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The method of optimal route selection in road transport of dangerous goods

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Abstract

Dangerous goods such as: liquid fuels, chlorine, ammonia, gases, corrosives, radioactive material, toxic and other substances are being transported by road in Poland on a daily basis. 'Dangerous goods' are materials or items with hazardous properties which, if not properly controlled, present a potential hazard to human health and safety, infrastructure and or their means of transport. However, from year to year a systematic growth of accidents of the substances mentioned has been observed. It is estimated that several hundred traffic collisions, involving vehicles carrying hazardous goods, are being registered. Those accidents lead to spills penetrating into the soil, groundwater and watercourses, causing degradation of biological life. Therefore, the question of safety is an important problem that must be faced by senders, recipients and transport companies. One way of improving safety conditions is risk assessment. Therefore, in the article present the method of selection model of road transportation of dangerous goods. The model generates routes that are optimal from the perspective of risk and losses minimization. In addition, the paper adopts the results of simulation research selected delivery routes in Poland, with the use of the Breadth First Search algorithm (BFS) and proprietary application called the Safest Path Finder.

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Keywords: dangerous goods, risk assesment, breadth fisrt search algorithm, optimal routes.

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1. Main text

The transport of dangerous goods poses a considerable threat to people and the environment. Every day in Poland 20,000 vehicles transport flammable, explosive, corrosive, toxic and radioactive substances. The number of interventions related to the elimination of the consequences of adverse events, i.e. accidents and collisions, increases proportionately to the volume of transported substances. The reasons for the increasingly growing number of accidents are different, mainly it is the failure to comply with the ADR agreement, which Poland ratified in 1975. According to the report of the Supreme Audit Office, in 2012-2017, the number of violations has more than doubled. What is also a cause of concern is the fact that the transport of dangerous goods usually takes place during rush hour, through the centers of big cities, which significantly increases the risk of danger. It is worth noting that Poland does not have a national system of monitoring the transport of dangerous substances, and companies are not obliged to carry out a risk assessment. Moreover, within a voivodship area, no analysis of potential threats is required, and there is no obligation to collect basic information on routes and conditions in which dangerous goods are transported. Such a situation is very alarming especially when we observe a worldwide potential terrorist threat. At the present time, the subject of transport safety should become a priority. The above considerations inspired the author to develop a universal method for the selection of the optimal route for the transport of dangerous goods based on the risk analysis criterion, taking into account selected factors. When optimizing transport solutions, IT support is indispensable, therefore the developed model has been implemented to the proprietary Safest Path Finder software program.

2. Method of optimal route selection

Various concepts are used in the area of risk. Starting with risk assessment, that is, determination whether to accept or not a specific level of risk and assessment of both of the above stages. Based on the standard formula to estimate the value of risk, it is the product of the two components: probability that the accident (loss) will occur and the magnitude of the loss [5]. This approach is limited to risk minimization, which can be achieved in two ways. On the one hand, by shaping the factors affecting the probability of an accident occurring and, on the other hand, by selection of the optimal route for the carriage of dangerous goods, characterized by the lowest magnitude of potential losses. The type of scenario that occurs as a result of an accident is a random variable and can be influenced in a limited way, although the construction solutions used in tank trucks may impact the sequence of events resulting from an accident. Selection of the route that is optimal from the risk minimization perspective required the construction of a risk-based model that would consider all the parameters discussed in the next chapter.

2.1. Model assumptions

In the model, it was assumed that there are three key elements that impact the risk level: human, road and means of transport (vehicle). The term "road" is characterized by different parameters: type of road / speed limit / distance, surrounding area and traffic intensity. The human / driver characteristics include certain individual features as well as organization and parameters of the work. The technical means, i.e. the vehicle - semi-trailer tank, is analyzed primarily from the technical standpoint. These factors are accounted for in the probability model of the accident. Figure 1 shows the factors influencing the probability of an accident. Factor groups were determined based on literature and expert research [1,2,6].

