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METHODOLOGY FOR SELECTING OPTIMAL ROUTES FOR THE TRANSPORTATION OF DANGEROUS GOODS IN CONDITIONS OF RISK UNCERTAINTY*

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* A risk situation is a type of uncertainty situation where events are likely to occur. In other words, risk is an estimated probability, and uncertainty is something that cannot be quantified. The greater the uncertainty when making a decision, the greater the degree of risk.

The investigation is devoted to the development of a unified methodology for selecting optimal (from the proposed alternatives) routes for transporting dangerous goods (any of the 9 standard classes) by road.

A model for determining two groups of risk components for transporting dangerous goods on separate routes is proposed, namely: parameters of risks of probability of occurrence of emergency situations and parameters that affect the risks of complexity of eliminating their possible consequences. This opened up opportunities for correct selection of criteria when forming a multi-criteria optimization problem of transportation.

Mathematical algorithms for a comprehensive solution of the multi-criteria optimization problem of routing dangerous goods transportation are developed using the classical criteria of Laplace, Wald, Savage, and Hurwitz.

To confirm the legal capacity of the proposed approach and mathematical apparatus, the optimal route for transportation of cylinders with technical gases through the transport network of Lutsk was calculated. Possible alternative transportation routes have been identified and safety criteria have been formalized for two groups of risk components

Keywords: Optimal routes, risk uncertainty, risk components, multi-criteria optimization, alternative routes

1. Introduction

The rapid development of new and improvement of existing technologies requires continuous improvement of production processes in industry. As a result, enterprises are increasingly using hazardous substances that pose a real threat to both humans and the environment. Various explosive or chemically or radially toxic substances are objects of consumption, production and disposal.

There are many enterprises that need to be provided with such cargo on a daily basis in order to avoid stopping production or activities in general. For example, construction companies (technical gases are constantly needed), hospitals (acids, medicines, technical gases), gas stations (gasoline, gas), airports and airfields (gasoline), etc.

As a result, transport flows to the storage, accumulation, concentration, distribution and processing of such substances are an integral part of logistics processes (Bhattarai, 2020; Soysal *et al.*, 2015).

It should be noted that for modern society, the risk of consequences of using potentially dangerous substances and materials is obvious, and the stages of handling these substances are legally fixed at the International and state levels Approved Requirements and Test Methods for the Classification and Packaging of Dangerous Goods for Carriage (1996) (Holeczek, 2019).

As indicated in the UN documents, the share of dangerous goods in the world cargo turnover now reaches half. In the volume of cargo transported in the EU countries by all modes of transport, the share of safe is about 20%. Road transport accounts for up to 65% of these and these figures are steadily growing.

The main trends affecting the increase in the share of transportation of dangerous goods by road in Ukraine are the expansion of the fleet of trucks for various purposes and the constant growth and improvement of the road network of settlements. The effective competitiveness of short-distance road transport also has a certain impact.

In addition, the leadership of road transport in the volume of cargo transportation is explained by its high manoeuvrability and the ability to deliver cargo according to the "from warehouse to consumer" scheme with the necessary urgency. Transportation of goods by road is characterized by low tariffs, in comparison with other modes of transport; provides availability of timely delivery of goods, the possibility of delivery in small batches; puts forward less stringent requirements for cargo packaging. At the same time, it should be noted that road transport is characterized by a wider range of dangerous goods allowed for transportation, compared to other types of cargo transport, of the European agreement on the international transport of dangerous goods (2019).

However, road transport is a potential source of increased danger in the transport of dangerous goods (Izdebski *et al*., 2022). Therefore, the problem of transportation of dangerous goods (hereinafter referred to as DG) is quite an urgent task, due to high risks (Guo and Luo, 2022), high probability of negative impact on the environment (Ellram, 2021; Ülkü, 2012), as well as causing damage to people's health and property.

2. Literature Review

The process of transporting DG is the weakest link in terms of vulnerability and susceptibility to unauthorized events, compared to stationary objects. The protection of DG on vehicles, unlike stationary objects, does not have such a multi-structured security system and cannot use the usual set of equipment and technical means for early detection of danger, its assessment and response measures (Derse *et al*., 2022; Batarliene, 2020). In this regard, risk management for the transportation of DG is reduced to ensuring conditions for trouble-free movement of the vehicle along the selected route (Lundin, 2018; Conca *et al*., 2016).

