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Improving the dependability of light vented foundations exposed to vibration load on frost soils

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Abstract. Aim. *Today, dynamically-loaded foundations of process equipment often prove to be oversized with significantly overestimated values of stiffness, mass and material consumption. Therefore, reducing the costs and time of construction of gas pipeline facilities, especially on permafrost, is of relevance to PJSC Gazprom. One of the primary ways of solving this problem is installing gas pumping equipment on light vented support structures. The disadvantage of such structures is the low vibration rigidity. A method [1] is proposed for improving the vibration rigidity of a foundation subjected to vibration load. The simulation aims to improve the dependability of light vented foundations by studying vibration displacements of foundations with attached reinforced concrete panels depending on the thermal state of frost soils, parameters of the attached panels and connectors.* **Methods.** *Vibration displacements of a foundation with an attached device were identified using the finite element method and the improved computational model of the foundation – GCU – soil system.* **Results.** *Computational experiments identified the vibration displacements of the foundation in the cold and warm seasons for the following cases of reinforced concrete plates attached to the foundation: symmetrical and non-symmetrical; at different distances; through connectors with different stiffness parameters; with additional weights; frozen to the ground. Conclusions were made based on the results of simulation of vibration displacements of foundations with an attached device in cold and warm seasons.* **Conclusion.** *The presented results of computational experiments aimed at improving the vibration rigidity of light foundations by using method [1] show sufficiently good indicators of reduced vibration displacements of the foundation. Thus, in the case of symmetrical connection of four reinforced concrete panels in summer, the reduction of vibration displacements is 42.4%, while increased stiffness of the connectors, attachment of additional weights and freezing of reinforced concrete panels into the ground will allow reducing the vibration displacements of the foundation up to 2.5 times. However, it should be noted, that applying the findings in the process of development of project documentation and construction of foundations requires R&D activities involving verification and comparison of the obtained results of numerical simulation with a natural experiment.*

Keywords: *reduction of vibration displacements, GCU foundation, dynamic load, connector, weight.*

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1. Introduction

Today, dynamically-loaded foundations of process equipment often prove to be oversized with significantly overestimated values of stiffness, mass and material consumption. Therefore, reducing the costs and time of construction of gas pipeline facilities, especially on permafrost, is of relevance to PJSC Gazprom. One of the possible solutions consists in installing gas pumping equipment on light vented support structures. The disadvantage of such structures is the low vibration rigidity, which is compensated by a massive reinforced concrete panel on top of the foundation, increased number and depth of pile penetration, which causes longer time of foundation construction and material consumption. Improved vibration rigidity of light support structures is made possible by the "Method for improving the dynamic stiffness of foundations exposed to vibration load and the device for its implementation" [1] (hereinafter referred to as the Method).

2. The Method

The Method involves the attachment of an additional structure to the foundation through connectors for the purpose of transferring dynamic loads from the foundation to the soil. That reduces the vibration displacements of the foundation, which saves costs associated with the vibration protection of foundations with minimal earthwork. As the additional structure, the paper considered the attachment of reinforced concrete panels (hereinafter referred to as RC panels) for transferring dynamic loads from the foundation to the soil (see Fig. 1). That reduces the vibration displacements of the foundation, thus saving costs associated with vibration protection of the foundation with minimal earthwork. Additionally, the installation of RC panels on the surface of the soil without penetration minimizes the problems of frost soil thawing in the course of operation.

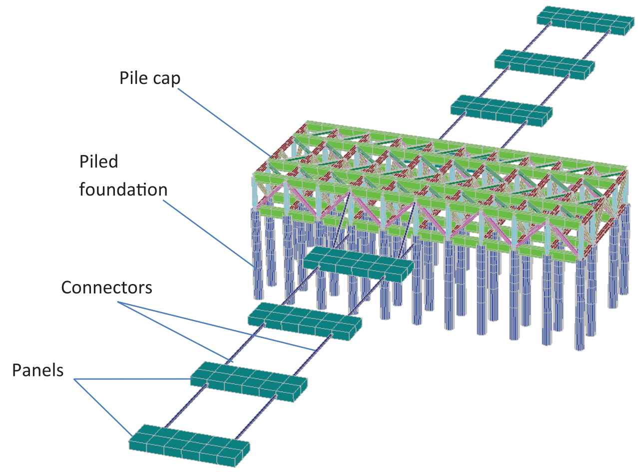


Fig. 1. Diagram of reinforced concrete panels attached to a foundation

The following measures are foreseen for the purpose of maximizing the effect of the Method: weighting of the attached RC panels and ground freezing, as well as selection of parameters (stiffness, dimensions, placement) of the connectors and the attached RC panels for transferring elastic oscillatory waves into the soil mass.

A number of computational models were developed for the purpose of identifying vibration displacements of the foundation of a 25 MW "Ural" gas compressor unit (GCU) caused by dynamic loads using the example of frost-bound soil. Frost-bound soil is characterized by the fact that the layer that thaws over the summer completely freezes over the cold season, thus forming a single frozen mass. The vibration displacements of the foundation were identified using an improved computational model of the underlying soil [2, 3]. Data for calculating the dynamic load caused by the rotation of the rotors of GPA-25 Ural are given in Table 1. For the purpose of demonstrating the simulation results, the eccentricity of the rotors, based on test data, is conventionally taken as

Table 1. Data for dynamic load identification

Name of moving part	Mass, kg	Rate of rotation		Centrifugal force, N
		n, rpm	ω, rad/s	
Power turbine (PT) rotor, m_3	670	5250 5000 3500	550 523 366	314 284 139
Low pressure turbine (LPT) rotor, m_1	753	4600 4300 3200	481 450 335	270 236 131
High pressure compressor (HPC) rotor, m_2	410	12000 11670 10150	1256 1221 1062	1003 947 717
Transmission of gas turbine power unit, m_4	160	5250 5000 3500	550 523 366	75 68 33
Compressor rotor, m_5	1350	5250 5000 3500	550 523 366	633 572 280

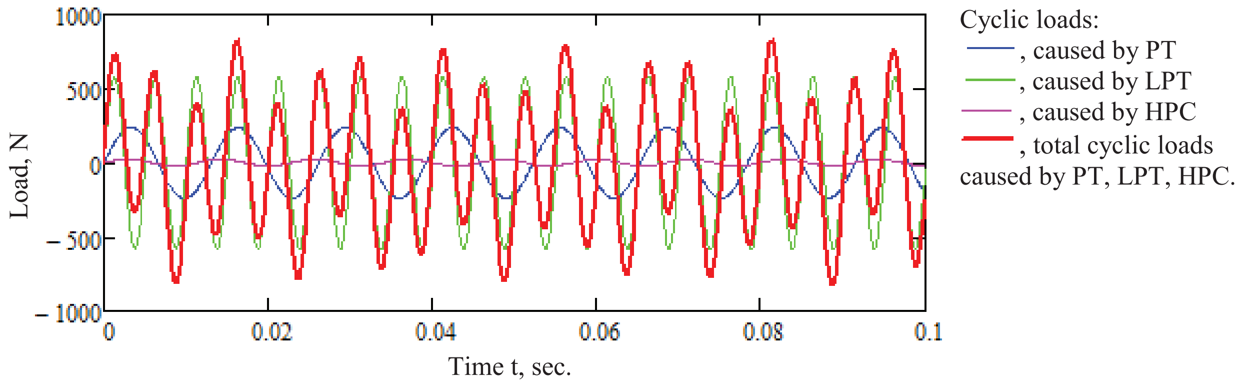


Fig. 2. Graphs of the intermittent loads affecting the engine support

e = 1.5 μm or 0.0015 mm. This parameter depends on the precision of rotor manufacture.

A simultaneous exposure of a foundation to rotors rotating at different speeds is a polyharmonic force [4], (see Fig. 2). The total vibration amplitude is found by adding component vibration displacements from each source individually.

$$\sum_{i=1}^{n} y_i = A_1 \sin(\omega_1 t + \delta_1) + A_2 \sin(\omega_2 t + \delta_2) + \\ + A_3 \sin(\omega_3 t + \delta_3) + A_4 \sin(\omega_4 t + \delta_4) + A_5 \sin(\omega_5 t + \delta_5) \quad (1)$$

where A_1, A_2 ... A_5 are the vibration amplitudes caused by intermittent loads R_1, R_2… R_5; δ_1, δ_2... δ_5 are phase angles; ω_1, ω_2 … ω_5 are angular frequencies of the sources of intermittent loads.

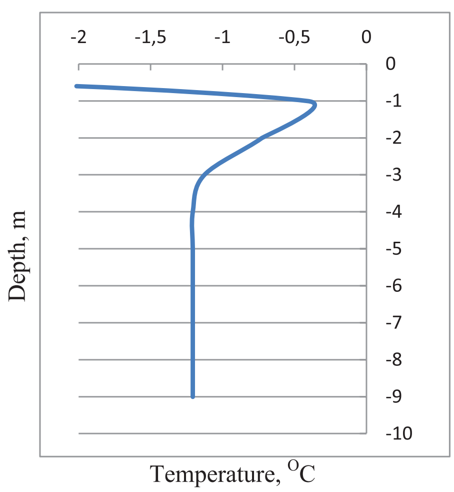
Obtaining the results of the computational experiment only requires defining one of the components of the vibration displacement of the foundation, e.g., the one caused by the intermittent load $P_3 \cdot \sin(\omega_3 \cdot t)$, where $P_3 = m_3 \cdot e_3 \cdot \omega_3^2$ is the dynamic load due to the rotation of the power turbine's rotor, H [5], ω_3 is the cycle frequency of the rotor's rotation, 1/s, t is the time, s.

The vibration displacements were determined for the warmest and the coldest times of the year for the following cases, respectively:

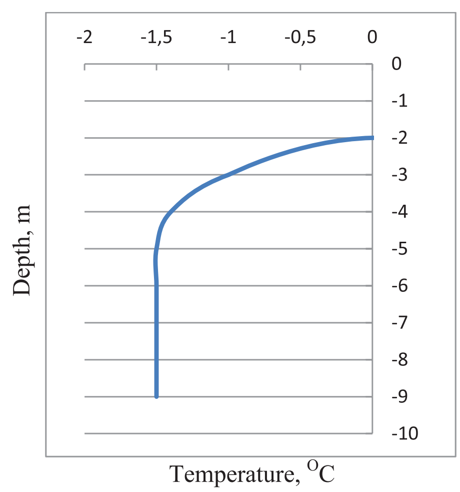
I. Symmetrical and non-symmetrical attachment of RC panels;

II. RC panel attached 5.25 m to 23.25 m away from the foundation's centre line;

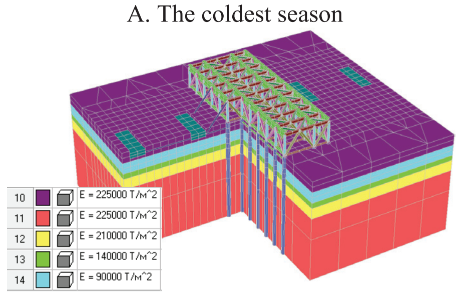
III. Attachment of RC panels through connectors with the stiffness ratio K ranging from $175560 \cdot 10^3$ to



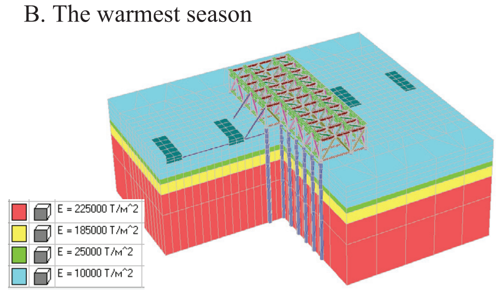
A. The coldest season



B. The warmest season



C. Modulus of elasticity of frost soils in the coldest season



D. Modulus of elasticity of frost soils in the warmest season

Fig. 3. Distribution of temperatures and elastic moduli of frost soils throughout the depth of the underlying soil

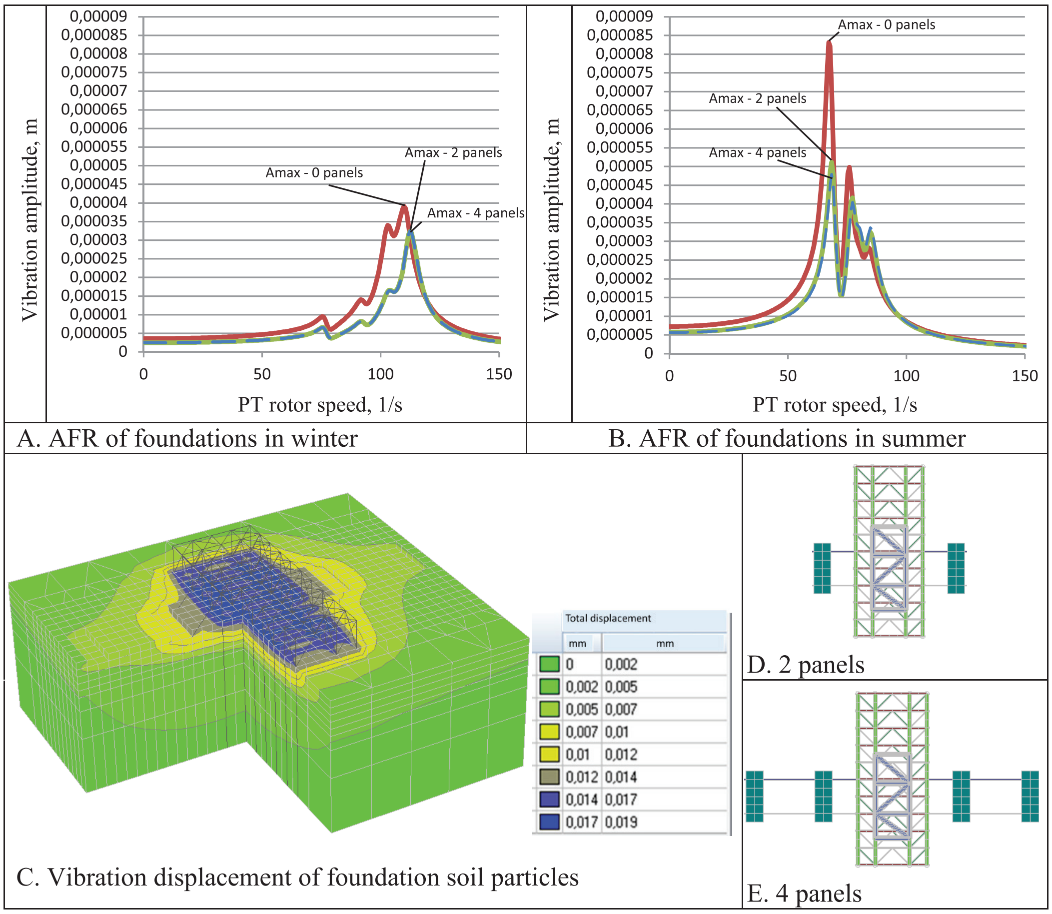
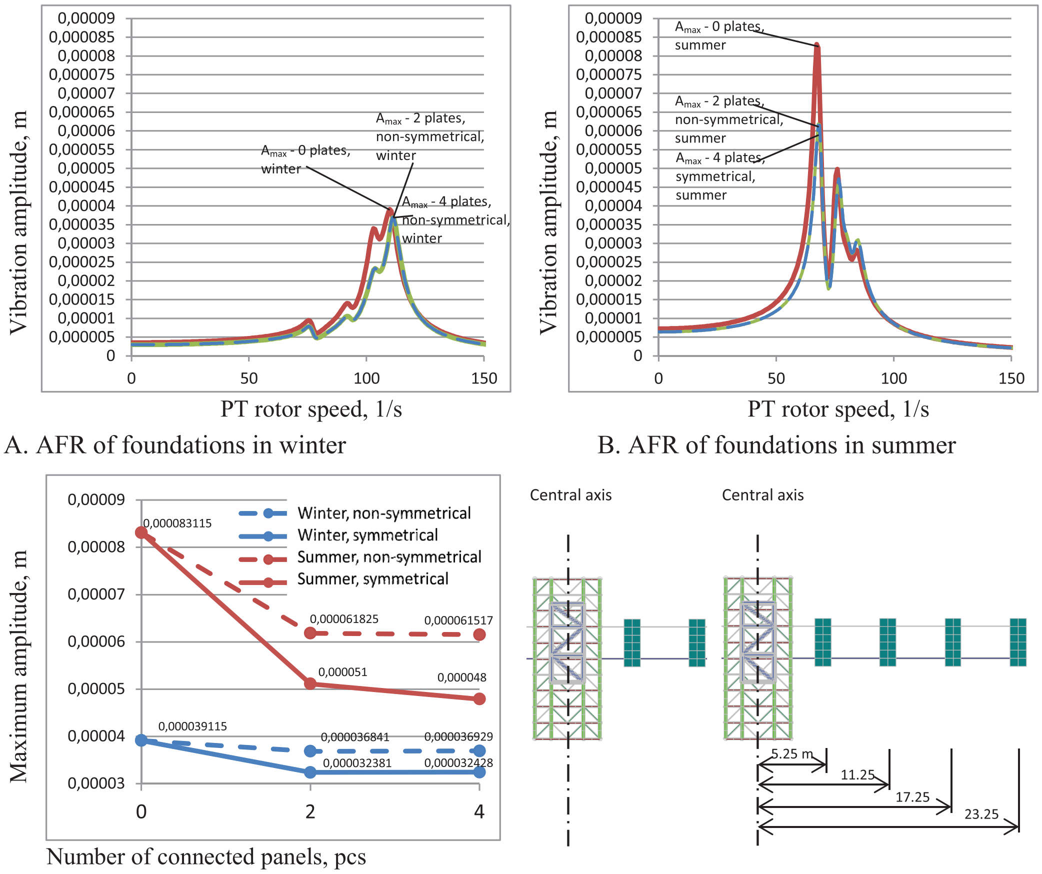


Fig. 4. Definition of vibration amplitude of foundations with symmetrically attached RC panels



C. Comparison of A_{max} D. 2 RC panels E. 4 RC panels

Fig. 5. Comparison of the AFRs of foundations with non-symmetrically attached RC panels

$2251200 \cdot 10^3$ $(H \cdot м^2)/м^2$, where $K = E \cdot S$, E is the elastic modulus of the connector's material, Pa, S is the cross section area of the connector, m^2;

IV. Weighting the surface of the RC panels;

V. RC panels freezing to the soil.

It is assumed that the pile cap and field under the GCU are identical to those of compressor stations no. 2 Olekminskaya and no. 6 Skovorodinskaya of the Sila Sibiri main gas pipeline. The foundation consists of a 77.6-ton surface steel pile cap and a field of 44 piles that are 426-mm pipes with 9-mm-thick walls made of the 09G2S steel (the depth of pile penetration is 12 m, the mass of a pile is 1158 kg). The underlying soil is 3 meters of made ground consisting of medium-grained sand. Below the depth of 3 meters lies icy loam in a solidly frozen state. In summer, the top layer of soil thaws to the depth of 2 meters, at the end of winter, the underlying soil, including the top layer of the made ground, is in a solidly frozen state. The temperature of the soil 12 meters below the grading level is – 1.5°C. The distribution of temperatures and elastic moduli of frozen soils through the depth of the underlying soil for the warmest and coldest times of the year is shown in Fig. 3.

3. Symmetrical and non-symmetrical attachment of the device

Let us take a look at the simulation results with symmetrical attachment of the device [1] to the foundation in summer and winter. Fig. 4 shows the resulting figures of the foundation's vibration amplitudes caused by one of the components of the total recurrent load $P_3 \cdot \sin(\omega_3 \cdot t)$.

Out of the graphs in Fig. 4A and 4B, it can be seen that the symmetrical attachment of 2 RC panels in winter reduces the maximum vibration amplitude A_{max} by 17.2%, while increasing the number of attached panels from 2 to 4 has practically no effect on the changes of A_{max}. At the same time, the attachment of 2 and 4 RC panels in summer reduces A_{max} by 38.5% and 42.4% respectively.

Due to the tight arrangement of the process equipment, a non-symmetrical attachment of the RC panels to the foundation may also be justified, e.g., on one side only (see Fig. 5). In this case, with the same number of attached RC panels, the simulation shows vibration displacements decrease by 5.8% in winter and by 25.6% in summer.

Simulations shows that increasing the number of non-symmetrically attached RC panels from 2 to 4 does not affect the change of A_{max} either in summer, or in winter. Thus, a non-symmetrical attachment of more than 2 RC panels is not advisable (see Fig. 5C). The positive effect of non-symmetrical attachment of RC panels is lower by 16.8…32.8% as compared to the symmetrical solution. The advantage of this layout though is its versatility, especially when the process equipment is spaced closely around the GCU foundation.

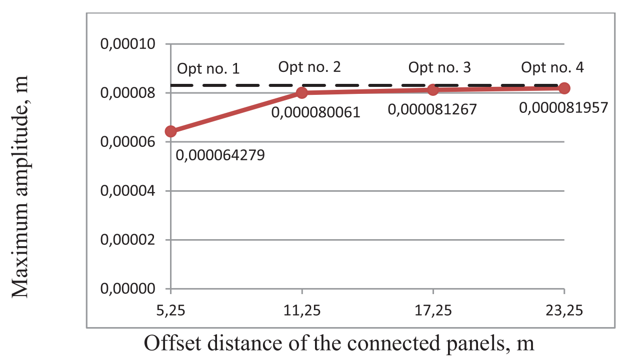
4. Attachment of RC panels at different distances from the central axis of the foundation

Let us consider A_{max} for four cases of one RC panel attachment at distances of 5.25 m, 11.25 m, 17.25 m and 23.25 m from the central axis of the foundation (see Fig. 6). The attachment of an RC panel at a distance of 5.25 m reduces the A_{max} by 22.7%, while the attachment of the same panel at distances of 11.25 m, 17.25 m, 23.5 m reduces the vibration amplitude by 3.7%, 2.2% and 1.4% respectively. Thus, if the length of the connector increases 4 times, the effect of reduced vibration amplitude decreases 16 times.

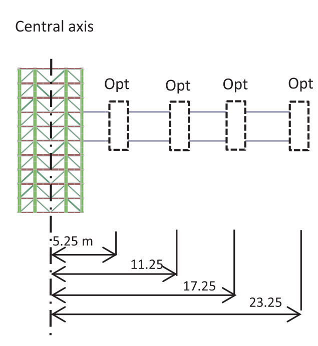
The efficiency of a connector with the rigidity ratio of 452760 $(H \cdot м^2)/м^2$ (made of a 90 x 90 mm square tube with a 7 mm-thick wall), provided that the distances between the panel and the foundation axis are more than 10 m and 20 m, is less than 5% and 2%, respectively. Obviously, in order to increase the effect of RC panel attachment, the connector stiffness should be increased as well.

5. Attachment of RC panels through connectors with different stiffness ratios

Based on the comparison of the AFRs of foundations with symmetrically attached RC panels with the connector stiffness ratios ranging from 175560 kN/m^2·m^2 to 2251200 kN/m^2·m^2, curves were constructed that show the dependence of A_{max} and λ_{Amax} on the stiffness of the connectors in

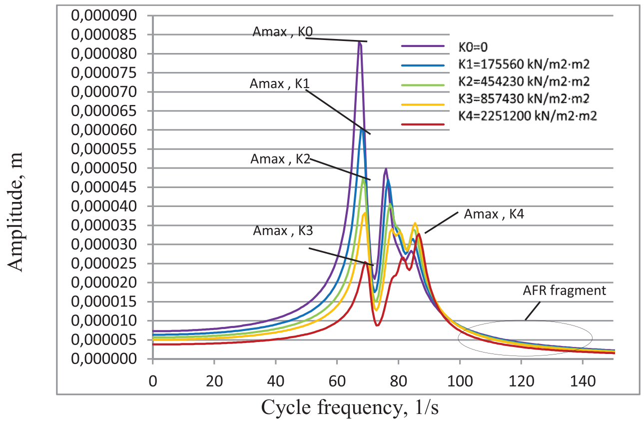


A. A_{max}/connector length curve



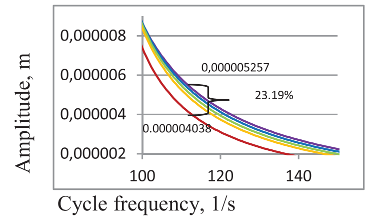
B. Connection options

Fig. 6. Comparison of A_{max} for four cases of attachment of equally spaced RC panels

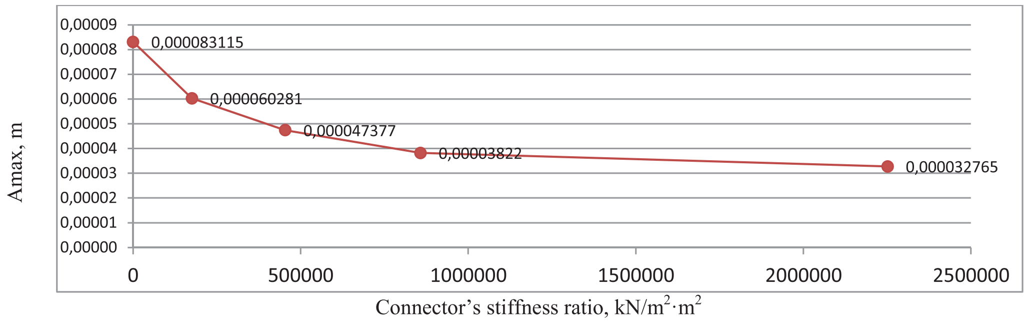


A. AFR of five variant connector stiffness ration

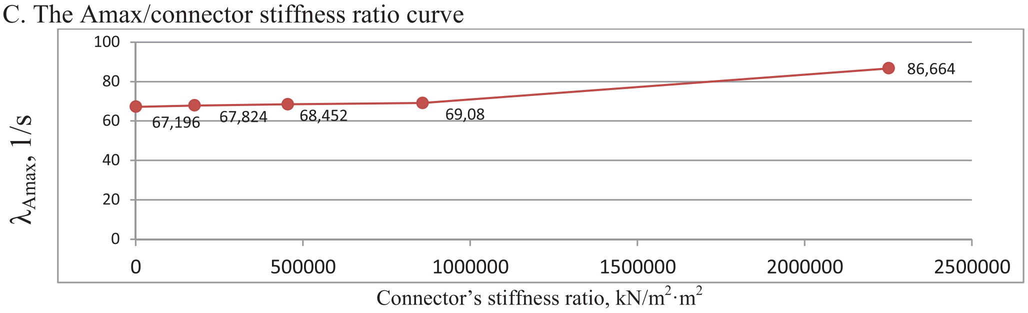
Designations:
K_n=E·a_n, the n-th variant of the connector's stiffness ration, kN/m^2·m^2;
n is the number of variant stiffness ratio from 0 to 4;
E is the elastic modulus of the connector's material, PA;
A_n is the connector's cross section area, m^2;



B. Fragment of AFR between 100 and 150 1/s



C. The Amax/connector stiffness ratio curve



D. The λ_{Amax}/connector stiffness ratio curve

Fig. 7. Correlation between the foundation's AFR and the connectors' stiffness ratio

Fig. 7 C, D, where: λ_{Amax} is the frequency of the foundation's own vibrations corresponding to A_{max}. As the stiffness of the connectors grows from zero to 2251200 kN/m^2·m^2 A_{max} decreases 2.53 times, while λ_{Amax} increases by 28.97%. Within the frequency range between 100 and 150 1/s, the vibration amplitude reduction is over 23% (see Fig. 7 B).