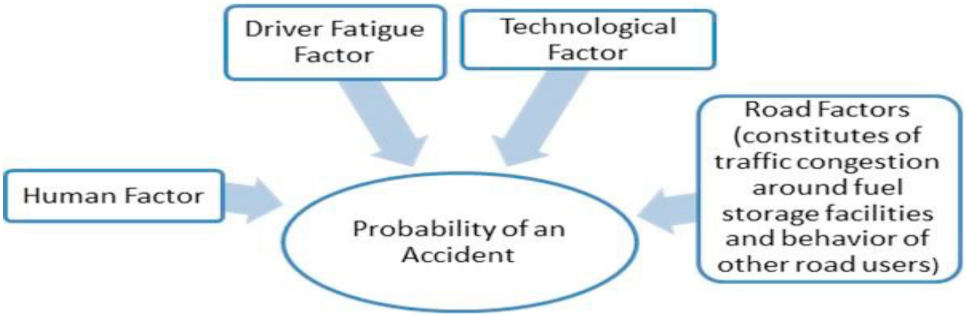

Fig. 1.: Factors influencing probability of a traffic accident

The developed risk model is limited to transportation of liquid fuels. Under this assumption various accident scenarios were determined and consequently, the magnitude and type of the resulting losses. The method, despite the limitation with regard to the type of carriage, is parameterized which makes it applicable to carriage of other classes of goods, and through appropriate selection of parameters it can even be applied to other modes of transportation.

Three categories of losses have been identified: human health or life, environmental (ecological) and total financial loss.

The following relation ties the probability of an accident and its consequences together:

$$risk = probability\ of\ accident\ occurrence \times consequences\ (measure\ of\ losses)$$

$$R = p_a \cdot L \qquad (1)$$

Where: R is a risk value and p_a– probability of accident occurring (in transportation of dangerous goods),
L – measure of losses. Selection of the optimal transportation route for fuels, can be done after the individual segments are characterized and their partial risk is defined. A 'segments' is defined as the distance between its origin and end in the form of a straight line or a curve, depending on the route followed in the area concerned. For segments with different road parameters, the values of the random variable of losses in different scenarios will be not the same. A 'segment' is separated if it differs from other 'segments' by at least one parameter. The following parameters have been assigned to the section route: x_{mn} - the length of the "segment", i.e. the distance between two adjacent vertices [km], (the length of the "section" is not a criterion for dividing the route into "sections"), $x_{mn} > 0$,
v_{qdop} - permissible speed on a specific "section" of the road [km/h], adopted in accordance with the road code / road type, type of development/, λ_L - the intensity of accident occurrence caused by driver's mistake, λ_Z - the intensity of accident occurrence caused by driver's fatigue, λ_T – the intensity of accident occurrence caused by a technological factor, λ_{NK} – the intensity of accident occurrence caused by conditions over which the driver has no influence, i.e. caused by other users of the road, t_n - undeveloped area, t_z - built-up area and previously discussed intensities. The specification of the methodology on accident intensity assessment in accidents caused by specific factors can be found in [1].

Thus, the formula for determining the risk value for a given segment will be (2), where: ER_q is partial risk estimated for the q-th segment of the route, p_{wq} – probability of accident in the q-th segment of the route and ES_q – expected value of loss on the q-th section of the route.

$$ER_q = p \cdot ES_q \qquad (2)$$

Whereas, the value of the total risk can be calculated as (3).

$$ER_T = \sum_{q-1}^{Q} ER_q \qquad (3)$$

where: ER_T – the estimated total risk for the transportation route, Q – the set of segments constituting the route, ER_q– the fragmentary risk estimated for the q-th segment of the route

Losses is understood as a random variable with discrete values. Probabilistic structure of a discrete random variable is defined as a function of probability distribution and description in [1].

Assessment of accident probability in transport and the key factors influencing the probability is a complex processes. In order to modeling probability of an accident a "band" model was proposed. It was built in Matlab_Simulink.

