The Impact of the Human Factor on the Safety of Transportation of Dangerous Goods

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Keywords: human factor, risk assessment, hazardous materials, transport

ABSTRACT

This article brings up important safety issues pertaining to the transportation of hazardous goods: estimating risk and modeling human factors as the main cause of road accidents. For the purposes of this article, the concept of risk assessment has been depicted in a general manner while the “band” model, which takes human, technical and road factors into account, has been depicted in detail. The band model was implemented in calculation of accident probability in the transportation of hazardous goods. Heuristic techniques or, more precisely, fuzzy set techniques were used in the modeling of human factors. The model was conceived based on the bibliography of the subject matter and personally conducted survey and expert research.

INTRODUCTION

The volume of freight transported by road has been at high levels for a long period of time in Poland. Unfortunately, this phenomenon, apart from positive aspects, has some negative and costly consequences. In Europe car accidents are causing death of approximately 1.3 million people each year. Therefore, the issue of ensuring safety in transport and reducing harmful emissions are now among the priority issues on the agendas of various governmental agencies and not just in Europe. Actions aimed at enhancing safety include among others introduction of normative documents (standards) as well as their enforcement. Safety should be ensured in every single link of the system. The key element to be analyzed in this article is the means of transport, defined as a part of an operator-vehicle-environment system. This system operates within the imposed legal and organizational framework, which means it is not an isolated system. The organization as well selected elements of the legal system, can influence human behavior in this system. They are reinforced by the organization, which can result in avoiding danger. Human, vehicle or environment are potential hazard generators and the result is human losses such as loss of health or human life, damage of property, cultural or ecological assets, resulting in significant financial

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losses. Issue of safety is a part of sustainable development, in particular sustainable transport, which nowadays is a key aspect of world’s environment and economy [1].

Accidents involving dangerous freight constitute a small percentage of the total number of accidents, but the impact of each of those accidents is unmatched compared to accidents involving carriage of other goods. Therefore, the issue of safety in the transport of dangerous goods has become a part of the research carried out at the Department of Transport of Poland and the key findings are presented in this article.

The available research on the causes of accidents in transport, irrespective of its nature [2], [3], [4] clearly indicates that human is the weakest link in ensuring safety. This trend has been constant since the nineteenth century when the world's first traffic accident was recorded. Human factor is the most common cause of accidents, followed by the road conditions, the weather and the technical condition of the vehicle [5]. Thus the importance of the research on the human factor and its reliability. The issue of human reliability is addressed by many scientific centers in Poland and in other countries [6], [7], [8]. In the literature, as many as 72 HRA (Human Reliability Analysis) methods have been identified. Those methods can be used to estimate the probability of a human error (error of a human technical operator) occurring throughout the completion of a specific task when influenced by other factors. In this article, the authors will focus on the problem of assessing the psychophysical condition of the driver expressed by the intensity of the driver's error resulting in the accident and its impact on the risk of transporting dangerous goods

RESEARCH METHOD

One of the proposals to increase the safety of the transport of dangerous goods by road is to choose the route that is optimal for minimizing the losses due to a potential accident. Driver's level of performance has a significant impact on the probability of an adverse event such as an accident occurring and thus increases the risk of carriage. Heuristic techniques or, more precisely, fuzzy set techniques were used in the modeling of the human factors. The choice of the method was dictated by the following premises. This is at least two facts. First, these models can describe human behavior using a verbal description, formulated by an expert (fuzzy models are called linguistic models.) The description of human behavior is implicit in terms of fuzzy logic. Secondly, such models naturally take into account the lack of precision in the definition of human behavior and the natural randomness of human perceptual processes [9], [10], [11]. Thus, the authors decided to use linguistic models to solve their problems. The impact of the human, technical and environmental factors will be reflected in the selection of the carriage route.

Assumption of Human Factor Modelling

In the human factor 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.
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.

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:

\[ R = p_a \cdot L \]  

where:

- \( R \) – risk value
- \( p_a \) – probability of accident occurring (in transportation of dangerous goods)
- \( L \) – measure of losses

Selection of the optimal transportation route for fuels from the starting point, e.g. the refinery to the final destination, i.e. a customer, can be done after the individual segments are characterized and their partial risk is defined. A ‘section’ 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 different. 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.

\[ P_q = \{ x_{mn}, v_{qdop}, v_{qrdc}, \lambda_L, \lambda_T, \lambda_{NK}, \lambda_{PK}, t_Z, t_n \} \]  

where:

- \( P_q \) – a set of parameters for \( q \)-th "segment" of the route, expressed in the form of nine ordered parameters,
- \( x_{mn} \) – 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/
- \( \lambda_L \) – the intensity of accident occurrence caused by driver’s mistake,
- \( \lambda_{Z} \) – the intensity of accident occurrence caused by driver’s fatigue,
- \( \lambda_T \) – the intensity of accident occurrence caused by a technological factor ,
- \( \lambda_{NK} \) – the intensity of accident occurrence caused by conditions over which the driver has no influence, i.e. caused by other users of the road,
- \( m \) – undeveloped area,
- \( t_Z \) – built-up area and previously discussed intensities.

