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Methods of traction rolling stock fire safety analysis

Olga B. Pronevich, *JSC NIIAS, Moscow, Russia, e-mail: O.Pronevich@vniias.ru*

Olga B. Pronevich

Abstract. Aim. *Fire safety of a protection asset is the state of a protection asset that is characterized by the capability to prevent the occurrence and development of fire, as well as the effects of hazardous factors of fire on people and property [1]. The traction rolling stock (TRS) is one of the primary protection assets on railway transport. Managing TRS fire safety involves a large volume of information on various TRS types: possible fire-hazardous conditions, fire safety systems, parameters of TRS-related processes. That means that efficient management must be built upon analysis that allows identifying trends and factors of fire hazard development. The analysis should be organized in such a way as to allow its results to be used in evaluation of composite safety indicators [2]. The required applied nature of such analysis is also obvious. Given the above, it should be noted that the applied research indirectly solves the task of using the results of fundamental research to address not only cognitive, but also societal issues [3]. The aim of this article is to structure the most efficient applied and theoretic methods of analysis and to develop a structure for systems analysis of TRS fire safety.* **Methods.** *The multitude of factors that affect the condition of TRS can be divided into two groups: qualitative and quantitative. Importantly, it is impossible to completely research the impact of all the elements of a complex technical system that is TRS on fire safety. We have to examine a part of the whole, i.e. a sample, and then use probabilistic and statistical methods to extrapolate the findings of sample examination to the whole [4]. An analysis of a data set requires a correctly defined sample. At this stage, the quality of information is the most important criterion. The list of raw data was defined based on the completeness of the description, reliability of the sources. Then, in a certain sequence, the data was analyzed by means of qualitative and semi-quantitative methods. First, given the impossibility to establish evident connections (destroyed by the hazardous effects of fire) between the condition of units that preceded the fire, the Pareto analysis was used. The research involved root cause analysis (Ishikawa diagram). Subsequently, cluster analysis of fire-hazardous situations was used. The main purpose of cluster analysis consists in establishing generic sequences of events that entail TRS fires. For that purpose, a description of possible fire-hazardous states of traction rolling stock is required, i.e. a multitude of events and states must be described. Dependability analysis can be successfully performed by representing the safety state information in terms of the theory of sets [5]. The sets of hazardous fire-related TRS events are represented in the form of partially ordered sets. Processing of such sets that are non-numeric in their nature cannot be performed by means of statistical procedures based on addition of parametric data. For that reason the research used mathematical tools based on the notion of type of distance. A part of data that have quantitative characteristics was analyzed statistically.* **Results.** *The TRS fire safety data analysis methods presented in this article that include methods of numeric and non-numeric data processing allowed developing a formatted list of fire hazard factors that enable the creation of a practical method of TRS fire risk calculation. An algorithm is proposed for application of qualitative and quantitative methods of analysis of data of various numerical natures. An example is given of the algorithm's application in the analysis of diesel engine fire safety. The proposed method can be used for analyzing anthropogenic safety in terms of listing the factors involved in risk assessment.*

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Introduction

Any statistical research starts with the description of the data type and structure. In the case of fire safety analysis, the statistical data represent the value of a property of traction rolling stock (TRS) that contributes to the possibility of initiation and propagation of fire. The values can be quantitative or qualitative. If measurement is made using several quantitative or qualitative properties, the resulting statistical data in the facility is a vector [6]. However, vector calculus involves using cumbersome mathematical tools, as well as developing a coordinate system and defining the list of operations that could be used in processing of heterogeneous data. Due to the applied nature of this research it is advisable to decompose the task to the analysis of one-dimensional observable values, define one-dimensional statistical research methods, the sequential use of which will provide as much information on the object as a multi-dimensional analysis would. Based on the type of raw data all available methods of analysis are divided into two parts: numerical statistics and statistics of non-numerical objects. The latter is crucial for two reasons. First, a significant proportion of the information on cases of TRS fires comes from reports of fire and reports on immediate (technical) causes of fire that are forms with open questions. These documents contain information in numerical and non-numerical form. The second reason is the nature of the assessment of the engine condition's contribution to the probability of fire. The main source of such information is the expert's opinion that is usually expressed in non-numerical form.

The approach suggested in this article aims to deliver a list of fire hazard factors that fall into the categories of numerical and non-numerical objects and make most complete information required for the construction of a fire risk assessment model.

