USING SIMULATION APPROACH IN TRANSPORT SAFETY RISK ASSESSMENT

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ABSTRACT

In the process of risk analysis with respect to a specific transport accident scenario there could be some problems, mostly related to the assessment of events. Examples are technical failures and the intensity and severity of their adverse effects, both of which have a probabilistic nature. One of the primary reasons for these problems would be the effect of uncertainty and natural variability. Uncertainty refers to a lack of knowledge about specific factors, parameters, or pathways. In this context and in terms of the above consideration, it must be stressed that the usage of a simulation approach could be an increasingly important tool to evaluate the uncertainty and variability associated with transport safety risk assessment. The main purpose of this paper is to provide guidelines for determining the applicability of Monte Carlo analysis (simulation) to certain accident scenarios.

Key words:
Transport, safety, accident, simulation

INTRODUCTION

There is no doubt that the rapidly evolving process of exchange of goods, services, knowledge and experience between different geographical regions and communities leads to significant technological and cultural progress worldwide. However, transport problems arise and one of the more important of them is that associated with the risk of accidents. The large number of transport accidents causing death or injury suggests the idea of globalization of this problem. It is important to note that all serious accidents are investigated, and the causes behind them analyzed, but only a minority of them lead to the implementation of significant measures to improve safety of a given transport system. The main purpose (and sometimes sole one

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- which is a serious weakness) of many investigations is the determination of a culprit to take responsibility for the accident.

The correct understanding of the problems associated with the operational safety in all transport modes suggests that accidents rarely result from a single event. Most of them are caused by the emergence of independent events which, for one reason or another, interact with each other. In most transport modes the human-operator is a key element in the causal chain of an accident. Operational experience shows that subjective errors usually do not have a deliberate nature but nevertheless, in most cases, they have significant consequences. However, whether a transport accident is a result of human error, technical failure, technological imperfection or other influencing factors a qualitative analysis of the causes and consequences should be conducted.

Modern and qualitative investigation and analysis of the risk of a transport accident must be based on improved and adapted methods and models to answer in the best possible way the questions: "How and why has an operational unwanted event occurred?", " What should be done to prevent it in the foreseeable future? ", "If, however, it occurs what must be done to reduce the effects?". These questions correspond to the three main fields of risk management, namely-hazards identification, determination of the occurrence probability and assessment of the consequences.

It should be noted that in the process of risk analysis with respect to a specific accident scenario there could be some problems, mostly related to the assessment of events. Examples are technical failures and the intensity and severity of their adverse effects, both of which have a probabilistic nature. One of the primary reasons for these problems would be the effect of uncertainty and natural variability. Uncertainty refers to a lack of knowledge about specific factors, parameters, or pathways. For example, a risk assessor may be uncertain about the intensity of human errors, technical failures rates, etc. Uncertainty could be regarded as a result of measurement errors, sampling errors, model uncertainty such as uncertainty due to simplification of real-world processes, incorrect model structure, misuse of models, use of any inappropriate assumptions, etc.

In this context and in terms of the above consideration, it must be stressed that the usage of a simulation approach could be an increasingly important tool to evaluate the uncertainty and variability associated with transport safety risk assessment. The main purpose of this paper is to provide guidelines for determining the applicability of Monte Carlo analysis (simulation) to certain accident scenarios.

1 BACKGROUND

1.1 SAFETY RISK ASSESSMENT PRINCIPLES AND STEPS AND THEIR APPLICATION FOR TRANSPORT ACCIDENTS ANALYSIS

Any human activity faces a set of potential hazards to its proper implementation. The occurrence of even the most insignificant hazard creates risk and could seriously disrupt the system, leading to serious financial and social consequences. This also applies to all transport modes whose proper functioning is the basis for the normal life of society as a whole. To achieve this, a continuous process of decision making in order to avoid adverse transport events (accidents) is necessary, which in other words means risk (safety) management.

The two most important and fundamental aspects of the general scheme of a safety management process are risk analysis and risk assessment. They characterize the so-called quantitative risk assessment. The quantitative risk assessment allows us to determine the acceptability or unacceptability of the risk level with respect to predefined hazards based on adapted methods and selected criteria.