For each segment, the partial risk was described by the dependence 2. Total risk is obtained by summing the values of the partial risk corresponding to the sections making up a given route (described by the dependence 4).

Thus, the formula for determining the risk value for a given segment will be (3):

\[ E\!R_q = p_{wq} \cdot E\!S_q \]  

where:

- \( E\!R_q \) – partial risk estimated for the \( q \)-th segment of the route
- \( p_{wq} \) – probability of accident in the \( q \)-th segment of the route
- \( E\!S_q \) – expected value of loss on the \( q \)-th section of the route

Whereas, the value of the total risk can be calculated as (4).
ER_T = \sum_{q=1}^{Q} ER_q \tag{4}

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

Four specific accident scenarios were assumed and each of them was assigned a certain probability of occurrence. Probabilities of occurrence for each specific scenario were determined based on statistical data, interviews with experts and the research of available publications. For a given segment \( q \) and each of the scenarios, a losses were determined that correspond to five specific categories of threat. A more detailed description is available in the publication [12].

**Modeling Probability of an Accident**

Assessment of accident probability in transport and the key factors influencing the probability is a complex process. In the modeling process, a “band model” was proposed. 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 \( \lambda \), or intensity, was introduced. The intensity is defined by the following relation and more detail is described in [12,13]:

\[ \lambda_q = \frac{p(x_q)}{x_q} \tag{5} \]

such that:

\( \lambda_q \) – 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 intensity of accidents caused by driver’s mistake is one of the section’s parameters. In order to determine its value, heuristic model was created [12], [13]. The specification of the methodology on accident intensity assessment in accidents caused by specific factors can be found in [12], [13]. For the purposes of this article, the modeling of the \( \lambda_d \) parameter, or the intensity of an accident as a result of a driver’s mistake, is described in more detail.

**Heuristic Modeling of the Human Factor and Numerical Implementation**

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 selected characteristics were grouped. The characteristics included in the external characteristic subset, that is those that are influenced by organizational and technical conditions, are: duration of work, level of training, vibrations, noise and familiarity with procedures. The set of internal characteristics, i.e. of psychological and physiological characteristics, includes: stress, age and the time of the day when the
driver is working. Monotony has been put separately, since it has a considerable role when driving through an unchanging environment, e.g. a highway, by inducing the dangerous so-called highway hypnosis phenomenon.

The next step in modeling was the assignment of the appropriate linguistic values to the characteristics, the former being described by fuzzy sets with their assigned membership functions. The most important element in modelling is the selection of the shape of membership functions. At the first attempt, a symmetrically shaped Gaussian curve of a membership function was chosen.

The intensity of accident occurrence caused by driver error $\lambda_L$ was described with fuzzy sets, accordingly: low, lower than average, average, above average, high. The minimum and maximum value of the real variable were set based on literature analysis, taking into account the data from the Central Statistical Office, the Transport Technical Supervision Service, the State Fire Service and the Police Headquarters. The value of $\lambda_L$ was obtained in the interval $\lambda_{L\text{min}} = 16 \times 10^{-7}$ km, $\lambda_{L\text{max}} = 28 \times 10^{-7}$/km.

The output data block is a fuzzy sets describing a linguistic variable - the intensity of an accident as a result of a human error $\lambda_L$. The input data underwent an aggregation and defuzzification process, which allowed for the obtaining of a not-fuzzy output value. The Mamdani model was implemented numerically in a Matlab_Simulink environment. It contains three linguistic input variables, as shown on fig. 1, i.e. monotony, external characteristics and internal characteristics.

![Figure 1. A Heuristic Mamdani model of the intensity of accident occurrence caused by driver error [12], where:
- the invariability (constancy) of the work process (IWP)
- the invariability (constancy) of the surroundings (EI)
- the necessity to constantly maintain focus (NPV)
- the easiness of work, excluding the necessity of intellectual process (reasoning) (WE).](image)

The details of the implementation of fuzzy structures are described in [12].