Probability of accident, under the assumptions as described in subsection 2.1., was defined for each q-th segment of the route, i.e. the connection between two adjacent vertices. It was assumed that the route is the sum of the analyzed segments. The first step in the band model was to assess impact of the human, technical and environmental factor on the probability of an accident in a particular q-th segment of the route. For this purpose, the parameter λ, or intensity, was introduced. The concept of intensity, with reference to technical damage, is applied, i.a. in the reliability theory and is understood as the probability of object damage over a period of time (t, t + Δt), where t is high. Unlike the reliability theory, the events analyzed in this article are local in the sense that the time traveled or the road traveled by a vehicle during a simulation is far lower than, respectively, the expected service life of the vehicle or the expected total distance traveled over the entire service life of a vehicle. The notion of accident occurrence intensity and the probability density of an accident over „short" road segments, relative to the total distance covered by a car during its service life, have the same values and are as such, in this case, identical.

The intensity is defined by the following relation:

$$\lambda_q = \frac{P(x_q)}{x_q} \tag{4}$$

where: λ_q – the intensity of accident occurrence on the q-th road segment, $P(x_q)$ – the probability of accident occurrence on the q-th road segment, x_q – the q-th road segment [m]

The newly-introduced intensity parameter expresses the influence of the human, technological and environmental factors on the probability of an accident occurrence. The following limitations have been imposed:

λ_L–the intensity of accident occurrence caused by the driver's mistake, $0 \leq \lambda_L < 1$, λ_Z–the intensity of accident occurrence caused by the driver's fatigue, $0 \leq \lambda_Z < 1$, λ_T–the intensity of accident occurrence caused by a technological factor, $0 \leq \lambda_T < 1$, λ_{NK}–the intensity of accident occurrence caused by conditions over which the driver has no influence, i.e. caused by other users of the roads, $0 \leq \lambda_{NK} < 1$, λ_{PK}–the intensity of accident occurrence near fuel storage facilities, $0 \leq \lambda_{PK} < 1$

Value ranges were introduced for each of the parameters as it was required that the weights assigned to each q-th segment are positive i.e.: $0 \leq (\lambda_L, \lambda_Z, \lambda_T, \lambda_{NK}, \lambda_{PK}) < 1$

The influence of a human driver on the probability of accident occurrence is taken into account by the risk assessment model in two aspects. On one hand, the characteristics that could determine the driver's efficiency and, if lowered, could cause mistakes: λ_L. On the other hand, the influence of the driver's fatigue on his performance are taken into account, adopting the linear relationship λ_Z in the time function at the first approach. In this model, only λ_Z changes over time. Increasing duration of the route along with the increasing total distance covered makes a significant impact on the efficiency of the driver, which decreases as his fatigue increases. In the majority of cases the values of the intensity for a specific "segment" are assumed to be constant. The values may depend on, for example, the type of road segment (road conditions, which is dependent on e.g. the maximum speed limit) or the traffic congestion level. Parameter λ_{PK}, assumes a constant value when the vehicle is in proximity of a fuel storage facility, or a value of 0 if otherwise. This value was determined based on data collected by the Central Statistical Office, Transport Technical Supervision Service, State Fire Service and Police Headquarters.

The values of the intensity of accident occurrence for specific factors assigned to their own "segment" x_q constituted the base of calculations of the probability of accident occurrence in the transportation of hazardous products for the given x_q "segment", (5):

$$P_{xq} = \begin{cases} \int_0^{x_{mn}} \left(\lambda_L + \lambda_T + \lambda_N + \lambda_{PK} + \lambda_Z(x)\right) dx \\ 1, if \ \int_0^{x_{mn}} \left(\lambda_L + \lambda_T + \lambda_N + \lambda_{PK} + \lambda_Z(x)\right) dx > 1 \end{cases} \tag{5}$$

The specification of the methodology on accident intensity assessment in accidents caused by specific factors can be found in [1].