Despite the fact that in Ukraine the number of accidents involving vehicles involved in the transportation of DG seems insignificant, compared to other transportation, the potential risk of serious emergencies that endanger the lives of a large number of people is much higher, and the damage caused to the environment is estimated in millions of hryvnias (Assael *et al*., 2015; Ma *et al*., 2022).

In world practice, there are a number of methods that solve the problem of determining, from a number of options, the safest routes for the transportation of DG. These include routing algorithms developed by Zografos and Androutsopoulos (2004, 2008), Leonelli *et al*., (2000), and others. For more information, methods for determining traffic risk are presented in Batarlienė (2018) and Rao *et al*., (2004).

However, in these works there is no general methodology and approaches to solving the problem of choosing, from alternative, optimal route of transportation of DG. The most important is the fact that the criteria for optimization are not ordered and the importance of everyone's influence on the results of solving the problem is not formalized. Therefore, the development of a methodology for choosing the safest route for transporting a particular dangerous cargo according to certain criteria is an extremely important task.

3. Research Methodology

It is clear that the developed methodology should include all possible, or at least the most important elements that affect or may affect the choice of the optimal route for the transport of dangerous goods from certain alternatives. The methodology should be based on a formalized representation and calculation of all possible risks in the delivery of DG from the point of delivery to the destination.

A car is a high-risk vehicle, primarily due to the rather high probability of a road accident, which is very likely to harm people's lives and health and create unfavourable conditions for the environment. Therefore, when developing possible routes for the transportation of DG, it is necessary to perform a number of procedures.

The stage of determining the main criteria and parameters for choosing transportation routes opens up the possibility of analysing them to meet the following conditions:

- the selected routes must comply with the current legislation on the transport of DG and must not have any legal or physical restrictions on the transportation of DG on all sections;
- each of the routes is able to ensure the possibility of unhindered (i.e., without delays) movement of vehicles on all sections of the route when transporting dangerous cargo;
- each provides the ability to move heavy-duty bulky vehicles with minimizing the distances of transportation of DG from the supplier to the destination;
- each selected route is able to minimize the number of zones and their area in case of emergencies during the transportation of DG.

After determining the basic alternative routes for the transportation of dangerous goods from a specific supplier to the consumer, parameters and criteria for choosing transportation schemes, it is necessary to study them according to the degree of risks.

To study the level of emergency risks on each of the basic routes, it is necessary to select assessment criteria and, based on them, build a model for determining the optimal route for transporting DG, based on possible risks.

Let us highlight two main components of risk. The first is the risk of an emergency and the consequences of its negative impact on the environment. The main parameters that affect the probability of an emergency during the transportation of DG include:

- highway class;
- traffic intensity on the route;
- geometric parameters of individual road sections;
- road surface condition;
- speed limit on land plots;
- length of curved and rectilinear sections;
- number of traffic lights, secondary intersections, pedestrian crossings, and railway crossings on the route;
- visibility on certain road sections;
- quality control of vehicle admission to Operation;
- accident statistics and other factors.

The second group of risk parameters is parameters that affect the difficulties of emergency response on the route:

- parameters of building density along the route, distance from the built-up area to the road;
- spatial scale parameters or affected area;
- parameters for assessing the impact of accident consequences over time;
- parameters of accident impact intensity;
- drainage system quality parameters on the route;
- environmental impact parameters;
- parameters for the location of emergency service units, and so on.

All of the above parameters of possible risks are not the same in terms of their impact on Route security. Therefore, when solving specific optimization problems for designing routes for transportation of DG it is necessary to rank the impact of each of them, using different methods, in particular the method of expert assessments.

When forming the criteria of the optimization problem for the transportation of DG, in addition to the classic parameters for choosing the optimal route related to the distance, time of transportation, cost of transportation. The criteria and parameters of transportation safety are of considerable importance, minimizing the risks of both transportation and elimination, in case of emergencies, the consequences of an accident.

