Dependability, vol. 17 no.1 2017 Original article
DOI: 10.21683/1729-2646-2017-17-1-40-45

Graph method for evaluation of process safety in railway facilities

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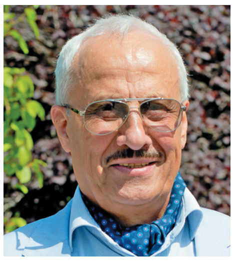

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Aim. *Industrial safety (OS) is the state of protection of operating personnel from harmful effects of manufacturing processes, energy, equipment, objects, conditions and schedule of work [1]. The most efficient evaluation of OS in railway transportation is ensured by composite indicators, one of which is the risk assessment indicator. That is also reflected in the Russian legislation that stipulates the requirement to evaluate fire, occupational and other types of risks that affect industrial safety. According to the definition set forth in GOST 33433-2015 [2] risk is a combination of the probability and consequences of an event. The most complicated task related to risk assessment is the choice of the evaluation model for the probability of an undesired event. The model must enable practical applicability of evaluation results for planning of risk compensation measures. Currently, there are a large number of probability evaluation methods that can be divided into two large groups, i.e. expert and quantitative. Expert methods have several well-known shortcomings. The quantitative methods require the construction of a system of equations or an analytical model. In the context of railway facilities the construction of analytical models of probability evaluation is of principal interest due to the possibility of demonstration of the factors that are taken into consideration by the model. The aim of the article is to formalize the analytical method for evaluation of the probability of railway facility transfer into a hazardous state (in the context of industrial safety).* **Methods.** *Undesirable events that cause industrial safety incidents in railway facilities are random; they can be represented as a random process. A random system development process, including objects transition from a safe state into hazardous (undesirable) states, i.e. system state change in time, can under some assumptions be described with a semi-Markov process. In general, the construction and solution of semi-Markov models comes down to building a system of homogenous differential equations. This procedure always involves mathematical difficulties. [3] shows the possibility of representation and solution of semi-Markov models with a coupled graph model. Such models are highly visual, and allow formalizing the wanted system states, as well as paths of transition from safe into hazardous states. The main problem of modelling random processes of industrial safety state changes is the requirement to identify the complete list of hazardous states and preceding non-hazardous or pre-hazardous states. The processes typical to railway facilities are characterized by a multitude of states that cause various events. The concept of "state" usually characterizes an instantaneous image, a "cross-section" of a system. Thus, at the first stage of construction and solution of a model of random process of a system's industrial safety state change, the finite sets of safe and hazardous states of the railway facility under consideration are identified in accordance with the known hazardous state criterion [4]. As the process of state change of a system's industrial safety in railway transportation is random in time, in this article system operation is described with a semi-Markov process with the assumption that the discrete process is described with an embedded Markov chain. The set of system states and their connections are represented with a directed state graph with defined topological concepts [3]. For a constructed model, the article provides the proof of the theorem identifying the probability of system transition from an initial non-hazardous into a hazardous state, as well as the formula for calculation of such probability.* **Results.** *The graph method for evaluation of industrial safety in railway facilities developed in this article includes both the rules of construction of a system's safety states graph and the tool for evaluation of the probability of system transition into a specific hazardous state. The graph is the basis of the practical method for calculation and forecasting of industrial safety incidents. The article provides the proof of the theorem identifying the probability of system transition from an initial non-hazardous into a hazardous state, as well as an example of application of graph method for evaluation of probability of fire in a fixed facility. The proposed probability evaluation method can be used in planning of industrial safety measures in terms of specification of new states or rules of transition into associated states.*

For citation: *Shubinsky I.B., Zamyshlyaev A.M., Pronevich O.B. Graph method for evaluation of process safety in railway facilities. Dependability. 2017, vol. 17, no. 1, pp. 40-45. (in Rus-sian) DOI: 10.21683/1729-2646-2017-17-1-40-45*