Selection of methods of acquisition and analysis of traction rolling stock fire safety data

A researcher involved in processing of traction rolling stock fire safety data has two sources of information at his/her disposal. The first one is the results of observation of TRS fire cases that produce information in the form of data sample retrieved from a population. The size of such

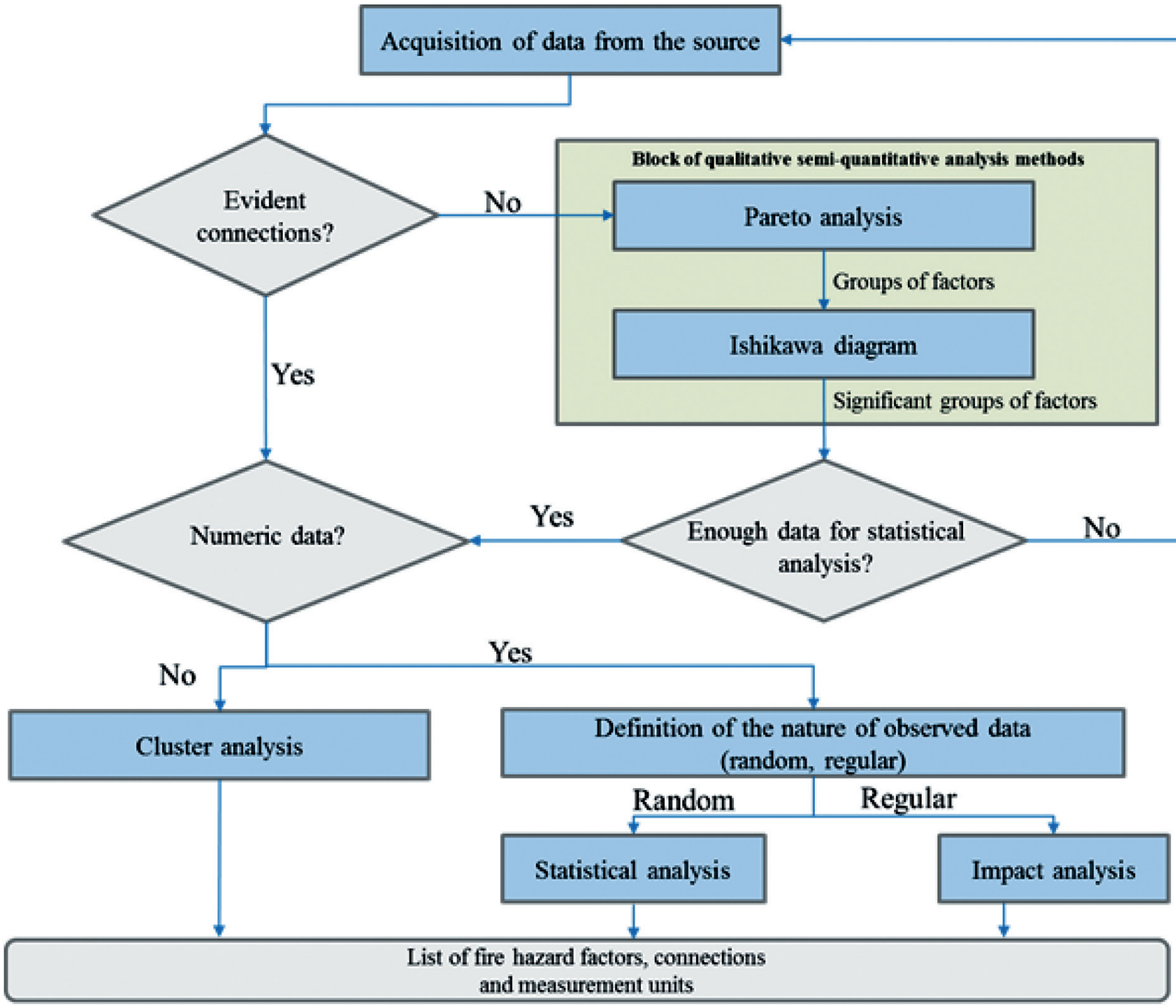

Figure 1. Algorithm of data analysis method selection

Table 1. Analysis and classification of methods of data acquisition of traction rolling stock fire safety

Type of source	Source	Method of data acquisition
Documental	Internal investigation report	Manual analysis: arrangement of data, classification of data
	Report on the immediate (technical) cause of fire	
	Report of inspection of traction rolling stock after fire	
	Engine technical condition log	Manual analysis: logical analysis, data classification, expert analysis
	Automated system for fire safety management	Data grouping, initial statistical analysis
Expert group	Analysis of JSC RZD facilities and rolling stock fire safety	Manual analysis: data integration and classification
Experiment	(observation under altered conditions)	Manual analysis: data registration, logical analysis and classification

samples is restricted by two factors: the observation period and the number of observed properties. The number of observed properties over the entire observation period (2011 – 2015) was not stable due to the changes in the data recording and storage procedure. The second source is the a priori information on the TRS design and possible violations of maintenance and operation procedures that cause fire-hazardous situations collected by the time the analysis started. Unlike the observed properties, this data is structured. Thus, when working with information sources, the primary task was to retrieve data, i.e. structuring data from non-structured or semi-structured documents. Table 1 provided the classification of fire safety information sources and methods of data acquisition from the sources for subsequent analysis.