Each scenario of a transport accident is basically characterized by the next two specific features: probability (intensity) of the occurrence and consequences (effect) after the occurrence (impact on the level of safety). The analysis of these features (by means of available methods and in accordance with the principles of risk management) involves the following sequence:

-Hazard identification

This is the first and very important step in conducting a qualitative risk analysis. In the transport area, hazard is any unwanted state of the transport system due to subjective errors, technical failures or other adverse effects. It is important to note that an unidentified hazard can not be assessed, which could seriously damage the quality of the ongoing risk analysis. FMEA/FMECA and HAZOP are the most used methods within hazards identification process.

-Determination of the probability (intensity) of occurrence of hazards

The disclosure of the logical connection between the events leading to the occurrence of a specific hazard is the main goal of this stage. Here, the determination of occurrence probability is the most important point and the Fault Tree Analysis (FTA) can be successfully applied to achieve this purpose. FTA is a deductive approach for qualitative and quantitative analysis aimed at identifying the causes leading to the main event being studied. As such an event, specific technical failures, subjective errors or (generally) hazardous event (for example: transport accident) may be considered. This method successfully allows the determination of occurrence probability of a type of transport accident (or occurrence conditions) with specific scenario.

-Consequences assessment

To assess the effects of the main event (accident cause) a detailed analysis of the possible resultant situations is required. There is a multi-variability of the consequences of the event in question. Because of this, the Event Tree Analysis (ETA) could be used to analyze and assess these effects. ETA is an inductive approach (method) for diagrammatic representation of the sequence of events which are the result of a predefined primary event. The ETA algorithm makes it possible to determine the probability of the final events. Fault and event trees concerning a sample kind of level crossing accident are discussed in the third section of this paper.

1.2 FEATURES AND ESSENCE OF THE MONTE CARLO ANALYSIS

The mathematical procedures for modeling complex stochastic processes that can not be decided theoretically are known as Monte Carlo analysis. The name of this method comes from studies of nuclear reactions in the 1940s, when the possibility of nuclear reaction emergence was investigated. The project was top-secret with code-name “Monte Carlo”. Its name was chosen because of the fame of the capital of Monaco as an European center of gambling.

Generally, the idea behind implementing a Monte Carlo analysis to a stochastic process and its model is relatively simple. What is specific to a deterministic model is that a single value for each of the model’s input parameters is used to compute a single output parameter. The stochastic (probabilistic) modeling, by contrast, is characterized by random input parameters (random variables). This feature means uncertainty and variability of output parameters making them unsuitable for an exact decision. Monte Carlo analysis is a powerful tool that involves a random number generator and simulates the behavior of a variable when the data is characterized by uncertainty and variability. The random number generation is based on a probability density function that defines the variable variation in the time. Thus, the description of events whose outcomes are uncertain (random variables count, times between specific events, etc) becomes possible.

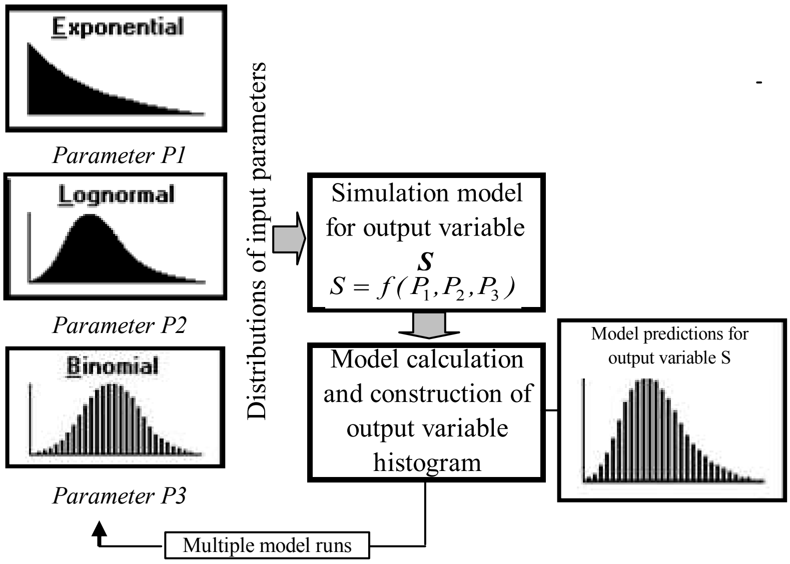


Fig.1.Main steps of Monte Carlo analysis

The main components of Monte Carlo analysis are:

-mathematical model with a set of logical relationships (between specific and predefined events) that simulates a real system;

-probability distribution function;

-random number generator.

