

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);

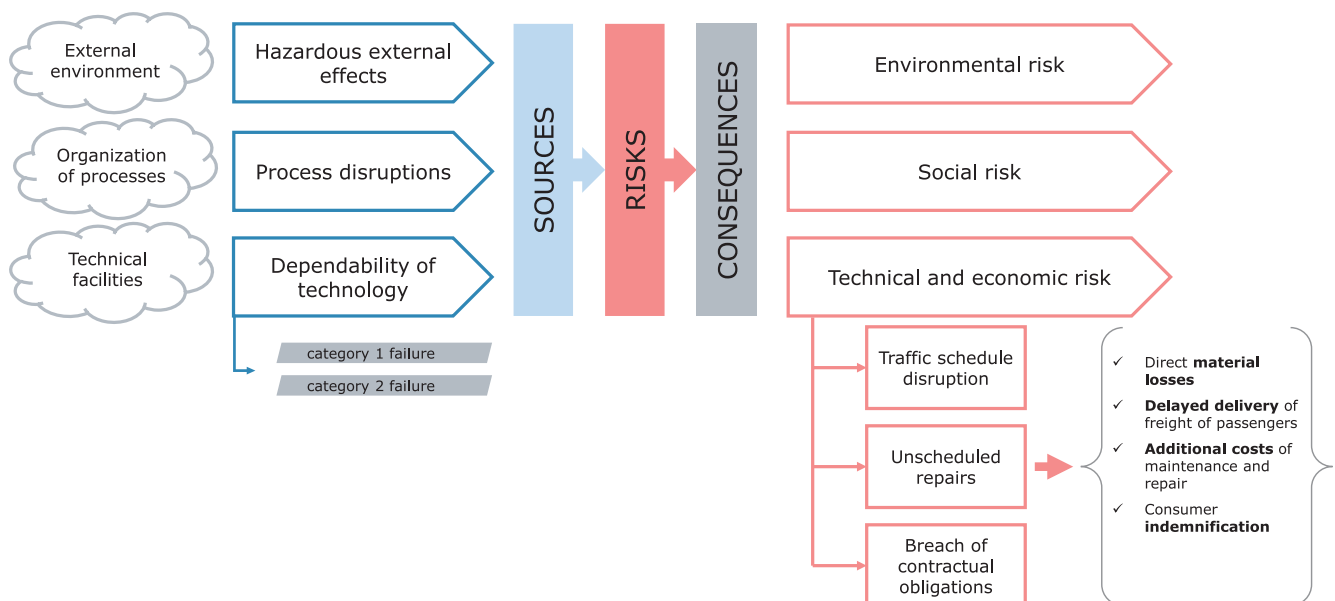


Fig. 1. General model of the onset of transportation process risks

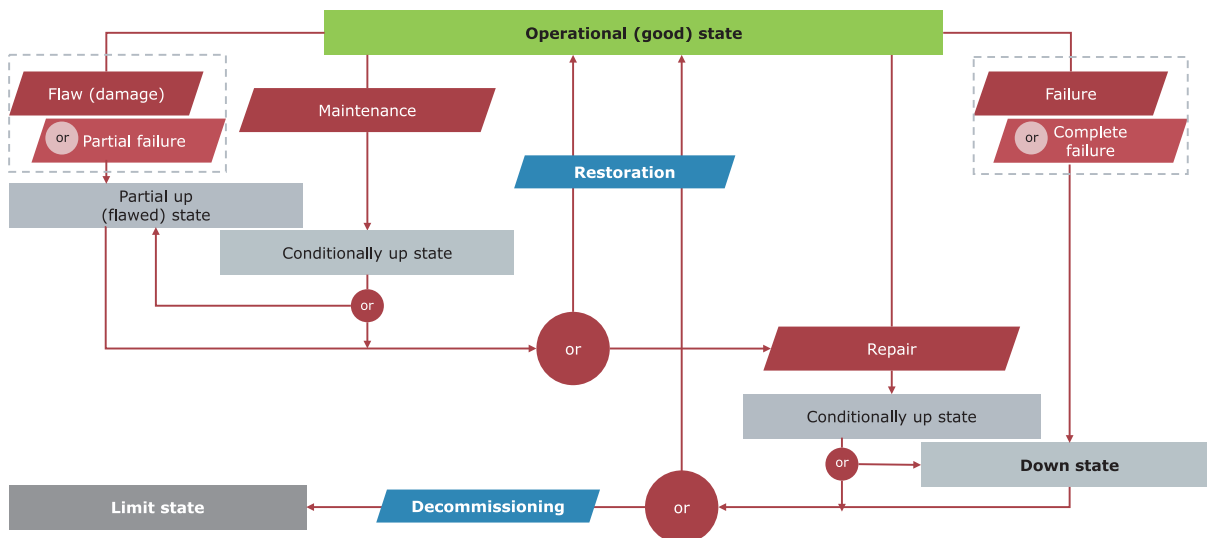


Fig. 2. States of a complex technical system

- 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-

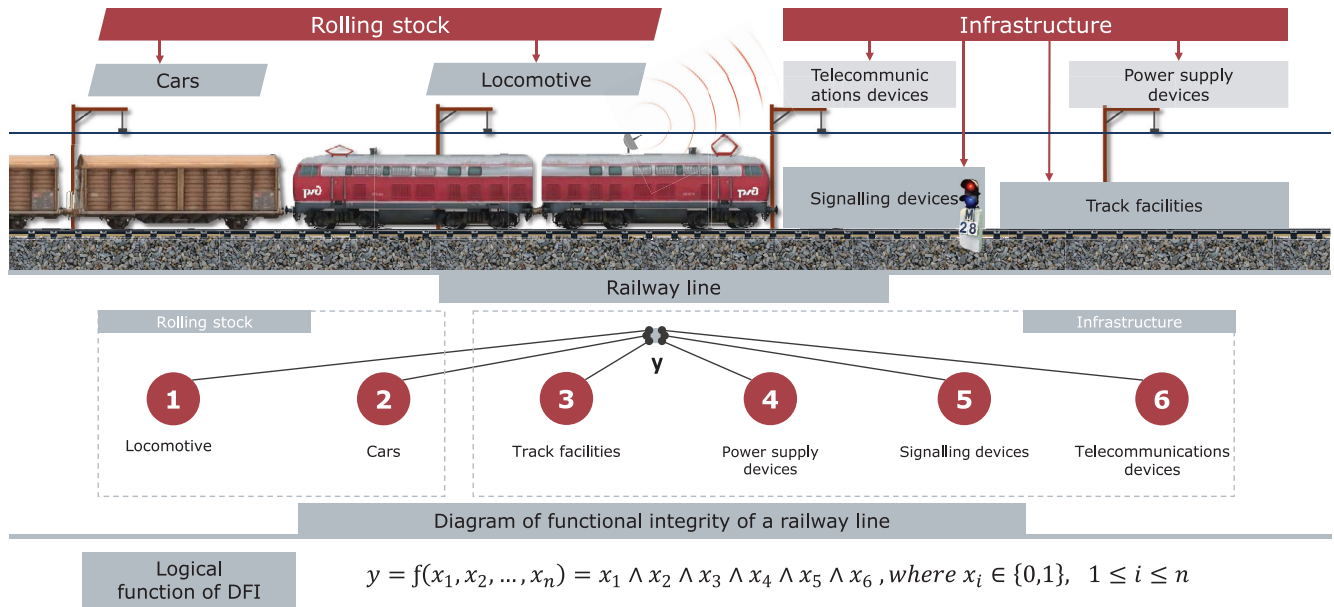


Fig. 3. Rolling stock as a component of the transportation process

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

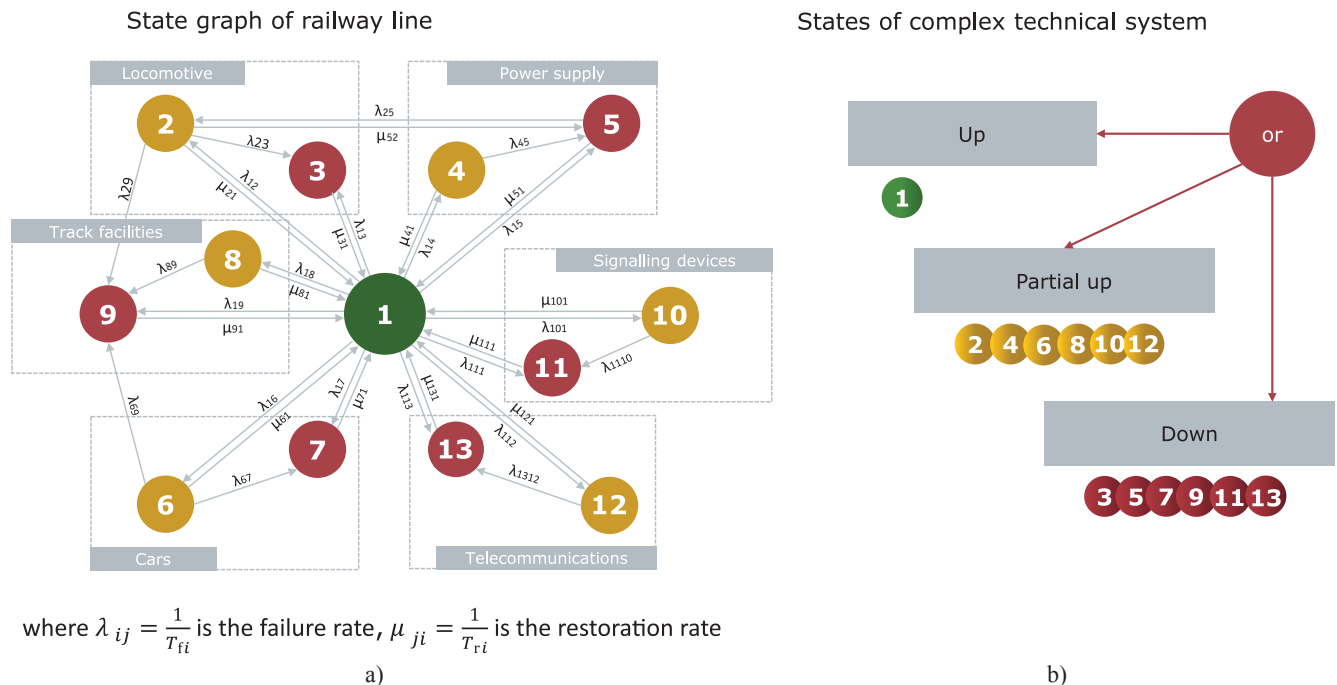


Fig. 4. State graph of a railway line (a) and state chart of a complex technical system (b)

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

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_{fi} and failure rate λ_{ij} , the mean restoration time T_{ri} 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

Classification feature for technical facilities (GOST 32192-2013)	Failure criterion per KAS ANT		System state
	Event	Restoration time	
Category 1 failure	Total failure	 over 1 h	Down
Category 2 failure	Partial failure	 6 min to 1 h	Partial up
		 15 min to 1 h	
Category 3 failure	Flaw (damage)	 with no delay	Partial up
		 up to 6 min.	
		 up to 15 min.	

a)

Classification feature (GOST 31187-2011)	Failure criterion			State of MP
	Event	Severity of failure elimination for the transportation process	Place of failure detection	
Type 1 failure	MP failure	Auxiliary locomotive	On line (operational state)	Down
Type 2 failure	MP failure	 Delay over 1 h	On line (operational state)	Down
Type 3 failure	MP failure	–	In the home depot	Down

*The criterion of a type 3 failure is the submission to unscheduled repairs

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;