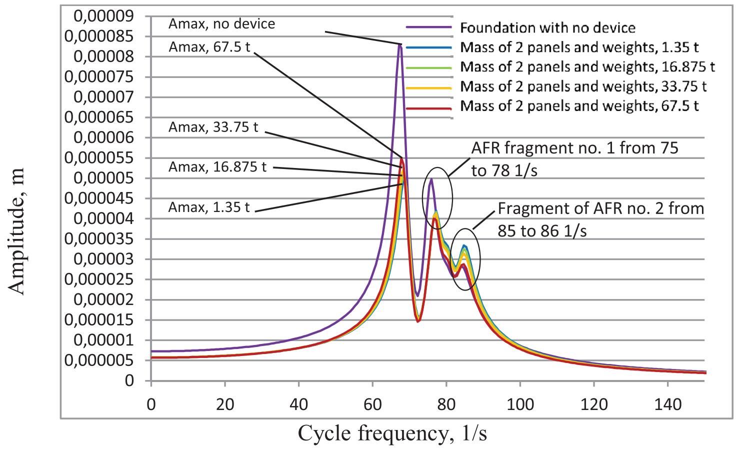
Thus, the approach that involves increasing the connectors' stiffness is well applicable to GCUs with a cycle frequency of exposure to dynamic loads of more than 100 1/s, e.g., gas turbine GCUs.

6. Weighting the surface of an RC panel

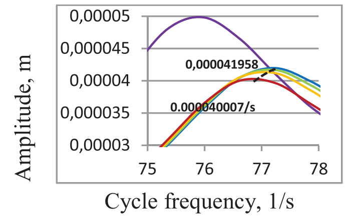
An analysis of the amplitude-frequency response has shown that increasing the total mass of M_{wt}, i.e., two RC panels with additional weights symmetrically attached to the foundation, does not affect the reduction of A_{max}, but, on the contrary, within the frequency range between 67.5 and 68.45 1 / s, as M_{wt} increases from 1.35 t to 67.5 t, the growth of A_{max} is 9.3%, while λ_{Amax} decreases by 0.93%. At the same time, within the frequency range between 76 and 78 1/s, the maximum vibration amplitude and the corresponding frequency decrease by 3.73% and 0.819%, respectively. A similar situation can be observed within the frequency range between 83 and 86 1/s (see Fig. 8 B, C).

The results of GCU analysis show that increased weight of the attached RC panels within the frequency range up to 70 1/s does not allow reducing A_{max}. At the same time, within the frequency range between 76 and 78 1/s, the increase of the mass of the RC panels from 1.35 t to 67.5 t decreases A_{max} by 3.7%, while within the frequency range between 83 to 87 1/s, A_{max} decreases by 16.1%.

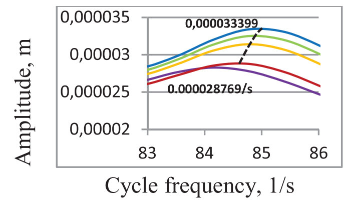
Increasing the mass of the attached RC panels is quite efficient in the case of GCUs with a cycle frequency of rotor rotation of more than 83 1/s, which roughly corresponds to 800 ... 850 revolutions per minute. At the same time, for GCUs with the speed of rotor rotation of less than 800 ... 850 revolutions per minute, the opposite effect is observed that involves increased vibration amplitude.



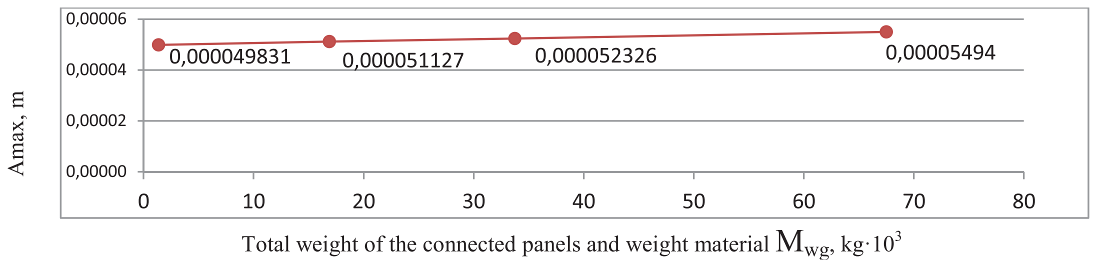
A. AFR of the foundation for 4 options for weighting the connected RC panels



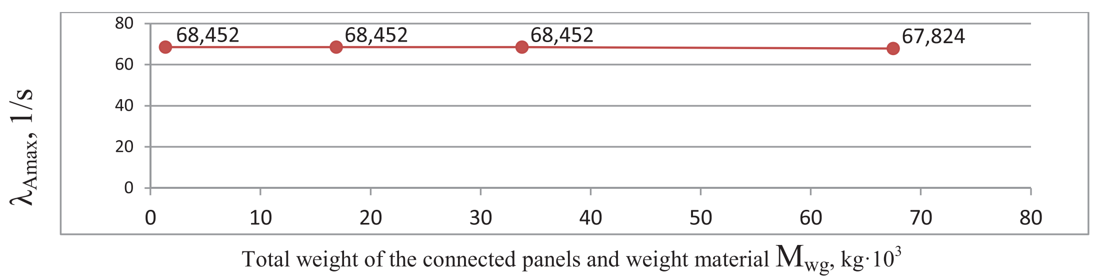
B. Fragment of AFR no. 1



C. Fragment of AFR no. 2



D. Amax/connected RC panel weight curve



E. λ_{Amax}/connected RC panel weight and weight material curve

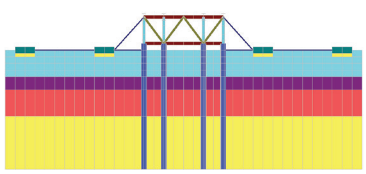
Fig. 8. Correlation between the foundations' AFR and the mass of the attached RC panels and weight material

7. RC panels freezing to the soil

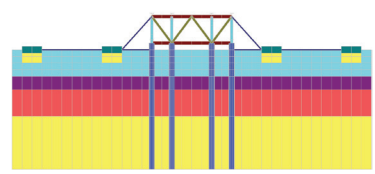
The authors identified the AFR of a foundation with attached RC panels for the cases of underlying soil freezing together with the RC panel to the depths of 0.5 m, 1.0 m, 1.5 m, 2 m, 2.5 m (see Fig. 9). An RC panel's freezing to the underlying soil is ensured by a refrigerant circulating through special cavities within the panel [1]. The freezing can also be done using a system for horizontal thermal stabilization of soil [6].

The comparison of the AFR of a foundation with attached RC panels for five cases of freezing and the case of no freezing shows a decrease of λ_{Amax} by 21.1% and 17.2% in cases of freezing of the RC panel with the underlying soil to the depths of 0.5 m and 2.5 m, respectively (Fig. 10 C).

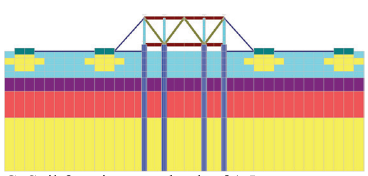
It must be noted that, on the one hand, the increasing volume of soil freezing with an RC panel adds more mass to the attached frozen soil, thus contributing to the decreasing frequency of the



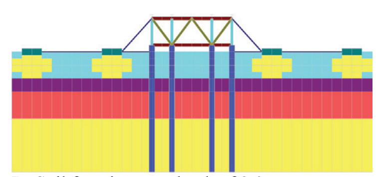
A. Soil freezing to a depth of 0.5m



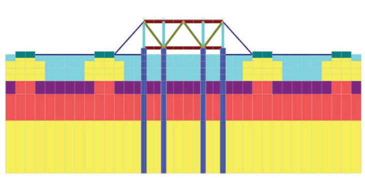
B. Soil freezing to a depth of 1.0m



C. Soil freezing to a depth of 1.5m

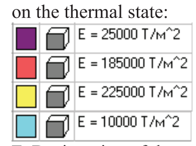


D. Soil freezing to a depth of 2.0m



E. Soil freezing to a depth of 2.5m

Moduli of elasticity of frost soils depending on the thermal state:



F. Designation of the soil elasticity moduli

Fig. 9. Possible depths of soil freezing to RC panels

foundation's own vibration, and, on the other hand, as the size of the frozen soil grows, the stiffness of the foundation – RC panel system and the frequency of own vibrations increases. When the underlying soil freezes to the RC panel to the depths of 0.5 and 2.5 meters, A_{max} increases by 118.1% and 46%, respectively (see Fig. 10 B).

Using simulation and numerical experiments, the AFR of a foundation was defined for the following cases: symmetrical and non-symmetrical attachment of the device, attachment involving varying numbers of RC panels at different distances with different connector stiffness ratios, as well as with additional weights on the surface of the RC panels and taking into account the depth of RC panel freezing with the underlying soil.

It should be noted that the best possible effect in the form of reduced A_{max} and λ_{Amax} in cases of attached RC panels is achieved when they are attached to the foundation symmetrically (see Fig. 5 B).

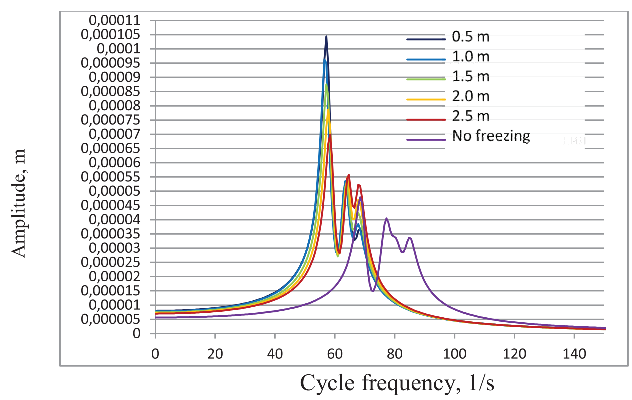
The effect can be enhanced by increasing the stiffness of the connectors (Fig. 7 C) or reducing the distance between the attached panel and the foundation, if that is allowed by the environment, in which the process equipment is installed (see Fig. 6 A). In this case, the desired result can also be achieved if the arrangement of the RC panels is non-symmetrical (see Fig. 5 C, D).

Increasing the mass of the attached RC panels by means of additional weights or soil freezing [1] also allows reducing A_{max} and λ_{Amax}, but only within the frequency range above 1000 revolutions per minute. That can be used for gas turbine GCUs with the minimum operating rotor speed of 3000…3500 rpm. At the same time, in the case of units with the rotation speed of 1000 rpm and less the use of this approach requires additional research.

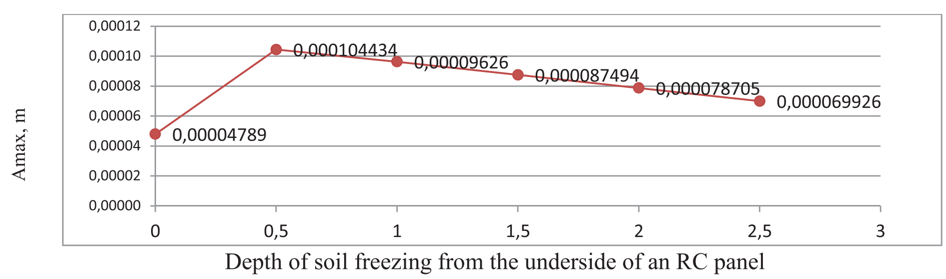
8. Conclusion

The Method examined in the paper is characterized by its simplicity and improved dependability, as it allows using concrete blocks, cement mortar, cemented sand, etc. for weighting RC panels.

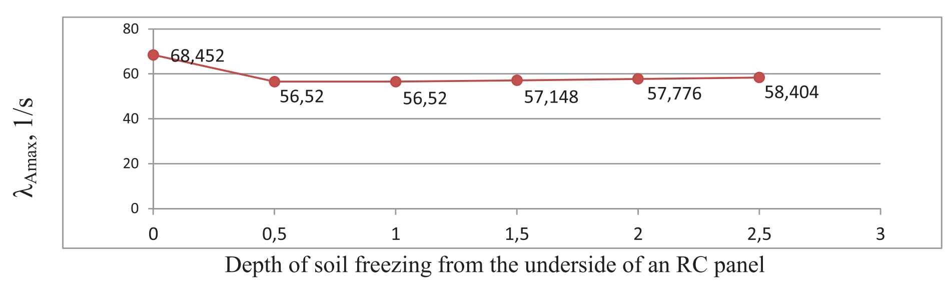
The study identified that in the case of symmetrical connection of four reinforced concrete panels in summer, the reduction of vibration displacements is 42.4%, while increased stiffness of the connectors, attachment of additional weights and freezing of reinforced concrete panels into the ground will allow reducing the vibration displacements of the foundation up to 2.5 times. Dependability simulation has shown the effectiveness of the method in the cold and warm seasons:



A. AFR of the five depths of soil freezing under a RC panel



B. A_{max}/soil freezing depths curve



C. λ_{Amax}/soil freezing depths curve

Fig. 10. Correlation between the foundations' AFR and the depths of soil freezing under an RC panel

• in case of symmetrical and non-symmetrical connection of RC panels;
• with RC panels at different distances from each other and from the foundation;
• with connectors with different stiffness parameters;
• with additional weights;
• when frozen to the ground.

Research dedicated to improving the dependability of foundations exposed to vibration load is underway not only in Russia, but abroad as well [7, 8, 9, 10, 11].

In conclusion, it should be noted that applying the Method requires additional research and development activities, since the above computational experiment results show sufficiently good indicators of reduced vibration displacements of foundations. However, applying the findings in the process of development of project documentation and construction of foundations requires R&D activities involving verification and comparison of the obtained results of numerical simulation with a natural experiment.

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The authors' contribution

Tyurin M.A. formulated the study's key idea, defined the task and developed the approach to its solution.

Bocharov M.E. analysed subject-matter literature, drawn up the paper's conclusions.

Vorontsov M.A. contributed to the task definition and solution development, discussion of the research methods and findings.

Melnikova A.V. contributed to the discussion of the research methods and analysis of the findings.

Conflict of interests

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On the classification of motive power failures

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Abstract. *The* **Aim** *of the article is to develop a motive power failure classification to enable substantiated definition of dependability requirements for motive power as a part of a railway transportation system, as well as for organizing systematic measures to ensure a required level of its dependability over the life cycle.* **Methods.** *The terminology of interstate dependability-related standards was analysed and the two classifications used by OJSC "RZD" for estimating the dependability of technical systems and motive power were compared. The dependability of railway transportation systems is studied using structural and logical and logical and probabilistic methods of dependability analysis, while railway lines are examined using the graph theory and the Markov chains.* **Results.** *An analysis of the existing failure classifications identified shortcomings that prevent the use of such classifications for studying the structural dependability of such railway transportation systems as motive power. A classification was developed that combines two failure classifications ("category-based" for the transportation process and technical systems and "type-based" for the motive power), but this time with new definitions. The proposed classification of the types of failures involves stricter definitions of the conditions and assumptions required for evaluating the dependability and technical condition of an item, which ensures correlation between the characteristics of motive power and its dependability throughout the life cycle in the context of the above tasks. The two classifications could be used simultaneously while researching structural problems of dependability using logical and probabilistic methods and Markov chains. The developed classification is included in the provisions of the draft interstate standard "Dependability of motive power. Procedure for the definition, calculation methods and supervision of dependability indicators throughout the life cycle" that is being prepared by JSC "VNIKTI" in accordance with the OJSC "RZD" research and development plan.* **Conclusion.** *The article's findings will be useful to experts involved in the evaluation of motive power dependability.*

Keywords: *dependability, failure, flaw, damage, failure classification, transportation process, motive power, life cycle.*

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Introduction

Railway transportation is of strategic importance to Russia. It ensures the stability of business operations and lives of citizens, transports millions of tons of freight and hundreds of thousands of people every day [1]. Transportation of goods and passengers by rail is impossible without railway motive power (MP) of high quality that is safe in operation.

Dependability is one of the most important characteristics of the quality of any technology, MP in particular. According to GOST 27.002-2015 [2], dependability is a composite property of an item that, depending on its purpose and operating condition, may include reliability, maintainability, recoverability, durability, storability or certain combinations of such properties, such as, e.g., availability [3].

As a composite property, dependability is quantified by the indicators of the above properties. Those indicators enable the integration of the technical, operational and economic characteristics of MP that ultimately define its consumer qualities. The interrelated technical, operational and economic characteristics are formed at the Development and Manufacture stages of the life cycle (LC), while outputs, including economic ones, are obtained as early as at the Operation LC stage. It is obvious that this situation causes possible operational risks that negatively affect the activities of the entities involved in the MP operation as part of the railway transportation system. Such risks can be distributed among the subjects granted there are scientifically substantiated requirements for the MP as regards the dependability and the coordinated effort of the parties involved for ensuring the MP dependability in the course of its LC [4].

Thus, a substantiated definition of dependability requirements for the MP as a component of a railway transportation system and organization of coordinated assurance of required MP dependability in the course of its LC is a problem of relevance. [5] also points out the requirement for a regulatory framework for the purpose of addressing the above problems.

The general approaches to a substantiated definition of the MP dependability requirements and the organization of MP dependability assurance in the course of its LC are set forth in [4, 6] and served as the foundation for the development of the draft interstate standard "Dependability of motive power. Definition procedure, calculation methods and monitoring of dependability indicators in the course of life cycle" that is being developed by JSC "VNIKTI" in accordance with the OJSC "RZD"'s plan for scientific and technological development as part of interstate and national standardization programs. The final version of the draft standard has been approved by TC119 Dependability in Technology and is being examined in TC045 Railway Transportation.

This article deals with the provisions of the draft standard that establish a classification of MP failures enabling correlation between the characteristics of MP and its dependability throughout the LC in the context of the above problems.

The transportation process implemented by OJSC "RZD" is subjected to a number of risk-related factors (Fig. 1). The sources of risks for the transportation process, including disruptions of the train schedule – along with external causes – may include transportation process violations or technical failures (TF). Incidents caused by TF, including MP, are classified according to the criticality to the transportation process. The criticality of an incident's consequences is affected by the duration of the train delay, delays of other trains and the amount of damage determined by the cost of restoring the equipment and covering the losses of consumers due to the delayed trains.

Thus, in cases of failure of equipment and MP in particular, the characteristics in terms of the consequences that allow establishing the fact of failure are as follows:

– failure to execute train schedule (train weight, speed, open line running and station dwell times, traffic interruption time);

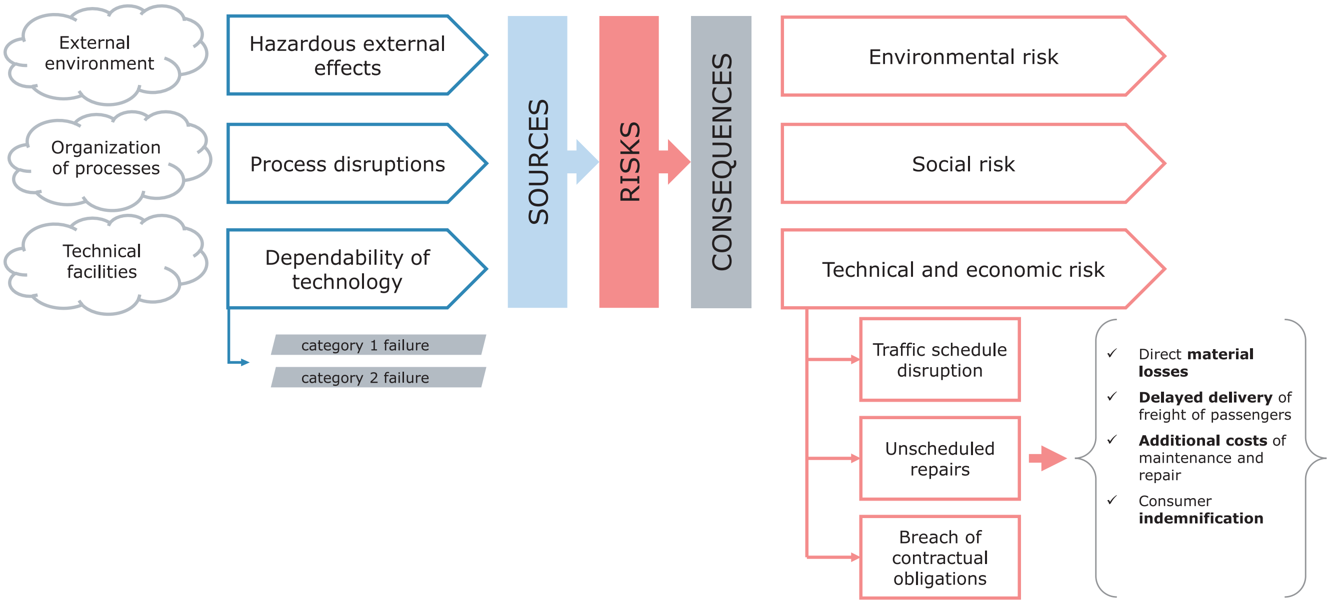


Fig. 1. General model of the onset of transportation process risks

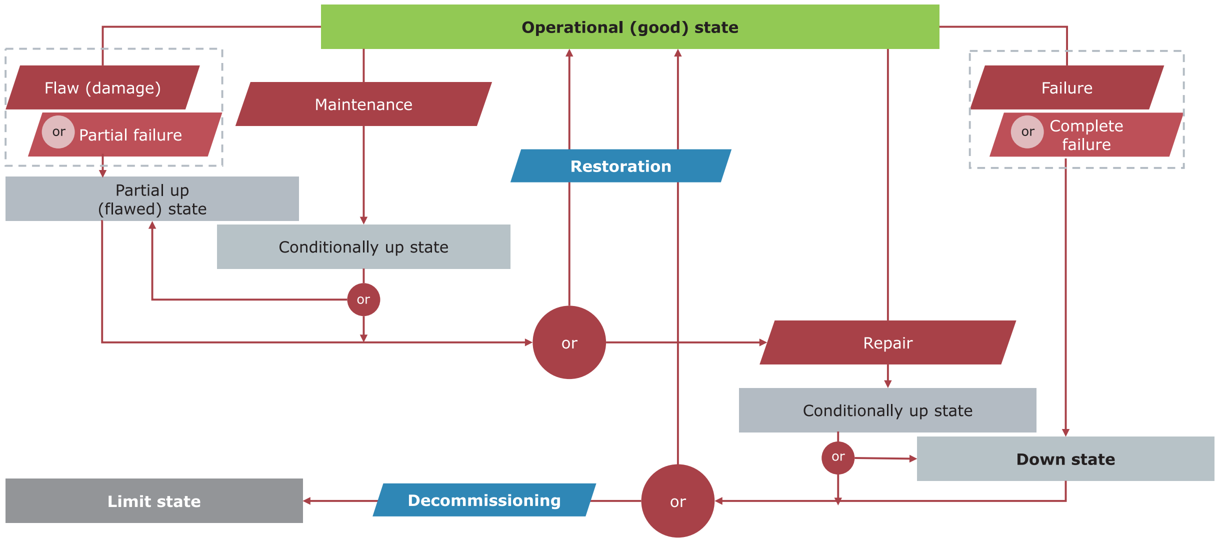


Fig. 2. States of a complex technical system

– requirement to restore rolling stock and fixed equipment while avoiding train schedule disruptions;

– requirement to perform unscheduled repairs;

– exceeding the specified scope of work (restoration, replacement, adjustment of any technical device) of scheduled maintenance or repair that causes increased downtime or labour input if the above activities are outside of the mandatory scope.

The above was the input for the development of the failure classification. The terms associated with the concepts of "failure", "flaw" ("damage") and aspects of MP as an element of the transportation process were taken into consideration.

Terms "failure", "flaw" ("damage")

Let us consider the concepts of failure and flaw (damage) taking into account the terminology standards GOST 27.002-2015, GOST 18322-2016, GOST 32192-2013 [2, 7, 8] (Fig. 2).

A *failure* is an event consisting in the disruption of the up state of railway equipment [8]. In terms of the classification feature of subsequent suitability for use of railway equipment, a failure can be complete or partial; the latter is typical for complex systems consisting of various elements and performing individual functions as part of a system. A failure causes equipment transition from the up into the down state with subsequent restoration or decommissioning upon reaching the limit state. The failure of some components of a system may not cause decreased performance of a complex system as regards a certain task, so as the result of the failure of its individual components or a flaw (damage) of a technical feature, the item goes into the partial up (flawed) state with subsequent restoration of the up state.

A *flaw (damage)* is an event consisting in the disruption of the good state of railway equipment under condition of retained up state.

A situation is possible when a flaw is only eliminated through repairs. Accordingly, through repairs, an item can transition from a partial up state into a conditionally down state until the up state has been restored, or transition into the down state associated with the detection of a hidden failure of railway equipment.

MP as a component of the transportation process

A railway is a complex transportation system consisting of a set of technical facilities (TF) integrated within a single business process of freight and passenger transportation. At the same time, each of the railway TFs is an element of its own complex system that performs a certain function as part of the transportation process. In terms of dependability, all of the system's elements are connected in series, i.e., a complete failure of one of them causes the failure of the entire system as shown in Fig. 3 with the diagram of functional integrity (DFI) of a railway line and its mathematical model represented as a logical function generated by the Arbitr software suite [9]. Assessing the dependability of such system, first of all, requires determining the indicators that characterize the dependability of each of its components. The level of dependability of individual TFs within a complex system affects the performance of the entire system, the efficiency and economic indicators of railways.

A warranty line between two line stations or between a line station and a marshalling station that is a complex single-function multiple-use system is used as the minimal target for system dependability evaluation [10].