The sampling is done at the stage of initial data processing. The result of data retrieval from the source is partially ordered numerical and non-numerical information. This information differs in the level of structuring, homogeneity and most importantly data interconnection. The algorithm shown in Figure 1 was developed for the purpose of analyzing such data.

Qualitative and semi-quantitative methods of traction rolling stock fire safety analysis

As the result of data retrieval from the source and grouping of data on the number and causes of fires it was established that out of 334 fires of diesel and electric engines over the considered period 201 fires occurred due to the fault of motive power maintenance depots (MPMD), 31 due to the fault of service enterprises, 35 due to the fault of motive power operation depots (MTOD), 15 due to the fault of locomotive repair shops, 5 through the fault of other third parties.

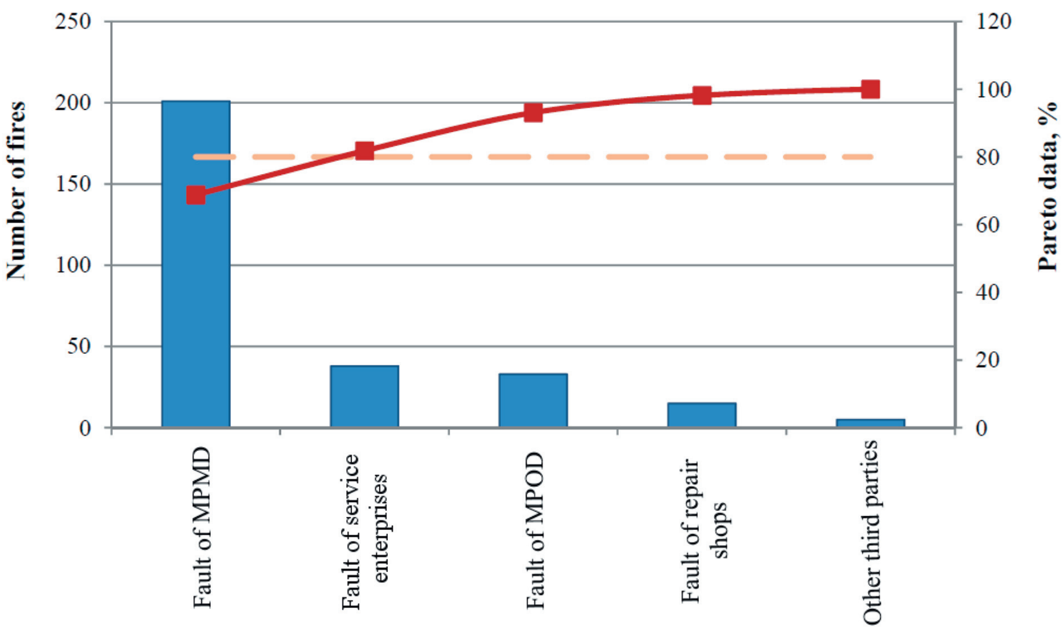

Figure 2. Pareto diagram of those guilty of diesel and electric engine fires for the record period