For modelling of the human factor λ_L, fuzzy sets and expert knowledge was applied. A heuristic linguistic model was conceived based on fuzzy structures to determine the intensity of accident occurrence caused by driver's error λ_L, which constitutes a parameter of the "band" model. This factor – human factor - in terms of methods of risk assessment in the carriage of dangerous goods, is often overlooked. The most common fuzzy models are models with Mamdani or Takagi-Sugeno type inference. The Mamdani model was used in the modeling due to the fact that Mamdani models [6] provide a qualitative description of the system that is closest to the natural language. The Mamdani inference is useful when dealing with a low number of variables. Otherwise, the following difficulties appear: the number of rules grows exponentially with the number of variables in the premise, the more rules there are, the more difficult it is to adapt them to the problem. If the number of variables in the premise is too large, it will be difficult to understand the relations between the premises and their consequences

The procedure of creating the model included: selection of features, that is, external characteristics formed by organizational and technical conditions, such as: working time, skills, vibrations, noise, knowledge of procedures; and internal psychological and physiological characteristics, such as: stress, age, time of day, monotony.
Assigning certain levels of selected features with their corresponding fuzzy sets, that is: monotony (low, mid, high), knowledge of procedures (good, poor), skills (good, bad), working time (standard, overtime), vibroacoustic conditions (bothersome, non-bothersome), stress (low, mid, high; treated as a "submodel" of internal characteristics), age (young, middle, mature), time of day (day, night).

The input parameters of the model are characteristics that have an influence on the driver's efficiency. Along with a decrease in efficiency comes a larger number of errors, which in turn increases the intensity of accident occurrence caused by driver's mistake. These characteristics were determined through our survey and expert study, which was performed among drivers dealing with transportation of dangerous goods. The following diagram (fig. 2) presents characteristics, or, linguistic variables chosen by the respondents.

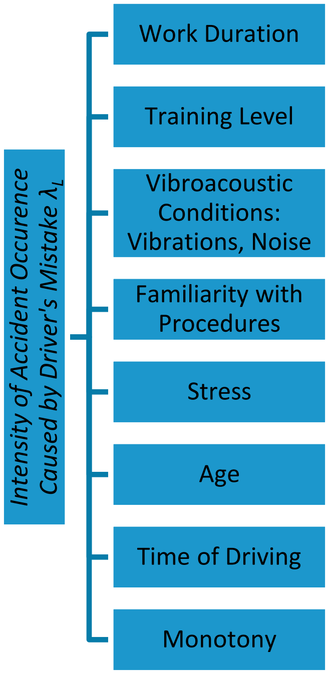

Fig. 2: Diagram of characteristics that impact parameter λ_L chosen by the respondents

The resulting values of λ_L are introduced into the risk assessment model and illustrate the impact of the change in the value level / efficiency of the human factor on the probability of an accident occurring in a given route section. Four specific scenarios were assumed: vehicle rollover without additional consequences, vehicle rollover and leak, vehicle rollover, leak and fire, vehicle rollover, leak and explosion. Each of them was assigned a certain probability of occurrence. Probabilities determined based on statistical data, interviews with experts and the research of available publications. Three categories of losses have been identified: human health or life, environmental (ecological) and total financial loss. For a given segment q and each of the scenarios, a losses S_{qSCi} were determined that correspond to five specific categories of threat. The loss in this case is a discrete random variable. The probabilistic structure of the discrete random variable is described by the mathematical function of probability distribution. The details of "band" model description is available in the publication [1].

3. Simulation study

In this point author presents the results of simulation research on selected delivery route in Poland, with the use of the Breadth First Search algorithm (BFS) and proprietary application called the Safest Path Finder. The author did not use the Dijkstra algorithm, neural networks or genetic algorithms, because the model assumes that the weight related to driver fatigue changes over time. These methods are used in the case of fixed scales. A good algorithm for route calculation is the A* algorithm. It works by calculating the shortest route on the basis of the cost of the route already travelled and a heuristic estimate of the cost the route remaining to be travelled. However, the quality of solutions provided by this algorithm depends on he quality of the heuristic function and the precision of its operation. It is therefore necessary to develop a good function heuristic what is most often a serious challenge and is difficult to achieve.