A warranty railway line as a complex system operates discreetly within the state space and continuous time. The purpose of this system is to ensure the required freight flow and unfailing traffic over a long period of time. The time interval for calculation is taken based on the line's capacity calculated for a given day. Train flows come from line sta-

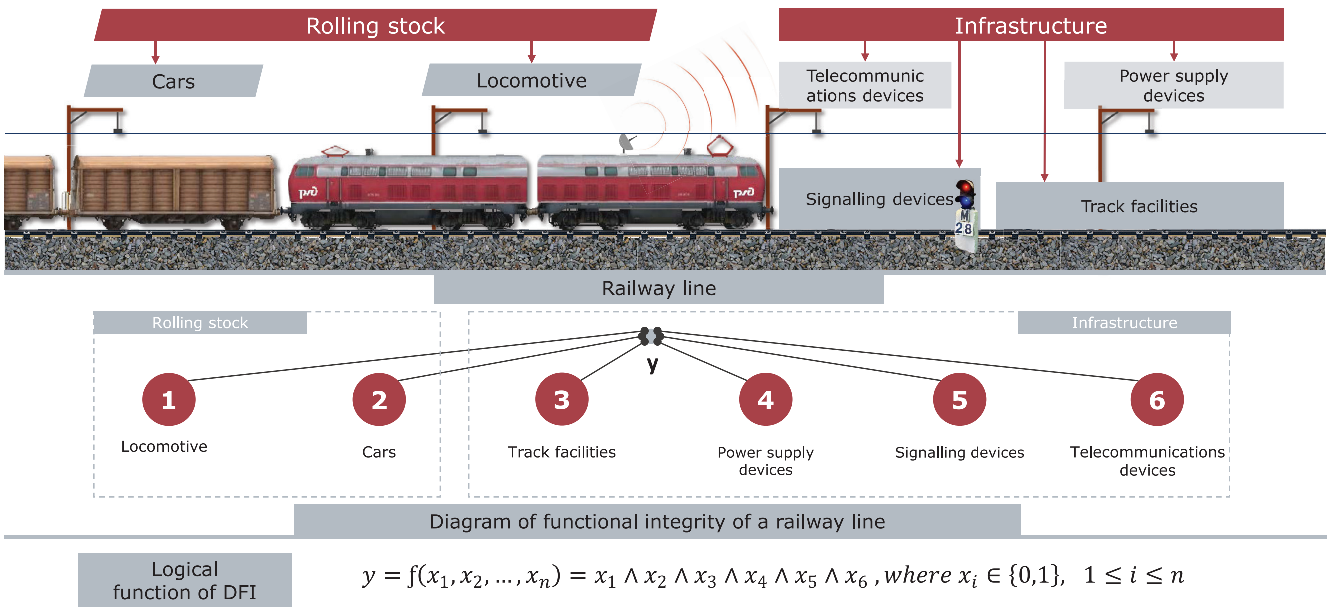


Fig. 3. Rolling stock as a component of the transportation process

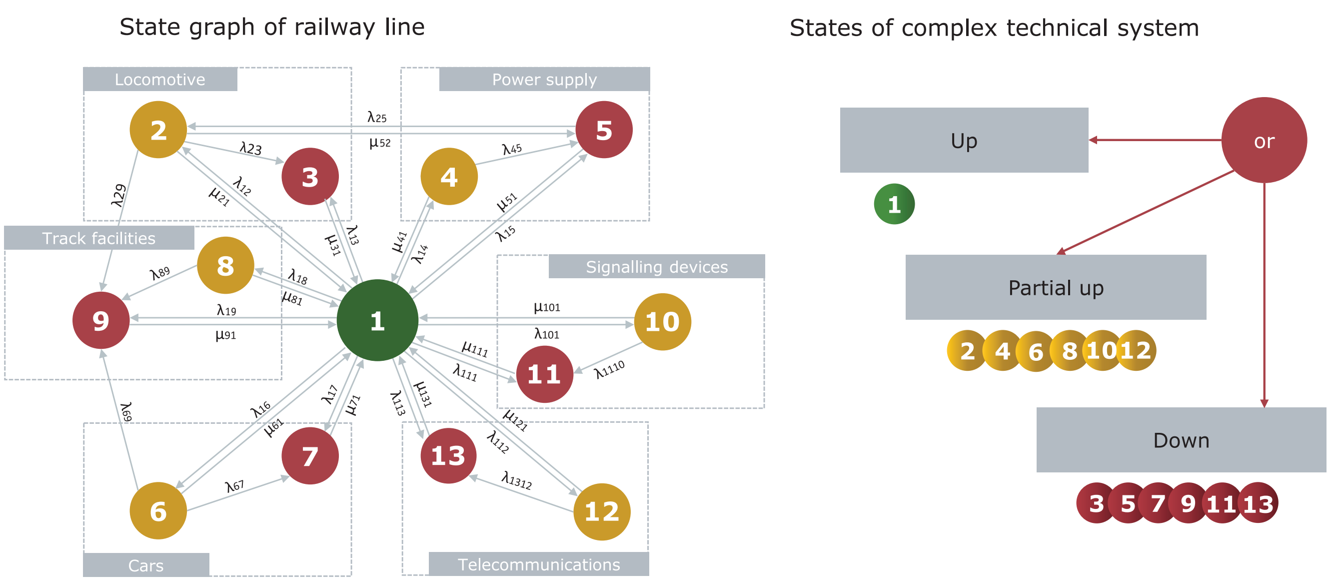
tions, trains depart on condition of observance of the minimum safe distance established in OJSC "RZD" and specified for block sections. Due to failures of MP (locomotives), cars, power supply, signalling, telecommunications and track assets causing the closure of individual track sections, train schedule is disrupted and, consequently, the quality and efficiency of the operations is reduced. As noted above, in terms of dependability, all elements of a line section are connected in series and a complete failure of one of them leads to the failure of the entire system. The time between failures of individual elements and the time of their restoration are random values. Using the pseudostate method, the present non-Markov process is reduced to a Markov one, i.e., when the system's future behaviour depends on the present one and does not depend on the history under the following assumptions:

1) system failure and restoration flows are *ordinary*, i.e., at any moment in time no more than one element can fail or be restored;

2) the operation of the system and its elements is *stationary*, i.e., the TF failure rate is not time-dependent and is a value equal to the average number of events per unit of time;

3) the system's state times are not exponentially distributed, but can be exactly or approximately represented by the Erlang distribution.

Fig. 4 shows the state graph of a railway line where the system can be in the up state (1) ensuring a 100% train schedule execution, operate with reduced efficiency due to partial



where $\lambda_{ij} = \frac{1}{T_{fi}}$ is the failure rate, $\mu_{ji} = \frac{1}{T_{ri}}$ is the restoration rate

a) b)

Fig. 4. State graph of a railway line (a) and state chart of a complex technical system (b)

failure (flaw (damage) of one of the components (states 2, 4, 6, 8, 10, 12) or in the down state due to the complete failure of one of the components as a result of the line closure and a 0% train schedule execution (states 3, 5, 7, 9, 11, 13). In this case, the system states do not include those associated with scheduled maintenance or repairs.

System transition between states is characterized by a failure or restoration of one system element only. Each element is characterized by the mean time between failures T_{fl} and failure rate λ_{ij}, the mean restoration time T_{rl} and the restoration rate μ_{ji}, where i is the state of the element before failure (after restoration), j is the state of the element after failure (before restoration). Within this model, the effect of some TFs on the performance of others can be taken into consideration, e.g., a flaw of an electric locomotive (namely, a failure of one of the pantographs) may lead to a failure of power supply devices, i.e., overhead wire break.

The system in this case is defined by the initial probabilistic states and the transition probability matrix. Based on the system's solution and the knowledge of the mean times between failures of TFs and their restoration times, the limit probabilities can be calculated that characterize the operation of a railway line with reduced efficiency or complete interruption of train traffic.

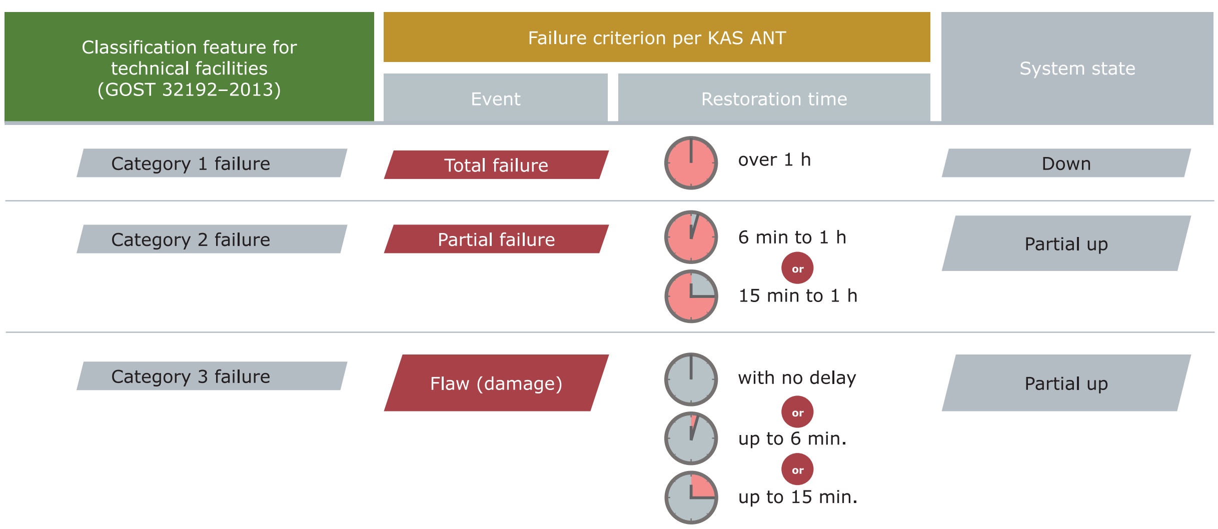
Analysis of the existing failure classifications

At present, OJSC "RZD" uses the Integrated Automated System for Technical Failures Tracking, Investigation and Dependability Analysis (KAS ANT) for assessing the operational dependability of the railway transportation system. The classification of cases of TF failure, depending on their effect on the transportation process, is specified in [11]. The following features are used: failure of the first, second and third categories (Fig. 5a).

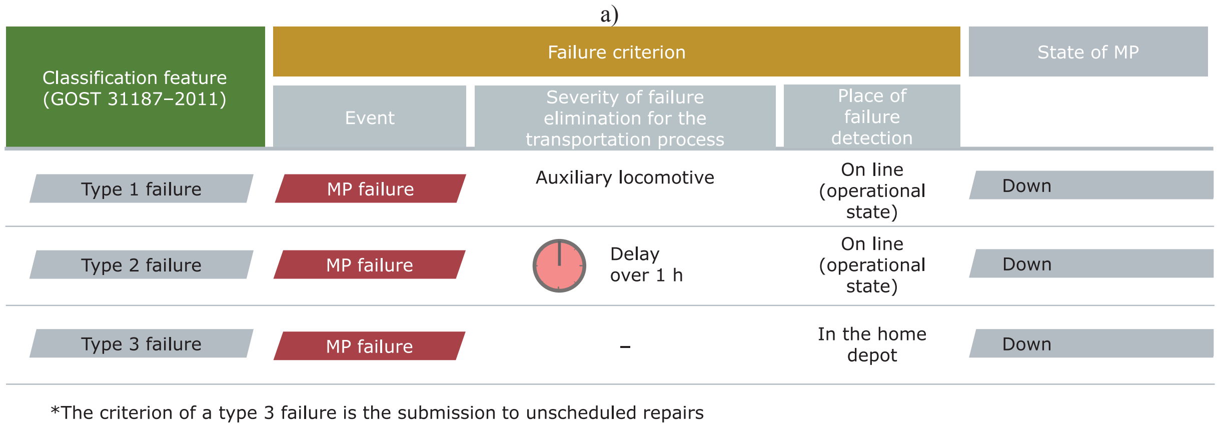
Failures of the 1-st category include TF failures that led to a passenger, commuter or freight train on an open line (station) being delayed by 1 hour or more or led to traffic accidents or events associated with violations of the railway traffic safety and operation regulations.

Failures of the 2-nd category include failures that led to a passenger or commuter train on an open line (station) being delayed by 6 minutes to 1 hour or a freight train being delayed by 15 minutes to 1 hour.

Failures of the 3-rd category include the following: flaws, cases of disrupted normal operation of TF that do not cause consequences associated with failures of the 1-st and 2-nd categories, while the flaws are initially recorded in the automated management systems of the respective



a)



b)

Fig. 5. Failure classification infographic: a) railway technical equipment by category; b) autonomous motive power by types

railway services; damage, disruptions of the good state of TF identified in the course of scheduled and preventive maintenance by the operating personnel, including with the use of diagnostic facilities, are taken into account regardless of the duration of train delays, except in the cases that caused transportation accidents or events associated with violations of the railway traffic safety and operation regulations that are taken into account in the 1-st category.

The 3-rd category also includes: violations of the cargo placement and fastening due to flaws of cargo fastenings in a car that is part of a freight train; violations identified in the course of maintenance of a locomotive, EMU and eliminated by locomotive crews or maintenance personnel; uncoupling of a freight car from a train due to a malfunction identified at a station at an end of a warranty line.

GOST 31187-2011, GOST 31428-2011 [12, 13] sets forth the following classification of failures for the purpose of evaluating the dependability of autonomous motive power (Fig. 5b):

– failure of the 1-st type, a failure of a diesel locomotive that caused a forced stop of the train on an open line or at an intermediate station if the train's subsequent movement required an auxiliary locomotive;

– failure of the 2-nd type, a failure of a diesel locomotive causing a delay of a train on at least one track of an open line or at a station exceeding the time specified in the train schedule by 1 hour or more;

– failure of the 3-rd type, a failure of a diesel locomotive requiring unscheduled repairs.

Fig. 6 shows the causal model of the technological and economic risk of the transportation process due to the dependability of MP (locomotives), as well as the correlation between the above classifications of failures (see Fig. 5).

The analysis of the above classifications, taking into consideration the causal model of the technological and economic risk of the transportation process that is due to the MP dependability, identified the shortcomings of both classifications that complicate their use as part of MP dependability assessment in the course of the LC.

The shortcomings of the "category-based" classification in terms of MP dependability assessment are:

1) it is built around the degree of railway TFs' effect on the transportation process;

2) the time factor is the criterion of the effect severity;

3) it is not applicable to the development stage.

The shortcomings of the "type-based" classification in terms of MP dependability assessment are:

1) a failure of the 1-st type is associated with locomotive failures when on the line (in the up state) and coupled to a consist;

2) a failure of the 2-nd type is also associated with failures of a locomotive when on the line (in the up state) and coupled to a consists, but is characterized by a temporal factor of the 1-st category of TF failures;

3) the criterion of a failure of the 3-rd type is subjective and does not reflect problems of the technical state.

Proposed failure classification for MP

For the purpose of dependability specification, it is suggested improving the existing classification of the types of failures and flaws of MP depending on the severity of their consequences for the transportation process, place of detection of such failures or damage of MP, method of elimination. In the draft GOST "Dependability of motive power. Definition procedure, calculation methods and monitoring of dependability indicators in the course of life cycle" currently under development, this classification is set forth as follows:

– failure of the 1-st type is due to defects identified in the operational state of the MP (MP goes into the down state), completion of the task being impossible, the transportation process is restored with the help of an auxiliary locomotive, the MP itself is restored through repairs;

– failure of the 2-nd type is due to defects identified in the operational state of the MP (MP goes into the partial up state), completion of the task being possible, the transportation process is restored on condition of limited use of the flawed MP that operates using various fallback circuits, the MP is restored through repairs;

– flaw of type A due to defects identified in the operational state (MP goes into the faulty up state) and the non-operational state of the MP (in scheduled maintenance or awaiting work), the MP is restored through repairs (if identified, or delayed);

– flaw of type B due to defects of the equipment ensuring hygienic and sanitary conditions of the passengers' transportation and crew operations, fuel (electricity) consumption accounting, as well as indirectly affecting the MP operation when used for the intended purpose, the MP being restored through repairs, if identified.

Flaws of type A include failures of the MP components directly associated with technically good MP operation when used for its intended purpose, while flaws of type B include equipment failures indirectly affecting the MP operation and ensuring consumer appeal, usability and maintainability, as well as compliance with the functional requirements not associated with the intended use of MP.

The restoration of the MP components with flaws of type A is defined by the requirements of the operation and repair documents, while the restoration of the equipment with flaws of type B is defined by the requirements of the customer, consumer, safety, regulatory, design documentation or environmental and sanitary standards.

Other defects of the equipment or MP components that cause their damage, while maintaining the MP up state, are not classified. Such defects are eliminated in scheduled repairs and/or maintenance, whereas the technical state of the MP is monitored with the frequency and within the scope defined by the reference documentation, while the scope and starting time of the repairs is defined by the technical state of the MP.

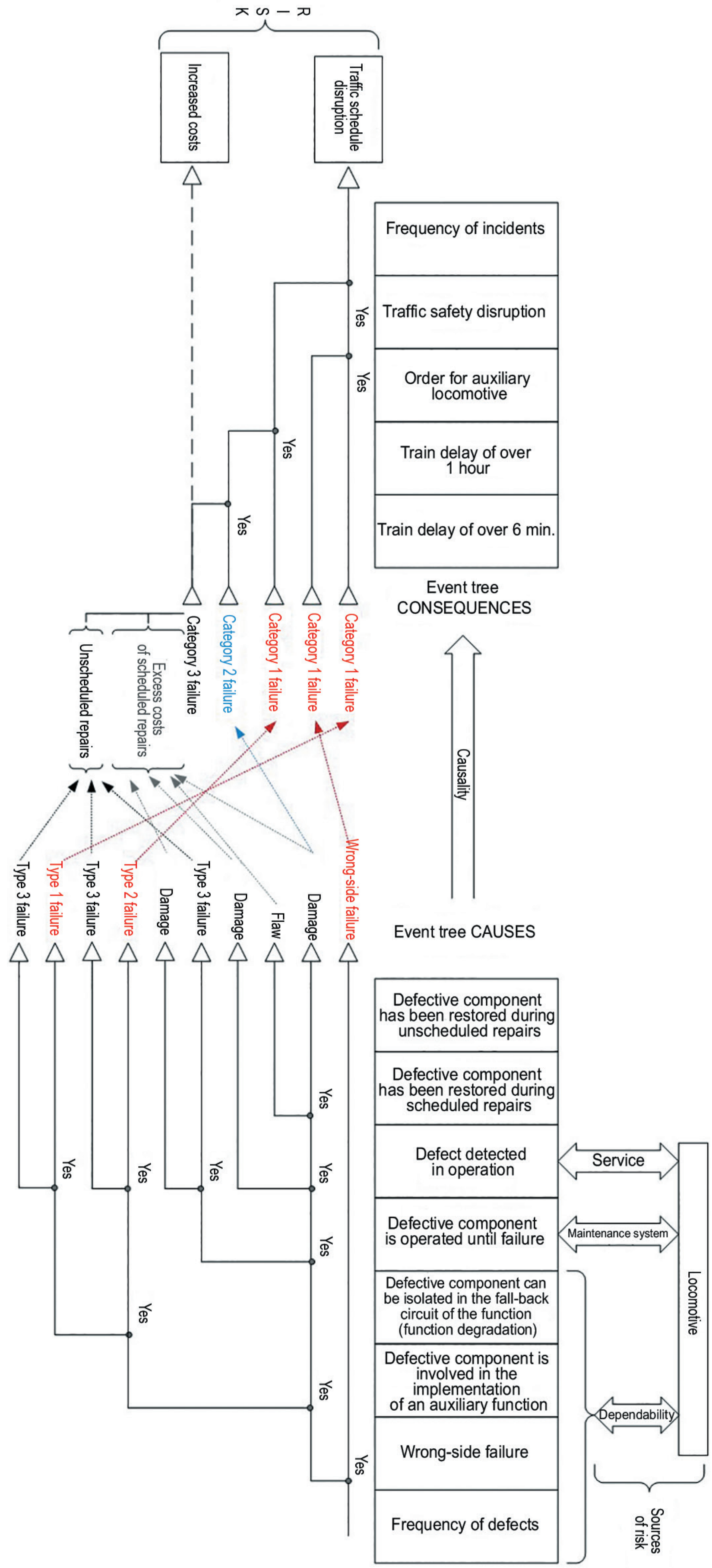


Fig. 6. Technical and economic risk of the transportation process due to the dependability of MP (locomotives)

Conclusion

For the purpose of ensuring substantiated definition of dependability requirements for MP as a component of the railway transportation system, as well as organization of systematic activities aimed at ensuring its required level of dependability throughout the LC, a classification was developed that combines the two classifications of failures, i.e., “category-based” for the transportation process and technical systems and “type-based” for the MP, but with new definitions. The proposed classification of the types of failure involves stricter definitions of conditions and assumptions required for evaluating the dependability and technical condition of an item, which ensures correlation between the characteristics of MP and its dependability throughout the LC in the context of the above tasks. The two classifications could be used simultaneously while researching structural problems of dependability using logical and probabilistic methods and Markov chains.

The developed classification is included in the provisions of the draft interstate standard “Dependability of motive power. Procedure for the definition, calculation methods and supervision of dependability indicators throughout the life cycle” that is now being prepared by JSC “VNIKTI” in accordance with the OJSC “RZD” research and development plan.

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The authors’ contribution

The authors’ contribution consists in the analysis of primary dependability-related terminology established in interstate standards as regards railway transportation and comparison of the two classifications used in OJSC “RZD” for the purpose of assessing the dependability of technical systems and motive power. For a substantiated definition of motive power dependability requirements, the authors proposed a solution that allows combining the two failure classifications. The authors’ contributions are equal.

Conflict of interests

The authors declare the absence of a conflict of interests.

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Use of exponential distribution in mathematical models of dependability

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Abstract. *The exponential distribution of time to event or end of state is popular in the dependability theory. This distribution is characterized by the strength that is a convenient parameter used in mathematical models and calculations. The exponential distribution is used as part of dependability-related process simulation. Examples are given to illustrate the applicability of the exponential distribution.* **Aim.** *The aim of the paper is to improve the dependability-related simulation methods when using the exponential distribution of periods of states or times to events.* **Methods.** *The assumption of the exponential distribution of time between events can be justified or discarded using methods of the probability theory and/or mathematical statistics or on the basis of personal or engineering experience. It has been experimentally established that the failure flow in an established mode of operation is stationary, ordinary and produces no consequences. Such flow is Poisson and is distinct in the fact that the time between two consecutive failures is distributed exponentially with a constant rate. This exponential distribution is reasonably extended to the distribution of an item's failure-free time. However, in other cases, the use of exponential distribution is often not duly substantiated. The methodological approach and the respective conclusions are case-based. A number of experience-based cases are given to show the non-applicability of exponential distribution.* **Discussion**. *Cases are examined, in which the judgement on the applicability or non-applicability of exponential distribution can be made on the basis of personal experience or the probability theory. However, in case of such events as completion of recovery, duration of scheduled inspection, duration of maintenance, etc., a judgement regarding the applicability of exponential distribution cannot be made in the absence of personal experience associated with such events. The distribution of such durations is to be established using statistical methods. The paper refers to the author's publications that compare the frequency of equipment inspections with regular and exponentially distributed periods. The calculated values of some indicators are retained, while for some others they are different. There is a two-fold difference between the unavailability values for the above ways of defining the inspection frequency.* **Findings and conclusions.** *The proposed improvements to the application of exponential distribution as part of dependability simulation come down to the requirement of clear substantiation of the application of exponential distribution of time between events using methods of the probability theory and mathematical statistics. An unknown random distribution cannot be replaced with an exponential distribution without a valid substantiation. Replacing a random time in a subset of states with a random exponentially distributed time with a constant rate should be done with an error calculation.*

Keywords: *dependability, exponential distribution, event rate.*

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Introduction

Exponential distribution is widely used in mathematical dependability models. The advantage of this distribution is that it is characterized by a single parameter, i.e., the event rate, which gives the model simplicity. In particular, a model with a constant event rate allows using Markovian methods. Event rates are also used while generating and solving differential equilibrium equations as part of transitions between states, which allows obtaining state probabilities in both a transient and steady state.

The exponential distribution of time to failure is substantiated using probabilistic and statistical methods. It has been experimentally established that an item's failure is a random event, while the failure flow in an established mode of operation is stationary, ordinary and produces no consequences. Such flow is of Poisson type; it has a simple analytical description. The characteristic feature of a Poisson flow is that the time between two consecutive failures is distributed exponentially with a constant rate. This exponential distribution is reasonably extended to the distribution of an item's failure-free time.

The exponential distribution simulates the random time between two consecutive events. The exponential distribution is also extended to various states and events. It is used for the duration of equipment recovery (repair), time between inspections of the technical state of equipment and for other cases. On the Internet, there are many use cases of exponential distribution and of associated problems.

However, in a number of cases, the use of exponential distribution is often not duly substantiated. The following rationale is presented:

– an exponential distribution of any random time period is used similarly to the distribution of the time to failure;

– the time period is random, so it is exponentially distributed;

– exponential distribution is conveniently used in mathematical models;

– everyone uses exponential distributions, so do I;

– in literature, there are many mentions of constant or random time periods with an unknown distribution being replaced with an exponential distribution;

– exponential distribution is commonly used;

– the transition from a constant-time state to a random-time state is due to the requirement of simulation.

Such substantiations are what might be called a sham. Hence, if exponential distribution was adopted without due substantiation, its use within mathematical models may be erroneous or unacceptable.

Let us try working out a substantiation for using exponential distribution.

Source overview

The failure rate as a parameter of exponential distribution is featured in many state standards: [2, 7, 8, 9, 10]. The restoration rate is referred to in [2, 9, 10], while the repair rate is mentioned in [7, 8]. Random maintenance (repair) duration is used in [5].

[10] describes the advantages of using the Markovian methods for the purpose of dependability research of various systems, as well as assumptions and limitations for cases where the failure and restoration rates are constant in time. The assumption of constant restoration rate is to be substantiated if the mean restoration time is not negligible compared to the corresponding mean time to failure. [10] also states that the state transition rates are used not only for failures and restorations. Such transitions may be caused by a variety of events.

According to [17], the assumption of exponential distribution is not always justified. That is especially true for the restoration time, as the assumption that the remaining restoration time is independent from the already spent time appears to be quite unnatural. However, if the average time to failure is significantly longer than the restoration time, many dependability indicators do not depend on the type of restoration time distribution.

The use of exponential distribution in dependability is widely covered in scientific and training literature, e.g., [15]. It should be noted that, in the dependability theory, not only the exponential, but other distributions are used, if required: normal, Weibull, binomial, Poisson, gamma [14, 16].