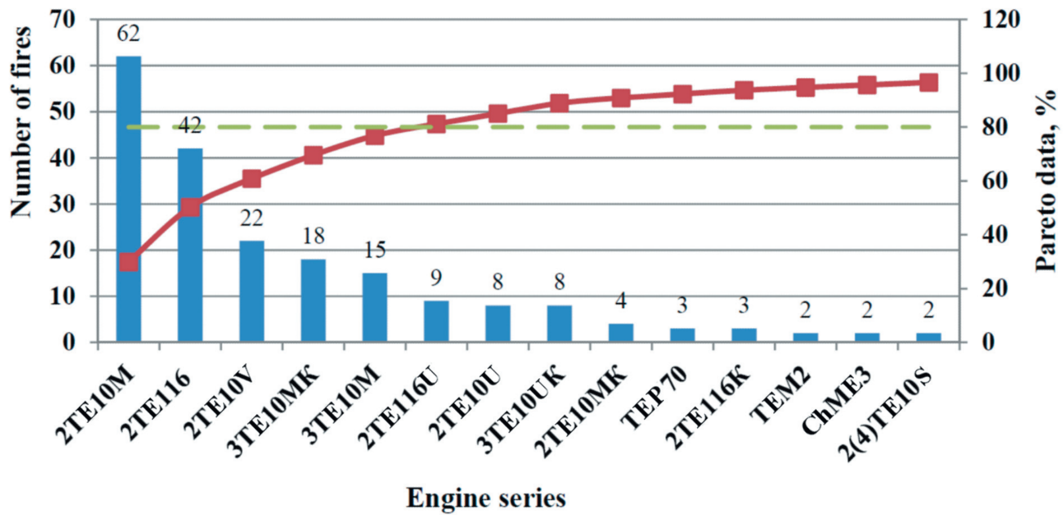

Figure 3. Number of fires between 2011 and 2015 per series of engines

It should be noted that most service enterprises that currently are not part of JSC RZD used to be motive power maintenance depots. Despite the reorganization and incorporation of a part of MPMDs as limited liability companies that are not part of the JSC RZD corporate structure the problem of fires caused by MPMDs and service enterprises still remains. Only the percentages changed. If between 2011 and 2013 the number of fires due to the fault of MPMD amounted to 80 percent, due to the fault of service enterprises to 4 percent, then in 2014 the MPMDs and service enterprises shared the guilt 46 to 41 percent respectively, i.e. 80 percent of fires over 4 years were due to the poor quality of maintenance. The Pareto analysis of the parties guilty of fires is given in Figure 2.

The Pareto diagram allows concluding that the main cause of TRS fires is the poor quality of technical inspections and maintenance. That means that further analysis