As an example let us comment how Monte Carlo analysis could be applied to model the time between failures of any railway technical device.

Firstly, based on known (but incomplete) statistical data an assumption regarding failure distribution has to be made. For instance, let the random variable t*ime between failures* be exponentially distributed with cumulative failure distribution:

$$F(t,\lambda) = \begin{cases} 1 - e^{-\lambda t}, & t \geq 0 \\ 0, & t < 0 \end{cases} \qquad (1)$$

where: λ-failure rate.

The usage of a random number generator allows us to select a random number ***n*** within the range $0 \div 1$. Then, from $F(t) = n$ it is possible to obtain ***t*** which denotes the time between failures. The implementation of this step for lots of random numbers means a simulation of random variable t*ime between failures*. Furthermore, the simulation process allows the computation of both the mean time between failures and device reliability. Figure 1 presents a diagrammatic representation of Monte Carlo analysis. Specific considerations, assumptions and conditions regarding the major steps in a Monte Carlo analysis for transport safety risk assessment are presented in the following section.

2 APPLICATION OF THE SIMULATION MODEL IN TRANSPORT RISK ASSESSMENT

The Monte Carlo simulation-based approach for risk assessment will be illustrated for a specific level crossing transport accident. This example accounts for the stochastic nature of a number of interacting human errors, technical failures and operational conditions. The basic events and their logical interconnections in respect to this kind of accident scenario are presented in figures 2 (FTA) and 3 (ETA) and can be summarized as follows:

A - presence of train within the dangerous zone of a railway level crossing (measured as a distance between the point of detecting sensor and the end of level crossing road zone);

B - failure of the sensor detecting the train approach towards a railway level crossing;

C - failure of the signaling system that provides an electrical signal (information for an approaching train) between detecting sensor and gates actuating device as a train approaches towards a level crossing area;

D - failure of the sensor detecting the train leaving of level crossing zone (premature opening of the gates before the clearance of railway level crossing);

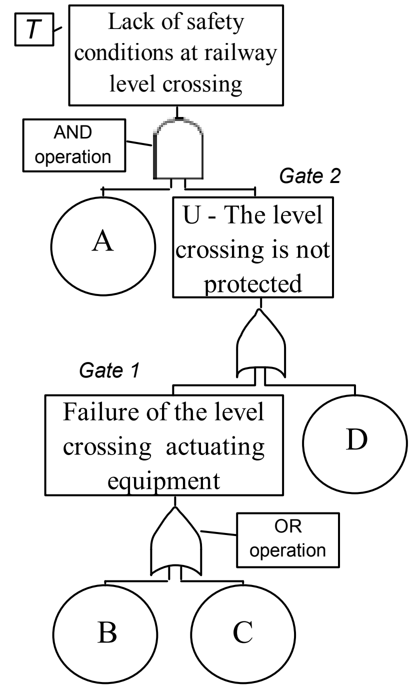


Fig.2.Faul tree logic for a level crossing accident

T - situation (conditions) favoring a potential conflict between train and road vehicle;

E - absence of a vehicle wishing to pass through the level crossing zone;

F - road vehicle driver notices the approaching train and manage to stop before entering the level crossing zone;

G – road vehicle clears the level crossing zone before collision.