Introduction

The industrial safety indicators are divided into two types, i.e. actual and calculated (planned). Among the actual indicators are occupational injuries frequency factors, size of insurance payouts, fire frequencies, charges for negative environmental effects, etc. The actual indicators can be represented in either absolute or relative values that are defined by means of direct measurements. The calculated indicators of industrial safety normally fall into the category of composite or integrated indicators. According to the Russian and global experience, the most efficient calculated indicator is the composite indicator that combines quantitative and qualitative evaluations, i.e. the indicator of risk. The risk matrix is widely used for risk evaluation [2, 5]. The consequences of a risk event are always negative. Those typical to operated railway facilities are well known. GOST 33433-2015 recommends standard gravity levels for railway transportation. Calculations of the probability of an undesired event involve the problem on choosing the method of calculation. Currently, there are a large number of probability evaluation methods that are divided into two large groups, i.e. expert and quantitative. The most important aspect of choosing the method for evaluation of the probability of undesired events is ensuring the practical applicability of the results, which means that the evaluation model must take into consideration the states of the system's controlled parameters. A system that allows managing the probabilities of hazardous events and accidents must be based on the information on the processes implemented in railway facilities and states that are associated with accident and undesired events. The approach proposed in this paper aims to create a demonstrable and well formalized method to identify the probability of system transition into hazardous state.

Subsets of states of railway facilities

A distinctive feature of a complex system, such as a railway facility, is its property to maintain the overall state of operability in case of failure of individual elements or even whole subsystems [1]. Such system states in many cases reduce its operational efficiency. This property of railway facilities significantly affects the specification and solution of the safety task. For instance, in terms of fire safety, the states of "violation of the Fire prevention rules (FPR)" and "development of fire due to violation of the FPR" are two different system states. The probabilistic characteristics of such states also differ. From the point of view of facility fire safety management, not only the probability of violation, but the probability of its timely elimination should be evaluated. This approach forms additional relations among various states. Let us formalize the concept of "safety state" in terms of the theory of sets:

State of operability S_{op} is state of a system under which the values of all parameters that characterize the ability to perform the specified functions comply with the requirements of technical documentation.

State of nonoperability $\bar{S}_{op}$ is state of a system under which the value of at least one parameter that characterizes the ability to perform the specified functions does not comply with the requirements of technical documentation.

Set of non-hazardous industrial states S_I is the system states under which safety of property, life, health of employees and third parties is ensured in accordance with regula-