Statistical methods are also widely described in literature. A number of state standards are dedicated to such methods. Thus, [3] lists procedures intended for item reliability indicator calculation based on data on similar items, operation and testing. Standard [6] establishes statistical methods for calculating point estimates, confidence, prediction and tolerance intervals for failure rates of items whose times to failure are exponentially distributed. The above quantitative methods are applicable to the rates of other events, times to which are exponentially distributed.

Standard [4] is intended for ensuring the safety, availability and cost-effective operation of items. Failure management involves maintenance, modification of application rules and other actions aimed at mitigating the impact of failures. The standard provides guidance on planning and performing reliability tests and applying statistical methods for analysing test data.

Method. Use cases of exponential distribution

Thus, the use of constant rate of various events (states) in Markovian models requires serious substantiation. The assumption of exponential distribution of time between events can be justified or discarded in several ways, e.g.:

1) using the methods of mathematical statistics;

2) using the methods of the probability theory;

3) on the basis of personal or engineering experience.

State standards describe the application of methods of mathematical statistics in sufficient detail.

A judgement regarding the applicability or non-applicability of exponential distribution may be made based on the assumption that the remainder of time is independent from the already spent time [17]. Additionally, a judgement on the applicability or non-applicability of exponential distribution may be made based on the personal experience of a modern person. The above use cases of exponential distribution are based on the meaning and personal experience.

First, let us set forth a value table for functions $P(t) = exp\ (-\lambda t)$ and $F(t) = 1-\exp\ (-\lambda t)$ in a number of points. This will allow analysing the above cases with no additional calculations.

Table 1. Values of functions $P(t)$ and $F(t)$

λt	0.125	0.25	0.5	1	2	3
$P(t)$	0.88	0.78	0.61	0.37	0.14	0.05
$F(t)$	0.12	0.22	0.39	0.63	0.86	0.95

In the table, $P(t)$ is the probability that the event will occur within interval $[t; \infty]$; $F(t)$ is the probability that the event will occur within the interval $[0; t]$. If λ is the failure rate, then $P(t)$ is the probability of no-failure within interval $[0; t]$, while $F(t)$ is the probability of failure within interval $[0; t]$.

The first case is associated with the annual medical examinations that certain categories of workers undergo. Let us suppose that the time between two examinations is exponentially distributed with the average time of 1 year. Then, the rate of event "Medical examination" will be λ = 1 1/year or λ = 1/12 1/month. Let us set forth the predicted percentage (more specifically, the average percentage) for the following cases:

1) only 63% of workers will be examined within a year, while 37% will be examined in more than a year;

2) within 2 years, 14% of workers will not be examined;

3) within 3 years, 5% of workers will not be examined;

4) workers start undergoing examinations within the first months upon the previous examination; thus, within 3 months 22% will be examined, while within 6 months 39% will.

That pattern does not reflect the reality. Hence, the conclusion is that exponential distribution of time between preventive examinations is unacceptable.

The second case is associated with life expectancy. As it is known, the average life expectancy in Russia is 70 years (females live on average longer than males). Let us make calculations, assuming an exponential distribution of life expectancy of a person with the mean time of m_t = 70 years. The rate of event "end of life" is λ = 1/70 1/year. The mean square deviation of a lifetime is $\sigma_t = 1/\lambda$ = 70 years. Let us calculate the probability of event $0 \le t \le m_t + \sigma_t$, i.e., the probability of a person living from 0 to 140 years: $P(0 \le t \le m_t + \sigma_t) = P(0 \le t \le 140) = 0.86$. The probability of the event is $t > 140$: $P(t > 140) = 0.14$.

According to this calculation, an average 14% of people live to the age of 140 or more. Next, 5% of people live up to 210 years old. Everyone knows that no such people exist in Russia. Hence, the conclusion is that the assumption of exponential distribution of a person's life expectancy is erroneous and must be rejected. This conclusion is based on personal experience and knowledge. If we did not have such knowledge, 14% would be accepted as a legitimate prediction. Thus, it can be concluded that the distribution of human life expectancy is not exponential. This distribution is to be substantiated using statistical methods.

The third case is associated with an 8-hour working day. Let us assume that due to the requirement of simulating a certain process, the assumption was made of exponential distribution of the working time with the rate of λ = 1/8 1/hour. According to that assumption, 12% of workers will leave their workstations within an hour, while within 2 hours 22% of workers will do so. Next. Only 37% of workers will be on the job during 8 hours, while 14% will be on the job for 16 hours and 5% will be there an entire day (24 hours).

It is evident that the conclusions made on the assumption of exponential distribution of working time are implausible and even absurd.

The fourth case. Mathematical models of dependability often assume exponential distribution of the time between an item's technical state inspections. Let T_{mn} be the mean time between two inspections (the average period) under such distribution. Then, using the data from Table 1, the following can be concluded:

a) only 63% of inspections are conducted within the average period;

b) 14% and 5% of inspections are conducted within periods that exceed the average period two and three times, respectively;

c) 39% of inspections are conducted within a period twice shorter than the average one.

It can be assumed that an expert with a sufficient engineering experience will not accept such probability distribution associated with an item's technical state inspection.

A use case of unjustified exponential distribution

It should be noted that an unjustified use of exponential distribution may be viable as regards some (special) problems. Examples may include the case of two aircraft crashes published in [13].

In some countries, deadly plane crashes occur on average once a year. According to the media, two planes on different routes had crashed at a one-minute interval. The initial explanation of the disaster came down to technical issues (failures) of equipment. Let us do a probabilistic analysis of the situation. This analysis aims to explain the cause of the disasters, i.e., to confirm or deny the cause associated with technical issues (failures). In order to do that, let us assume an exponential distribution of the time between the disasters (with no due substantiation).

Let us denote as follows: A is the first plane crash; B is the second plane crash one minute after the first disaster. The probability of joint events, according to the multiplication theorem on probability, is: $p(AB) = p(A) \cdot p(B/A)$, where $p(B/a)$ is the conditional probability of the second plane crash provided that the first one occurred. Obviously, $p(A) < 1$. Out of that follows that $p(AB) < p(B/A)$.

Let us calculate the conditional probability $p(B/A)$ under the assumption of exponential distribution of the time between the plane crashes. Under the conditions of the problem, the rate of disasters is $\lambda = 1$ 1/year. Let us convert the rate of disasters and the time between the two disasters into the same unit of time, namely, hours: $\lambda = 1/(365\cdot24) = 1$/h; $t = 1$ min $= 1/60$ h. Let us calculate the product λt: $\lambda t = 1/(365\cdot24\cdot60) = 2\times10^{-6}$. The formula for calculating the conditional probability of the second plane crash, provided that the first one happened a minute before: $p(B/A) = 1 - e^{-\lambda t}$. Let us expand the exponential function into a power series, limiting ourselves to two terms: $e^{-\lambda t} \approx 1 - \lambda^{t}$. Let us calculate the conditional probability: $p(B/a) = p(B/A) = \lambda t = 2\times10^{-6}$. The probability of joint events can be estimated from the upper inequality: $p(AB) < 2\times10^{-6}$.

Thus, the upper bound of the probability of two joint plane crashes is obtained assuming an exponential distribution of the time between the disasters: 2×10^{-6}. This probability is close to zero. Therefore, the examined AB event should be considered almost impossible. In terms of the probability theory, the fact that this event did occur should be interpreted as follows: it can almost certainly be claimed that the two plane crashes did not occur by accident.

Notes. 1. The aim has been achieved. It was shown that the examined random event is practically impossible.

2. The problem can be solved using other distributions. Thus, if the time between disasters is distributed uniformly, the result is $p(AB) < 10^{-6}$. Both results are comparable and produce identical conclusions.

Background. On August 24, 2004, two airliners were attacked by suicide bombers. Airliners that departed from the Domodedovo airport crashed three minutes apart (Novaya Gazeta, 14.09.2011).

Case of substitution of a certain distribution with an exponential distribution

Let us provide an example of a distribution of time in a subset of states being substituted with an exponential distribution of such time. [18] considered continuous-time transitions between the operable, pre-failure and inoperable states. The operable state can transition into a pre-failure, while a pre-failure can transition into an inoperable state as the result of failure.

The probability of no-failure, or the probability of operable or pre-failure state with the initial operable state, obtained by solving differential equations:

$$P_{ds}(t) = \frac{\lambda_{pff}\cdot\exp(-\lambda_{pf}\cdot t) - \lambda_{pf}\cdot\exp(-\lambda_{pff}\cdot t)}{\lambda_{pff} - \lambda_{pf}}, \quad (1)$$

where λ_{pf} is the pre-failure rate; λ_{pff} is the rate of failures after pre-failures.

The distribution function of the time to failure

$$F_{ds}(t) = 1 - P_{ds}(t). \quad (2)$$

Within this model, the mean time to failure (or the mean time in the operable or pre-failure states) is

$$T_{ds} = \int_0^\infty P(t)dt = \frac{1}{\lambda_{pf}} + \frac{1}{\lambda_{pff}}. \quad (3)$$

Hence

$$T_{ds} = T_{pf} + T_{pff}, \quad (4)$$

where $T_{pf} = 1/\lambda_{pf}$ is the mean time before pre-failure; $T_{pff} = 1/\lambda_{pff}$ is the mean time between pre-failure and failure.

Formula (4) is presented in [1]. Additionally, the distribution of the time in this subset of states is substituted with an exponential distribution of time to failure with the rate of λ_f that is associated with the rates λ_{pf} and λ_{pff} and formula:

$$\frac{1}{\lambda_f} = \frac{1}{\lambda_{pf}} + \frac{1}{\lambda_{pff}}. \quad (5)$$

Thus, it was assumed that the time to failure with the rate λ_f is exponentially distributed. However, substituting distribution (1) with an exponential distribution requires substantiation. Out of (5) follows:

$$\lambda_f = \frac{\lambda_{pf}\cdot\lambda_{pff}}{\lambda_{pf} + \lambda_{pff}}, \quad (6)$$

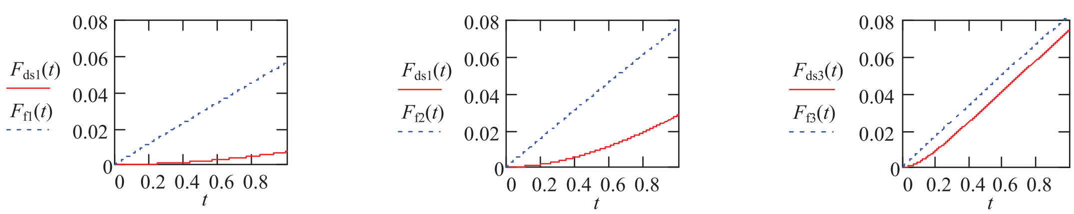
while the probability of no-failure $P_f(t)$ and the time to failure distribution function $F_f(t)$ under an exponential distribution with the failure rate of λ_f are calculated using the following formulas:

$$P_f(t) = \exp(-\lambda_f\cdot t);\ F_f(t) = 1 - \exp(-\lambda_f\cdot t). \quad (7)$$

Let us consider the different relationships between the initial parameters within this model. Let us take the pre-failure rate $\lambda_{pf} = 10^{-5}$ 1 / h as a basis. For convenience, let us count time in years. For that purpose, let us represent the pre-failure rate as $\lambda_{pf} = 10^{-5}\cdot365\cdot24 = 0.0876$ 1/year.

Let us consider three types of relationships between λ_{pf} and λ_{pff}:

1) $\lambda_{pff} = 2\lambda_{pf}$, $\lambda_f = 2\lambda_{pf}/3$;
2) $\lambda_{pff} = 10\lambda_{pf}$, $\lambda_f = 10\lambda_{pf}/11$;
3) $\lambda_{pff} = 100\lambda_{pf}$, $\lambda_f = 100\lambda_{pf}/101$.



a) $\lambda_{pff} = 2\lambda_{pf}$ b) $\lambda_{pff} = 10\lambda_{pf}$ c) $\lambda_{pff} = 100\lambda_{pf}$

Fig. 1. $F_{ds}(t)$ and $F_f(t)$ distribution functions over the time period of 1 year under different relationships between the initial parameters

Fig. 1 a, b, c show the dependency graphs of the $F_{ds}(t)$ and $F_f(t)$ distribution function for these types respectively. The above graphs show that under the adopted relationships between the initial parameters, the $F_{ds}(t)$ and $F_f(t)$ distribution functions differ in every case.

It can be seen that the differences between $F_{ds}(t)$ and $F_f(t)$ decrease as the failure rate grows after pre-failures. This fact is referred to in [1]. Cable trunk operation data show that $T_{pf} >> T_{pff}$ is true in the overwhelming majority of cases. Then, $\lambda_f \approx \lambda_{pf}$.

It should be noted that the time period of 1 year in Fig. 1 suffices to conclude that calculating dependability indicators using F_{ds}(t) and F_f(t) will produce different results. Out of that follows that replacing the original process with an exponentially distributed process requires an error calculation.

Discussion

The paper considered examples of certain events and made a judgement on the applicability of exponential distribution. However, in case of such events as completion of recovery, duration of scheduled inspection, duration of maintenance, etc., a judgement regarding the applicability of exponential distribution cannot be made in the absence of personal experience associated with such events.

Similar conclusions can be made regarding the frequency of technical inspections of various equipment. For example, the time between verifications of water and electrical meters cannot be exponentially distributed, since the consumers will not significantly reduce the time between inspections, while companies will not allow long intervals between verifications. The real situation is that the time between inspections is still random. But it is not exponentially distributed. The distribution of such times is to be established using statistical methods.

[11] and [12] examined the models of operation of an item that is submitted to inspections with a constant period and with an exponentially distributed period. Those models were compared under the same constant period and average time between inspections. Formulas were obtained for calculating the availability coefficient, the non-availability coefficient and some other operational indicators. The calculated values of some indicators based on those models are identical, e.g., the average frequency of inspections, while some differ. Thus, there is a two-fold difference between the unavailability values for the above ways of defining the inspection frequency.

The use of exponential distribution or constant event rate (end of state) are to be clearly substantiated. Such substantiation may be based on the probability theory, mathematical statistics or otherwise.

Findings and conclusions

Thus, the above examples show that using exponential distribution for simulating random time between events is unacceptable after the semantic content of the example has been analysed.

The paper's findings allow making the following conclusions.

1. An unknown random distribution cannot be replaced with an exponential distribution without a valid substantiation. In other words, the use of exponential distribution as part of unknown distribution simulation is to be substantiated.

2. Replacing a random time in a subset of states with a random exponentially distributed time with a constant rate requires a valid substantiation.

3. Approximate calculations are to be provided with an error calculation.

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The author’s contribution

The author analysed the application of the exponential distribution of time between states when used in mathematical models. This approach could be used to better substantiate the recommendations for applying the exponential distribution in matters of dependability.

Conflict of interests

The author declares the absence of a conflict of interests.

Original article
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Strength and life estimation for assigning the useful life of wheelpairs of high-speed flat wagons

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Abstract. Aim. *The most vital unit of railway rolling stock is a wheelpair, as a broken wheel or axle may have catastrophic consequences. Therefore, before the production of a high-speed flat wagon designed for operation at speeds of up to 140 km/h, which is unique for the 1520 mm gauge space, could commence, it was required to research the applicability of the standard wheelpair for high-speed movement. Ensuring the safe operation of a wheelpair involves compliance with the requirements that are to be confirmed by means of assessment of strength and durability parameters [1]. Product conformity assessment may be based on the requirements of standards, whose voluntary fulfilment ensures compliance with [1], or other documents.* **Methods.** *The paper describes the computational and experimental methods used for confirming the strength and estimating the life (durability) of wheelpair elements in the probabilistic setting. As experimental data, the authors used the results of full-scale bench testing of wheelpairs for fatigue using the method of rotational bending as it best approximates the loading conditions in operation. The results confirmed the endurance limits of the axle and wheel as parts of an assembled wheelpair. Using design analysis, the authors examined the stress-strain state of the wheelpair caused by installation and operational loads in various running modes.* **Results.** *The conducted studies confirmed the wheelpair's compliance with the requirements of [1–3] in terms of safety factors of fatigue strength and endurance, which eliminates the possibility of hazardous situations in the course of high-speed flat wagon operation. The time to fatigue crack nucleation in wheelpair components was evaluated using the fatigue resistance figures of the parts and equivalent amplitudes of dynamic stress caused by operational loads. It appears that this assessment allows establishing – with the assumed probability of destruction – the assigned useful life of a wheelpair axle at 32 years, which corresponds to the assigned useful life of the flat wagon according to the combined criterion. Corresponding standards and regulations required for developing the container-carrying flat wagon are being updated and a new State Standard is being developed.* **Conclusion.** *The conducted conformity assessment established that the flat wagon wheelpair meets the safety requirements of [1] and ensures the absence of unacceptable risks associated with harm to life and health of people, animals and plants, the environment and property of individuals and companies in the course of flat wagon operation.*

Keywords: *wheelpair, stress-strain state, fatigue resistance, endurance limit, S-N curve, life, assigned useful life.*

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Introduction

Today, a six-axle container-carrying 80-foot flat wagon with three-axle freight bogies with the operational speed of up to 140 km/h and axle load of up to 20.5 tons is under development jointly with Federal Freight for the purpose of gross weight freight container transportation. The flat wagon as part of a fixed train set is unique within the 1520-mm gauge space in terms of its design features and permissible speeds of operation. The platform is suitable for operation both as part of trains consisting of similar wagons, and as single flat wagons as part of a freight train throughout the 1520-mm gauge railway network (Russian Federation, CIS countries, Finland, Poland, Ukraine, Latvia, Lithuania, Estonia, Georgia).

In accordance with Annex 2 of [1], the flat wagon is subject to mandatory confirmation of conformity (in the form of certification). In accordance with Article 6, Item 5 of [1], product conformity assessment [1] may be based on the requirements of standards, whose voluntarily fulfilment ensures compliance with [1], or other documents.

The most vital component of the flat wagon is a wheelpair that – as a unit and its components (axle and wheel) – is subject to mandatory certification [1, 2]. The above regulatory documents specify safety requirements that are to be confirmed by assessing the strength and durability (life) of the axles and wheels of wheelpairs. Thus, Article 4, Item 57 of [1] contains the following requirement for rolling stock: “wheels, axles ... of wheelpairs of railway rolling stock ... of freight wagons shall have a safety margin of static strength and a required fatigue resistance margin that guarantee resistance to the formation and development of defects (cracks) during the useful life per the design documentation.”

[3] is the supporting standard for the purposes of strength assessment of axles and wheels of wheelpairs (of freight and passenger cars) and non-motored wheelpairs of electric multiple units (including high-speed).

Strength assessment

Items 4.3.11 and 4.3.12 of [3] contain requirements for the fatigue resistance, static strength and fatigue endurance coefficients of the axle and wheel as part of a wheelpair for wheelpairs not specified in Annex A. According to Annex A of [3], mass-produced wheelpairs have a maximum design speed of 120 km/h. Therefore, a wheelpair with the design speed of 140 km/h (Fig. 1) is to prove compliance with the requirements of Items 4.3.11 and 4.3.12 of [3].

Estimating the fatigue strength assurance coefficients of wheelpair components requires an experimental confirmation of the fatigue endurance obtained as the result of fatigue tests and S-N curve construction.

The results of benchmark fatigue tests of axles and wheels by the method of circular bending as the most similar to the loading conditions of operation [4] previously conducted by JSC VNIKTI experts were used as experimental data.

Following the wheelpair manufacturing process, three axle test objects and three wheel test objects (modified axles with temporary hubs and wheels with modified axles) were installed in the testbench (Fig. 2). Resistive strain sensors were mounted in line in the longitudinal and tangential directions as sockets on the most heavily loaded side of the wheel. Then the measurement circuits were mounted and the stress amplitudes (deformations) were measured using a measuring and computing system. The test object was loaded by rotating an unbalanced mass installed at the end of its axle . The bending moment created stress amplitudes (deformations) within the test object. The required values of the stress amplitudes were established by changing the rate of rotation of the unbalanced mass.

The fatigue test results confirmed an actual fatigue endurance with a 50% probability of failure of the most heavily loaded part of the axle behind the wheel seat equal to 180 MPa (against the required 160 MPa [2]) and the actual fatigue endurance of the all-rolled wheel equal to 225 MPa (against the required 150 MPa [2]) on a standardized test basis of 50 and 20 mil load cycles [3].

The estimation of the strain-stress state of the wheelpair showed that the maximum stress amplitudes that occur in the most heavily loaded part of the wheel in operation (Fig. 3) amount to 97 MPa. Based on wheel test results and computed coefficients that take into account the dependence of the fatigue strength on the total average cycle stress in operation and on bench tests, the fatigue resistance margin is defined that amounts to 2.54 against the minimal allowed 1.5.

The axle calculation showed that the most heavily loaded part of the axle is behind the wheel seat where the

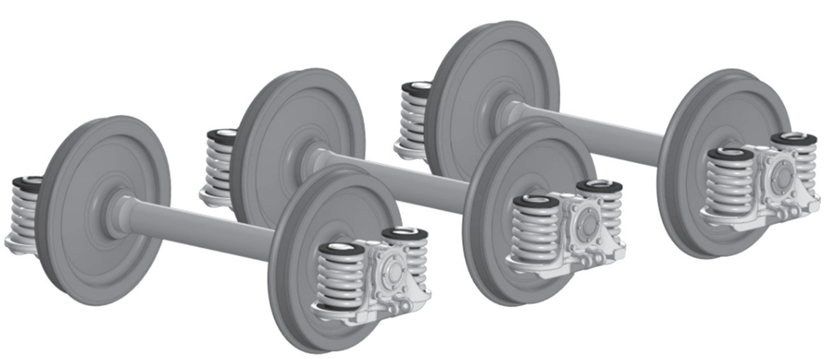


Fig. 1. Wheelpairs of a three-axle bogie of a high-speed flat wagon

a) b)

Fig. 2. Testbench with installed test objects, axle (a) and wheel (b)

maximum amplitude of the mechanical stresses in operation is 144 MPa, taking into account the fatigue endurance identified as the result of the tests, the safety coefficient is 1.25 with the minimum allowable value of 1.2.

Thus, the above calculations and experimental evaluation has confirmed the wheelpair's compliance with the requirements of [1,3] in terms of the fatigue resistance figures and endurance limits.

Life evaluation

According to Article 5, Item 3 of [1]: "The safety of railway rolling stock and its components shall be ensured by: ... c) establishing the assigned useful life of products, as well as conducting maintenance and repairs with the required frequency; ... f) establishing the criteria for identifying limit states of the product."

According to Article 4, Item 7, "the design of the railway rolling stock and its components chosen by the designer (developer) shall be safe over the course of the assigned useful life, the assigned storing life, as well as withstand the effects and loads that they may be subjected to in the course of operation."

Therefore, the safety of the axles and wheels of wheelpairs shall be ensured over the course of the assigned useful life that is to be specified on the basis of their limit state and life taking into account a certain safety margin.

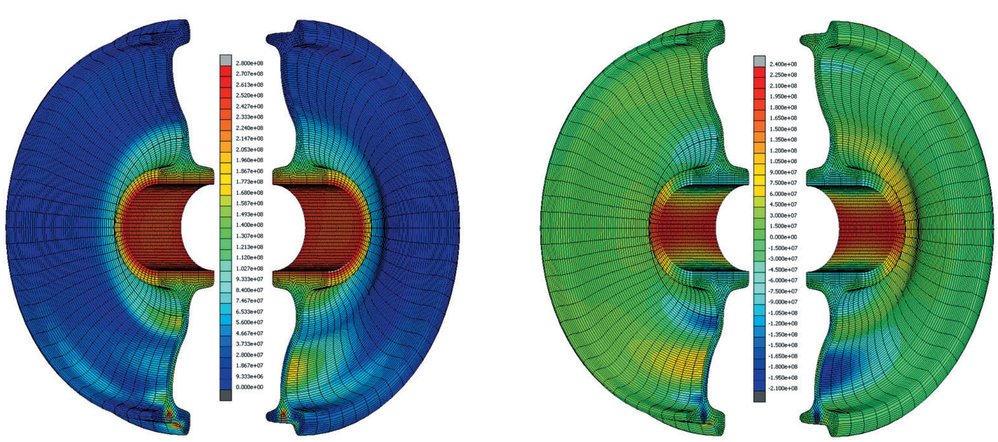
Since rolling stock is used throughout the railway network (therefore, the operating conditions – temperature, current track condition, terrain, etc. – can differ significantly, which affects the load intensity), the life of the axle and wheel in terms of fatigue damage accumulation is to be specified subject to the totality of differences in the operation of a specific type of rolling stock. Axle or wheel failure may have detrimental consequences, therefore crack nucleation is taken as the limit state criterion (the process of its formation is not controlled).

Estimating the life of the axle and wheel of a wheelpair requires identifying the following:

– strength characteristics of the parts in probabilistic terms;

– operational loading.

Based on the obtained data, the life is defined with the required probabilistic parameters. This life assessment



a) b)

Fig. 3. Distribution of equivalent (a) and radial stresses (b) with the wheel tread worn to the limit from movement in curves

of the axle and wheel of a wheelpair was performed using the analytical and experimental method.

The analytical solution [5] implies calculations that involve the part's fatigue strength characteristics (based on the results of fatigue bench tests) and the amplitude (equivalent) of the dynamic stress caused by the operational loads. For this purpose, out of the S-N curve (the second sloped branch) we find the number of the loading cycles of the part before the exhaustion of the load-carrying capacity (failure) N_f:

$$\sigma_{-1p}^{m_2} \cdot N_0 = \sigma_{\text{ea}}^{m_2} \cdot N_p = \text{const} \quad (1)$$

where σ_{-1p} is the fatigue endurance of the part based on N_0 test cycles;

σ_{ea} is the equivalent amplitude of stress;

m_2 is the slope of the curve.

The calculation used an S-N curve with two sloped branches: for numbers below 10^7 cycles, the slope of the left-hand branch of the curve $m_1 = 7$, for numbers above 10^7 cycles, i.e., for the right-hand branch, $m_2 = 2m_1 - 1 = 13$.

The resulting curve allows determining the median value of durability that corresponds to the 50% probability of failure. For the purpose of calculating the failure with the probability of (P)%, according to normal distribution tables, the corresponding quantiles are determined and the equation is solved:

$$U_p = \frac{1-\tilde{n}}{\sqrt{\tilde{n}^2 \nu_{\sigma_{-1\partial}}^2 + \nu_{\sigma_a}^2}}, \quad (2)$$

out of where the relative safety factor $\tilde{n}$ is determined and, based on the latter, the overload factor n_p is defined:

$$n_p = \tilde{n} \cdot n, \quad (3)$$

where $n = \frac{\sigma_{a_{\max}}}{\sigma_{-1\partial}}$ is the actual loading factor;

$\nu_{\sigma_{-1\partial}}$, ν_{σ_a} are the variation coefficient of normally distributed values of the fatigue endurance σ_{-1p} and maximum stress $\sigma_{a_{\max}}$ in operation, respectively.

