Formulation of the mathematical model for the planning system in the carriage of dangerous goods by rail

To cite this article: S Bibik *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **985** 012024

Formulation of the mathematical model for the planning system in the carriage of dangerous goods by rail

S Bibik[1], O Strelko[2], H Nesterenko[1,4], M Muzykin[1,5] and A Kuzmenko[3,6]

[1]Dnipro National University of Railway Transport named after academician V Lazaryan, Lazaryan Str., 2, 49010, Dnipro, Ukraine
[2]State University of Infrastructure and Technology, Kyrylivska Str., 9, 040071, Kyiv, Ukraine
[3]University of Customs and Finance, St. Volodymyra Vernadskoho, 2/4, 49010, Dnipro, Ukraine

[4]galinamuzykina@rambler.ru, [5]mihailmuzykin@gmail.com, [6]alia1971@i.ua

Abstract. The paper aims to the topical issue of improving the system in the planning of carriage of dangerous goods by rail subject to ensuring a high level of safety of the transport process and minimal costs for its implementation. Formalization of this process leads to the formation of an optimization task of the two-stage mathematical model. To implement the first stage, a mathematical model in searching the best route based on risk minimization is developed. In order to exclude the unacceptably complex and expensive options for the carriage of dangerous goods from the many possible routes, the authors abided by the condition not to exceed the critical operating costs. The second stage in the process of planning routes for dangerous goods takes into account the hazard identification study in the technological process of car movement with dangerous goods. Considering that the probability of a potential traffic accident is a complex random variable, which is due to a set of elementary previously unknown events, its estimation was made on the basis of the Bayesian approach. Based on the simulation results, the following reliability values are determined at which a transport accident should not emerge.

1. Introduction

The analysis of reporting data shows that the volumes of carriage of dangerous goods (DG) by Ukrainian railways is constantly increasing. Depending on the basic properties and type of hazard, these goods are transported in covered cars and containers by carloads and part load consignments, and liquid dangerous goods are in tanks. But in case of non-compliance with safe conditions of carriage or storage, such goods can cause disease, poisoning, burns of people and animals, explosion, fire, as well as cause damage to other goods, rolling stock, structures and devices, environmental pollution. Therefore, it is much-needed to pay special attention to the rational organization in the planning of rational routes of trains with dangerous goods and control of their timely and safe movement.

It should be noted that more than 70% of the total turn-around time, freight cars among which there are ones with DG, are located at the stations under technical operations, during which the risk of accidents increases significantly. Thus, railway stations are objects of increased danger associated not only with a high degree in the probability of emergence of accidents but also with the scope of their potential consequences. This determines the relevance of this work, which aims to improve the system in the planning of carriage of dangerous goods by rail subject to ensuring a high level of safety of the transport process and minimal costs for its implementation.

2. Formulation of the problem

Railway transport is a complex logistics system, in which a man always takes part in the management structure. Therefore, achieving absolute security is impossible. But any technology for the carriage of dangerous goods should be based on the use of a criterion of improving traffic safety. The question accordingly arises of the system improvement in the planning of carriage of DG by rail with ensuring the high level in the safety of the transport process and the minimum costs for its implementation by choosing the optimal functioning criteria at the tactical level.

3. Analysis of literary data

Many scientists and practitioners have made a significant contribution to the development in the research on the development of planning and operational management systems for railway transport, technology in the organization of carriage of DG, determination of optimal patterns for the car movement, application of information technology in operational management. For example, authors of article [1] aim to develop a mathematical model that allows to construct the intelligent control system for the operating technique of the station and will be able to minimize the total operating costs, provide simultaneously an acceptable level of risk while the breaking up/making-up of trains including the cars with DG, as well as when performing technological operations with them at the station.

Article [2] highlights a method for determining the rational traffic intensity of car traffic volume on railway transport on the basis of a mathematical model. The mathematical model based on stochasticity and allows optimizing, under risks, the interval between the train movement and the transfer of cars at stations. The simulation results make it possible to find a balance between the costs of railways and cargo owners, including the carriage of DG.