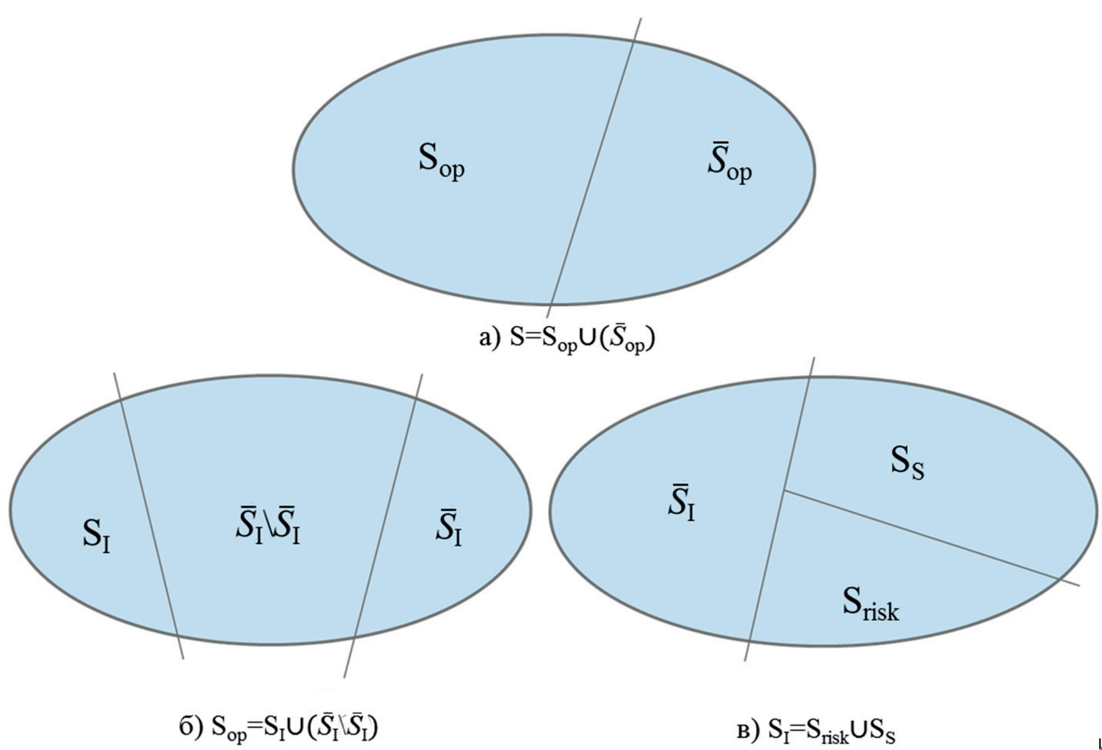


Figure 1. Safety states of system

tory documents [1]. This set includes the sets of safety and pre-hazardous system states.

Set of safety states S_S is the system states under which safety of property, life, health of employees and third parties is ensured in accordance with technical, process control documentation, operational conditions.

Set of pre-hazardous states S_{risk} is such states of operability under which the system approaches the limits of the specified hazardous state criterion at such speed that it can pass into a hazardous state before the next maintenance inspection or repair.

Set of hazardous states $\overline{S}_I$ is the state that may cause harm to property, health and life of employees, as well as third parties.

Figure 1 shows diagrams of sets of safety states of system.

In this article we focus our attention on states S_I, S_{risk}, $\overline{S}_I$

Safe system states graph

Events of fire, accidents with environmental consequences, occupational injuries are random. Let us represent the considered system with the previously designed sets of states as a directed state graph *G(S,H)*, where S is the finite set of system states; H is the finite set of arcs between vertices i,j (states s_i, s_j). System development can be described as follows: if a system is in state s_i, then with probability p_{ij} it can pass into state s_j. The criterion of hazardous event is the system transition into a set of hazardous states $\overline{S}_I$.

System safety graph construction must take into consideration the following requirements:

1) From each state of set S_i there is a possibility of transit into state of set S_{risk} or $\overline{S}_I$.

2) From each state of set S_{risk} the system transits either into state S_i, or state $\overline{S}_I$.

Let us give an example of state graph description of fire safety in premises of a fixed facility (see Table 1):

S is the complete set of object states, S=*{S0, S1, S2, S3, S4, S5};*

S_I is the subset of non-hazardous states, SI=*{S0};*

S_{risk} is the subset of pre-hazardous states, SP=*{S1, S2, S3};*

$\overline{S}_I$ is the subset of hazardous states), $\overline{S}_I$={S4, S5}.

Thus, S= $S_I \cup \overline{S}_I$, S_{and}=$S_{risk} \cup S_S$.

Table 2 shows the values of probabilities of one-step transitions from the i^{th} state to the j (p_{ij}) state. Those probabilities are a priori, they are specified by means of expertise based on the analysis of fire development cases.

Table 2. Transition probabilities matrix

		States						
		0	1	2	3	4	5	∑
S	0	0,7	0,3	0	0	0	0	**1**
t	1	0,5	0	0,3	0,2	0	0	**1**
a	2	0	0	0,7	0	0,3	0	**1**
t	3	0	0	0	0,3	0,2	0,5	**1**
e	4	0	0	0,3	0	0,7	0	**1**
s	5	0	0	0	0	0	1	**1**

Figure 2 shows the state graph

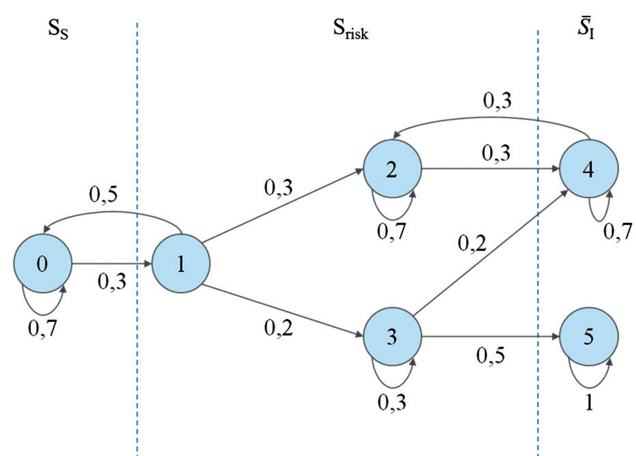


Figure 2. State graph of fire safety in premises of fixed facility

The aim is to identify the probability of system transition from a specific non-hazardous state into any hazardous one. The calculation data must be taken into consideration when taking decisions regarding the changes of transition probabilities through the deployment of fire safety systems, carrying-out of preventive repairs and other accident prevention measures.