The first group of risk components, as noted above, are parameters that affect the probability of occurrence of dangerous situations during the transportation of DG. To formalize the risks of emergency situations during the transportation of dangerous goods on sections of the route using the method of final accident criteria is proposed. According to this method, the degree of danger of individual sections of the route is characterized by the final accident criterion K_n:

$$K_n = \sum_{s=1}^{m} \varphi_s K_{n,s} \,, \qquad (1)$$

where n is number of criterion; s is number of route section; $K_{n,s}$ is selected accident criterion in a characteristic area; φ_s is percentage influence of the section on the value of the final route criterion.

According to (Lobashov, 2011), each selected accident criterion on a route section represents the ratio of the number of registered “emergency events” to the number of accidents on the reference section. Reference-a straight section of a two-lane road without longitudinal slopes, with solid roadsides, asphalt or cement-concrete pavement, and a roadway width of more than 7.5 m is considered a straight section.

Each K_i criterion selected for risk assessment should take into account the impact on the safety of DG transportation: the traffic intensity on the section and route as a whole, the width of the roadway, the width and type of roadsides, the number of slopes, the composition of traffic flow, etc.

The method of accident criteria (Table 1) is particularly convenient for predicting the risks of transportation of DG on the route and allows you to find, from alternative schemes, the most optimal route option when planning transportation.

Table 1. Significance of accident risk criteria (Lobashov, 2011)

Indicator	**Value**					
Traffic intensit cars/day	500	1000	3000	5000	7000	>9000
K_1	0.4	0.5	0.75	1.0	1.3	1.7
Roadway width, m.	4.5	5.5	6	7.5	>8.5	
K_2 (with reinforced roadsides)	2.2	1.5	1.35	1	0.8	
K_2 (for loose rims)	4	2.75	2.5	1.5	1	
Sidewall width, m.	0.5	1.5	2	3		
K_3	2.2	1.4	1.2	1.0		
Longitudinal slope, %	20	30	50	70	80	
K_4	1.0	1.25	2.5	2.8	3.0	
Radius of curves in the plan, m.	<50	100	150	200–300	400–600	1000–2000
K_5	10	5.4	4	2.25	1.6	1.25
Road visibility, m.	100	200	300	400	>500	
K_6 in the plan	3	2.25	1.7	1.2	1.0	
Length of straight sections, km.	3	5	10	15	20	25
K_7	1.0	1.1	1.4	1.6	1.9	2.0
List of intersections at the same level as the road, m.	>60	60–40	40–30	30–20	<20	
K_8	1	1.1	1.65	2.5	10	
Number of lanes on the roadway			4 without a dividing line	4 with a dividing line		
K_9	1	1.5	0.8	0.65		
Distance from the building to the roadway and its characteristics, m.	50-20 are local traffic lanes and sidewalks	20-10 are local traffic lanes and sidewalks	10 no local traffic lanes, there are sidewalks	10 no local traffic lanes or sidewalks		
K_{10}	2.5	5	7.5	10		
Coefficient of adhesion. Coating characteristics.	0.2–0.3 Slippery, dirty	0.4 Slippery	0.6 Clean, dry	0.7 rough	0.75 Very rough	
K_{11}	2.5	2	1.3	1.0	0.75	

The scheme of the transport network, in the general statement of the problem, is defined as a graph. It is necessary to transport dangerous goods from the starting point to the final point and choose the best route for transportation, based not only on economic, but also on safety criteria.

Several alternative routes of delivery of DG are defined, where the main criteria for their selection are the average distance between the points of "departure-delivery" and the time of transportation. For each of the alternative routes, a set of criteria is selected by which it will be analysed.

The next step is to determine the characteristic sections of the route based on a specific criterion of accident risks. The results of the analysis are summarized in a table.

The impact of each section on the resulting final criterion along the route as a whole is calculated taking into account the relative length of the section as a percentage.

For example, according to (1), The Criterion K_1 – traffic intensity on the route can be determined by the formula:

$$K_1 = 0.35K_{1,1} + 0.25K_{1,2} + 0.4K_{1,3} \, . \tag{2}$$

The same method is used to determine the impact of all risk criteria on the route.