Authors of article [3] discuss the substantial point of non-destructive monitoring and control of mechanical and geometric parameters for the roadbed, which are one of the most important in the practice of safe operation of railways during the organizing of the carriage of DG. It is established that the uncertainty in the motion process of trains over long distances significantly complicates the procedure in the planning of the transport process and ensuring traffic safety. This is due to risk factors in the organization of train traffic. In order to ensure the high reliability of all railway subsystems, the method is proposed for a more accurate analysis of the diagnostic parameters for the roadbed to predict possible deformations and destructions.

Scientific research in the field of the carriage of DG in international traffic is primarily aimed at solving the problems of increasing the safety of transportation and reducing the delivery time of cargo. Paper [4] argues that the issues of improving the technology of passing the trains through the border crossings, where the railways with different track gauge connect, are of great importance. The traditional technology of cars crossing through joints of railways of different standards by means of transshipment or handling, which is connected with the change of track gauge, does not meet the current carriage safety requirements. One of the most effective measures to speed up the carriage and improve safety is to launch the continuous operation of international trains with the use of technologies in the automatic crossing the break-of-gauge with different track width – 1520 mm and 1435 mm. At the carriage of DG, it is proposed to use bogies with a variable gauge SUW-2000 system.

Notably, the concept of risk has been introduced and is widely used in the world science and practice of technogenic safety [5, 6] which made it possible to subsume the danger under the position of categories that are measured. This means that in determining the safety of functioning, it is necessary to scientifically justify from the economic point of view the level of risk (in natural exponents) that can be achieved while ensuring the optimal functioning of transport, taking into account the need to maintain this level of risk with resource facilities The implementation of the transport process associated with dangerous goods is accompanied by the risk of unfavorable events [7]. Therefore, it is important to consider risks when solving the task to justify the process of managing the movement of cars with DG.

The first works to solve the routing task in the carriage of DG appeared in the eighties of the twentieth century. In 1991, George F. List, Pitu B. Mirchandani, Mark A. Turnquist and Konstantinos G. Zografos [8] proposed several mathematical models to optimize the carriage of dangerous goods. In them as a criterion for choosing a route, there were respectively: minimizing the number of people affected by the accident and minimizing the length of the route. In 1985, a model was proposed [9], which allowed to precisely and accurately formulate the consequences of an accident and its impact on the population. A model is constructed on the basis of two criteria. They are the criterion of minimum risk and the criterion of minimum probabilities of an accident. The above models have a different concept of risk, the risk is often interpreted as a subjective value that cannot be measured. In addition, the formulation of multicriteria models at that time did not allow solving large-dimensional problems for choosing a route on a real transport network.

Since the 1990s, with the advent of the Value-At-Risk concept [6], risk began to be identified through the probability of losses. This approach has led to structure the statement of the task in finding the optimal route for the carriage of dangerous goods on condition of risks treatment. This task, as a ruler, boils down to making a choice of the shortest tracks in the transport network, that is, to choose one low-risk route or to find a Pareto-optimal solution where different methods, models and criteria can be used [10].

The model for optimization at the carriage of DG with the use of mathematical programming to calculate the optimal routes is of scientific interest [11]. The optimization task is set in terms of finding the minimum cost of the traffic in the network, where the purpose of seeking is to minimize the total cost of the carriage along the route. Work [12] proposes a distributed decision support system (DDSS) to choose the route for the carriage of dangerous goods. The user's interface was designed involving a geo-information system (GIS) to visualize the optimal route, while in the model the main criterion was to minimize travel time between departure and destination points. But other objectives of the task were presented in the form of a large number of restrictions, in particular a traveled distance, traffic accident probability, population density, and population risk.

4. Research results

One of the most difficult stages in the organization of the carriage of DG by rail is the planning process at the tactical level. Planning at the tactical level involves decisions concerning the choice of the route for cars with dangerous goods, including the direction of movement and train class, station stops and time-schedule, with regard to the current plan in the formation of the freight trains. Fail-safeness in the process of carriage of DG and the efficiency in the implementation of the quality of the declared services by rail depends on the planning level, therefore it is necessary to improve the existing information and control system for managing the carriage of dangerous goods by rail.