The variation coefficients characterize the scattering of the corresponding values: the lower are the coefficients, the more stable are the results in terms of design and manufacturing processes and operating condition.

Thus, the fatigue endurance is recalculated for the (P)% probability of failure according to the formula:

$$\sigma_{-1\partial} = \overline{\sigma}_{-1\partial}(1 - U_p \cdot \nu_{\sigma_{-1\partial}}). \quad (4)$$

Under the accepted variation coefficients of normally distributed values of the axle fatigue endurance $\nu_{\sigma_{-1\partial}} = 0.1$, maximum operating stress $\nu_{\sigma_a} = 0.2$, probability of failure $P = 0.1\%$, quantile $U_p = -3.09$, according to formula (1) we deduce $N_p = 8.2 \times 10^9$ loading cycles.

According to dependence $n_N = \varphi\ (n_\sigma)$ between the safety factors in terms of stress and durability, we deduce $N_{\text{sum}} = 2.9 \times 10^9$ loading cycles to the exhaustion of the load-bearing capacity. Upon recalculation into running kilometres, the life of an axle will be $8.7 \cdot 10^6$. Based on the established average annual run of a high-speed flat wagon of 250 ths km, the estimated operating life with the adopted probability of failure of 0.1% will be 34.7 years.

The wheels as part of a wheelpair are replaceable components, and, in operation, wheels are rejected when they reach the limit state in terms of geometry, which occurs between 300 and 800 ths km. The estimation of a wheel's life has shown that life in terms of the fatigue of the disc part is significantly higher than the run in service, meaning that the wheel will not fail.

The calculation assumed that the stress-related characteristics of the material do not change over the course of the useful life, are not subject to corrosion and other hostile environments. Given the limited scope of experimental data, as well as the probability of its growing scattering due to the impossibility of taking into account all the affecting factors for the purpose of ensuring the dependability and safety of axle and wheel operation, it appears possible to establish the assigned useful life of an axle at 32 years, which corresponds to the assigned useful life of a flat wagon according to the combined criterion.

Thus, the above calculation determined the durability of elements of a wheelpair as a vital part of rolling stock.

Conclusions

The above calculations and experimental strength evaluation have confirmed the wheelpair's compliance with the requirements of [1, 3] in terms of the fatigue resistance figures and endurance limits. The paper presents the results of calculation and experimental evaluation of the life of the axle and wheel of a wheelpair of a high-speed flat wagon currently under development. The evaluation is based on an S-N curve in the probabilistic setting. The assigned useful life of the axle was defined at 32 years.

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The authors' contribution

Volokhov G.M. analysed regulatory documents as regards rolling stock safety confirmation.

Oganian E.S. analysed literature on the estimation of the life of railway rolling stock components.

Gajimetov G.I. defined the problem, analysed and selected the methodological approaches to testing, analysed the results and prepared the conclusions.

Knyazev D.A. carried out benchmark fatigue tests of axles and wheels of wheelpairs of a high-speed flat wagon.

Chunin V.V. assessed the stress-strain behaviour and carried out strength calculations.

Timakov M.V. carried out life assessment and defined the assigned useful life of a wheelpair axle.

Conflict of interests

The authors declare the absence of a conflict of interests.

Original article
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On the safety assessment of an automatic train operation system

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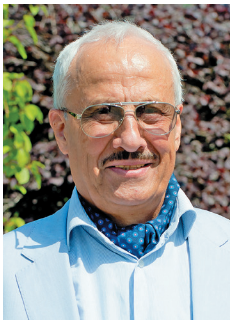

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Abstract. *The paper examines the automatic train operation system as part of the locomotive control and protection system, the remote supervision centre's means for control of onboard and trackside machine vision facilities. The focus is on the dependence of the system's safety and dependability on the dependability characteristics of its components and adverse weather effects. The criteria of a system's wrong-side and right-side failures were defined, the graph models were constructed of the safety and dependability states of an automatic train operation system. The Markovian graph method of calculating the safety and dependability of complex systems was substantiated. That allowed defining such key safety indicators of an automatic train operation system as the mean time to wrong-side failure, probability of wrong-side failure, wrong-side failure rate. The study established that the safety of an automatic train operation system primarily depends on the dependability of machine vision facilities. The growth of the system's wrong-side failure rate is limited to half the failure rate of machine vision facilities. It was also established that the dependability of an automatic train operation system is defined by the failure rate of a locomotive control and protection system and the failure rate of machine vision facilities. The conducted analysis allows concluding that in order to achieve an acceptable level of safety of an automatic train operation system, efforts should focus on machine vision redundancy, ensuring the SIL4 functional safety of on-board and trackside machine vision facilities, as well as regular comparison of the outputs of on-board and trackside machine vision facilities, redundant output comparison, integration of the outputs in motion. Additionally, adverse weather effects are to be countered by improving the efficiency of machine learning of the machine vision software.*

Keywords: *automatic train operation system, machine vision, safety, dependability, Markovian model, state graph, hazardous failure, right-side failure.*

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1. Introduction

Ensuring the safety of a complex technical system, in which information is processed using neural networks, requires special methods of safety case preparation [1].

The primary problem associated with the development of such method consists precisely in the fact that the above computer system is unstable in terms of the structure of the information processing algorithm, and classical methods of probabilistic estimation in the form of two and more independent hardware and software information processors, application of different software products in the processors, etc. [2] are difficult to use as part of the safety case preparation.

That is why redundant information processors in the form of onboard machine vision cameras for safe obstacle detection are unlikely to achieve the required safety level due to the unknown testing time of such self-trained, i.e., ever-changing, system for vital information processing.

Braband and Shäbe [1] intended to use statistical methods for safety case preparation, as well supposed the obligatory inclusion in the processing system of an additional device, whose safety could be proven by conventional means due to its unchanging structure.

Shubinsky and Rozenberg [3, 4] proposed using the so-called multi-level structures for safety case preparation that allow integrating safe systems and information systems with the introduction of the information processing criterion subject to the safety requirements. This approach has shown good results in the development of advanced onboard and trackside safety systems. An extremely important property of system safety evaluation was also used, i.e., obtaining reliable information on a facility's background in terms of safety.

For the purpose of safety case preparation of an intelligent system with a neural network, the principles of multi-level safety system should be used. The difference is that, in this case, the focus should be not on an individual intelligent device, i.e., an onboard machine vision camera, but on an entire system of technical assets within the locomotive's area of operation.

Indeed, the operation of a locomotive camera with a pre-designed software for processing obstacle information depends not only on the prior measures aimed at training the neural network, but also on specific factors that affect the operation of the camera hardware, software faults, etc. In addition, it should be noted that the effects of the external environment, i.e., snow, fog, rain, cause changes within the obstacle acquisition area, which directly affects safety, as it is associated with the length of the trains' braking path.

In this context, the situation ahead of the train is additionally monitored from the special control centre, where an operator driver supervises several locomotives [5].

The difficulty of this method consists in the fact that the critical component is the operator driver's response that, in turn, depends on the stability of the video image transmission from the onboard camera and the dependability of the broadband radio communications in a particular location.

On the other hand, dividing the information processing into two sub-processes (in the form of internal intelligent processing of information onboard for the purpose of decision-making on the track vacancy and in the form of communication of the original visual information to the operator driver for decision-making) allows improving safety. The criterion in this case is that the onboard system should have a high probability of false alarm, while the operator driver can rectify this situation using a special command transmitted to the locomotive by radio. In practice, if this principle was not used, driverless systems would stop, for instance, because of a plastic bag on the track.

It should be noted that the system includes trackside devices that supervise track vacancy in places with poor visibility [5]. Information from those trackside systems is communicated to the locomotive in real time, which greatly improves train safety. Thus, the used model is simplified, but it enables an analytical study of the problem. That constitutes the superiority of this approach to the construction of the research model as compared to more complex models. An interesting feature of the interaction between trackside and onboard machine vision assets is that, under the same environmental conditions, they can see the same objects either in the line of sight, or from different, including inverse, observation points.

The existence of objects acquired by two independent systems allows using this feature for cross-supervision of intelligent equipment, especially for the purpose of development of correct solutions by onboard intelligent systems that operate in more severe operating conditions (speed of movement, visibility limitations, etc.). The object comparison output can have the form of a comparison of images processed by trackside and onboard cameras represented as pre-processed image models, or it can contain an assumed inversion of the image of the same object if it is aimed by machine vision cameras from opposite points. This predefined feature of the output comparison safety system enables an improved independence of information processing. Each technical asset, including video cameras, contains elements of internal testing as a prerequisite factor when calculating their level of safe operation. Given that a comprehensive testing of an intelligent system with a neural component is a difficult matter, self-diagnosis using predefined observation objects should be employed. For instance, near the railway tracks, within the area covered by machine vision cameras or lidars, there are traffic lights, control cabinets, power and communication masts that are clearly associated with the linear coordinates, moreover if the locomotive uses a 3D map of the infrastructure assets.

Thus, the acquisition of such assets actually allows testing onboard cameras and sensors taking into account the parameters of detection distance and type of asset identification. If the rate of acquisition of such objects is high enough, then, for the distance of the locomotive's movement between these points, the probability of no failure or distortion of the information processing algorithm onboard can be calculated. The advantage of such method is the completeness of information processing, when, along the internal hardware testing, the required level of system safety can be achieved. The system itself in this case is a "black box", but with absolutely known outputs within an absolutely known space coordinate.

2. Conceptual safety model of an automatic train operation system

An automatic train operation system includes the following key facilities:

• onboard train control and protection equipment;
• supervision centre equipment;
• trackside machine vision facilities;
• onboard machine vision facilities.

The conceptual safety model of an automatic train operation system contains a description of the dependability and safety states of the system's component facilities, their interrelations, as well as the effects of adverse weather conditions. This model is presented in the form of a system safety state graph (Fig. 1).

For the purpose of system safety model construction, the following criterion of **wrong-side failure** is adopted: the failure of machine vision facilities and the remote supervision centre or undetected failure of the locomotive's control and protection system. Criterion of **right-side failure**: the failure of trackside machine vision facilities, remote supervision centre and adverse weather effects or detected failure of the locomotive's control and protection system.

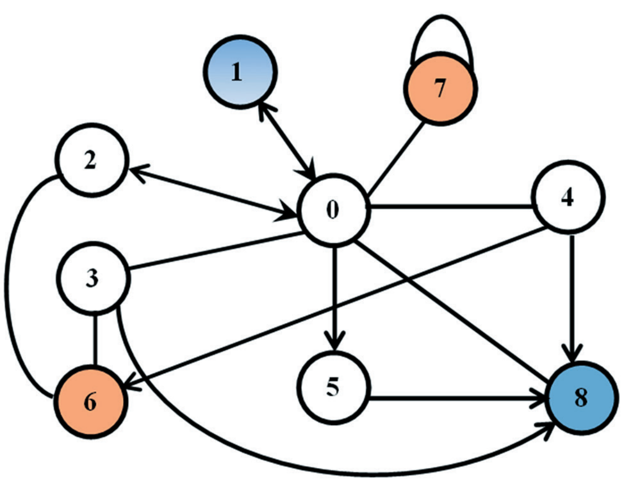

Fig. 1. State graph of the safety of an automatic train operation system

Graph states:

0 – good state, no adverse weather effects;

1 – detected failure of the locomotive control and protection system – **right-side failure;**

2 – failure of remote supervision centre equipment;

3 – failure of trackside machine vision facilities;

4 – failure of onboard machine vision facilities;

5 – adverse weather effects;

6 – failure of all machine vision facilities and the supervision centre – **wrong-side failure** of the automatic train operation system;

7 – undetected failure of the locomotive control and protection system – **wrong-side failure;**

8 – failure of trackside machine vision facilities, supervision centre and adverse weather effects – **right-side failure.**

The whole set of system states – according to the state graph in Fig. 1 – is divided into the following subsets:

– subset of up states S_U={0, 2, 3, 4, 5};
– subset of protective states S_P={1, 8};
– subset of hazardous states S_H={6, 7};

The up and protective states form the set of good states.

Given below are the model's good state transitions that need clarification: 1-0, 2-0, 3-0, 8-0, equipment restorations after failure; 3-8, failure of the supervision centre equipment on condition of failure of trackside machine vision facilities; 4-8, failure of the supervision centre equipment on condition of failure of onboard machine vision facilities; 7-8, failure of trackside machine vision facilities on condition of adverse weather effects.

The mathematical description of the model will be based on the following considerations. The system is new and unique, no statistical information about it is available. Therefore, the system's random values distribution laws are not established. Based on the existing experience in railway control systems, it can be safely assumed that failures of such electronic devices, as the locomotive control and protection system, supervision centre equipment and machine vision facilities, are exponentially distributed. This assumption does not apply to random values of time to device restoration after failures, much less to random adverse weather effects. The problem of disturbing effects was theoretically examined by Schäbe and Viertl in [6]. Those models are also applicable to adverse weather effects. In order to ensure adequate results, the authors were forced to use a complex mathematical description of the random process of adverse effects on the locomotive's control system. The above circumstances complicate their practical application in mathematical simulation of the safety of the automatic train operation system.

In the absence of practical information, it is very difficult to predict the quantitative safety indicators of the automatic train operation system. In this paper, in the context of great uncertainty, we aim to identify the most significant factors affecting the system's safety. The assumption of the simplest flows of random events in the automatic train operation system fits this purpose. The simplest flows are ordinary, stationary and have no aftereffect. Due to the great uncertainty of the initial conditions their application, on the one hand, does not favour an accurate prediction of the safety characteristics of the system's behaviour. On the other hand, the resulting outputs can be considered as prerequisites guaranteed from below (as the worst case) to the construction of a safe automatic train operation system through neutralization of the most significant identified negative factors. Thus, the used model is simplified, but it enables the analysis of the problem. That constitutes the advantage of this approach over more complex models.

Based on the above assumptions, let us adopt an exponential distribution of failures $F_i(t)$ and restorations $Q_i(t)$ of equipment components:

$$F_i(t) = 1–\exp(–\lambda_i t),\ i = 1...4;\ Q_i(t) = 1–\exp(–\mu_j t),$$

where λ_1 is the failure rate of the locomotive control and protection system;

λ_2 is the failure rate of the supervision centre equipment;

λ_3 is the failure rate of the trackside machine vision facilities;

λ_4 is the failure rate of the onboard machine vision facilities;

μ_1 is the restoration rate of the locomotive control and protection system;

μ_2 is the restoration rate of the supervision centre equipment;

μ_3 is the restoration rate of the onboard machine vision facilities;

μ_4 is the restoration rate of the trackside machine vision facilities and supervision centre equipment.

It is assumed that a failure of the locomotive control and protection system is detected with the probability of correct detection α. A possibility of non-detection of a failure of the locomotive's system exists and is $\bar{\alpha} = 1 - \alpha$.The probability of false detection is negligible.

Based on the above assumptions, let us assume that the law of distribution of random adverse weather conditions has the form of $H(t)=1–\exp(–\gamma t)$, where γ is the rate of their effect on the safety of the automatic train operation system.

Under the above assumptions, the safety-specific behaviour of the automatic train operation system is represented by a Markov process.

For that purpose, we find the input parameters of the system safety model in the subsets of good (up and protective) states according to the graph in Fig. 1.

The distribution functions of the unconditional good time of the system presented with the state graph in Fig. 1 are as follows:

$$F_0(t) = 1 - \exp\left(-\left[\gamma + \sum_{i=1}^{4}\lambda_i\right]\cdot t\right);\ F_1(t)=1–\exp(–\mu_1 t);$$

$$F_2(t)=1–\exp(–[\lambda_3+\mu_2]\cdot t);\ F_3(t)=1–\exp(–[\lambda_2+\lambda_4+\mu_3]\cdot t);$$

$$F_4(t)=1–\exp(–[\gamma+\lambda_2]\cdot t);$$

$$F_5(t)=1–\exp(–\lambda_4 t);\ F_8(t)=1–\exp(–\mu_4 t). \qquad (1)$$

Hazardous states 6 and 7, as well as the edges that are part of those states, are excluded from the mathematical description as the study covers the behaviour of the automatic train operation system before it enters hazardous states.

The mathematical expectations of the system's good times are as follows:

$$T_0 = \int_0^\infty \left(1 - F_0(t)\right)dt = \frac{1}{\gamma + \sum_{i=1}^{4}\lambda_i};\ T_1 = \int_0^\infty e^{-\mu_1 t}dt = \frac{1}{\mu_1};$$

$$T_2 = \int_0^\infty e^{-\lambda_3 t}e^{-\mu_2 t}dt = \frac{1}{\lambda_3 + \mu_2};$$

$$T_3 = \int_0^\infty e^{-\lambda_2 t}\cdot e^{-\lambda_4 t}\cdot e^{-\mu_3 t}dt = \frac{1}{\lambda_2 + \lambda_4 + \mu_3};$$

$$T_4 = \int_0^\infty e^{-\gamma t}e^{-\lambda_2 t}dt = \frac{1}{\gamma + \lambda_2};$$

$$T_5 = \int_0^\infty e^{-\lambda_4 t}dt = \frac{1}{\lambda_4};\ T_8 = \int_0^\infty e^{-\mu_4 t}dt = \frac{1}{\mu_4}. \qquad (2)$$

The probability of transitions between states i, j of the system is identified using formula $p_{ij} = \int_0^\infty \lambda_{ij}[1 - F_i(t)]dt$, where λ_{ij} is the rate of the system's transition from state i to state j. For example, the rate of transition from initial state 0 to state 1 (Fig. 1) of detected failure of the locomotive control and protection system is $\lambda_{01}=\alpha\cdot\lambda_1$, whereas the rate of transition from state 0 to state 7 of the system's undetected failure (hazardous system failure) is calculated as $\lambda_{07} = \bar{\alpha}\cdot\lambda_1$.

Thus,

$$p_{01} = \frac{\alpha\lambda_1}{\gamma + \sum_{j=1}^{4}\lambda_j};\ p_{0i} = \frac{\lambda_i}{\gamma + \sum_{j=1}^{4}\lambda_j},\ i = 2,3,4;$$

$$p_{05} = \frac{\gamma}{\gamma + \sum_{j=1}^{4}\lambda_j};\ p_{10} = p_{58} = p_{80} = 1;\ p_{20} = \frac{\mu_2}{\lambda_3 + \mu_2};$$

$$p_{30} = \frac{\mu_3}{\lambda_2 + \lambda_4 + \mu_3};\ p_{38} = \frac{\lambda_2}{\lambda_2 + \lambda_4 + \mu_3};\ p_{48} = \frac{\gamma}{\lambda_2 + \gamma}. \qquad (3)$$

3. Results of the analysis of the safety indicators of the automatic train operation system

Using Shubinsky's Markovian graph method of calculating the safety of complex systems [7], such key safety indicators of an automatic train operation system as the mean time to wrong-side failure T_{WS}, the probability of wrong-side failure $G_{WS}(t)$, wrong-side failure rate λ_{WS} can be identified.

The key safety indicator, mean time to wrong-side failure T_{WS} is identified using method [8] according to formula

$$T_{WS} = \frac{T_1\Delta G^1_{S_{WS}} + \sum_{(k)}\sum_{i,j} l_k^{ij}\Delta G_k^j T_j}{\Delta G_{S_{WS}}}, \qquad (4)$$

where $\Delta G^1_{S_{WS}}$ is the weight of the expansion of the graph without the initial node 1 and set of hazardous states $S_{WS}=\{6,7\}$ and associated graph edges; $\Delta G_{S_{WS}}$ is the weight of the expansion of the graph without the set of hazardous states and associated graph edges; l_k^{ij} is the weight of the k-th path from node i to node j; ΔG_k^j is the weight of the expansion of the graph without the nodes situated on the

k-th path and without node j in the set of non-hazardous states $S_{NH}=\{0,1,2,3,4,5,8\}$.

The expansion weights can be defined using Mason's gain formula [8]

$$\Delta G = 1 - \sum_i C_i + \sum_{ij} C_i C_j - \sum_{ijk} C_i C_j C_k + ...,$$

where the weights of boundaries are found within the set of non-hazardous states (Fig. 1)

$$C_1=p_{01}\cdot p_{10};\ C_2=p_{02}\cdot p_{20};\ C_3=p_{03}\cdot p_{30};\ C_4=p_{03}\cdot p_{38}\cdot p_{80};\ C_5=p_{04}\cdot p_{48}\cdot p_{80};\ C_6=p_{05}\cdot p_{58}\cdot p_{80}. \quad (5)$$

All boundaries intersect, since they have a common node 0.

According to the graph in Fig. 1 and substituting expressions (1), (2), (3) into formula (4), we find within the set of non-hazardous states $S_{NH}=\{0,1,2,3,4,5,8\}$

$$T_{WS} = \frac{T_0 + \sum_{i=1}^{5} p_{0i} T_i + (p_{03} p_{38} + p_{04} p_{48} + p_{05} p_{58}) \cdot T_8}{\Delta G_{S_{WS}}}, \quad (6)$$

where the expansion weight of the graph without the hazardous states $\Delta G_{S_{WS}} = 1 - \sum_{i=1}^{6} C_i$ and the weight of the boundaries is calculated using formula (5).

Since, in actual control systems, between the rates of restorations and failures of electronic equipment the correlation is $\lambda_i << \mu_i$, with an error not exceeding the first order of smallness, the explicit expressions of the model's initial parameters can be significantly simplified. It is to be taken into account that the recovery rates of such trackside electronic assets as the supervision centre and machine vision facilities, are almost identical and deviations of tens of percentage points do not significantly affect the final results in the context of the above ratio between the failure and restoration rates. Then, $\mu_2=\mu_4=\mu$ and $\mu_1=\mu_3=k\mu$, $(0<k\leq 1)$, where k is the coefficient of logistical delays of restoration of onboard assets of the automatic train operation system.

The above changes in the initial parameters apply to the distribution functions $F_1(t) \cong 1 - \exp(-k\mu \cdot t)$, $F_2(t) \cong 1 - \exp(-\mu \cdot t)$, $F_3(t) \cong 1 - \exp(-k\mu \cdot t)$, expectations $T_2 \cong \frac{1}{\mu}$ and $T_1 \cong T_3 \cong \frac{1}{k\mu}$, transition probabilities $p_{20} \cong p_{30} \cong 1$, $p_{38} \cong \frac{\lambda_2}{k\mu}$.

Indeed, according to NPRD-2011 camera sub-assembly [9], the failure rate of the machine vision facilities is to be $\lambda_2 = \lambda_4 = 2{,}3 \cdot 10^{-5}$ and $\lambda_3 = 2{,}8 \cdot 10^{-5}$ for the supervision centre. According to EN 50129 [10], the failure rate of the locomotive control and protection system must be SIL4, i.e., $\lambda_1 \leq 10^{-8}$. According to IEC 61508-2 (A4, first line) [12], the probability of non-detection of failure is to be less than $\bar{\alpha} \leq 0{,}01$. In most cases, the restoration rate of the electronic programmable equipment of the automatic train operation system exceeds $\mu \geq 2$, which is higher than the failure rate by four or more orders of magnitude. This allows – within an acceptable margin of error – excluding from the explicit expression those terms of the sum that are several orders of magnitude smaller than the other terms.

The above considerations allow developing the explicit expression (6) of the mean time to wrong-side failure of the automatic train operation system to an acceptable applied mathematical expression

$$T_{ws} = \frac{\dfrac{k\mu + \alpha\lambda_1 + \lambda_3 + k(\lambda_2 + \lambda_4)}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)k\mu} + \dfrac{\gamma}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)\lambda_4} + \left[\dfrac{\lambda_3 \cdot \lambda_2}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)k\mu} + \dfrac{\lambda_4 \cdot \gamma}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)(\lambda_2 + \gamma)} + \dfrac{\gamma}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)}\right] \cdot \dfrac{1}{\mu}}{\Delta G_{S_{ws}}},$$

where

$$\Delta G_{S_{ws}} = 1 - p_{01}p_{10} - p_{02}p_{20} - p_{03}p_{30} - p_{03}p_{38}p_{80} - p_{04}p_{48}p_{80} - p_{05}p_{58}p_{80} \cong 1 - \frac{\alpha\lambda_1 + \lambda_2 + \lambda_3 + \gamma}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)} - \frac{\lambda_3}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)} \frac{\gamma}{(\gamma + \lambda_2)} - \frac{\lambda_4}{\left(\gamma + \sum_{i=1}^{4}\lambda_i\right)} \frac{\lambda_2}{k\mu}. \quad (7)$$

Upon transformation of formula (7), we deduce that – with an error not exceeding the first order of smallness – the mean time to wrong-side failure of the automatic train operation system can be represented as

$$T_{WS} \cong \frac{\lambda_4(\gamma + \lambda_2 + \lambda_4) + \gamma \cdot (\gamma + \lambda_2)}{\lambda_4(\bar{\alpha} \cdot \lambda_1 + \lambda_4)(\gamma + \lambda_2)}, \quad (8)$$

The limit value of the time to wrong-side failure of an automatic train operation system occurs in the absence of adverse weather effects ($\gamma \to 0$) and when compliance with IEC 61508-2 [11] ($\alpha \to 0$) is ensured. By substituting these values into formula (8), we deduce the output of the mathematical simulation. It indicates that the safety of an automatic train operation system primarily depends on the dependability of the machine vision facilities, i.e.,

$$T_{LIM} \leq \frac{\lambda_2 + \lambda_4}{\lambda_2 \lambda_4} = \frac{1}{\lambda_4} + \frac{1}{\lambda_2}.$$

If the failure rate values of the trackside and onboard machine vision facilities are close, this expression modifies into

$$\lambda_2 \cong \lambda_4 = \lambda; \text{ therefore } T_{LIM} \leq \frac{2\lambda}{\lambda^2} = 2 \cdot T,$$

where T is the mean time to failure of the machine vision facilities.

As the system's flow of wrong-side failures is multiply rarefied in relation to the right-side failure flow of the initial item that is a simplest one, then, according to [12, 13] a multiply rarefied, irregularly simplest failure flow is also a simplest one with constant parameter

$$\lambda_{\text{WS}} = 1/T_{\text{WS}} = \frac{\lambda_4(\bar{\alpha}\cdot\lambda_1+\lambda_4)(\gamma+\lambda_2)}{\lambda_4(\gamma+\lambda_2+\lambda_4)+\gamma(\gamma+\lambda_2)}. \quad (9)$$

In the limit, the rate of wrong-side failures of the automatic train operation system tends to

$$\lambda_{\text{WS}} \to \frac{\lambda_2\cdot\lambda_4}{\lambda_2+\lambda_4} \cong \frac{\lambda}{2}(\lambda_2 \approx \lambda_4), \quad (10)$$

i.e., half of the failure rate of the machine vision facilities.