In the used algorithm, the graph search begins with the given node and consists in visiting all the reachable nodes, regardless of their consistency. The algorithm works fine for both directed and non-directed graphs. This is one of many methods of searching graphs and, according to literature, there is no optimal algorithm for a problem formulated that way [1,7]. For the purpose of model verification, a proprietary software program named Safest Path Finder has been implemented. The main task of the application is to simulate the transport of dangerous goods on a preset road infrastructure. The program consists of three main modules: data entry, calculation procedure, result presentation.

The input parameter of the simulator is a CSV file describing the graph associated with the road network. The file structure is as follows: each row corresponds to the new node in the graph. The row structure itself includes: - node's id number (integer number, node identifier), x coordinate [km], y coordinate [km]. Description of the following edges: - neighbour's id (identifier of the neighboring node), v_max (the maximum speed within the rode unit) and subsequent assumptions described in the parameters (including distance, speed limit, information about whether it is a built-up or undeveloped area, etc.). After downloading the input file, the application visualizes the downloaded road network and allows the user to manually modify the network parameters. As a result of the research, the application will allow to estimate the potential consequences of accidents and choose a route that minimizes the risk of road accidents.

The goal of the application is to determine all possible routes between the starting and ending points and to estimate the risk existing for each of them. The tool can support transport of dangerous goods optimized from the point of view of minimizing human, ecological and financial losses, covering the costs of all analyzed losses.

The purpose of the simulation experiment was to generate an optimal route for the transport of dangerous goods (liquid fuels), burdened with the lowest total risk of financial losses. Fuel transport was planned from Płock to Gdańsk. The following assumptions were adopted: time of transporting liquid fuels - daytime, traffic intensity - large, technical condition of the vehicle - good, intensity λ_L generated from the fuzzy model, with the following assumptions: monotony - small, external features - less than medium, internal features - less than medium, driver's fatigue increasing linearly over time $\lambda_L = 1{,}7\cdot10^{-6}$ [1/km], $\lambda_T = 1{,}5\cdot10^{-6}$ [1/km], $\lambda_N = 2{,}8\cdot10^{-6}$ [1/km], $\lambda_{PK} = 2{,}5\cdot10^{-8}$ [1/km]. The probability distribution of the scenarios was based on expert knowledge and road accident statistics: vehicle rollover without additional consequences P_{SC1}=0,1, vehicle rollover and leak P_{SC1}=0,7; vehicle rollover, leak and fire P_{SC1}=0,1; vehicle rollover, leak and explosion P_{SC1}=0,1.