After the simulation model establishment a very important aspect should be taken into account – this is the model parameterization. In the context of the Monte Carlo approach this means an adaptation of the statistical and expertise data to the model parameters (which are usually uncertain ones). In the stochastic approach (and developed on this basis models), the variables that involve uncertainty should be defined with a probability density function. The fitting of input events with probability distributions makes possible the computation of outputs (as forecasts) by the simulation of the model hundreds of times – each

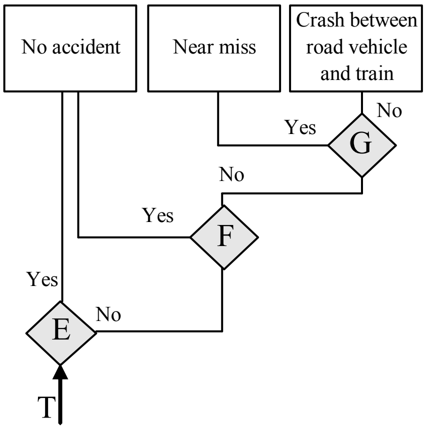


Fig.3.Event tree logic for a level crossing accident

iteration result is stored. After the end of simulation, the results are displayed as a histogram. Thus, it is possible to find the probability of the top event. The simulation process and the determination of output estimates seem to be too complicated, but with the usage of computers, the procedures for outputs estimation become easier. The *Oracle®Crystal Ball* program is used for the implementation of a Monte Carlo analysis (simulation) in respect of the risk assessment concerning the transport accident scenario mentioned above. This is a graphically oriented forecasting and risk analysis program that runs on several versions of Microsoft Windows within the environment of Microsoft Excel spreadsheets.

The simulation procedures with respect to the risk assessment using FTA and ETA (described in figure 2 and figure 3) comprise the next several stages:

-*Determination of the probability of event A*

This probability can be computed by the usage of the next expression:

$$P_A = \frac{\sum_{i=1}^{N} t_i}{T} \tag{2}$$

where:

t_i - approaching time of i-th train towards the level crossing (the time that a train travels from the point of detecting sensor to the point of level crossing clearance);

N - total number of trains passing through the investigated level crossing;

T -exploitation period (total exploitation uptime) during which N trains runs through the investigated level crossing (in accordance with daily train schedule).