**THE RESULTS OF THE SIMULATION STUDY**

Dangerous goods may be transported in Poland on different routes, each of which, due to the characteristics of the sections of which it is composed, may present different risks. From the point of view of transport safety, it would be appropriate to choose a route that would be at the lowest risk. Let us assume that the goods are transported from
point A to point B. Thus, the transport route is the sum of the \( x_q \)'s sections', and it has a form:

\[
T(A, B) = \sum_{(m, n) \in T(A, B)} x_{mn} = \sum_{q=1}^{Q} |x_q|
\]  

(6)

Each route section has been assigned an appropriate expected value of losses resulting from its parameters (described by equation (2)) as well as from the type of potential accident scenario [12], [13]. It has been assumed that the probability distribution of the scenarios, the methodology of which is described in the works [12], [13], is based on the values from Table 1.

Table 1. Probability distribution of scenarios.

| Scenario S_Ci | The probability of a scenario |
|---------------|-----------------------------|
| Overturning of the vehicle without any consequences - S_C1 | \( P_{S_C1} = 0.1 \) |
| Overturning of the vehicle and outflow - S_C2 | \( P_{S_C2} = 0.7 \) |
| Overturning of the vehicle and outflow and fire- - S_C3 | \( P_{S_C3} = 0.1 \) |
| Overturning of the vehicle and outflow and fire and explosion- S_C4 | \( P_{S_C4} = 0.1 \) |

For the purposes of the risk assessment model, a simulator based on the Breath First Search algorithm was created [13]. The implementation of the original Safest Path Finder (SPF) simulator made it possible to verify the model.

In order to carry out the simulation, a specific transport network was adopted, described in the works [12], [13], [14], covering selected points - cities in Poland. An example of a transport task concerns the transport of class 3 goods, i.e. liquid fuels, carried out between Gdańsk and Toruń.

The purpose of the simulation experiment was to generate a route with the lowest overall risk resulting in minimal financial losses. The following assumptions and values were adopted: the time of transporting liquid fuels—day, traffic intensity—large, technical condition of the vehicle - good; intensity \( \lambda_L \) generated from the fuzzy model, with the following assumptions: monotony - large, external features - less than average, internal features - less than average, driver fatigue increasing linearly with time; values of individual intensities: \( \lambda_L = 1.7 \cdot 10^{-6} \text{ [1 / km]} \), \( \lambda_T = 1.5 \cdot 10^{-6} \text{ [1 / km]} \), \( \lambda_N = 2.8 \cdot 10^{-6} \text{ [1 / km]} \), \( \lambda_{PK} = 2.5 \cdot 10^{-8} \text{ [1 / km]} \).

The program has determined the optimal route (Fig. 2 - dashed line, black), which in this case is also the shortest possible route between Toruń and Gdańsk. This is the A1 motorway. Previous simulation studies show that the shortest route is not always the least risky [14]. In the event of a collision on the motorway due to time constraints, it is necessary to find other routes leading to the destination, although they will not always meet the expectations of carriers from the point of view of accepted risk. A road marked with a “solid line” generated in the program is a cue for such a route. It is not only longer but unfortunately it is characterized by a much higher risk resulting from potential ecological losses. In the case of the need to choose the route with the highest risk, a driver carrying dangerous goods, having information on a given route, should take special precautions.
The total risk on the optimal route (A1 motorway) was $ER_T = 0.002$. In the case of the "solid" route - the ecological risk $ER_{sgw} = 0.01$. In both cases, the intensity value $\lambda_L$ remained the same. The higher value of the ecological risk results from the environment in which the route runs. These are mixed areas, i.e. urban and forest areas. In the event of an undesirable event such as an accident, ecological losses, i.e. contaminated areas, might be very large.

Using the developed risk assessment model to select the optimal transport route on a wider scale requires entering into the simulator detailed data characterizing the road network in Poland and the environment in which it runs, in order to determine the size and types of losses as well as the input parameters to the model.

A comprehensive monitoring system would provide the possibility to variance routes on the basis of "on-line" data on the current traffic situation.

**DISCUSSION AND CONCLUSIONS**

In the available literature in the field of risk assessment in the transport of dangerous goods, despite a number of described methods, no method has been noted that takes into account the impact of human error on the probability of an accident. However, statistical data clearly indicate the human factor as the cause of most transport accidents. Having the above in mind, the presented original method is undoubtedly a new approach in this field.

It was assumed that in consequence to a decrease in efficiency of the driver, errors may arise, leading to an accident. Human errors are a common phenomenon and their number depends on many factors. Even in comfortable conditions, the employees fail to perform correctly one in ten thousand accomplished activities. In the situation of additional impediments, fatigue, time pressure or reduced risk tolerance, the frequency of erroneous actions increases as much as to one in a thousand. This leads to attempts to learn the causes of accidents and interdependencies in this area. The developed submodel of the human factor based on heuristic methods allowed to formulate qualitative interdependencies, based on expert knowledge. The model also benefitted from a proprietary expert survey on the selection of specific features and input data to the accident intensity model as a result of human error. Therefore, human influence is expressed by the parameter of the intensity of the probability of human error, which can
result in an accident. This parameter is determined from a fuzzy model which takes into account the impact of selected features of varying levels on the driver’s performance. The resulting values of $\lambda_L$ 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.