The topological concepts used in mathematical simulation:

path, a chain of series-connected unidirectional arcs beginning in state *i* and ending in state *j*, the weight of a path l_k^{ij} is identified with the formula:

Table 1. Set of system states

Set	Subset	№	Notation	Description	Breached regulatory document
S	S_I	0	S_0	Cables/wires not damaged	
	S_{risk}	1	S_1	Open cables/wires (without protective sleeves/pipes/conduits) in places where mechanical damage may occur.	IEC 2.1.47
		2	S_2	Sharp bends, micro-damage (non-visible damage of insulation)	
		3	S_3	Use of cable/wire with visibly damage insulation	FPR 42 a)
	$\overline{S}_I$	4	S_4	Cable heating due to rising transition resistance	
		5	S_5	Short circuit and melting of insulation, sparks due to SC	

$$l_k^{ij} = \prod_{i,r,j \in S} p_{ir} \cdot p_{rj}, \quad (1)$$

where p_{ir} is the probability of one-step transition from state i into state r;

closed circuit is a chain of series-connected unidirectional arcs, in which the output of the final vertex in a circuit is connected to the initial vertex of the circuit. The weight of the j^{th} circuit is identified by the formula:

$$C_j = \prod_{i,j \in S} p_{ij} \cdot p_{ij}; \quad (2);$$

loop is a case of closed circuit, in which the incoming and outgoing arcs merge into one arc, the weight of the loop is $C_j = p_{ij}$;

graph resolution is a part of a graph that does not contain marked vertices and connected arcs; the weight of resolution ΔG_i is calculated subject to exclusion of vertex i and connected arcs from the graph; the weight of resolution $\Delta G_{\overline{S}_I}$ is calculated subject to additional exclusion from the graph of the vertices of set $\overline{S}_I$ and connected arcs; the weight of resolution ΔG_k^f is calculated subject to exclusion from graph of vertex f, as well as the vertices situated on the k^{th} path from the initial vortex into vertex i, as well as the connected arcs;

the weight of resolution (determinant) is found using Mason's formula:

$$\Delta G = 1 - \sum_j C_j + \sum_{rj} C_r \cdot C_j - \sum_{irj} C_i \cdot C_r \cdot C_j + \ldots \quad (3)$$

Theorem

The probability of system transition from the specific i^{th} initial non-hazardous state ($i \in S_I, S_I \cap \overline{S}_I \neq \varnothing, S_I \cup \overline{S}_I = S$) into any hazardous state $f \in \overline{S}_I$ is determined from the formula

$$b_{if} = \frac{\sum_{f \in \overline{S}_I} \sum_k l_k^{if} \Delta G_k^f}{\Delta G_{\overline{S}_I}} \quad (4)$$

where l_k^{if} is the k^{th} path leading from non-hazardous state of graph $i \in \overline{S}_I$ into hazardous state f;

ΔG_k^f is the weight of graph resolution without the f^{th} vertex and graph vertices situated on the k^{th} path:

$\Delta G_{\overline{S}_I}$ is the weight of graph resolution without the vertices of the hazardous state set.

Let us prove the correctness of formula (4). A random system transition from initial non-hazardous state i into any hazardous one is possible as follows:

- by preliminary transition into associated non-hazardous states. That is described with the sum of products of the probabilities of transition from the initial non-hazardous state into another non-hazardous state and the probability of system transition from those non-hazardous states into any hazardous state, i.e. this probability equals to: $\sum_j p_{ij} \cdot b_{if}$.