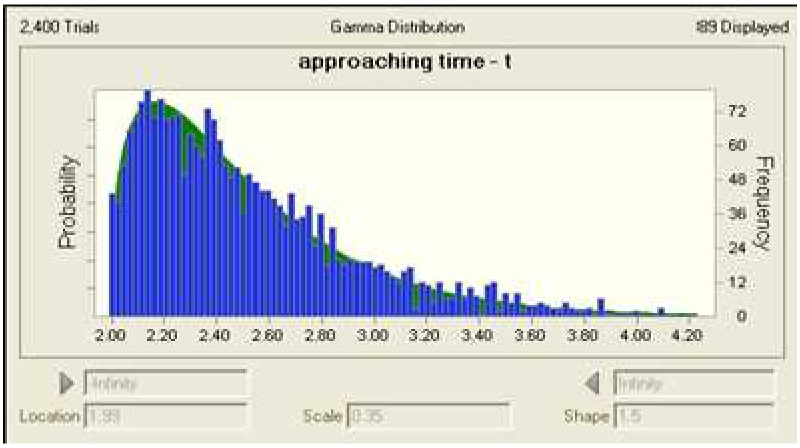


Fig.4.Probability distribution of approaching time t

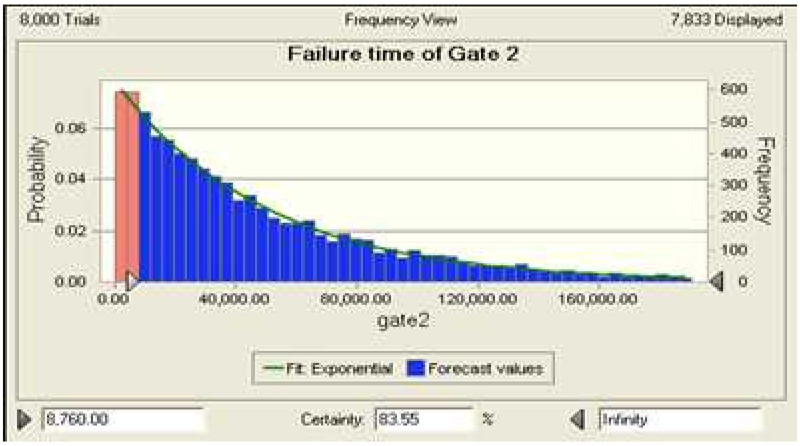
The time t is a random variable that depends primarily on the type of trains passing through the level crossing (special rolling-stock, passenger or freight trains, differing from one another by the length and speed of movement). Having all this in mind, an assumption of Gamma probability distribution (with parameters: *Location - 1,99*; *Scale – 0,35*; *Shape – 1,5*) is made to model the random variable t [in minutes]. The number of trains N depends on time T. In this article (for the purposes of the simulation analysis) these parameters are assumed to be: $N = 80$ trains per time of $T = 20$ hours (it is assumed that there are no trains from 0 AM to 4.00 AM). A simulation with 2400 trials (30-days implementation of the daily schedule of 80 trains) was made (Fig.4) and the mean of time t was determined to be 2,52 minutes. In accordance with expression (2) the probability of event A was obtained: $P_A = 0,17$.

-*Determination of the probability of event U (the level crossing to be unprotected)*

It is assumed that all basic events (**B**, **C** and **D**) have exponentially failure distributions with failure rates: $\lambda_B = 0,0000073\,h^{-1}$, $\lambda_C = 0,0000069\,h^{-1}$, $\lambda_D = 0,0000061\,h^{-1}$. The calculation methodology (rules) of the failure time of each gate (Gate 1 and Gate 2) is as follows:

-*AND Gate* (AND Operation) fails only after all its input events have failed. Thus, the output failure time of this type of gate is equal to the largest failure time of its inputs;

-*OR Gate* (OR Operation) fails when one or more of its input events have failed. The output failure time of this type of logical gate is equal to the lowest failure time of its inputs.



8.760.00 Certainty: 83.55 % Infinity

Fig.5.Probability distribution of failure time of Gate 2

The described methodology is taken into account in determining the probability of event U (Gate 2). What is special here is that there are only OR Gates (two OR logical operations). Figure 5 shows the probability distribution of output failure time of Gate 2 obtained after 8000 trials in respect of failure times of input events (**B**, **C** and **D**). On this basis, the average output failure time (*Mean Time To Failure -MTTF*) is also computed (136986,30 hours). It can be seen that the probability of event U occurrence is $P_U = 0,1645$. It is computed as the probability of output failure time of gate 2 to be smaller than 8760 hours=1 year ($P_U = 0,1645$ is graphically characterized by the area under probability distribution between 0 and 8760 hours-Fig.5). The fact that the events **A** and **U** are independent of each other allows the determination of the probability of event **T**: $P_T = P_A P_U = 0,17.0,1645 = 0,028$.

-*Determination of the probabilities of event E*

This probability could be determined in a manner similar to that for event A. Let $t_{vehicle}$ be the time for which vehicles pass through the level crossing (the time needed for vehicles to traverse the distance between the point of visibility to an approaching train and the end of level crossing area -$l_{vehicle}$, Fig.6). Naturally, this time is a random variable whose value depends on the characteristics of vehicles (length, speed, etc). Let us also assume that the time $t_{vehicle}$ has Gamma distribution with parameters: *Location – 4,00*; *Scale – 0,65*; *Shape – 2*. A simulation with 10000 trials (10000 vehicles per day passing through the level crossing) was made

