow \min,$$

where  $M$  is the number of possible routes;  $d_{ij}$  is a distance of disaster relief facilities to the conditional geographical center of the  $i^{\text{th}}$  settlement on the  $j^{\text{th}}$  route;  $V_{ij}$  is estimated speed of delivery of means of elimination of consequences of accidents;  $t_{jk}$  is time of emergency deployment of works from the arrival of a fire (recovery) train to the beginning of liquidation for a  $k$ -type vehicle.

The time to eliminate the consequences of accidents, of course, depends on the technical equipment, the provision of facilities and substances to eliminate the consequences of transport events. Nevertheless, the main factors that determine the timing of the elimination of traffic events are its nature and scale. Therefore, to take into account the time of elimination of the accident itself and the impact of its dangerous factors on people, the environment, etc. is almost impossible, and, therefore, the corresponding additional partial criterion would not make sense.

Therefore, to evaluate the safety of the transportation system, one can apply the two criteria above and evaluate the safety of the selected route taking into account its geographical, demographic, and other characteristics, as well as the deployment of remedies through a complex criterion

$$\bar{R} = \frac{L_j}{V_j} \sum_{i=1}^{S_j} \sum_{j=1}^M P_{ij} \sum_{i=1}^{S_j} \sum_{j=1}^M \left( \frac{d_{ij}}{V_{ij}} + t_{jk} \right) P_{ij} K_n \rightarrow \min.$$

It is worth noting that the criterion  $\bar{R}$ , which is equal to  $K_1 \cdot K_2 \cdot K_n$ , is sufficient for the purpose of this study and is not necessarily comprehensive, covering all factors of the dangerous goods transport system.

For example, the criterion  $K_2$  takes into account only the period from the occurrence of transport events (accident, catastrophe) with dangerous goods until the beginning of its consequences. However, even during the entire period of liquidation, dangerous factors of the accident continue to affect peo-

ple, the environment, infrastructure and rolling stock, which is theoretically possible to be considered by another criterion (conditionally  $K_n$ ). However, this is beyond the scope of this study.

**Conclusions.** The parameters of the transport network and their influence on the magnitude of the risk of an emergency situation and possible accidents in the transportation of hazardous waste (THW) have been established. Hazardous effects that can be caused by THW with the parameters of road, transport network, type and modes of transport, and so on are analyzed. To minimize the risk of accidents during THW, it is proposed to use appropriate approaches and a comprehensive safety criterion  $R$  based on the products of the criteria  $K_n$  of relevant risks, which allow assessing the safety of the transportation system and the chosen route.

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## Удосконалення методології обґрунтування безпечних маршрутів транспортування небезпечних речовин і вантажів

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**Мета.** Удосконалення існуючих методів прокладання безпечних маршрутів при транспортуванні небезпечних речовин і матеріалів, у тому числі відходів.

**Методика.** У роботі використовуються методи математичного моделювання, методи статистики, методи прогнозування ризиків і віддалені наслідки для навколишнього середовища. З урахуванням часових факторів ураховується розподіл населення на різні ділянки автомобільних доріг і залізничних колій.

**Результати.** У роботі встановлені параметри транспортної мережі та їх вплив на величину ризику аварійної ситуації й можливих нещасних випадків при транспортуванні небезпечних відходів (ТНВ). Здійснено аналіз небезпечних ефектів, що можуть бути викликані ТНВ з урахуванням параметрів дороги, транспортної мережі, типу й видів транспорту тощо. Для мінімізації ризиків аварій під час ТНВ запропоновано використовувати відповідні підходи та критерії  $K_1$  і  $K_2$ , що враховують найменші значення небезпечних впливів на людину протягом часу перевезень, які дозволяють оцінити безпечність системи перевезень і обраного маршруту, а їх добуток урахує всі можливі основні фактори системи перевезень. Визначені типові схеми ТНВ автомобільним і залізничним транспортом, що забезпечують мінімальну кількість аварійних випадків і зменшують небезпеку для довкілля й людини.

**Наукова новизна.** Удосконалені підходи до перевезення небезпечних речовин автострадою та залізницею, зокрема, урахувані параметри кривизни та кута нахилу дороги, наявність населених пунктів і мостів, метеоумови й вантаженість шляху, що дозволяє підвищити ефективність і безпечність транспортування небезпечних речовин і матеріалів.

**Практична значимість.** Запропоновані оригінальні та вдосконалені існуючі математичні моделі побудови маршруту транспортування небезпечних речовин, що включають такі параметри дороги, як масштаб зони, потенційно залученої в нещасний випадок і щільність населення в зоні можливого впливу. Отримані результати досліджень можуть бути використані транспортними компаніями, органами державної влади при перевезенні небезпечних речовин і логістиці небезпечних виробництв.

**Ключові слова:** екологічна безпека, транспортування небезпечних відходів, безпечні маршрути перевезень, ризику аварій

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