The probability of wrong-side failure with an error not exceeding the first order of smallness is defines as

$$G_{\text{WS}}(t) \cong \lambda_{\text{WS}}\cdot t \to \frac{\lambda}{2}t.$$

4. Results of the analysis of the dependability indicators of the automatic train operation system

The dependability model of the automatic train operation system is transformed from the conceptual safety model of such system (Fig. 1) by eliminating hazardous states and associated edges. The state graph of the dependability model is shown in Fig. 2.

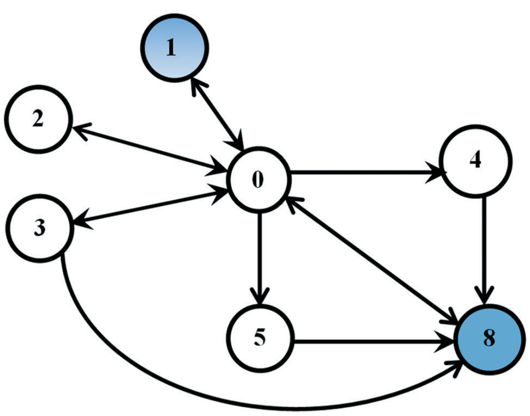

Fig. 2. State graph of the dependability of an automatic train operation system

For the purpose of the system's dependability analysis, let us restrict ourselves to the definition of the mean time of it being in the set of up states $S_U = \{0, 2, \rightleftarrows 3, 4, 5\}$. This indicator is none other than the system's mean time to right-side failure. This indicator is to be analysed due to the fact that improving safety involves bringing the system into the safe (non-operational) state in every alarm case, whenever possible. It is therefore important to identify which factors affect the dependability of a system with machine vision in the course of its design according to this architecture.

Using the graph in Fig. 2 and method [7] we deduce

$$T_{RS} = \frac{T_0 + p_{02}T_2 + p_{03}T_3 + p_{04}T_4 + p_{05}T_5}{1 - p_{02}p_{20} - p_{03}p_{30}}.$$

Under the assumptions of Items 2 and 3, this expression transforms into

$$T_{RS} = \frac{(\lambda_2+\gamma)(\lambda_4+\gamma)+\lambda_4^2}{\lambda_4(\lambda_2+\gamma)(\lambda_1+\lambda_4+\gamma)} + \frac{\lambda_2\mu_3+\lambda_3\mu_2}{\mu_2\mu_3(\lambda_1+\lambda_2+\gamma)}. \quad (11)$$

As noted above in Item 2, in accordance with NPRD-2011 camera sub-assembly [9], the failure rate of the machine vision facilities is to be $\lambda_2 = \lambda_4 = 2{,}3\cdot10^{-5}$ and that of the supervision centre is to be $\lambda_3 = 2{,}8\cdot10^{-5}$. Therefore, $\lambda_2 \cong \lambda_3 \cong \lambda_4 = \lambda$ can be assumed without noticeable loss of evaluation accuracy. In addition, the machine vision and supervision centre equipment overwhelmingly contain electronic assets whose restoration rate is about the same $\mu \geq 2$. Therefore, we can assume that $\mu_2 \cong \mu_3 = \mu$ and expression (11) modify into

$$T_{RS} = \frac{(\lambda+\gamma)^2+\lambda_4^2}{\lambda(\lambda+\gamma)(\lambda_1+\lambda+\gamma)} + \frac{2\lambda}{\mu(\lambda_1+\lambda+\gamma)}. \quad (12)$$

As with the system's safety assessment, let us assume that the limit value of time to right-side failure of the automatic train operation system takes place in the absence of adverse weather effects ($\gamma \to 0$). Then, formula (12) will modify into

$$T_{RS} \to \frac{2}{\lambda_1+\lambda}\left(1+\frac{\lambda}{\mu}\right).$$

As noted in Item 2, for the purpose of the problem at hand, $1 >> \frac{\lambda}{\mu}$. Given the above, we deduce the marginal estimate of dependability of the automatic train operation system in terms of mean time to right-side failure:

$$T_{RS} \to \frac{2}{\lambda_1+\lambda}. \quad (13)$$

Consequently, the dependability of an automatic train operation system is defined by the failure rate of the locomotive control and protection system (λ_1) and the machine vision facilities (λ). These components of the automatic train operation system must be the focus of attention in the context of ensuring an acceptable level of the system's dependability.

5. Conclusion

The above analysis allows concluding that in order to achieve an acceptable level of safety of the automatic train operation system, the efforts should focus on the following:

– redundancy of machine vision facilities;

– ensuring the SIL4 functional safety of onboard and trackside machine vision facilities (dual channel and dual versioning of software, use of independent channels, etc.);

– regular comparison of the outputs of onboard and trackside machine vision facilities, redundant output comparison, integration of the outputs in motion.

Additionally, it is required to ensure compliance with EN 50129 in terms of SIL4 functional safety of the locomotive control and protection system. Adverse weather effects should also be countered by increasing the efficiency of machine learning of the machine vision software.

The study confirmed that the reliability of the locomotive control and protection system has a decisive effect on the dependability of the automatic train operation system.

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The authors' contribution

Shubinsky I.B. developed and solved the safety and dependability models of the automatic train operation system, analysed the results.

Shäbe H. analysed publications dedicated to the safety of automatic train operation systems, prepared experimental data, participated in the development of safety and dependability models of an automatic train operation system and analysis of the findings.

Rozenberg E.N. defined the research problem, participated in the development of the safety model of an automatic train operation system, participated in the analysis of the findings.

Conflict of interests

The authors declare the absence of a conflict of interests.

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Decision support for preventing safety violations

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Abstract. Aim. *The aim of the paper is to examine the experience of reducing the effect of the human factor on business processes, to develop the structure and software of the decision-support system for preventing safety violations by train drivers using machine learning and to analyse the findings.* **Methods.** *The study presented in the paper uses machine learning, statistical analysis and expert analysis. In terms of machine learning, the following methods were used: logistical regression, random forests, gradient boosting over decision trees with frequency-domain representation of categorical features, neural networks.* **Results.** *A set of indicators characterizing a train driver's operation were identified and are to be used as part of the system under development. The term "train driver's reliability" was defined as the ability not to violate train traffic safety over a certain number of trips. Algorithms were designed and examined for predicting violations in a train driver's operation that are used in defining reliability groups and lists of preventive measures recommended for the reduction of the number of safety violations in a train driver's operation. Major violations with proven guilt of the driver that may be committed within the following 3, 7, 10, 20, 30, 60 days were chosen as attributes for the purpose of safety violation prediction. Analysis of the results on the test sample revealed that the model based on gradient boosting over decision trees with frequency-domain representation of categorical features shows the best results for binary classification on the prediction horizon of 30 and 60 days. The developed algorithm made a correct prediction in 76% of cases with the threshold value of 0.7 and horizon of 30 days and in 82% of cases with the threshold value of 0.9 and horizon of 60 days. The solution of the problem can be found in the integration of different approaches to predicting safety violations in a train driver's operation. Additionally, 10 of the most significant indicators of a train driver's operation were identified with the best of the considered models, i.e., gradient boosting over decision trees with frequency-domain representation of categorical features.* **Conclusion.** *The paper presents an overview of methods and systems of assessing human reliability and the effect of the human factor on the safety of transportation systems. It allowed choosing the most promising directions and methods of predictive analysis of a train driver's operation, including methods of machine learning. The resulting set of indicators of a train driver's operation that take into consideration the changes in the quality of such operation allowed obtaining initial data for training the models implemented as part of the system under development. The implemented models enabled the aggregation of information on train drivers and adoption of targeted and temporary preventive measures recommended for improving driver reliability. The resulting approach to the definition of preventive measures has been implemented in three depots of JSC RZD in trial operation mode.*

Key words: *intelligent management, advisory systems, decision support system, machine learning, gradient boosting, human factor, train driver, transportation system.*

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Introduction

One of the subjects matters of the research of the human factor as part of man-machine systems is the problem of human errors in the process of operations and their predictability. Today, train drivers' operation has no objective assessment system. Recording and defining the significance of the indicators that characterize the quality of a train driver's operation primarily depend on his/her direct superior, i.e., the presence of the human factor can be observed. Therefore, a decision support system (DSS) should be developed for preventing safety violations in the driver's operations that would enable their objective assessment by predicting possible violations and defining preventive measures recommended for improving the driver's reliability.

Let us introduce the concept of "train driver's reliability" that will be defined as the ability not to violate train traffic safety over R trips, $R \geq 1$. A traffic safety violation will be understood as any of a set of incidents causing the violation of a provision of the current classifier of violations and emergencies of JSC RZD. The list of incidents is made by decoding speed tapes, whose information is recorded in the network-level information system for registration, analysis and investigation of traffic safety violations [1]. The probability of no traffic safety violations is calculated through the probability of the opposite event:

$$P(R)=1-P_N(R), \tag{1}$$

where $P_N(R)$ is the probability of traffic safety violation within R trips. Identifying this value requires knowing the correlation between the driver's performance and the committed violations.

The concepts of structural and functional dependability are examined in detail in [2, 3]. For the purpose of this study, it would be logical to rely on the concept of functional dependability that is defined as the driver's readiness to perform the predefined tasks within R trips. The tasks can be defined as follows:

– ensuring the performance of the traffic schedule;

– performing the established procedures of train driving and shunting operations;

– when driving passenger trains, ensuring quality service of passengers, preventing violations of smooth train running, ensuring electric heating/ventilation of cars, boarding and alighting of passengers.

1. Source overview

Despite the advances in automated control systems (ACS), it is still impossible to completely eliminate the human involvement in business processes. Human reliability analysis (HRA) is a relatively new discipline. HRA methods are applied in many industries. These methods aim to assess human reliability and the human factor affecting ACS. A number of HRA methodologies have been developed by the scientific community over the last few years [4, 5, 6]. The developed methodologies can be divided into two macrocategories, i.e., the first and second-generation methods.

The first generation includes 35 to 40 methods of ensuring human reliability. Many of them are modifications of one method. The common theoretical foundation of most first-generation methods is: the method of error classification according to the concept of "inaction"; definition of the "performance influencing factors"; cognitive model (based on skills, rules and knowledge). The most popular first-generation theory for identifying and classifying incorrect actions is the error classification method according to the concept examined in [7] that is based on the "action – inaction" principle. In accordance with those principles, "inaction" defines an action that has not been performed or was performed late. An "action" is an action performed by a person that is not required for the process. Based on that principle, the first-generation prediction models were developed. *THERP* became the most popular out of them [8]. That is a method for generating predictions of error by a person based on the frequency of past errors of the same person. The method was developed for a nuclear power plant for the purpose of probabilistic risk assessment. Using this technique, the authors quantified the probability of human error.

The second-generation methods (a term first coined in [8, 9, 10]) were developed for the purpose of overcoming the limitations of the first-generation methods. These methods are based on mental process models developed in the cognitive psychology. They extended the ways an error can be described beyond a simple binary classification. The paper considers the dynamic aspects of human – machine interaction and their application as the foundation for the development of operator simulators.

The examined subject matter is associated with railway traffic safety that is one of the key concerns of JSC RZD. There is a great number of works dealing with various aspects of safety. Let us look into some of them [11, 12, 13, 14]. In railway transportation, safety in terms of control and driver's behaviour supervision is ensured through a number of means. The comprehensive on-board safety and protection capabilities include the following components:

– All-Purpose Automatic Train Operation System (USAVP) [15];

– Automatic Brake Control System (SAUT-TsM) [16];

– Integrated On-Board Train Protection System (KLUB-U) [17];

– Remote Driver Vigilance Supervision System (TSKBM) [18];

– Driver Vigilance Handle (RBM) [19].

In addition to the safety systems that use indirect control and restriction of driver behaviour, there are methods for assessing the personal characteristics of drivers, as well as methods designed for psychological support of drivers' professional activities. Using the above methods, a detailed description was prepared of the motivation and personal qualities that characterize the sample of drivers, the correlation was analysed between the selected characteristics and the rate of accidents in the drivers' operations [20].

Among the works dedicated to the evaluation of human activity in railway transportation, [21] deserves a special attention. Its authors rely on the methods of expert assessment used for determining the significance coefficients of indicators, evaluates the risks of potential – caused by the human factor – disruptions in the business processes of railway stations. The work revealed that the primary cause (50-75% of the total number of causes) of incidents in railway transportation is the technical staff errors.

JSC RZD has already rated its train drivers [22]. The algorithm was based on collecting and analysing experts' opinions. The experts selected the features and rated their significance. A classical linear combination of a feature vector and weight vector was used that was normalized by the number of trips made by a driver during a month. The method's significant limitation consists in the subjectivity of experts' opinions that may cause a bias or a strong spread of the estimates of the quality of the driver's work.

This paper's findings can be integrated into the intelligent system for centralized traffic management of rapid transit under heavy traffic [23].

2. The methods

The DSS for preventing safety violations by train drivers includes the following units (Fig. 1):

1. The object of control, a driver or group of drivers that share the same depot or railway line. The unit receives inputs in the form of control actions $[E_1, E_2, \ldots, E_n]$ and outputs a set of reactions by the object of control, $[O_1, O_2, \ldots, O_n]$.

2. The information collection module that records (measures) information on the drivers and saves it to the database. Importantly, the information is recorded in various ACSs of JSC RZD. The module outputs set D.

3. The database, a single physical storage of big data collected from various ASCs of JSC RZD using the Automated System Trusted Environment of the Locomotive Service [24]. This storage contains raw information on the drivers and the calculation data on their performance. The unit outputs the vector of indicators $[F_1, F_2, \ldots, F_n]$.

4. The violation prediction module calculates the probability of violations by drivers based on their performance indicators. The unit outputs probability vector $[P_1, P_2, \ldots, P_n]$ that stores information on the probability of a major violation and probabilities of specific violations.

5. The driver operations analysis module aggregates driver ratings [25], number and types of committed violations, driver risk groups, driver's medical indicators in past trips. In addition to the above, the following information is supplied to the module's input:

– C_v, the classifier of recorded violations and emergencies identified as the result of decoding of speed tapes and other media;

– C_s, the safety requirements approved by JSC RZD;

– $[F_1, F_2, \ldots, F_n]$, the vector of driver's features and characteristics.

The module outputs values $[R_1, R_2, \ldots, R_n]$ of a driver's reliability group membership and the criteria of the list of preventive measures recommended for improving driver reliability.

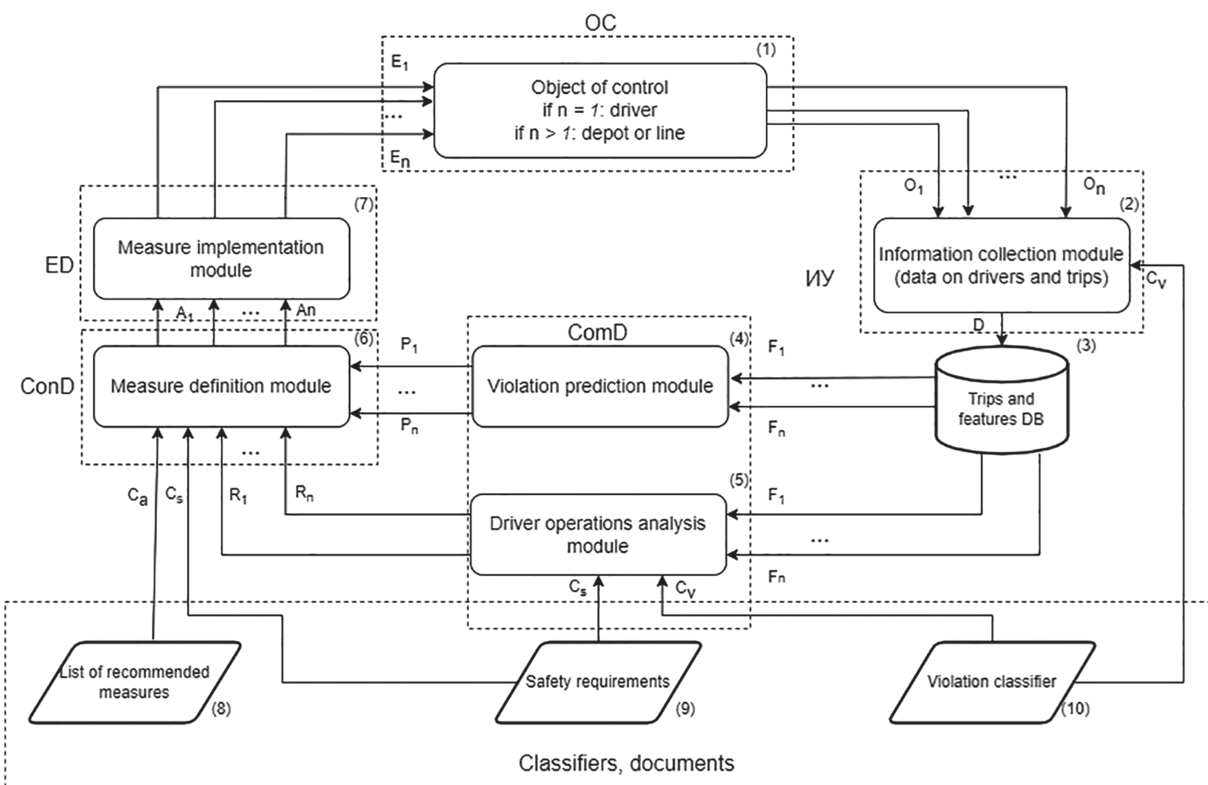


Fig. 1. Structure diagram of the DSS for preventing safety violations by train drivers (OC, the object of control); MD, measuring device; ComD, comparing device; ConD, control device; ED, executive device

Table 1. Outputs of a binary classification model for a 30-day prediction horizon

No.	Algorithm	Metric	Method of categorial feature transformation				
			Label encode + Scale	One hot encode + Scale	Principal components method	Frequency-domain representation + scale	Autoencoder
1	Logistic regression	Accuracy	0.7535	0.7767	0.7535	0.7682	0.7511
		F-measure	0.0854	0.1090	0.0854	0.1140	0.1865
		AUC_ROC	0.7239	0.6930	0.7239	0.4078	0.4242
2	Random forests	Accuracy	0.8043	0.6961	0.6294	0.9829	0.6811
		F-measure	0.1235	0.2246	0.2461	0.2048	0.2342
		AUC_ROC	0.7495	0.6100	0.6367	0.8177	0.6379
3	Gradient boosting over decision trees	Accuracy	0.7732	0.7637	0.6396	0.9712	0.9023
		F-measure	0.1860	0.3620	0.4242	0.7248	0.5574
		AUC_ROC	0.6920	0.7532	0.7658	0.9885	0.7322
4	Neural networks	Accuracy	0.5331	0.6740	0.5913	0.6142	0.9083
		F-measure	0.1432	0.3215	0.2832	0.2776	0.2223
		AUC_ROC	0.7421	0.6860	0.7192	0.6743	0.8822

6. The measure planning module defines the list of preventive measures recommended for improving the reliability of a particular driver, depot, railway. In addition to the above information, the module receives the list of preventive measures C_a that can be recommended for improving a driver's reliability.

The module outputs a list of measures and actions $[A_1, A_2, \ldots, A_n]$ aimed at improving traffic safety.

7. The measure implementation module creates a set $[E_1, E_2, \ldots, E_n]$ of control actions that affect the object of control.

Based on the generated structure diagram of the DSS for preventing safety violations by train drivers (see Fig. 1), let us define the problems whose solution is examined in this paper:

a) identification of the set of indicators of a driver's operation used in the DSS;

b) development of the algorithm for predicting violations in the drivers' operations for the purpose of defining reliability groups within the DSS;

c) development of the algorithm for defining the list of preventive measures recommended for improving driver reliability based on the analysis of the outputs of the algorithms for predicting violations in the driver's operations;

d) implementation of DSS for preventing safety violations in drivers' operations as part of JSC RZD's automated information management system.

3. Identified set of driver performance indicators used in the DSS for preventing safety violations in drivers' operations

The study analysed 90 indicators that characterize a driver's operations obtained from seven ACSs of JSC RZD. All indicators can be classified into the following groups: fuel and energy consumption; disciplinary (associated with past safety violations); medical; operational discipline; interaction with the assistant; level of knowledge; interaction with train driving instructor; basic information (e.g., service record, class, etc.). In total, data for over 4.2 million trips between 01.01.2020 and 01.08.2020 were analysed.

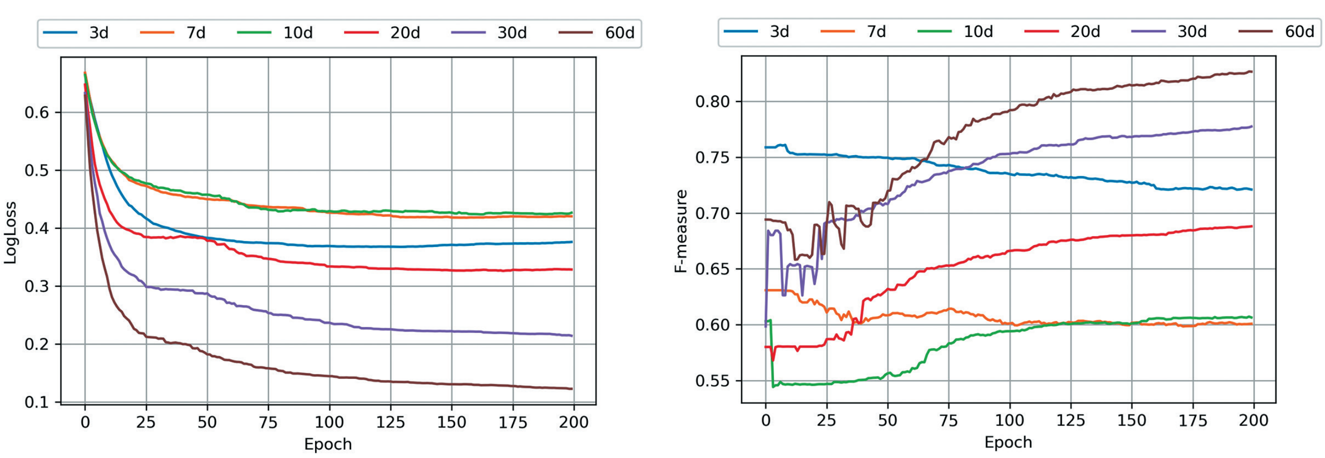
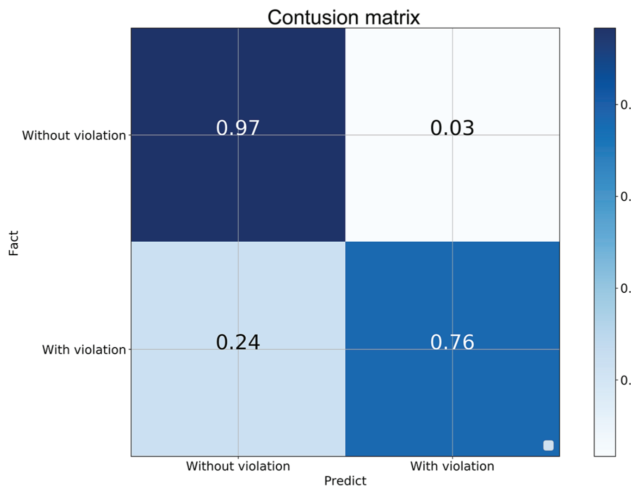
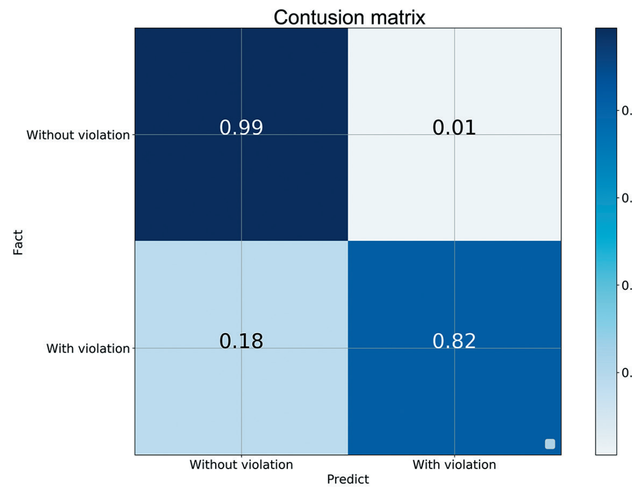


Fig. 2. The outputs of gradient boosting over decision trees with frequency-domain representation of categorical features under various prediction horizons



a)



b)

Fig. 3. Error matrix for prediction horizons: a) 30 days; b) 60 days

4. Development of the algorithm for predicting violations in the drivers' operations for the purpose of defining reliability groups within the DSS for preventing safety violations in drivers' operations

The algorithm for predicting violations in the drivers' operations is intended for binary classification as part of prediction of imminent violations by a driver. The test sample consisted of about 850 ths driver trips.

Major violations with proven guilt of the driver that may be committed within the following 3, 7, 10, 20, 30, 60 days were chosen as attributes for the purpose of safety violation prediction. The driver sample is unbalanced. This problem and its possible solutions are covered in [26].

Solving the problem of binary classification involves using only such method of assessing the model performance that reflects the objective reality. In the context of the problem at hand, accuracy, harmonic mean (F-measure) and area under the receiver operating characteristics curve (AUCROC) should be used. Table 1 shows the prediction outputs using various machine learning algorithms and representation of categorical attributes [27]. Fig. 2 shows the outputs of gradient boosting over decision trees with frequency-domain representation of categorical features under various prediction horizons.

The results of binary classifier training show (Fig. 3) that identifying the probability of a violation within the following few days is not a trivial and easy task. The results are given for two prediction horizons, i.e., 30 and 60 days. It turned out that the algorithm made a correct prediction: in 76% of cases with the threshold value of 0.7 and horizon of 30 days; in 82% of cases with the threshold value of 0.9 and horizon of 60 days. The solution of the problem can be found in the integration of different approaches to predicting safety violations in a train driver's operation. Gradient boosting over decision trees with frequency-domain representation of categorical features showed the best data processing results.

Additionally, 10 of the most significant indicators of a train driver's operation were identified with the best of the considered models, i.e., gradient boosting over decision trees with frequency-domain representation of categorical features (Fig. 4).