The risk assessment model enables the generation of an optimal route for the transport of dangerous goods with a view to minimizing risk, resulting in minimizing overall losses. The route selection shall take into account the impact of the different factors on the probability of the accident occurring, i.e. human factors including driver fatigue, technical factor (vehicle), road condition. It also makes it possible to distinguish between routes with the same overall risk, but different proportions of human and environmental losses. The model is parameterized so that it can be used to assess the risk of transport of dangerous goods of different classes, after modifying scenarios and consequences of accidents.

Many questions arose during the study, for which there presently are no unequivocal answers and they require additional research, though because of its specific subject—human beings—modeling and simulation may be the only effective research tools.

REFERENCES

1. Kostrzewski, M., and Wrona, K. 2017. An Evaluation of the Efficiencies and Priorities for Sustainable Development in the Transportation System for the Manufacturing and Trade Industry. Vol. 17, No. 3 (43):577-595.
2. Grabarek, I. 2003. Diagnozowanie Ergonomiczne Układu Operator – Pojazd Szywnowy— Otoczenie (Ergonomic Diagnosis of the Operator – Railway Vehicle – Environment System). Prace Naukowe Wydziału Transportu Politechniki Warszawskiej, Zeszyt 51, Warszawa.
3. Karrer, K., Briest, S., Vöhringer-Kuhnt, T., Bauungarten, T., and Schleicher, R. 2005. Driving without Awareness. In: Underwood G. (ed.), Traffic and Transport Psychology. Proceedings of the ICTTP 2004 (pp. 455-470). Elsevier, Amsterdam.
4. Krystek, R. (red.) 2009. Zintegrowany System Bezpieczeństwa Transportu (Integrated System of Transport Safety). Tom I. WKŁ, Gdańsk.
5. Łuczak, A. 2001. Wymagania Psychologiczne w Doborze Osób do Zawodów Trudnych i Niebezpiecznych (Psychological Requirements in the Selection of People for Difficult and Dangerous Profession). Centralny Instytut Ochrony Pracy, Warszawa.
6. Bell, J., and Holroyd, J. 2009. Review of Human Reliability Assessment Methods - Prepared by the Health and Safety Laboratory for the Health and Safety Executive (HSE). Buxton, Derbyshire.
7. Matthews, G., Desmond, P., and Neubauer, C. 2012. Handbook of Operator Fatigue. Hancock P.A., Great Britain.
8. Szopa, T. 2009. Niezawodność i Bezpieczeństwo (Reliability and Safety). Wydawnictwo Oficyna Wydawnicza PW, Warszawa.
9. Grobelny, J. 1986. Fuzzy logic controller as a model of thermal regulations process in man. In: Karwowski W. and Mital A. (eds.) Applications of Fuzzy Set Theory in Human Factors. Elsevier Science Publishers B.V., Amsterdam, pp. 315-328.
10. Mamdami, E. H. 1977. Applications of Fuzzy Logic to Approximate Reasoning Using Linguistic Synthesis. IEEE Transactions on Computers, Vol. C-26, 12:1181-1182.
11. Evans, G.W., Karwowski W. 1998. A Perspective on Mathematical Modeling in Human Factors. Applications of Fuzzy Set Theory in Human Factors, Elsevier, pp. 3-11.
12. Bęczkowska, S. 2014. Ocena i Minimalizacja Rzywu w Drogowym Transporcie Towarów Niebezpiecznych, (Risk Assessment and Minimization in the Road Transportation of Dangerous Goods). Praca doktorska, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.
13. Bęczkowska, S., Grabarek L., and Choromański W. 2012. Modelowanie Rzywu w Drogowym Transporcie Towarów Niebezpiecznych z Uwzględnieniem Czynnika Ludzkiego, (Risk Modelling
in the Transport of Dangerous Goods by Road, Taking into Account the Human Factor). In: Ergonomia w Gospodarce Opartej na Wiedzy, Komitet Ergonomii PAN, pp. 183-197.

14. Bęczkowska S., Grabarek I., and Choromański W. 2014. The Role of Human Factor in the Transport of Hazardous Materials, In: Ahram T., Renliu Jang R. (eds.), Advances in Physical Ergonomics and Human Factors. Part I, AHFE Conference, pp. 44-53.