The second group of risk components is the risks associated with the complexity of eliminating the consequences of "emergency situations" during the transportation of dangerous goods. It is proposed to formalize the significance of the consequences of possible accidents during the transportation of DG due to their impact on the environment and the population.

In most assessments of emergency situations that may occur during the transportation of DG it is difficult to determine the quantitative significance and rate of spread of negative consequences of an accident for the social sphere and the environment. Our proposed methodology is a "semi-quantitative" assessment, which is based on the expression in points of certain environmental and social changes in the environment in the event of accidents on routes.

The significance and complexity of anthropogenic environmental disturbances at all levels can be assessed by the following parameters:

- parameters of the spatial scale of building density on Route sections;
- parameters of the building distance from the roadway of the Route section;
- parameters of public traffic activity on sections of the route;
- parameters of the intensity of emergency exposure;
- parameters of proximity to the base of emergency services.

Comparison of the values of the action measure for each parameter is evaluated on a point system according to the developed criteria. Each criterion is based on the practical experience of specialists obtained when performing similar studies and measurements. At the same time, a 4-point assessment system has been adopted, since any cargo transportation activity will have a certain negative impact of transport processes on the environment. Zero effect will be only in the complete absence of transportation, even safe cargo.

The procedure for determining the parameters of the spatial scale of building density on sections of the route is proposed to be carried out by calculating and comparing fractal indicators of characteristic zones of the city development plan, which are formed on the route and are 50 m in each direction of the road (Figure 1). In the works (Pustiulha *et al.*, 2017, 2020), a fractal technique is proposed that makes it possible to link the fractal dimension of objects with the technological properties of production processes, including in the field of Transportation. Algorithms for preparing the studied models and methods for determining their fractal characteristics have been developed to predict the influence of fractal dimension on trends in finding effective solutions to production problems. Using the results of the above-mentioned studies, the characteristic of the density of buildings on the route section is determined through the fractal dimension of individual sections of road transport on the route of the calculated length and is presented:

$$K_{b.d.} = \frac{D}{L}, \tag{3}$$

where D is fractal dimension of the calculated section; L is length of the calculated section,
and the gradation of building density levels is adopted on the basis of expert assessments and is presented in Table 2.

Table 2. Gradation of building density levels

Gradation	Characteristics $K_{b.d.}$	Risks of damage to buildings	Point K_{12}
Lack of buildings	<1.1	up to 10%	1
Moderate building density	1.1-1.4	up to 40%	2
Average building density	1.4-1.6	to 60%	3
High building density	>1.6	more 60%	4

By analogy, for each of the alternative routes of the transport network, when transporting DG, the points for the remaining indicators of the criteria of the first (K_1, ..., K_{12}) and second groups (K_{13}, ..., K_n) are formed.

The resulting final criterion for the route as a whole for each group of parameters is taken as the worst, which characterizes the risks of an accident and the complexity of eliminating its consequences when transporting DG along the route.

Above, many criteria were defined that directly and indirectly affect the risks of transporting dangerous goods along a particular route. That is, in addition to the basic indicators for cargo transportation (delivery cost and time), the choice of the optimal route is significantly influenced by two groups of transport safety components. These groups are the risks of the likelihood of accidents on the route and the risks associated with the difficulties of eliminating their consequences. Such optimization problems belong to the class of multi-criteria, and the choice of the most rational route for certain impact parameters is based on the method of decision-making under conditions of uncertainty.