5. Development of the algorithm for defining the list of preventive measures recommended for improving driver reliability based on the analysis of the outputs of the algorithms for predicting violations in the driver's operations

A method is proposed of defining driver reliability groups based on quantiles of the distribution of estimates of the likelihood of violations and identification of imminent reliability. The following quantiles were taken as delimiters of reliability groups defined based on the probability values of the absence of traffic safety violations by the driver: 0.2, 0.1, 0.01. These values were selected by the authors experi-

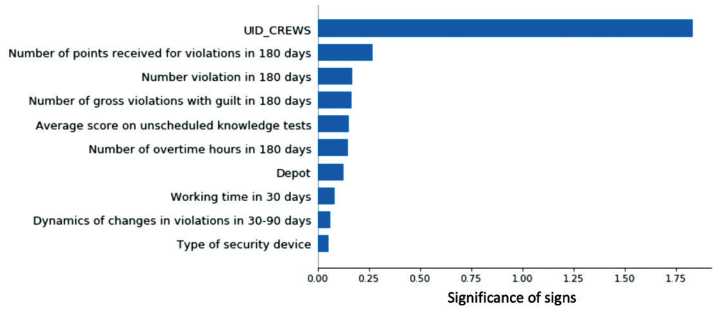


Fig. 4. Significance values of categorical features for the algorithm of gradient boosting over decision trees with frequency-domain representation of categorical features

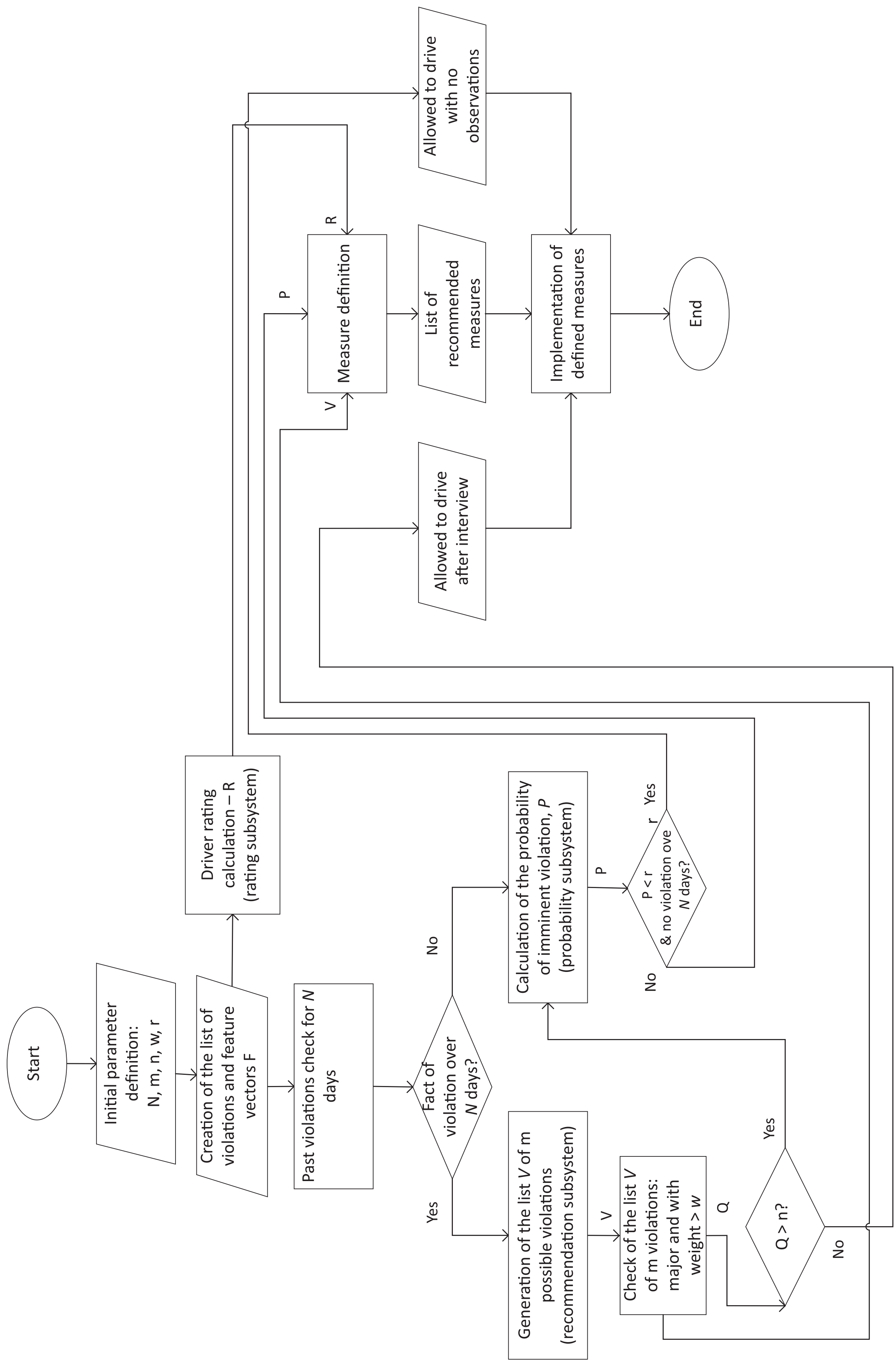


Fig. 5. Structure diagram of the decision rule for the list of recommended preventive measures

mentally and may change as the size of the examined data grows or the model is modified.

Based on the obtained quantiles, four driver reliability groups were identified:

a) high level of reliability (0.96; 1];

b) acceptable level of reliability (0.73; 0.96];

c) unacceptable level of reliability (0.39; 0.73];

d) critical level of reliability (0; 0.39];

Besides the algorithm for predicting violations themselves, an algorithm was developed that allows predicting the type of the safety violation. This algorithm is covered in sufficient detail in [28]. The approaches used for predicting the type of violation belong to the domain of advisory systems and are built on neural networks.

6. Implementation of DSS for preventing safety violations in drivers' operations as part of JSC RZD's automated information management system

Let us examine the approach to defining the list of recommended preventive measures that is based on the analysis of a driver's membership in a reliability group, probability of a major violation, past and predicted violations.

The operation of the algorithm (Fig. 5) is initiated by a user of the information system who requests the assignment of a driver to a trip. The depth of past violations check (number of days) *N* is a parameter specified by the management of the relevant Central Directorate of JSC RZD. The recommended default setting in the system is *N*=20, which is the average monthly number of a driver's trips. If no violations were identified in *N* days, the probability of imminent violation is calculated (Block 7). The vector of the driver's features and characteristics is used as the input information for this block *F*. Its output is the calculation of the probability of an imminent major violation *P*. Then, after calculating *P*, it is compared with the permissible threshold *r* that is to be specified by the management of the relevant Central Directorate of JSC RZD. If *P* did not exceed threshold *r*, the driver is allowed to drive.

If violations have been identified within *N* days, the advisory subsystem or model (Block 8) is initiated and makes a list of violations that the same driver is likely to commit in the future. The input information for this block is vector *F* and the prediction horizon *m* (configurable parameter). The output is an *m*-long list of predicted violations *V* sorted by significance. The list of violations *V* is then used as the input for Block 9 where the number *Q* of major violations or violations whose weight is above the specified threshold coefficient *w* is calculated. If $Q>n$, the imminent violation probability algorithm is initiated. If $Q<n$, the driver is allowed to drive after an interview with the manager. The input for Block 12 is the list of violations *V*, probability *P* and the driver's current rating *R*. Based on values *V* and *R*, the set of recommended measures is defined. *P* can be interpreted as a value that completes the driver's level of reliability with respect to one.

The recommendations and actions for the driver are based on the information on the predicted and past violations. Each violation is characterized by two groups of factors, i.e., the general characteristic (major or minor violation, with breach of regulations, with possible violation of safety, with violation of safety) and the human factor (insufficient knowledge, lack of experience, carelessness, distraction, haste, negligence).

The measures pertaining to the driver are divided into two classes: "short-term", i.e., before the trip; "long-term", i.e., after the trip.

The algorithm for defining the measures consists of the following steps:

1. For all the violations committed by driver *K* in the last *N* days, the accumulated significance levels of the above factors multiplied by the weights (2) are summarized:

$$F_v = \sum_{i=1}^{K} w_i \cdot f_i, \quad (2)$$

where w_i is the weight of the *i*-th violation, f_i is the vector of the factors of the *i*-th violation, F_v is the sum vector of the levels of effect (vector of ranks).

2. The cooccurrence matrix of factors *f* and events *E* is multiplied with the vector of the levels of effect (vector of ranks) F_v.

3. All measures are sorted in nondecreasing order of importance. Each measure is ranked.

The importance of a measure is determined by its rank. The higher the rank, the more important is the measure for the driver.

Conclusion

The paper presents an overview of methods and systems of assessing human dependability and the effect of the human factor on the safety of transportation systems. It allowed choosing the most promising directions and methods of predictive analysis of a train driver's operation, including methods of machine learning.

As part of the structure of the DSS for preventing safety violations by train drivers, machine learning models were constructed and implemented that allow identifying a driver's level of reliability, probability of future violations, as well as defining preventive measures recommended for improving a driver's operational reliability.

A set of indicators defining a train driver's operations that are used for determining the effect of the driver's reliability on the traffic safety were identified by creating and applying a method for estimating drivers' performance that takes into account the past dynamics of a driver's quality of operation, which allowed collecting input data for the construction of mathematical models for the DSS for preventing safety violations by train drivers.

An analysis was carried out of the outputs of machine learning algorithms on a test sample that revealed that a model based on gradient boosting over decision trees with frequency-domain representation of categorical features shows the best results for binary classification on the prediction horizon of 30 and 60 days. The models enabled the aggregation of information on train drivers and adoption of targeted and temporary preventive measures recommended for improving driver dependability.

The resulting approach to the definition of preventive measures has been implemented in three depots of JSC RZD in trial operation mode.

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The authors’ contribution

Kulagin M.A. Defined the set of indicators of a train driver’s operations, developed algorithms for predicting operational disturbances and defining preventive measures recommended for improving the train driver’s dependability, analysed the results.

Sidorenko V.G. Analysed the ways in which the human factor affects automated control systems, reviewed methods of human dependability analysis.

Conflict of interests

The authors declare the absence of a conflict of interests.

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A method of testing relay protection and automation involving exposure to cascading effects for improved power supply reliability and electric power system stability

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Abstract. *The* **Aim** *of the paper is to show that improved power supply reliability and electric power system stability are achieved by applying new methods of testing relay protection and automation (RPaA). Major cascading failures in electric power systems are caused by cascading effects, i.e., effects involving several successive effects of various nature. Cascading effects allow extending the functionality while testing RP&A and taking into account the time factor in the context of effects of various nature.* **Method.** *A method is proposed for testing relay protection and automation taking into account the cascading effect that is used in the process of development, calibration and installation of protection devices for operation in predefined modes for the purpose of improved power supply reliability and unfailing stability of electric power systems.* **Result.** *Intermittent cascading effects do not allow the relay protection and automation recover the electric power system from the post-emergency mode, thus reducing the dynamic stability to the critical level. The diagram of relay protection and automation exposure allows taking into consideration the environmental effects in the process of testing the relay protection and automation.* **Conclusion.** *The proposed method of cascading exposure as part of testing relay protection and automation can be used in the process of development, calibration and installation of electric power systems protection and will enable improved stability of electric power systems and reliability of power supply.*

Keywords: *relay protection and automation, cascading effect, electric power system, stability, dependability, normal mode, emergency mode, post-emergency mode, emergency mode with loss of stability.*

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Introduction

Protection and emergency control systems enable sufficiently quick localisation of damaged areas and their removal from operation, while maintaining (with minimal losses) system operability. At the same time, there are major system (cascading) failures that cause the interruption of large numbers of consumers, disruption of parallel operation of power plants and electric power systems.

The major electric power emergency of August 14, 2003 in the US was caused by the power system structure having overgrown the control system capabilities. In the major cascading failure of May 25, 2005 in Moscow, Russia, the cause was the absence of several classes of safety protection and insufficient consideration of the nature of system (cascading) failures [1, 2].

The scope, societal and economic consequences of such accidents depend on the consideration of their nature in the course of the design, development and testing of the methods and means of electric power system protection.

An electric power system is the part of an electric system, in which heat and various types of energy are transformed into electric energy that is transmitted, distributed to consumers, where it is transformed again [3].

Power supply reliability is the ability of an electric power system to supply connected consumers with electric energy of a given quality over any time interval [4].

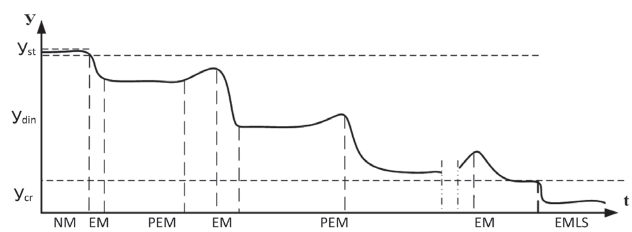
The stability of an electric power system is understood as the system's ability to recover the original mode of operation after its disruption Y_{st}, Y_{din} [3, 5, 6].

Relay protection and automation include the relay protection, grid automation, emergency automation, operation mode automation, emergency event and process recorders, process automation of electric power facilities [7].

We will consider RP&A as a single system that is a set of interconnected subsystems of relay protection, automation and emergency event and processes recorders that operate jointly or separately for the purpose of maintaining – at all levels – the equipment operability and protection, control and monitoring of operating modes with the purpose of reliable power supply and unfailing stability of an electric power system (Fig. 1).

Each exposure of the electric power system causes stability degradation (Fig. 2). The role of relay protection and automation in this case comes down to restoring the normal mode of system operation associated with improving the stability.

Repeated exposure causes a gradual decrease in the stability of the electric power system to what can be called the critical level Y_{cr}, while the electric power system itself goes into the emergency mode with loss of stability (EMLS), in



NM, normal mode; EM, emergency mode; PEM, post-emergency mode; EMLS, emergency mode with loss of stability

Fig. 2. Graph of decreasing electric power system stability under multiple effects

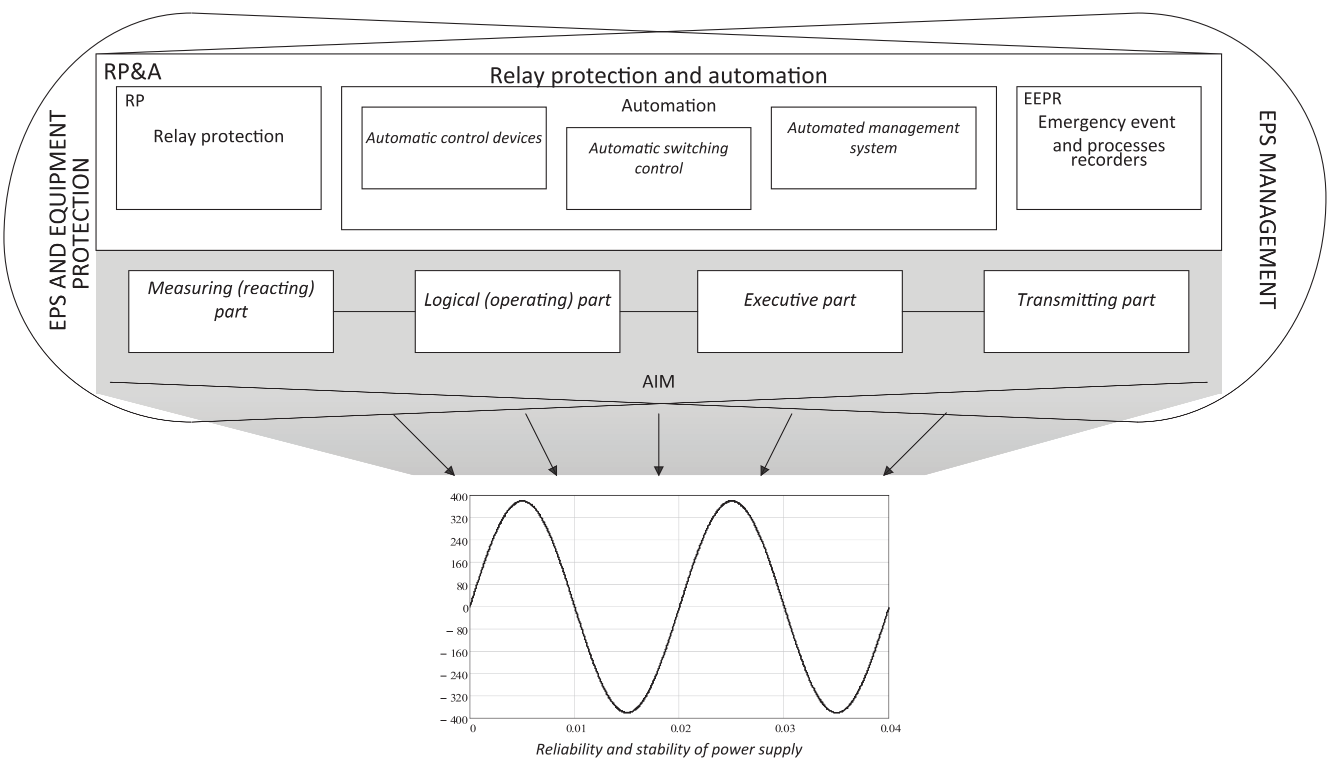


Fig. 1. Relay protection and automation: composition; objectives

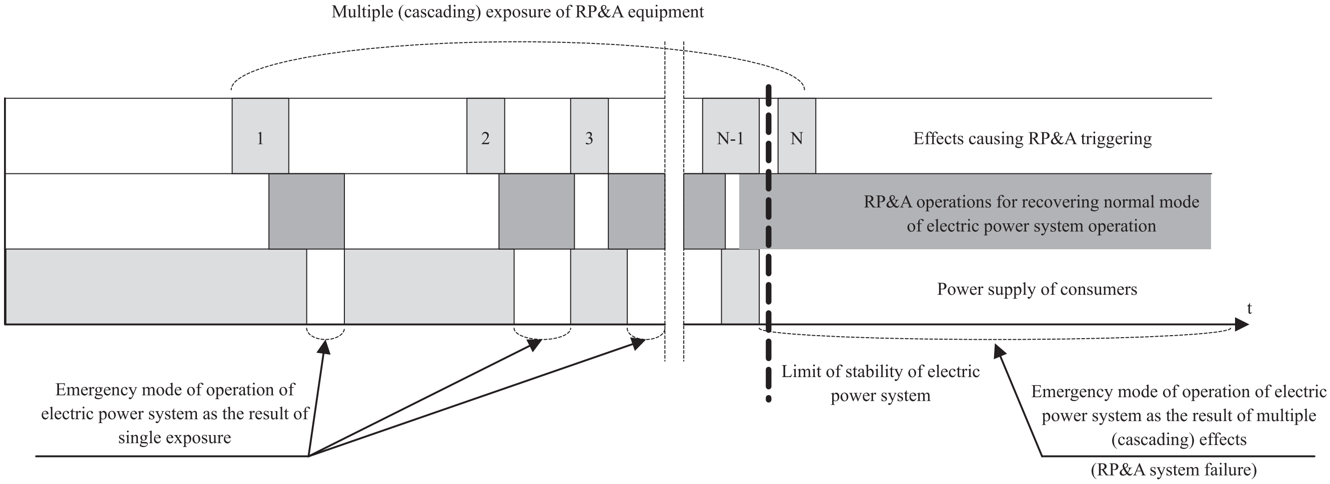


Fig. 3. Performance diagram of relay protection and automation when supplying power to consumers when exposed to effects that trigger its action

which the relay protection and automation are unable to restore its normal operation.

The effects of this repeated exposure are multiple and varied in their nature. Such multiple exposures are a cascading effect, i.e., an effect involving several successive effects of varied nature.

Since the operational state is a state of an item, in which it is able to perform (or is performing) the specified functions, while maintaining the values of the specified parameters within the limits set in the technical documentation [4], with the onset of EMLS, an electric power system is incapable of performing its primary function of transmitting electric power to the consumer. Therefore, an EMLS is a system failure. The failure will be primarily associated with the operation of relay protection and automation as a single system specifically, i.e., a set of interconnected subsystems of relay protection, automation and recorders of emergency events and processes (Fig. 3).

There is a significant number of both means, and methods of constructing and verifying RP&A [8, 9]. However, they are functionally limited to their respective scopes of application and do not imply repeated system exposure in cases of cascading failures.

Improving the power supply reliability and the stability of electric power systems is achieved by extending the RP&A testing functionality at the stages of development, calibration and installation of the protection devices.

1. Exposure of relay protection and automation

The diagram of relay protection and automation exposure (Fig. 4) includes direct environmental effects on relay protection and automation, environmental effects through electric equipment of electric power systems and effects of electric equipment.

The direct environmental effects on relay protection and automation may include cyber attacks against computer-based equipment and electronics of terminals; intentional failure to follow the dispatcher's commands by operating personnel, physical damage of relay protection and automation equipment.

The environmental effect through the electric equipment of an electric power system on relay protection and automation includes deliberate actions, i.e., terrorist attacks against electric power system facilities; use of specialized weapons in the form of graphite munitions in the course of armed conflicts; property abuse associated with theft of metal structures of high-voltage power transmission lines and substation equipment, repeated shooting of power line insulator strings and accidental effects, i.e., natural weather events (wire breaking and short-circuiting due to high wind, falling trees and structures, short circuits due to lightning strike, failure of power transmission line supports due to earthquakes, floods, fires, landslides, etc.); non-observance of overhead clearances of construction and other heavy

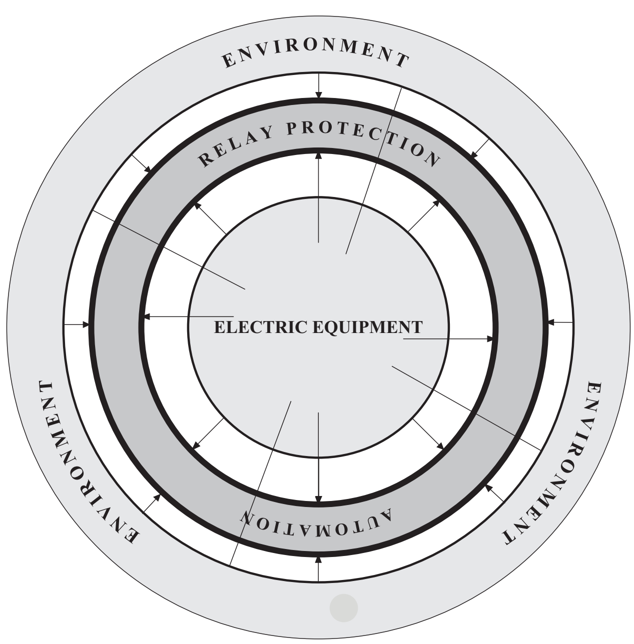


Fig. 4. Diagram of relay protection and automation exposure

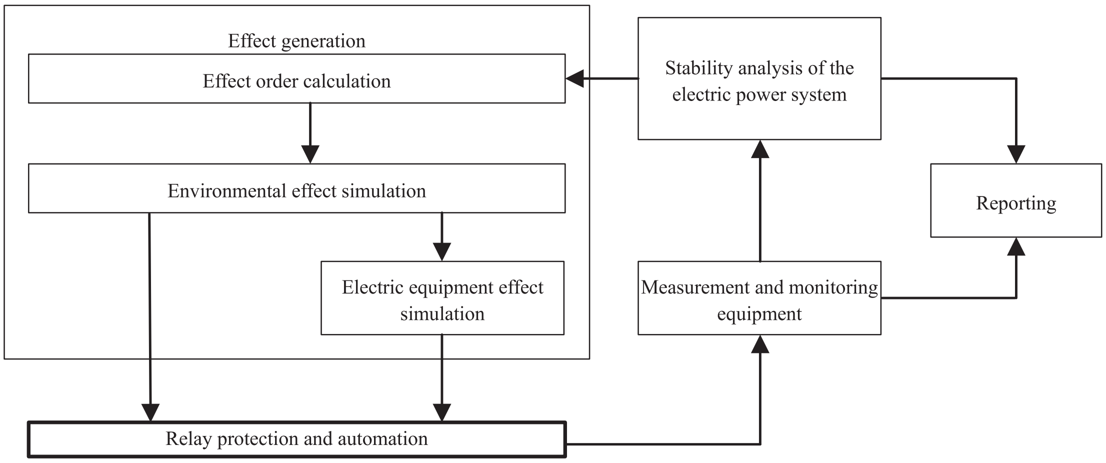


Fig. 5. Testing of relay protection and automation under cascading effects

machinery passing under the overhead power transmission line; light aircraft, unmanned aerial vehicles and balloons falling onto overhead power transmission lines and outdoor switchgear; errors by operating and dispatch office personnel in the course of maintenance, operation and switching at electric power facilities.

The effects caused by the electric equipment of an electric power system that trigger relay protection and automation include equipment failures due to operational deficiencies, repair defects, manufacturing defects, end of life (wear), transmission congestions (power consumption exceeds design limits).

2. Testing of relay protection and automation under cascading effects

In the course of development, calibration and installation of protection devices for operation in predefined modes, the relay protection and automation exposed to cascading effects are tested subject to the changes in the stability of the electric power system and the environmental effects [10].

The testing consists of a set of actions that implement individual functions in a predefined order (Fig. 5).

The electric power system operates in normal mode (NM) until the first exposure. Its static stability Y_{st} is ensured (Fig. 6).

In the block of effect order calculation, the command to initiate exposure is generated. In the block of environmental effect simulation, the first command is generated to select the exposure of relay protection and automation through electric equipment.

Then, in the block of electric equipment effect simulation, a command is generated to simulate the effect on the block of relay protection and automation caused by the electric equipment. The operation of an electric power system in emergency mode (EM) is simulated.