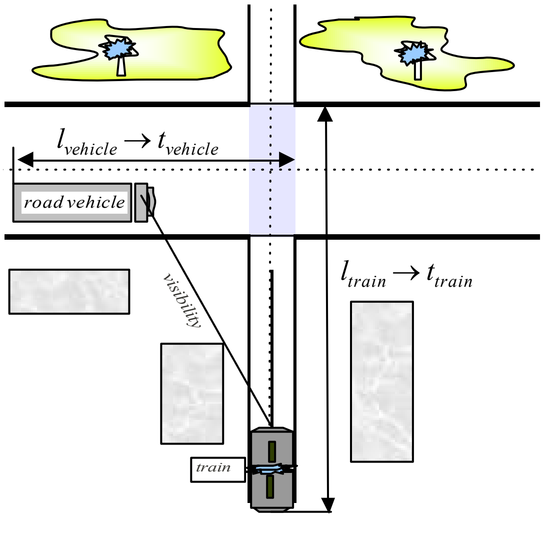


Fig.6.Vehicle and train movements

(Fig.7) and the mean of $t_{vehicle}$ was determined to be 5,30 seconds. In accordance with expression (2), the probability of vehicle presence at level crossing was obtained: $P_{E,No} = 0,74$. The probability $P_{E,Yes} = 1 - 0,74 = 0,26$.

-Determination of the probabilities of event F

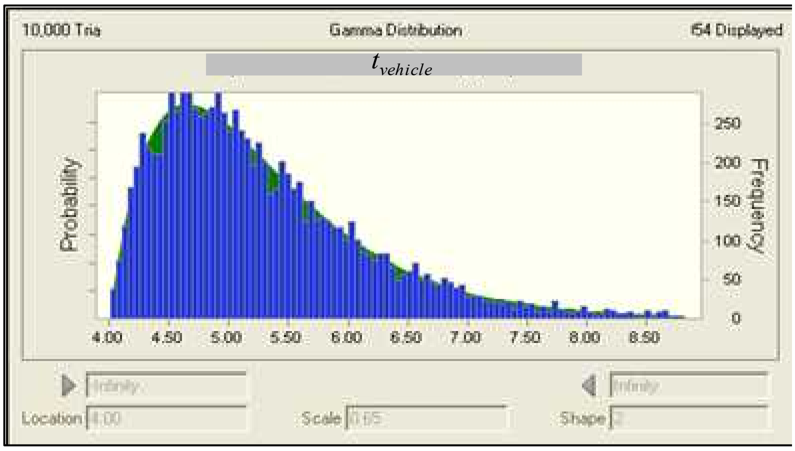


Fig.7.Probability distribution of $t_{vehicle}$

The determination of probabilities $P_{F,Yes}$ and $P_{F,No}$ is a very difficult task and requires more detailed analysis. For the purposes of the present paper their values are assumed to be $P_{F,Yes} = 0,7$ and $P_{F,No} = 0,3$.

-Determination of the probabilities of event G

Event G is essential for this whether or not the consequence event *Crash between road vehicle and train* will occur. Let us define a time t_{train} as a time needed for a train to traverse the distance between the point of visibility from a vehicle wishing to cross the level crossing and the end of level crossing - l_{train} (Fig.6). According to this assumption, the event *Crash between road vehicle and train* will occur when $t_{train} \le t_{vehicle}$. Both times t_{train} and $t_{vehicle}$ are random variables whose values depend on trains and vehicles characteristics: type, length, speed, etc. (the random variable t_{train} has been modeled by Gamma distribution with parameters: *Location – 7,80*; *Scale – 0,68*; *Shape – 2*, Fig.8). Then, the probability $P_{G,No}$ could be characterized by the overlay area of the probability distributions regarding the two random variables: t_{train} and $t_{vehicle}$ (Fig.9). After 10000 simulation trials this probability is computed to be 0,0198.