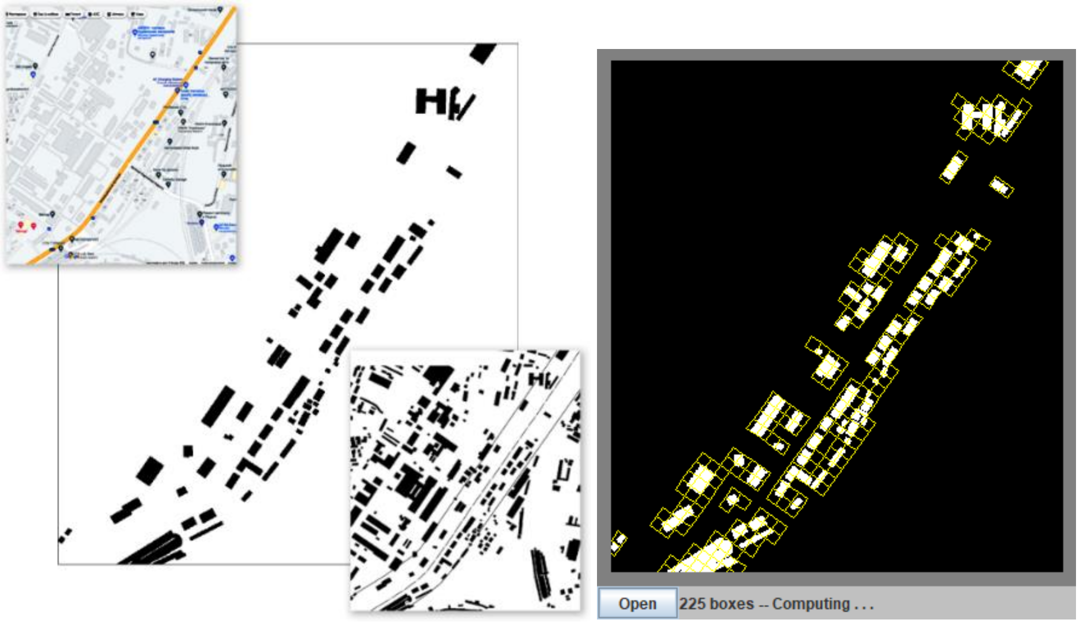


Figure 1. Fractal model of the Route section and determination of the fractal dimension that characterizes the level of building density on the Route section

The most well-known criteria for making a decision under uncertainty are the Laplace, Wald, Savage, and Hurwitz criteria (Blecher, 2011). The basis for calculations (in our case) is a set of alternative route schemes for transportation of DG and technological parameters of routes determined according to the proposed method. The data is generally represented by a matrix with normalized values of transportation parameters:

$$\begin{vmatrix} R_1 & C_1/\min C & T_1/\min T & K_{1,1}/\min K_1 & K_{2,1}/\min K_2 & \dots & K_{12,1}/\min K_{12} & K_{13,1}/\min K_{13} & K_{14,1}/\min K_{14} & \dots & K_{j,1}/\min K_j & W_1(R_1) & W_2(R_1) & W_3(R_1) & W_4(R_1) \\ R_2 & C_2/\min C & T_2/\min T & K_{1,2}/\min K_1 & K_{2,2}/\min K_2 & \dots & K_{12,2}/\min K_{12} & K_{13,2}/\min K_{13} & K_{14,2}/\min K_{14} & \dots & K_{j,2}/\min K_j & W_1(R_2) & W_2(R_2) & W_3(R_2) & W_4(R_2) \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ R_n & C_n/\min C & T_n/\min T & K_{1,n}/\min K_1 & K_{2,n}/\min K_2 & \dots & K_{12,n}/\min K_{12} & K_{13,n}/\min K_{13} & K_{14,n}/\min K_{14} & \dots & K_{j,n}/\min K_j & W_1(R_n) & W_2(R_n) & W_3(R_n) & W_4(R_n) \end{vmatrix} \quad (4)$$

where R_i – *i-th* route; C_i is cost of transportation; T_i – time; $K_1 ... K_{12}$ are parameters that affect the risks of accident probability; $K_{13} ... K_j$ are parameters that affect the risks of complexity of emergency response; W_1 is Laplace Criterion; W_2 is Wald Criterion; W_3 is Savage Criterion; W_4 is Hurwitz Criterion,

the analysis of which does not allow you to immediately choose the optimal route for transporting dangerous cargo, taking into account all the parameters of transportation and their ranking by importance. In addition, to get comparable results, the values of the parameters in the columns are normalized to relative values by dividing each of them by the minimum.

Choosing a decision-making criterion in conditions of complete uncertainty is the most difficult and responsible stage of the problem-solving process. In particular, if even minimal risk on the route is unacceptable, then the Wald criterion is crucial for the decision. If, on the contrary, certain risks may occur and the DG transportation specialist wants to get a greater financial result, it is necessary to focus on the Savage criterion.