Or, in matrix form, T·V, where T is *nxn* dimension transition probability matrix, while n is the number of vertices in the set of non-hazardous states; V is *nx1* dimension column-vector of probability of transition into hazardous state;

- by direct one-step transition into any hazardous state that is described with a column-vector of probabilities of one-step system transitions from state i into any hazardous state f: P=(p_{if}). This column-vector has the size of (nx1), where n is the number of vertices in the set of non-hazardous states.

Thus, the probability of random system transition from initial non-hazardous state i into any hazardous state f can be expressed with the following matrix equation:

$$V = TV + P \quad (5).$$

In this equation, the unknown quantities are the elements of the column-vector V. After their grouping in the left part of the matrix equation we deduce:

$$V(I - T) = P \quad (6)$$

where the right part of the equation is the column-vector of free terms of the probabilities of one-step transitions from vertices $i, j, \ldots, z \in S_I$ into vertex $f \in \overline{S}_I$.

Then, according to Kramer's rule, we deduce $B_i = \Delta_i / \Delta$, where the graph determinant in the set of non-hazardous states $\Delta = |I - \Pi|$, while Δ_i is the determinant deduced by substituting the i^{th} column in the matrix $I - \Pi$ with the free term vector P under the condition that Δ_i and Δ are not equal to 0.

Determinant Δ_i differs from determinant Δ in that in column i element p_{ij} is replaced with element p_{if}. In accordance with [2], let us use the graph form of representation of determinant and minors, as well as graph paths, i.e.:

$$\Delta = \Delta G_{\overline{S}}, \ \Delta_i = \sum_{f \in \overline{S}_I} \sum_k l_k^{if} \Delta G_k^f, \quad (7)$$

where $\Delta G_{\overline{S}_I}$ is the weight of graph resolution without the set of hazardous vertices;

ΔG_k^f *is* the weight of graph resolution without hazardous vertices, as well as the vertices situated on the k^{th} path;

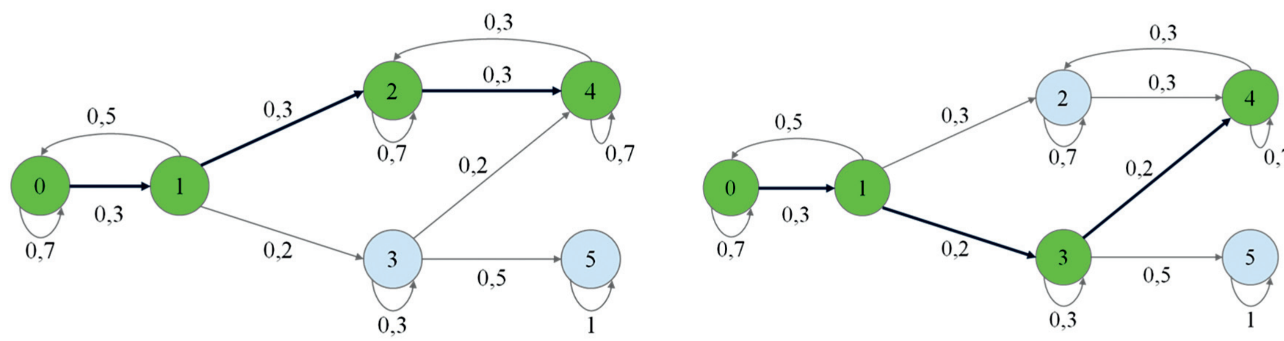
l_k^{if} is the weight of the k^{th} path from the non-hazardous vertex i to the hazardous vertex f.

By substituting formulas (7) into formula (6) we deduce that

$$b_{if} = \frac{\sum_{f \in \overline{S}_I} \sum_k l_k^{if} \Delta G_k^f}{\Delta G_{\overline{S}_I}}.$$

Example of evaluation of probability of cables in a fixed facility passing into fire-hazardous state

For the above system hazard state graph, let us calculate the probability of transition from state S_0 "Cables/wires not damaged" into state S_4 "Cable heating due to rising transition resistance". Figure 3 shows paths of transition into hazardous state S_4.