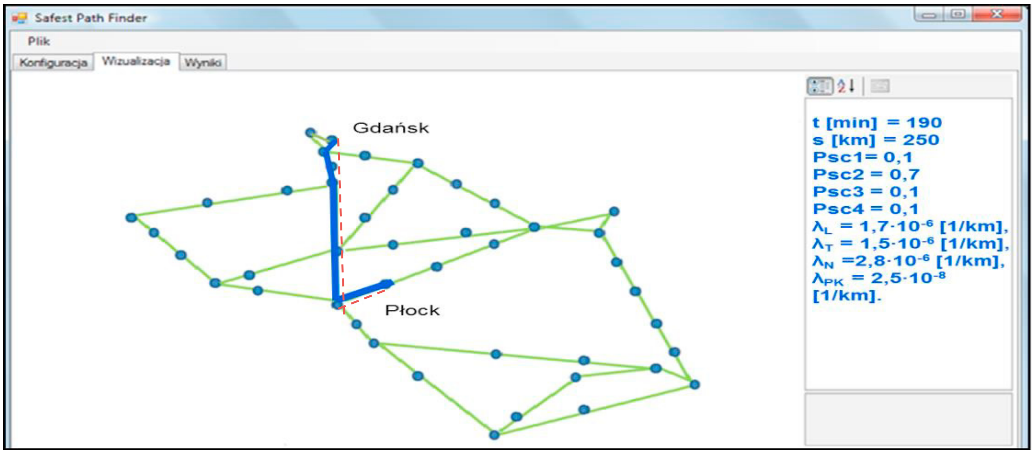

Fig. 3. Visualisation of optimal route in program Safest Path Finder

The generated route is also the shortest route and includes a toll road. The time of travel along the route is 190 minutes and 250 km. In the next option, it was decided to assess whether a change in the probability distribution of the event scenarios would affect the route change. It was assumed that: vehicle rollover without additional consequences PSC1=0.1, vehicle rollover and leak PSC1=0.1; vehicle rollover, leak and fire PSC1=0.1; vehicle rollover, leak and explosion PSC1=0.7. Other parameters have not changed. As a result of the simulation the same route (dashes line) was obtained. The probability distribution of event scenarios in this case did not affect the route change. It can be concluded that this is the optimal route for each probability distribution, not depending on the event scenario. The length of time required to perform a computational process was the same in the first and second variant and it was the same. Program analyzed the same target function. The calculation time depends on the grid of connections. As the number of points increases, the complexity of the task increases and computation time increase.

The program also allows for generating other routes depending on the target function given, i.e. to minimize losses. It should be realized that any damage to a tank filled with petroleum derivative substances, regardless of the tanker's size, leads to the creation of spills and overflows that penetrate into the ground, groundwater, water courses, causing degradation of biological life. The range of the danger zone depends on the type, physicochemical properties and amount of released substance. There are three ways of spreading hazardous substances: 1) soil, where there is no immediate danger to humans, but the ecological threat is serious, 2) water, where there is no immediate danger to humans, but it exists for aquatic ecosystems, 3) air, where it can cause an immediate threat to human health and life. It is, therefore, of critical importance to assess the risk on dangerous goods transportation routes. Of course, the program offers many different possibilities of risk simulation and estimation on selected transport routes in Poland and worldwide. The article only throws some light on the software's potential and value. Due to the volume of the article, the author cannot present all the features of the program. In future research, it is possible to enrich the described tool by integrating it with an additional simulation model (module) presented in the paper [4], which discusses a simulation model for analyses of a distribution system. This would enable, among other things, the analysis of the duration of dangerous goods transport with simultaneous consideration of what-if analyses, particularly important in dangerous transport.

4. Conclusion

Hazardous materials constitute an important sector of transportation market and they are indispensable for the functioning of industry and urban agglomerations. The transport of hazardous goods poses a potential threat to human, road and environmental safety, regardless of the mean of transportation used for that purpose. Therefore, actions aimed at reducing the risk mentioned are becoming of key importance.

Appropriate knowledge and proper tools allow for increasing safety while planning cargo processes. Due to the lack of: integrated, nationwide monitoring system, obligatory risk assessment and data collection, the transport of dangerous goods can become a "Trojan Horse" to be used in large agglomerations. It is not difficult to imagine disastrous consequences if a truck transporting hazardous materials would be detonated. For this reason, the crucial aspect is to accurately assess the risk and choose the optimal route so that the consequences of a potential adverse event are minimized. The issues raised in the article cannot be ignored in times of terrorist threat around the world. Downplaying the risks posed by goods qualified as hazardous may lead to irreversible consequences for people and the environment. Nowadays, issues of such type require a customized approach, an out-of-the box solution. This is due to the fact that despite the immense danger that may occur as a result of the "Trojan horse" effect, the awareness of the society and, above all, decision-makers and governing bodies may be too of low significance in this context. Scenarios of this type may be analyzed by interested parties, e.g. using innovative and creative design methods [3].

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