In general, the most optimal route for transporting dangerous goods is the one where all 4 criteria in matrix (4) have minimal values.

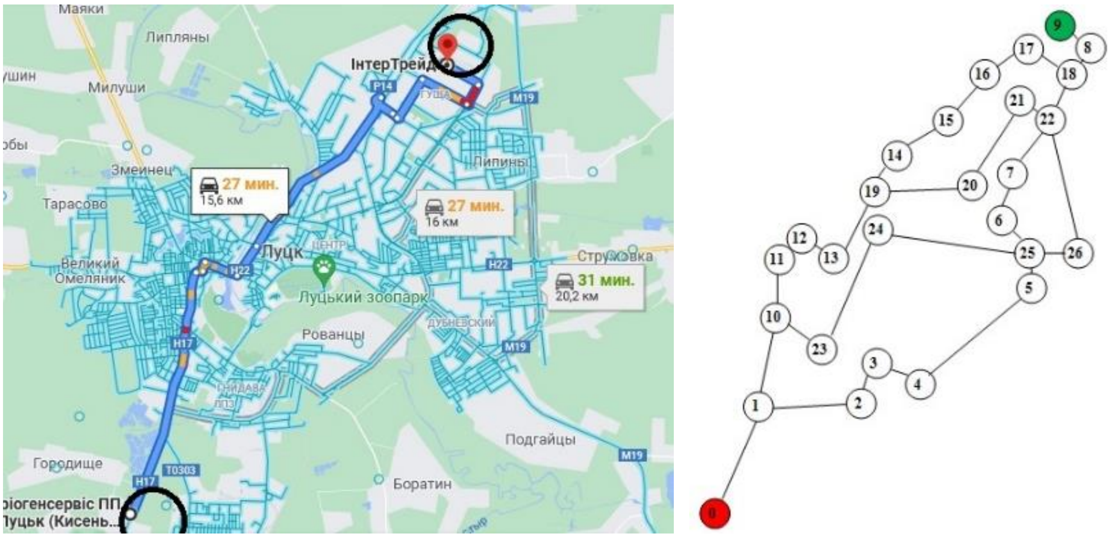
4. Results and Discussions

To confirm the legal capacity of the developed methodology for choosing the optimal route for the transportation of dangerous goods, the task was set to develop a model for the transportation of technical gases (oxygen, acetylene, carbon dioxide) from the manufacturer “Cryogenservice” to the enterprise “Intertrade” in Lutsk. The company “Intertrade” is a powerful manufacturer of reinforced concrete products in Lutsk. For the manufacture of reinforcing frames and grids for floor slabs, staircases, various kinds of lintels, the company needs a large amount of industrial gases. Such a supplier is the company “Cryogenservice”. The location of both businesses is shown on the map (Figure 3).

According to the state standard of Ukraine DSTU 19433-88 “Dangerous goods. Classification and marking” technical gases transported by “Cryogenservice” belong to Class 2, namely compressed, liquefied and dissolved gases under pressure. For the delivery of technical gases, the supplier uses a MAZ 5340C3-520 vehicle with a load capacity of 10 tons. Transportation can be carried out on 5 alternative routes with a length from 14.83 km to 17.22 km each (Figure 2a).

Based on alternative route schemes, a graph is constructed with characteristic sections of each route (Figure 2b). According to the column, the routes are numbered as follows:

- Route 1 – 0-1-2-3-4-5-6-7-8-9 is 15.71 km long;
- Route 2 – 0-1-11-12-13-19-14-15-16-17-18-8-9 is 15.2 km long;
- Route 3 – 0-1-2-3-4-5-25-26-22-8-9 is 16.08 km long;
- Route 4 – 0-1-10-23-24-25-6-20-21-22-8-9 is 17.22 km long;
- Route 5 – 0-1-11-12-13-19-20-21-22-8-9 is 14.83 km long.



a *b*

Figure 2. Routes of delivery of industrial gases from the manufacturer “Cryogenservice” to the enterprise “Intertrade” (Lutsk):
a – diagram of alternative delivery routes;
b – graph with characteristic sections of alternative routes

In accordance with the developed methodology and critical parameters of transportation safety, the specific sections for each of the accident risk criteria for each of them are selected, using the values (Table 1). An example of collecting parameters for route 1, with values normalised to relative values, is shown in Table 3. The same principle is used to generate parameters for all routes that affect the risks of accidents during transportation.