a) Path to hazardous state No. 1 b) Path to hazardous state No. 2

Figure 3. Paths of transition into hazardous state S_4

Table 3. Path weight calculation

№	Notation	Path	Formula	Path weight calculation	Path weight
1	l_1^{04}	$S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow S_4$	$p_{01} \cdot p_{12} \cdot p_{24}$	0,3·0,3·0,3	0,027
2	l_2^{04}	$S_0 \rightarrow S_1 \rightarrow S_3 \rightarrow S_4$	$p_{01} \cdot p_{13} \cdot p_{34}$	0,3·0,2·0,2	0,012

In accordance with the theorem for evaluation of the probability of system transition from initial non-hazardous state into hazardous state, the probability of system transition from S_0 to S_4 is defined with the formula:

$$b_{04}=\frac{\sum_{f\in \bar{S}_l}\sum_k l_k^{04}\Delta G_k^4}{\Delta G_{\bar{S}_l}}.$$

As it is seen from Figure 3, the number of transition paths from S_0 to S_4 k=2.

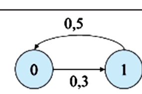
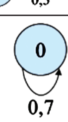
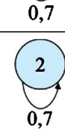
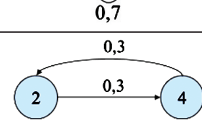
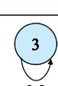
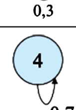
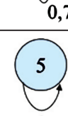
Table 3 shows the calculation of weights of paths from state S_0 to state S_4. Table 4 shows circuit weight calculations.

For the considered case, the weight of graph resolution without the vertices of the hazardous state set equals:

$$\Delta G_{\bar{S}_l}=1-(0,7+0,15+0,7+0,3)+$$
$$+(0,105+0,045+0,49+0,21+0,21)-$$
$$-(0,0315+0,147)=0,0315.$$

Then, the probability of transition from state S0 (wires and cables not damaged) into state S4 (heating due to rising transition resistance):

Table 4. Circuit weight calculation

№	Circuit code	Vertices	Form	Formula	Circuit weight, C_i	Circuit with hazardous states
1	C_1	$S_0 \rightarrow S_1 \rightarrow S_0$		$p_{01} \cdot p_{10}$=0,5·0,3	0,15	
2	C_0	$S_0 \rightarrow S_0$		p_{00}=0,7	0,7	
3	C_2	$S_2 \rightarrow S_2$		p_{22}=0,7	0,7	
4	C_4	$S_2 \rightarrow S_4$		$p_{24} \cdot p_{42}$=0,3·0,3	0,09	V
5	C_3	$S_3 \rightarrow S_3$		p_{33}=0,3	0,3	
6	$C_{4.4}$	$S_4 \rightarrow S_4$		p_{44}=0,7	0,7	V
7	C_5	$S_5 \rightarrow S_5$		p_{55}=1	1	V

$$b_{04} = \frac{\sum_{f \in \bar{S}_I} \sum_k l_k^{04} \Delta G_k^4}{\Delta G_{\bar{S}_I}} =$$

$$= \frac{0,027 \cdot 0,7 + 0,012 \cdot 0,3}{0,0315} = \frac{0,0225}{0,0315} = 0,71.$$

In the same way, the probability of transition from state S0 (wires and cables not damaged) into state S5 (Short circuit and melting of insulation, sparks due to short circuit) is calculated.

$$P_{05} = \frac{\sum_{f \in \bar{S}_{op}} \sum_k l_k^{05} \Delta G_k^5}{\Delta G_{\bar{S}_{op}}} = \frac{0,03 \cdot 0,3}{0,0315} = \frac{0,009}{0,0315} = 0,29.$$

Conclusion

It was shown that random events of fire, accidents with environmental consequences, occupational injuries can be evaluated with a model of semi-Markov process on the assumption that transitions between system states are described with a discrete-time embedded Markov chain. A graph model of system fire safety analysis was demonstrated that includes the states of a multitude of hazardous, pre-hazardous and non-hazardous events.

A tool for evaluating the industrial safety risk by means of a graph model of safety analysis was developed. The theorem was proven for identifying the probability of system transition from initial non-hazardous or pre-hazardous state into desired hazardous state that allows finding the analytical or numerical value of the probability of hazardous state of a railway facility. A practical application was shown.

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Received on: 28.12.2016