Given the level of danger that arises at the carriage of DG, the most important criterion for route planning is to ensure a higher level of traffic safety. Within the transport planning at the tactical level in compliance with the clearly defined regulations and rules for the carriage of DG, various organizational decisions are possible on the procedure for sending cars with such cargoes. This can further reduce the risk of traffic accidents during carriage. The application of enhanced safety measures for the carriage of goods is accompanied by an increase in the service time of cars at stations. They include regulatory compliance in holding and special rules for shunting operations, the need in some cases to increase the car-mileage when choosing a route other than the shortest one, for reasons of avoiding the large transport nodes and so forth. Implementation of such measures leads to an increase in operating costs, which is not always acceptable in the economic expediency at the carriage of DG. In such circumstances, in addition to ensuring a high level of safety in the rail transport process, the criterion of minimizing operating costs is required.

Therefore, in the conditions of the transport market development in the segment for the organization of carriage of DG, the railway is faced with the task of improving the planning system of carriage of DG at the tactical level, provided that a high level of safety of the transport process and minimal costs for carriage. Formalization of this process leads to the formation of an optimization task. With regard to the contradictions between the proposed criteria in choosing the optimal route of carriages, it is advisable to solve the task on the basis of the two-stage mathematical model.

In order to implement the planning system at the tactical level, in the research authors propose to formulate such a mathematical model, the idea of which is to choose a set of possible routes in cars movement with dangerous goods, its power is limited by the established critical operating costs and finding the optimal route based on minimizing the risks [13].

The criterion of the effectiveness in choosing the route for the car movement with DG is to minimize the total cost concerning the car movement in trains and handling at the stations

$$F = \sum_{i=1}^{M} \sum_{j=1}^{M} c_{ij} x_{ij} \to \min_{\{x_{ij}\}}. \quad (1)$$

Restrictions take into account the continuity of the route, and each intermediate point along the route can be visited only once:

to enumerate all k -th arcs, incoming to i -th vertex of a route:

$$\sum_{k} x_{ki} = 1, i = \overline{2, M}; \quad (2)$$

to enumerate j -th arcs, outgoing from i -th vertex of a route

$$\sum_{j} x_{ij} = 1, i = \overline{1, M-1}. \quad (3)$$

If the i -th vertex is not included in the shortest route, the corresponding sum for both the incoming and outgoing arcs of the graph vertex must be equal to zero. Then, for any point in the network, except origin and destination, the condition must be satisfied:

$$\sum_{k} x_{ki} - \sum_{j} x_{ij} = 0. \quad (4)$$

Origin point is $\sum_{j} x_{sj} = 1$, destination is $\sum_{k} x_{kt} = 1$, $x_{ij} \geq 0$ for all i, j.

The transport system in the task is an oriented graph, it is a two-pole net, S is the origin station number, t is the destination number. All way-points of the route can be divided into origin, intermediate and destination. Obviously, there should be one incoming and one outgoing arc at each intermediate point, and for the origin and destination points, it can be only one outgoing or incoming arc, respectively. Thus constraints (2-3) reflect the requirement that at each vertex along the route there is only one arc exiting the input and one arc enters the input. Constraint (4) ensures equality in the number of arcs incoming and outgoing into each intermediate vertex.

Using criterion (1) and constraints (2-4) allows to find the shortest route for cars movement with dangerous goods from vertex S to t one, but to form an option in moving the cars under the condition of high reliability it is necessary to determine on the graph G' several k -rather short simple tracks (chains) from the origin vertex to the destination vertex.

To solve this task it is proposed to use the Yen algorithm [14], the scheme of which involves the application of the Floyd-Worschell algorithm [15] to find one optimal route between two vertices on the network.

The essence of a logical-functional scheme of the algorithm is to find with Floyd-Worschell technique [16] one of the shortest routes at k -bundle graph of the railway network. After this, searches are made for the next suboptimal k routes, every of which has to differ from already found in at least by one arc e'_{ij}. As the suboptimal route, one should be interpreted the route that leads from the origin to the destination vertex but differs from the optimum route by at least one arc.

The model is launched to search for many routes in the carriage of DG with minimizing operating costs is performed in the m-file init_train_route.m. The results of this program to choose routes for car movement with dangerous goods based on minimizing operating costs and risks for the arbitrary rail network graph $G' = (V', E')$ are shown in Figure 1 and Figure 2.