Similarly, according to the point system, for each of the routes, criteria for the parameters of the second Hazard group are formed, which affect the risks of complexity of eliminating the consequences of possible emergencies during the transportation of DG.

Table 3. An example of collecting parameters for route 1 according to the criteria of the first group

Routes	L, km	Parameters that affect the risks of accident probability									
		K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{11}
Route 1 0-1-2-3-4-5-6-7-8-9	15.71 km	0.53	1.18	1.16	1.15	3.14	2.02	1.4	1	0.83	1.25
0-1-2-3-4-5	60%	0-1-2-3-4-5	0-1-2-3-4-5	0-1-2-3-4-5	0-1-2-3-4-5	2-3-4	1-2-3	0-1-2-3-4-5-6-7-8-9	0-1-2-3-4-5-6-7-8-9	1-2-3	1-2-3
		0.5	1.35	1.2	1.25	4	2.25	1.4	1	0.8	1.3
5-6-7	15%	5-6-7	5-6-7	5-6-7	5-6-7	6-7	5-6	5-6-7	5-6-7	5-6-7	5-6-7
		0.75	0.8	1	1	2.25	1.7	1.4	1	1	1
7-8-9	25%	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9	7-8-9
		0.4	1	1.2	1	1.6	1.7	1.4	1	0.8	1.3

The resulting matrix of characteristics of five alternative routes (R_1 – R_5) for the transportation of industrial gases from the supplier to the final destination, company Intertrade, is shown in Table 4.

To determine the optimal route for transporting DG, the criteria of Laplace, Wald, Savage and Hurwitz will be used. The methodology for calculating the criteria will be shown using the example of the first route R_1 0-1-2-3-4-5-6-7-8-9.

Laplace Criterion. According to Table 4, the assessment is carried out on 12 parameters, including both economic indicators of DG transportation and safety parameters.

Table 4. Calculation of risk criteria for transportation on alternative routes for the transportation of industrial gases

Routes	Route length km	Travel time min	Cost of Transportation, UAH	Components of DG transport risks									
				Parameters that affect the probability of an accident					Parameters that affect the risks of complexity of eliminating the consequences of a possible emergency				
				Traffic intensity on Route-K_1	Geometric parameters of the road – K_2, K_3, K_4, K_5, K_6	Lengths of straight and curved sections – K_7	Visibility of secondary road intersections on route – K_8	Road surface condition, coefficient of adhesion – K_{11}	Parameters of the spatial scale of building density – K_{12}	Parameters of the distance to the roadway – K_{10}	Parameters of population movement activity – K_{13}	Emergency intensity parameter – R_{14}	Parameter for the proximity of the emergency rescue base. Services – K_{15}
R_1 0-1-2-3-4-5-6-7-8-9	15.71	1	1	1.26	1.08	1.09	1	1.2	1.5	2	2	2	1.5
R_2 0-1-11-12-13-19-14-15-16-17-18-8-9	15.2	1.25	1.05	1	1	1	1	1.21	1.5	2	1	2	1.5
R_3 0-1-2-3-4-5-25-26-22-8-9	16.08	1	1	1.14	1.03	1.03	1	1	1	1	2	1	1
R_4 0-1-10-23-24-25-6-20-21-22-8-9	17.22	1.44	1.12	1.21	1.13	1.05	1.2	1.25	1.5	2	3	2	1
R_5 0-1-11-12-13-19-20-21-22-8-9	14.83	1.19	1.02	1.45	1.08	1.05	1.2	1.25	1.5	1	3	2	1.5

According to the Laplace principle "states of nature", and therefore the parameters of the optimization problem are equally probable, risks are calculated from the expression:

$$W_1(R_1) = \frac{1}{12}\ (1+1+1.26+1.08+1.09+1+1.2+1.5+2+2+2+1.5) = 0.083 \cdot 16.63 = 1.38\ .$$