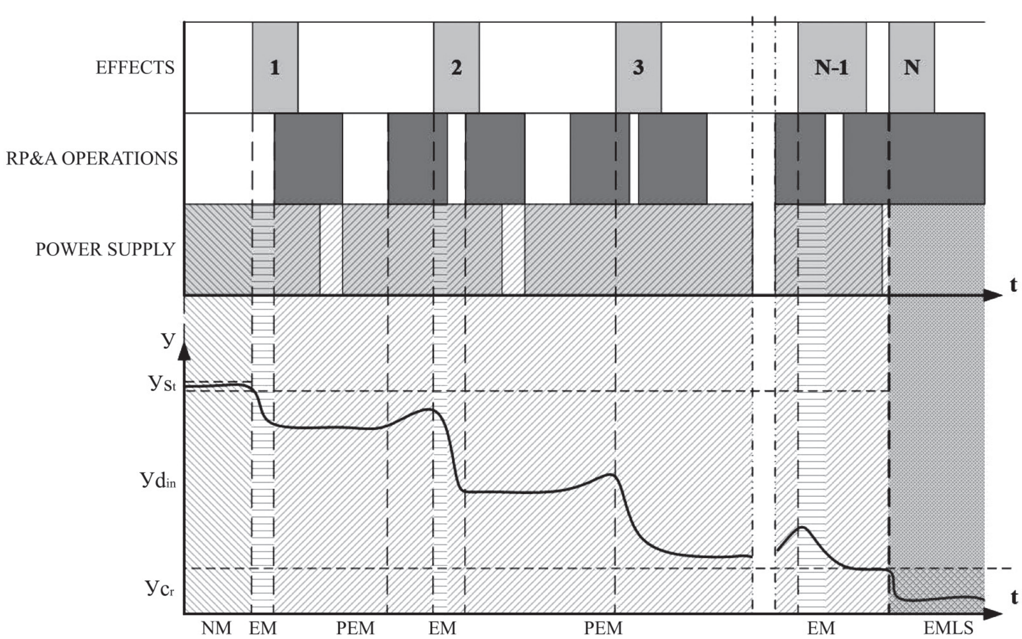


Fig. 6. Combined graph of the decreased level of electric power system stability under cascading effects and diagram of relay protection and automation testing when supplying power to consumers when exposed to cascading effects

In the block of relay protection and automation, the protection algorithm corresponding to the nature of the effect operates. Operating in accordance with its functional purpose, relay protection and automation eliminate the emergency mode (EM) and initiate a sequence of actions aimed at restoring the normal mode (NM) in the electric power system and improving the stability. At that moment, the electric power system is in the post-emergency mode (PEM). Information on the condition of the relay protection and automation components, as well as that reflecting the state of the electric power system – based on the evaluation of the output parameters of relay protection and automation – enters the block of measurement and monitoring equipment.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

The electric power system operates in the PEM. Its dynamic stability Y_{din} is ensured.

Next, in the block of effect sequence calculation, a command is generated to initiate the second exposure, taking into account the time, within which the relay protection and automation are unable to complete the sequence of actions to restore the NM of the electric power system. In the block of environmental effect simulation, a second command is generated to select the exposure of relay protection and automation through the electric equipment and, in the block of electric equipment effect simulation, a command is generated to simulate an exposure of the block of relay protection and automation through the electric equipment.

The operation of an electric power system in emergency mode (EM) is simulated.

In the block of relay protection and automation, the protection algorithm corresponding to the nature of the effect operates. Relay protection and automation eliminate the EM and initiate a sequence of actions aimed at restoring the NM in the electric power system and improving the stability. At that moment, the electric power system is in the post-emergency mode (PEM). Information on the condition of the relay protection and automation components, as well as that reflecting the state of the electric power system – based on the evaluation of the output parameters of relay protection and automation – enters the block of measurement and monitoring equipment.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

The electric power system continues operating in the PEM. Its dynamic stability Y_{din} is ensured.

In the block of effect sequence calculation, a command is generated to initiate the next exposure, taking into account the time, within which the relay protection and automation are unable to complete the sequence of actions to restore the NM of the electric power system. In the block of environmental effect simulation, the next command is generated to select the environmental exposure of relay protection and automation, as well as a command to simulate an environmental exposure of relay protection and automation.

A fault of the relay protection and automation is simulated that is caused by environmental effects. The mode restoration fails and the stability of the electric power system drops. The latter remains in the PEM.

In the block of stability analysis of the electric power system, the incoming information is processed and – on its basis – the changes in the stability of the electric power system are evaluated.

In the reporting block, a report is generated on the current state of the relay protection and automation and on the stability assessment of the electric power system.

In the block of measurement and monitoring equipment, RP&A parameters are measured, the completeness of the requirements for the number and sequence of exposures is evaluated, the achieved and specified parameters are compared for the purpose of decision-making regarding further exposures.

In the block of exposure priority calculation, the exposure sequence is defined based on the set of temporal conditions:

$$\begin{cases} t_{\text{EI}}^{1} > 0, \\ t_{\text{PI}}^{1} < t_{\text{ET}}^{1} < t_{\text{STLPS}}^{1}, \\ t_{\text{PI}}^{2} < t_{\text{EI}}^{2} < t_{\text{PT}}^{2}, \\ t_{\text{PI}}^{3} < t_{\text{ET}}^{2} < t_{\text{STLPS}}^{2}, \\ t_{\text{PI}}^{3} < t_{\text{EI}}^{3} < t_{\text{ET}}^{3}, \\ t_{\text{PI}}^{4} < t_{\text{ET}}^{3} < t_{\text{PT}}^{3}, \\ \ldots, \\ t_{\text{PI}}^{N-1} < t_{\text{ET}}^{N-1} < t_{\text{STLPS}}^{N-1}, \\ t_{\text{PI}}^{N} < t_{\text{ET}}^{N-1}, \\ t_{\text{IEMLS}} \le t_{\text{EI}}^{N}. \end{cases} \tag{1}$$

where $t_{\text{EI}}^{1}, t_{\text{EI}}^{2}, \ldots, t_{\text{EI}}^{N}$ is the time of effect initiation, $t_{\text{ET}}^{1}, t_{\text{ET}}^{2}, \ldots, t_{\text{ET}}^{N}$ is the time of effect termination, $t_{\text{PI}}^{1}, t_{\text{PI}}^{2}, \ldots, t_{\text{PI}}^{N}$ is the time of protection initiation (relay protection and automation), $t_{\text{PT}}^{1}, t_{\text{PT}}^{2}, \ldots, t_{\text{PT}}^{N}$ is the time of protection termination (relay protection and automation), $t_{\text{STLPS}}^{1}, t_{\text{STLPS}}^{2}, \ldots, t_{\text{STLPS}}^{N}$ is the start time of the short-term loss of power supply after the effect and triggering of protection (relay protection and automation), t_{IEMLS} is the time of initiation of emergency mode with loss of stability.

The content of the blocks is any sequence of actions or any method associated with the functional content of the respective block.

Conclusion

As mentioned above, repeated exposure causes a gradual decrease in the stability of the electric power system, which eventually leads to a situation whereas, after the N-th exposure, the stability falls to a critical level Y_{cr}, while the electric power system itself goes into EMLS, in which the relay protection and automation are unable to recover normal operation.

Thus, intermittent exposure to a cascading effect that prevents the relay protection and automation from recovering an electric power system from post-emergency mode, allows reducing the dynamic stability to a critical level, while the use of the diagram of exposure of relay protection and automation allows taking into account the external effects as part of relay protection and automation testing. Additionally, cascading exposure as part of testing of relay protection and automation is an important part of the development, calibration and installation of electric power systems protection that will enable improved stability of electric power systems and reliability of power supply.

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The authors' contribution

Koniukhov A.M. analysed the changes in the stability of an electric power system and its effect on the power supply reliability when relay protection and automation are exposed to adverse effects, as well as the combination of processes under cascading effects, operation of relay protection equipment and automation when supplying power to consumers during triggering effects and changes in the level of stability of an electric power system.

Khlebnov A.V. analysed major cascading failures in electric power systems, analysed and structured the effects on relay protection; drawn up the diagram of exposure of relay protection and automation.

Timanov V.A. constructed the sequence of testing relay protection and automation exposed to cascading effects taking into account the changes in the stability of the electric power system and the external effects on the relay protection and automation; drew up the block diagram of testing relay protection and automation exposed to cascading effects.

Conflict of interests

The authors declare the absence of a conflict of interests.

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Evaluation of the effect of JSC RZD transportation infrastructure availability on the risks of losses in the process of transportation

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Abstract. Aim. *The availability of transportation infrastructure facilities affects the quality of the transportation services provided by JSC RZD. At the same time, this effect may significantly differ depending on the operating conditions of the transportation infrastructure or a specific railway line and can cause various degrees of risk of damage to the transportation process. Such risks are defined as risks of train-hour losses due to transportation infrastructure failures. Planning dependability management activities under conditions of scarce resources requires targeted identification of the transportation infrastructure facilities whose availability most significantly affects the magnitude of the risks of damage to the transportation process. The aim of the paper is to develop a method for evaluating daily availability and identifying its correlation with the risk of train-hour losses.* **Methods.** *The authors used the methods of risk management, probability theory and mathematical statistics, correlation and regression analysis.* **Results.** *The paper suggests representing the daily availability indicator of JSC RZD's transportation infrastructure facilities as a two-parameter gamma distribution and describing its effect on the risks of the transportation process with a regression model.* **Conclusions.** *The paper's findings can be used as part of transportation infrastructure dependability planning and targeted allocation of resources, as well as for substantiating the dependability indicator when evaluating the practical capacity of railway lines and utilization ratio and in a number of other operational tasks.*

Key words: *risk of train-hour losses, capacity, dependability of transportation infrastructure facilities, daily equipment availability, interval estimate.*

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Introduction

The transportation process performed by Russia's railways involves technical operation of a territorially distributed transportation infrastructure that represents a set of facilities assigned to various services [1].

The operational dependability of transportation infrastructure facilities (TIF) significantly affects the quality of transportation operations. Inoperable TIF cause a risk of damage in the form of delayed train departures, passing or arrivals.

The concept of risk allows taking into account both the probabilistic nature of TIF failures, and the magnitude of the resulting damage to the transportation process. In this context, as regards technical operation of infrastructure, JSC RZD has adopted the concept of risk management [1, 2]. Risk is regarded as a combination of the probability (rate) of risk events, i.e., failures, and the magnitude of damage caused by an event, i.e., loss of train-hours. Loss of train-hours is understood as train delays caused by an individual TIF failure. In this case, the failures themselves, depending on the magnitude of the associated damage to the transportation process, are conventionally classified into three categories. Category 1 and 2 failures include those that cause significant train-hours losses, while category 3 includes those that cause insignificant or no loss.

Based on the information regarding category 1 and 2 failures, TIF functional dependability indicators are calculated that characterise the process of implementation, by means of TIF, of various functions that ensure the transportation process (service delivery).

Functional dependability is used for estimating certain indicators of the transportation process, e.g., practical capacity of railway lines, as well as for assessing the risks of train-hour losses due to TIF failures. The functional dependability calculations are often based on averaged values for long time intervals, e.g., annual. It is worth noting that practical capacity is calculated for daily time intervals. Given that category 1 and 2 failures are fairly rare, the associated time budget losses in the context of practical capacity calculation, as well as train-hour losses, fall within specific days, whereas within the remaining time no losses are observed. Accordingly, the functional dependability indicators should be regarded as random values on the same time intervals, i.e., daily.

As input information for estimation, statistical data on the moments of identification of category 1 and 2 failures, their duration and associated train-hour losses for each TIF can be used. As the result of the industry's digital transformation, they are now available in the company's information systems, including KASANT, AS-ANSh, ASU Sh-2, EK ASUI, etc.

As a functional dependability indicator, let us consider the TIF availability coefficient in terms of category 1 and 2 failures that, for a number of years, has been used in JSC RZD's infrastructure units. This coefficient is understood as the probability of TIF being in a state that does not cause a significant delay (more than 6 minutes) in the train traffic at a random moment in time.

Estimation of the availability coefficient of transportation infrastructure facilities in terms of category 1 and 2 failures

Individual realisations of K_{a12}, the TIF availability coefficient in terms category 1 and 2 failures over daily intervals, can be identified using formula:

$$K_{\text{a12}} = \frac{T_{\text{day}} - T_{\text{t12}}}{T_{\text{day}}},$$

where T_{day} is the daily time budget (taking into account maintenance possessions);

T_{t12} is the total down time of TIF caused by a category 1 or 2 failure within the daily time budget.

Statistical estimation of K_{a12} should be done parametrically [3, 4] using the moment method and subsequent approximation with a two-parameter gamma distribution [5].

In order to do that, all realisations of TIF's K_{a12} within the daily intervals where category 1 and 2 failures were recorded over the monitoring period are submitted to statistical processing.

The first statistical moment m_t is found using the formula:

$$m_t = \frac{\sum_{j=1}^{r}\left(1 - K_{\text{a12}j}\right)}{r},$$

where r is the number of realizations of K_{a12} within the observation period.

The second statistical moment σ_t is determined from formula:

$$\sigma_t = \sqrt{\frac{\sum_{j=1}^{r}\left[\left(1 - K_{\text{a12}j}\right) - m_t\right]^2}{r-1}}.$$

The probability density for a random value is described using formula:

$$f(\beta) = \begin{cases} \dfrac{\beta^{k-1} \cdot e^{-\frac{\beta}{\theta}}}{\theta^k \cdot \Gamma(k)}, & \beta \geq 0; \\ 0, & \beta < 0, \end{cases}$$

where

$$\Gamma(k) = \frac{1}{k} \cdot \prod_{n=1}^{g} \frac{\left(1 + \frac{1}{n}\right)^k}{1 + \frac{k}{n}},$$

while k and θ are the shape and scale parameters.

In turn, the shape and scale parameters are found using formulas:

– shape parameter k:

$$k = \frac{m_t^2}{D_t};$$

– scale parameter θ:

$$\theta = \frac{D_t}{m_t},$$

where D_t is the sampling variance defined as: $D_t = \sigma_t^2$.

Next, an interval estimation of random value K_{a12} can be performed for daily intervals.

The confidence interval is defined in the form of a single-ended estimate using expression:

$$P\left(K_{a12\partial} \le K_{a12} \le 1\right) = 1 - \int_0^{1-K_{a12\partial}} f\left(K_{a12}\right) dK_{a12}, \quad (1)$$

where $P\left(K_{a12\partial} \le K_{a12} \le 1\right)$ is the confidence probability of K_{a12} being not lower than the predetermined value $K_{a12\partial}$.

Using formula (1), confidence probability $P\left(K_{r12\partial} \le K_{r12} \le 1\right)$ can be found that the true value of K_{a12} is within [1; $K_{a12\partial}$]. The inverse problem can also be solved that consists in determining the boundary value $K_{a12\partial}$ that specifies the range [1; $K_{a12\partial}$], within which its true value is found with the specified confidence probability.

Transportation-related risk of loss estimate and estimation

While TIF remains inoperable, a risk of damage to the transportation process may arise in the form of train delays of varied duration. Moreover, the duration of train delays has a complex dependence not only on the duration of TIF inoperability, but on many other factors as well, i.e., the class and specialization of the line, granted track possessions, train schedule, type of facility, etc.

Risk matrices have proved to be useful in assessing the risk of train-hour losses due to TIF failures in JSC RZD's infrastructure units [6].

An example of a risk matrix is shown in Fig. 1.

In order to evaluate the effect of TIF availability on the risks of train-hour loss, it is required finding, for the calculated value $K_{a12\partial}$, a point in the risk matrix cell at the intersection of the corresponding row on the frequency axis and column on the loss axis [7].

For the purpose of assessing the effect of the K_{a12} TIF availability coefficient in terms of category 1 and 2 failures on the magnitude of losses for the transportation process, the authors extracted from information systems and examined statistical data on K_{a12} realizations and the corresponding train-hour losses T_{12} per failure.

Correlation analysis revealed a persistent statistical relationship between the K_{a12} of the TIF that operate within railway lines of a certain class and specialization and the magnitude of train-hour losses T_{12} per failure. The evaluation was performed using the linear correlation coefficient, while the closeness of the correlation was analysed using the Chaddock scale. A weak to strong negative correlation was identified with the correlation closeness for the TIF of railway lines of various classes and specializations.

In this context, the following linear approximation can be used for estimating the effect of K_{a12} on the damage in the form of train-hour losses:

$$\tilde{T}_{12} = \Theta \cdot K_{a12\partial}$$

where Θ is the proportionality coefficient between K_{a12} and T_{12} that is single for all TIFs within railway lines of individual classes and specializations, but different for different railway lines. For each combination of line class and specialization, it is found using a single formula:

$$\Theta = \frac{\sum_{j=1}^{u} T_{12j}}{\sum_{j=1}^{u} K_{a12j}},$$

where u is the number of K_{a12} realizations on a set of TIFs within a railway line of a single class and specialization over the observation period.

The rate of category 1 and 2 TIF failure rate is estimated using formula:

$$\tilde{f}_{12} = \frac{\sum_{k=1}^{G} f_{12k}}{G}, \quad (2)$$

where G is the number of years in the TIF observation period;

f_{12k} is the number of category 1 and category 2 TIF failures in the k-th year of observation.

		Damage in the form of failure-specific train-hour losses, T_{12}			
		Insignificant	Significant	Major	Critical
Category 1 and 2 failure rates, f_{12}	Frequent	Tolerable	Undesirable	Intolerable	Intolerable
	Probable	Tolerable	Undesirable	Undesirable	Intolerable
	Occasional	Tolerable	Tolerable	Undesirable	Intolerable
	Remote	Negligible	Tolerable	Undesirable	Undesirable
	Improbable	Negligible	Tolerable	Tolerable	Undesirable
	Incredible	Negligible	Negligible	Tolerable	Undesirable

Fig. 1. Risk matrix of train-hour losses

Thus, for the calculated value of K_{a12} of TIF, using formula (1), the target value of damage in the form of train-hour losses is found, while using formula (2), the target category 1 and 2 failure rate is calculated and according to the matrix (see Fig. 1), the cell with the target risk level is found.

Conclusion

The above findings can be used for transportation infrastructure dependability planning and targeted allocation of resources, as well as for substantiating the dependability indicator when evaluating the practical capacity of railway lines, utilization ratio and in a number of other operational tasks.

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The authors' contribution

Gorelick A.V. analysed the current situation, defined the lines of research.

Orlov A.V. collected empirical data and implemented a method of statistical evaluation of the effect of failures on the risk of train-hour losses.

Malykh A.N. processed the empirical data and developed a method for statistical evaluation of the availability coefficient of transportation infrastructure facilities.

Conflict of interests

The authors declare the absence of a conflict of interests.

GNEDENKO FORUM

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The Gnedenko Forum was founded in 2004 by an unofficial international group of experts in the dependability theory for the purpose of professional support of researches from all over the world who are interested in studying and developing the scientific, technical and other aspects of the dependability theory, risk analysis and safety in the theoretical and practical domains.

The Forum exists on the Internet as a non-for-profit organization. It aims to involve into joint discussion and communication technical experts interested in developing the dependability theory, safety and risk analysis regardless of their home country and membership in whichever organization.

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The Forum is named after Boris V. Gnedenko, an outstanding Soviet mathematician, expert in the probability theory and its applications, member of the Ukrainian Academy of Sciences. The Forum is the platform for distribution of information on educational grants, academic and professional positions related to dependability, safety and risk analysis all over the world.

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Structure of the article

The following structural elements must be separated with an *empty line*. Examples of how they must look in the text are shown *in blue*.

1) Title of the article

The title of the article is given in the English language.

Presentation: The title must be in 12-point Times New Roman, with 1.5 line spacing, fully justified, with no indentation on the left. The font face must be bold. The title is not followed by a full stop.

An example:

Improving the dependability of electronic components

2) Author(s)' name.

This structural element for each author includes:

In English: second name and first name as "First name, Second name" (John Johnson).

Presentation: The authors' names must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with no indentation on the left. The font face must be bold. The authors' names are separated with a comma. The line is not followed by a full stop.

An example:

John Johnson[1], Karen Smith[2*]

3) The author(s)' place of employment

The authors' place of employment is given in English. Before the place of employment, the superscripted number of the respective reference to the author's name is written.

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An example:

[1] Moscow State University, Russian Federation, Moscow

[2] Saint Petersburg Institute of Heat Power Engineering, Russian Federation, Saint Petersburg

4) The e-mail address of the author responsible for maintaining correspondence with the editorial office

Presentation: The address must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with no indentation on the left. The font face must be normal, all symbols must be lower-case. Before the address reference, symbol * is written. The title is not followed by a full stop.

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5) Abstract of the article

This structural element includes a structured summary of the article with the minimal size of 350 words and maximum size of 400 words. The abstract is given in the English language. The abstract must include (preferably explicitly) the following sections: Aim; Methods; Results/Findings; Conclusions. The abstract of the article should not include newly introduced terms, abbreviations (unless universally accepted), references to literature.

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An example:

Abstract. Aim.Proposing an approach … taking into consideration the current methods. **Methods.** The paper uses methods of mathematical analysis,…, probability theory. **Results.** The following findings were obtained using the proposed method … **Conclusion**. The approach proposed in the paper allows…

6) Keywords

5 to 7 words associated with the paper's subject matter must be listed. It is advisable that the keywords complimented the abstract and title of the article. The keywords are written in English.

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An example:

Keywords: dependability, functional safety, technical systems, risk management, operational efficiency.

7) Text of the article

It is recommended to structure the text of the article in the following sections: Introduction, Overview of the sources, Methods, Results, Discussion, Conclusions. Figures and tables are included in the text of the article (the figures must be "In line with text", not "behind text" or "in front of text"; not "With Text Wrapping").

Presentation:

The titles of the sections must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with no indentation on the left. The font face must be bold. The titles of the sections (except the Introduction and Conclusions) may be numbered in Arabic figures with a full stop after the number of a section. The number with a full stop must be separated from the title with a no-break space (Ctrl+Shift+Spacebar).

The text of the sections must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with a 1.25-cm indent. The font face must be normal. The text of the sections must be paragraphed. There must be no indent in the paragraph that follows a formula and contain notes to such formula, e.g.:

where n is the number of products.

An example:

1. State of the art of improving the dependability of electronic components

An analysis of Russian and foreign literature on the topic of this study has shown that …

Figures (photographs, screenshots) must be of good quality, suitable for printing. The resolution must be at least 300 dpi. If a figure is a diagram, drawing, etc. it should be inserted into the text in editable form (Microsoft Visio). All figures must be captioned. Figures are numbered in Arabic figures in the order of their appearance in the text. If a text has one figure, it is not numbered. References to figures must be written as follows: "Fig. 3. shows that …" or "It is shown that … (see. Fig. 3.)." The abbreviation "Fig." and number of the figure (if any) are always separated with a no-break space (Ctrl+Shift+Spacebar). The caption must include the counting number of the figure and its title. It must be placed a line below the figure and center justified:

Fig. 2. Description of vital process

Captions are not followed by a full stop. *With center justification there must be no indent!* All designations shown in figures must be explained in the main text or the captions. The designations in the text and the figure must be identical (including the differences between the upright and oblique fonts). *In case of difficulties with in-text figure formatting, the authors must – at the editorial office's request – provide such figures in a graphics format (files with the* *.tiff, *.png, *.gif, *.jpg, *.eps extensions).

The tables must be of good quality, suitable for printing. The tables must be editable (not scanned or in image format). All tables must be titled. Tables are numbered in Arabic figures in the order of their appearance in the text. If a text has one table, it is not numbered. References to tables must be written as follows: "Tab. 3. shows that …" or "It is shown that … (see. tab. 3.)." The abbreviation "tab." and number of the table (if any) must be always separated with a no-break space (Ctrl+Shift+Spacebar). The title of a table must include the counting number and its title. It is placed a line above the table with center justification:

Table 2. Description of vital process

The title of a table is not followed by a full stop. *With center justification there must be no indent!* All designations featured in tables must be explained in the main text. The designations in the text and tables must be identical (including the differences between the upright and oblique fonts).

Mathematical notations in the text must be written in capital and lower-case letters of the Latin and Greek alphabets. Latin symbols must always be oblique, except function designators, such as sin, cos, max, min, etc., that must be written in an upright font. Greek symbols must always be written in an upright font. The font size of the main text and mathematical notations (including formulas) must be identical; in Microsoft Word upper and lower indices are scaled automatically.

Formulas may de added directly into the text, for instance:

Let $y = a \cdot x + b$, then…,

or written in a separate line with center justification, e.g.:

$$y = a \cdot x + b.$$

In formulas both in the text, and in separate lines, the punctuation must be according to the normal rules, i.e. if a formula concludes a sentence, it is followed by a full stop; if the sentence continues after a formula, it is followed by a comma (or no punctuation mark). In order to separate formulas from the text, it is recommended to set the spacing for the formula line 6 points before and 6 points after). If a formula is referenced in the text of an article, such formula must be written in a separate line with the number of the formula written by the right edge in round brackets, for instance:

$$y = a\cdot x + b. \qquad (1)$$

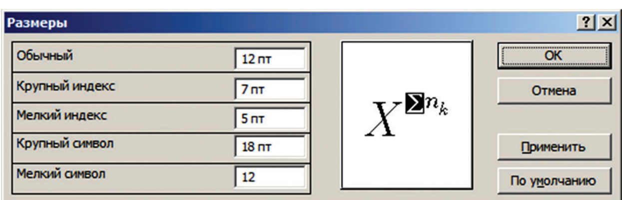
If a formula is written in a separate line and has a number, such line must be right justified, and the formula and its number must be tab-separated; tab position (in cm) is to be chosen in such a way as to place the formula roughly at the center. Formulas that are referenced in the text must be numbered in Arabic figures in the order of their appearance in the text.

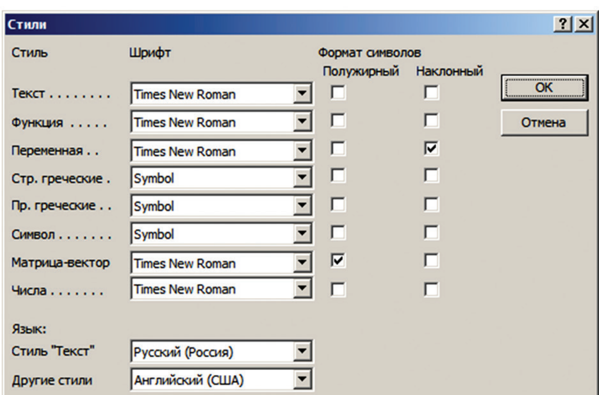
Simple formulas should be written without using formula editors (in MS Word, Latin should be used, as well as the "Insert" menu + "Special Characters", if Greek letters and mathematical operators are required), while observing the required slope for Latin symbols, for example:

$$\Omega = a + b\cdot\theta.$$

If a formula is written without using a formula editor, letters and +, –, = signs must be separated with no-break spaces (Ctrl+Shift+Spacebar).

Complex formulas must be written using a formula editor. In order to avoid problems when editing and formatting formulas it is highly recommended to use Microsoft Equation 3.0 or MathType 6.x. In order to ensure correct formula input (symbol size, slope, etc.), below are given the recommended editor settings.





When writing formulas in an editor, if brackets are required, those from the formula editor should be used and not typed on the keyboard (to ensure correct bracket height depending on the formula contents), for example (Equation 3.0):

$$Z = \frac{a\cdot\left(\sum_{i=1}^{n} x_i + \sum_{j=1}^{m} y_j\right)}{n+m}. \qquad (2)$$

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8) Acknowledgements

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