According to the second stage in the process of planning the routes for dangerous goods, except minimizing the operating costs of carriage, hazard identification is the most important in the technological process of car movement with dangerous goods. Given the technological specifics of rail transport, we use the risk concept of the traffic accident. It means the probability of a potentially possible traffic accident and its related losses when performing train or shunting operation or while stopping/ trains standing/cars carrying dangerous goods. It is established that the decision-making process regarding the choice of the least accident-free route for cars carrying the dangerous goods is accompanied by uncertainty. Its main source is information on the reliability of railway infrastructure and rolling stock, impossibility in the reliable prediction of personnel errors in traffic management, intervention of unauthorized persons into the railways activity, or the emergence of natural disasters.

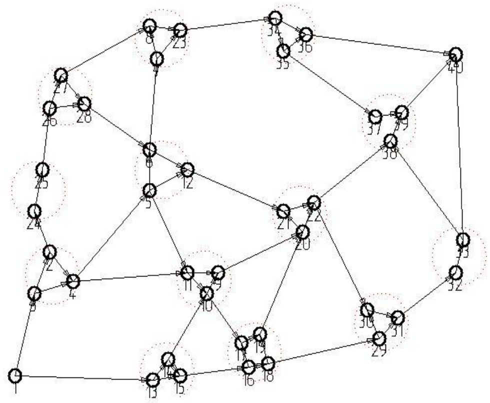

Figure 1. Visualization of an arbitrary graph for the railway network $G'=(V',E')$.

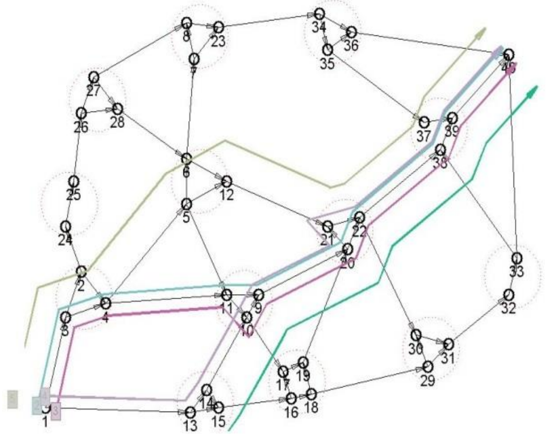

Figure 2. Optimal (number one) and suboptimal routes (No. 2-4) at cars movement with DG on an arbitrary rail network graph $G'=(V',E')$.

Assuming that reducing the risk of danger on the route under uncertainty is the main criterion for choosing the best route from the k -found shortest simple tracks on the graph $G'=(V',E')$, it is advisable to use a mathematical model based on a theory of conflict, which reproduces the independence of players' actions or a game theory [13].

It should be noted that the uncertainty of the game regarding the route of car movement with dangerous goods can be reduced by conducting a statistical experiment that will allow the "statistics" to obtain additional probabilistic information about the strategies of "nature".

To determine strategies of nature at the emergence of a traffic accident, it is necessary to calculate the function of risk values $R(\Theta,d)$ by expression:

$$R(\Theta,d)=M\left[L(\Theta,\mu)\right]=\int_x L(\Theta_q,\mu_k)dF(x\,|\,\Theta_q), \tag{5}$$

where $M\left[L(\Theta,\mu)\right]$ – expectation operator,

Θ_q – individual state of nature.

It is proposed to use the Bayesian Belief Network [16, 17] to find the probabilities in the emergence of a traffic accident on a route (probability in state of nature). Given that the probability in the emergence of a traffic accident is a complex random variable, which is caused by a set of elementary that is not known in advance. Reliability indices are determined on the basis of probabilistic and statistical assumptions, and therefore, if there is information concerning the traffic safety along the route, quantitative evaluation in the reliability of subsystems is a simple procedure and can be solved in accordance with [18]. Construction of the Bayesian Belief Network that describes route safety in the HUGIN system is to create vertices of the network graph and establish cause-and-effect relationships between them using special BBN network software. The system interface is shown in Figure 3. After plotting the network graph for each vertex, their state is established.

The next step in designing is the correct table compiling (matrices) of conditional probabilities (CPT) of each vertex. The list of conditional probabilities may include "Incident", "Collision", "No fence", "Incorrect actions", "Wrong route" and others. After the network design is completed, HUGIN system moves to the compute mode. For this purpose, the procedure of network compilation is carried out at which the correctness of the introduced probabilities is checked. The sum of opposite events should not exceed unity.