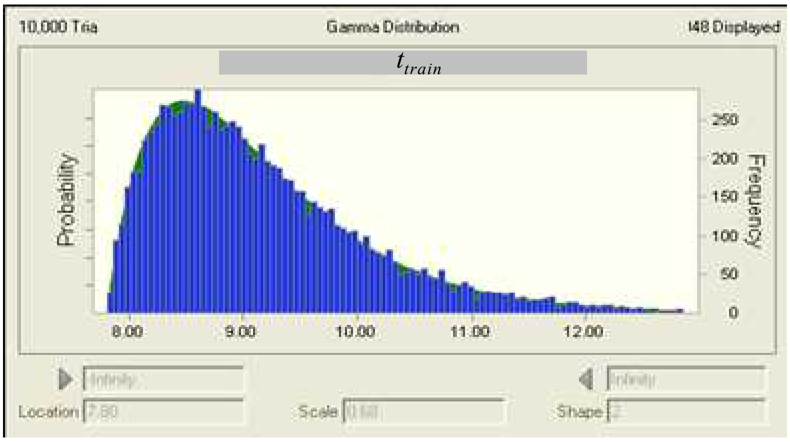


Fig.8.Probability distribution of t_{train}

Having probabilities of all mentioned above events, it is possible to compute the probabilities of final (consequence) events (results). Following the rules with respect to the quantitative FTA and ETA analysis, these probabilities are obtained as follows: $P_{No\ accident} = P_T P_{E,Yes} + P_T P_{E,No} P_{F,Yes} = 0,021784$; $P_{Near\ miss} = P_T P_{E,No} P_{F,No} P_{G,Yes} = 0,00609$ and $P_{Crash} = P_T P_{E,No} P_{F,No} P_{G,No} = 0,000123$.

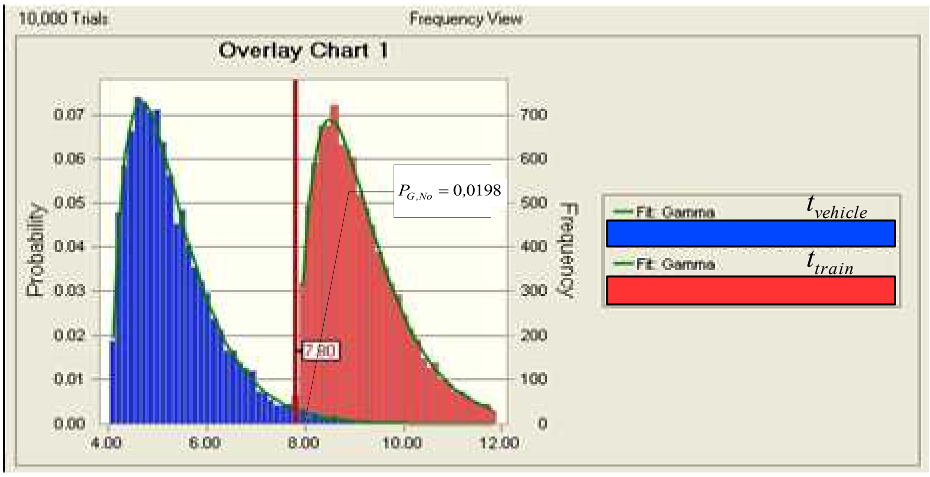


Fig.9.Overlay area of $t_{vehicle}$ and t_{train} probability distributions

Furthermore, finding the probabilities of final events and especially the probability P_{Crash} allows us to quantify the accident losses, primarily associated with people killed and injured. This procedure requires the determination of the so-called *equivalent mortality* - a general indicator converting the number of seriously and lightly injured people into killed. The quantification of accident losses (usually computed for one year period) helps to compare various measures for transport safety improvement (a basic stage in the overall process of decision-making in the field of safety).

3 CONCLUSION AND DISCUSSION

This paper has presented an overview of the performance of safety risk assessment with the support of the Monte Carlo simulation. The development of such a simulation approach regarding transport safety risk assessment was necessary to take into account the effects of variability and uncertainty connected with stochastic events and interactions between a variety of agents (human-operators and technical systems). The procedure of risk analysis presented above clearly shows the effectiveness of the combination between three very powerful methods: FTA, ETA and Monte Carlo simulation. Such a procedure is applicable to effectively analyze and solve different problems concerning operational reliability and safety in all transport modes. It is capable of providing the required information to safety decision-makers about the occurrence and consequence probabilities in respect of a variety of hazards which are characteristic of a specific transport technological system.

The only difficulties associated with the usage of simulation approach for risk assessment are those concerning the correct choice of assumptions for input parameters of the simulation model. Thus, the safety decision-makers wishing to implement Monte Carlo analysis for risk assessment should utilize experts with good knowledge not only in the area of risk management but also in statistics.

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Článok recenzoval:
prof. Ing. Ladislav Šimák, PhD.