Wald criterion. Since this is a criterion for guaranteed results, it is based on the principle of least risks, that is, choosing the best value from the worst routing strategies:

$$W_2(R_1) = \max(1, 1, 1.26, 1.08, 1.09, 1, 1.2, 1.5, 2, 2, 2, 1.5) = 2\ .$$

Savage criterion (minimum risk criterion) is calculated in terms of risks using the formula:

$$W_3(R_1) = \max(0, 0, 0.26, 0.08, 0.09, 0, 0.21, 1, 1, 1, 1, 0.5) = 1\ .$$

Hurwitz criterion. Let $\alpha = 0.5$. The optimal solution is to calculate $W_4(R_1)$ using the formula:

$$W_4(R_1) = (0.5 \cdot 1 + 0.5 \cdot 2) = 1.5\ .$$

Using the same principle, the criteria for all alternative routes of transportation of DG are found, and the results are entered in Table 5.

Table 5. Laplace, Wald, Savage and Hurwitz criteria for all alternative industrial gas transport routes

Routes	**Route length, km**	**Laplace criterion**	**Wald criterion**	**Savage criterion**	**Hurwitz criterion**
R_1, 0-1-2-3-4-5-6-7-8-9	15.71	1.38	2	1	1.5
R_2, 0-1-11-12-13-19-14-15-16-17-18-8-9	15.2	1.29	2	1	1.5
R_3, 0-1-2-3-4-5-25-26-22-8-9	16.08	1.08	2	0.4	1.07
R_4, 0-1-10-23-24-25-6-20-21-22-8-9	17.22	1.49	3	2	2
R_5, 0-1-11-12-13-19-20-21-22-8-9	14.83	1.43	3	1	2

Analysis of the table shows that the optimal route for 12 calculated parameters is Route R_3 – (0-1-2-3-4-5-25-26-22-8-9), which has minimal indicators, i.e. risks, for each of the assessment criteria in conditions of uncertainty. The result obtained is explained by the significant influence of such parameters of route characteristics as: traffic intensity of vehicles on the Route, road surface parameters, the number of traffic lights and pedestrian crossings on the route, the density of buildings and the activity of the population on sections of the route.

5. Conclusions

The above studies allow us to conclude that the process of transporting dangerous goods by road is the most complex type of freight planning in terms of the risks of unforeseen emergencies along the route. It requires the analysis and consideration of a number of sometimes contradictory criteria that can be used to select the optimal route from the point of view of accident-free transport.

Therefore, in accordance with the purpose of the research, the paper develops a methodology and formalised algorithms for selecting optimal routes for the transportation of dangerous goods, taking into account the risks according to two groups of criteria: group 1 – parameters characterising the risks of the probability of emergency situations and their impact on the environment, group 2 – parameters describing the risks of the complexity of eliminating the possible consequences of such emergency events.

The authors have found that all the risk parameters under consideration do not have the same impact on predicting the safety of both the route of transportation of dangerous goods as a whole and its individual sections. To solve this problem, the paper proposes expert methods for ranking the importance of safety criteria on the route and algorithms for calculating the final accident rate.

In order to verify the reliability of the results of formulating and solving a multi-criteria optimisation problem with consideration of 2 groups of safety criteria, the paper considers a specific practical task of choosing the optimal route for the transportation of dangerous goods, namely, technical gases, in terms of safety indicators. These calculations can serve as a basis for planning logistics chains for the transport of other categories of dangerous goods, taking into account economic and safety requirements.

The scope of the publication did not allow the authors to include the results of all the studies conducted, which could have removed some controversial issues. However, the approach proposed in this paper to the multi-criteria optimisation problem of selecting routes for the transport of DG and the methods for solving it is universal in nature and has prospects for expanding both the number of numerical parameters for analysing the two risk groups and the ways to improve the calculation model itself.

Another promising area for further research concerns the problem of selecting characteristic areas on alternative routes for the transport of dangerous goods, which in this paper is based on the methodology of expert assessments and ranking. The authors have already tested algorithms for the formalised selection of characteristic sections using fractal evaluation of the route map according to one of the criteria, and are conducting research on algorithmisation and consideration of the remaining safety criteria based on their fractal representation.

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