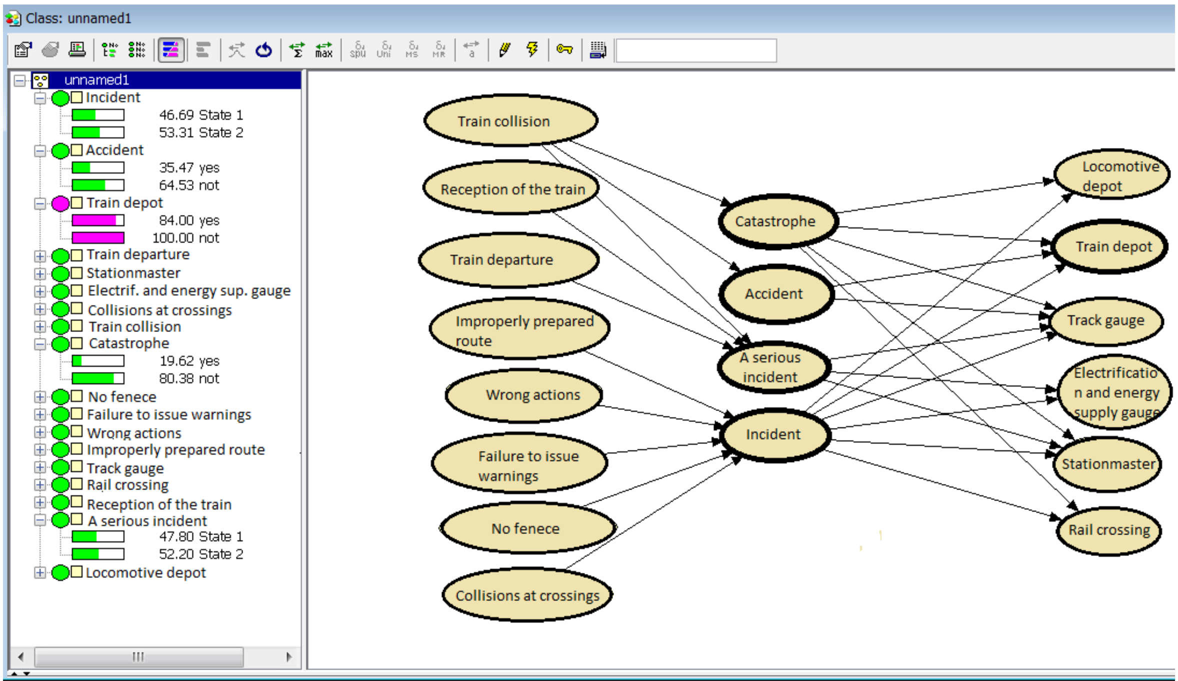

Figure 3. System interface while determining the probabilities for the state of all vertices of the network, subject to establishing the reliability in "Car facilities" subsystem is 84%.

Based on the receipt of values for the reliability of the subsystems into the BBN network, in accordance with the current situation on the route, the process of distribution through the network of newly received evidence of nodes state is carried out. Since the graph is acyclic, the equilibrium is set in the recalculation of estimations: the messages cease to spread and the probability values cease to change. According to the results of the simulation, the following reliability values were determined at which no traffic accident should occur. For example, in the case of the permissible state in the "Car facilities" subsystem, see Figure 3) it is found by using the Max propagation tool that the most probable state of all vertices is 84% in reliability. According to the developed network, the most probable fact is that with such a value of the subsystem reliability, no traffic accident should emerge.

5. Conclusion

Considering the level of danger that the process of carriage of DG entails, the most important requirement for planning the appropriate route is to ensure the high level of traffic safety. Therefore, the task of improving the system of planning for the carriage of DG at the tactical level can be solved, provided that the high level of safety of the transport process and minimum costs for the implementation of carriage. Given the contradictions between the proposed criteria when choosing the optimal route of carriage, it is advisable to solve the task on the basis of the two-stage mathematical model. To this end, a mathematical model of finding the optimal route based on risk minimization was proposed and a probabilistic model based on the Bayesian Belief Network was constructed. This model is a set of variables and their cause-effect relationships, that is, their probabilistic dependencies. The implementation of models in to the practice of organizing carriage of dangerous goods by rail allows the logistics operator to make the decision on the planning of optimal routes with minimal risk of traffic accidents. Also, the model can be easily customized to other case studies and adapted to different routing problems.

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