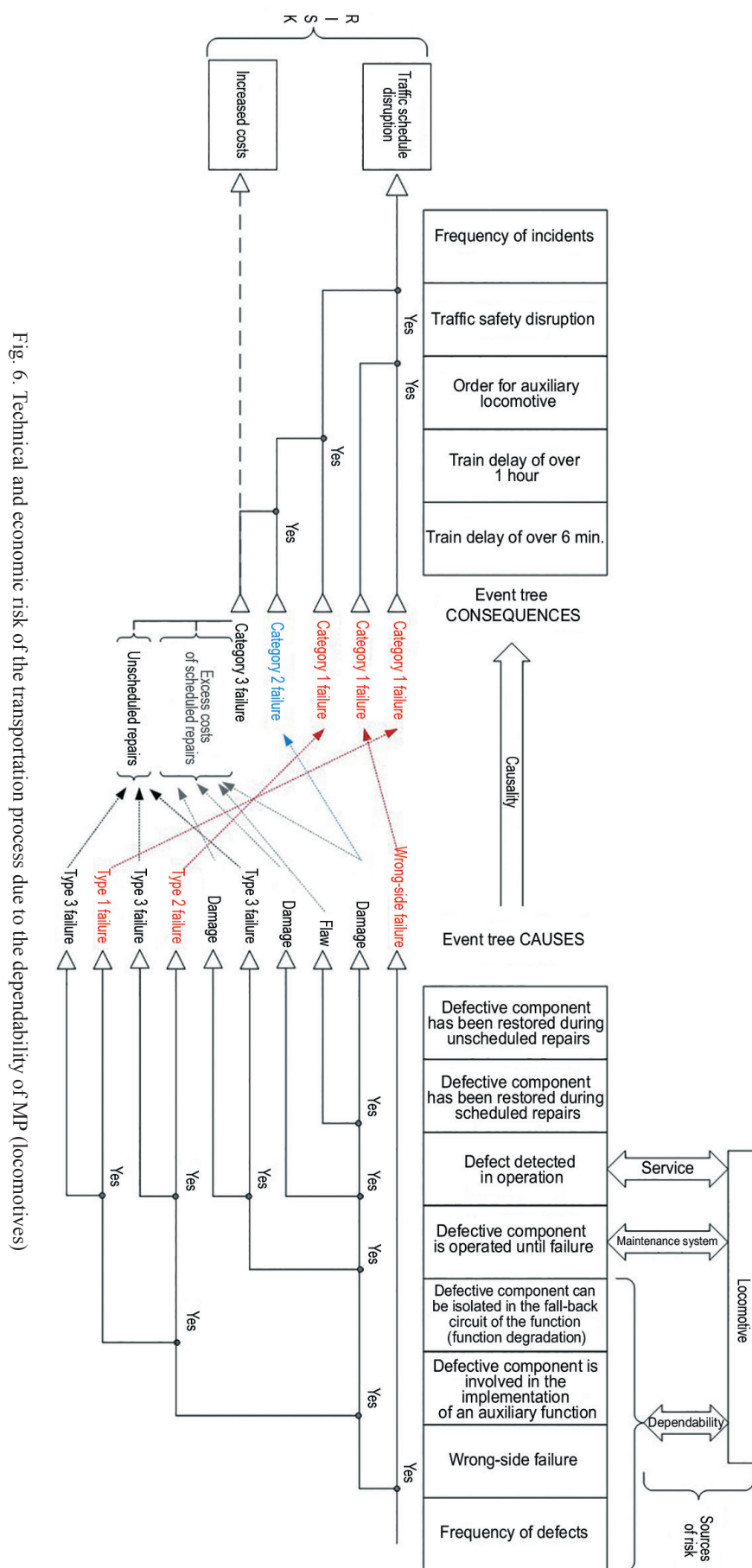
- flaw of type A due to defects identified in the operational state (MP goes into the faulty up state) and the non-operational state of the MP (in scheduled maintenance or awaiting work), the MP is restored through repairs (if identified, or delayed);

- 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.



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.