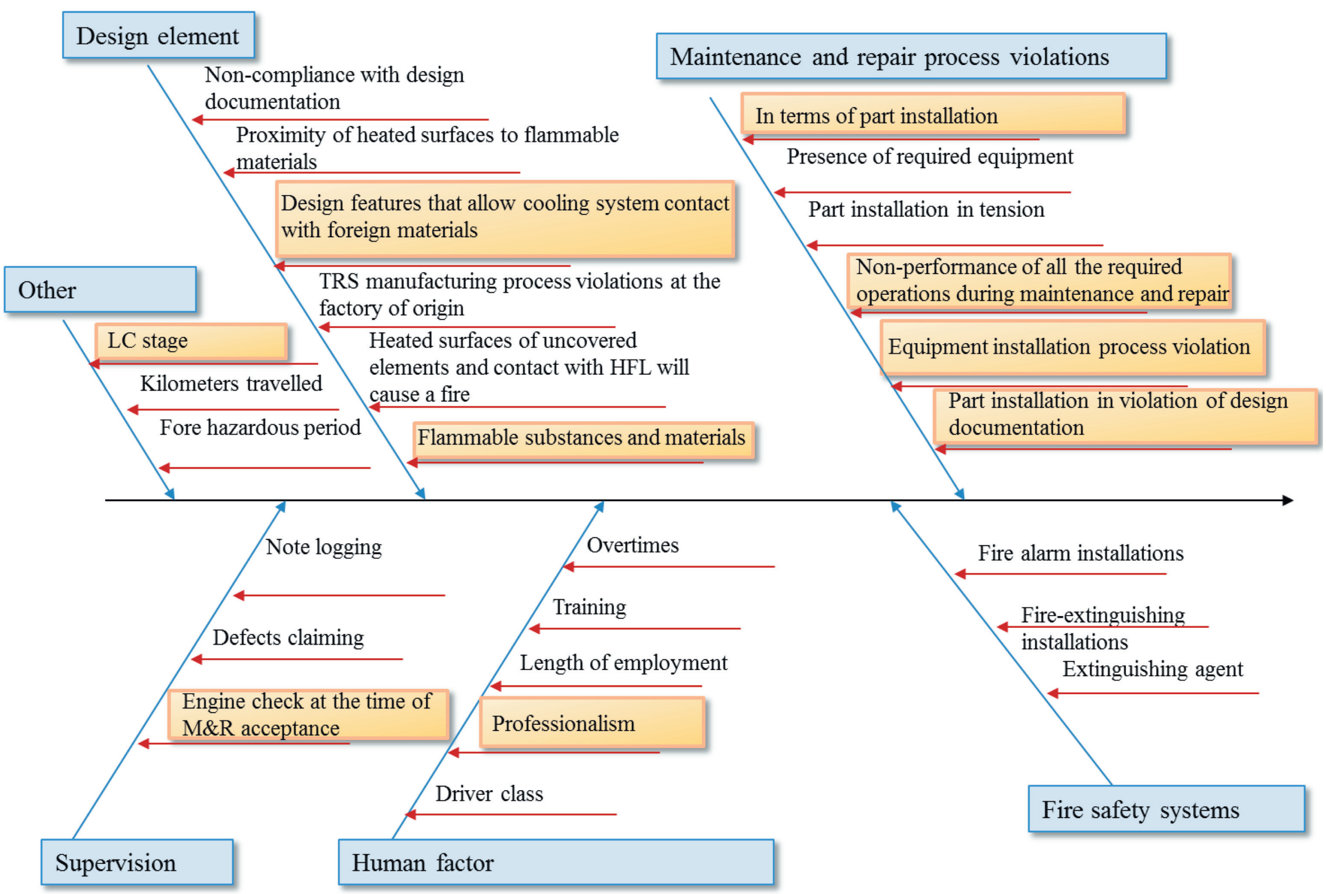

Figure 4. Cause-and-effect relationships between diesel and electric engine fires and the contributing factors

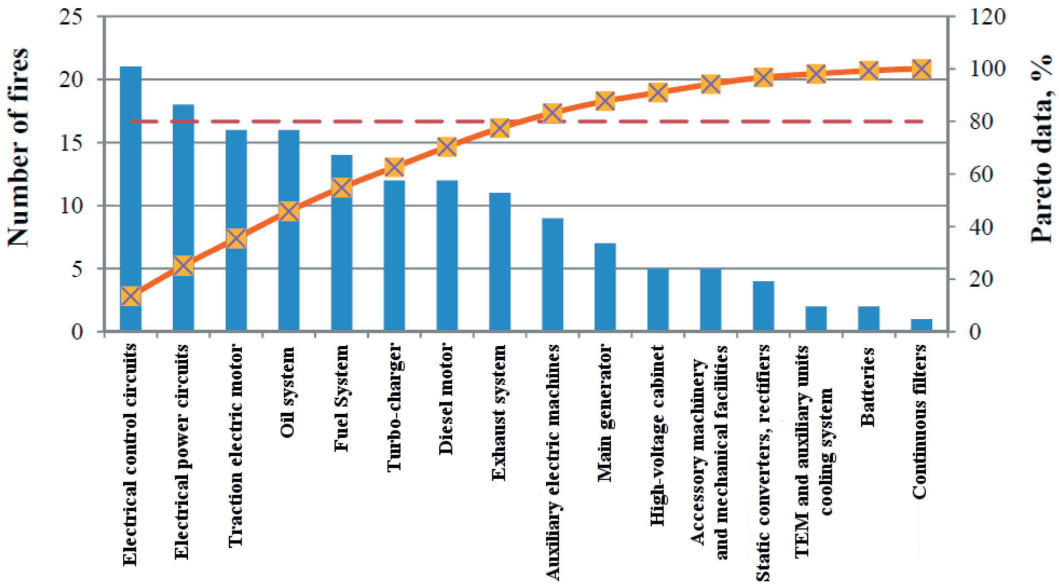

Figure 5. Number of fires per fire-hazardous engine components

should concentrate on detailing and structuring of the data on specific engine conditions that entail fires or the actions of the employees involved in their operation and maintenance. However, before proceeding to such analysis it is important to take into consideration the design differences of the engines of various series. Figure 3 shows the number of fires over the considered period per engine series. As we can see in Figure 3, 37.6 percent of all fires over the considered period is attributed to the 2(3)TE10M series engines, 19 percent to the 2(3)TE10MK series engines, 12.4 percent to 2(3) TE10V series engines, 10.1 percent to the 2(3)TE10MK series engines. That can be explained by the fact that most (63 percent) locomotives operated throughout the JSC RZD network belong to the 2TE10 and 2TE116 series. Those are the most commonly operated engines, which also contributes to the high fire statistics figures for those series. The remaining 37 percent of the operated diesel engine fleet of the JSC RZD network belong to the series, for which statistical data is not available or fires are rare.

Out of the Pareto diagram shown in Figure 3 it can be concluded that most fires are associated with the 2TE10M, 2TE116, 2TE10V, 3TE10MK series of diesel engines. A research of fire analysis materials allowed establishing cause-and-effect relationships between fires and technical malfunctions. Figure 4 shows the Ishikawa diagram of the cause-and-effect relationship between engine fires and the contributing factors. According to the Ishikawa diagram construction rules, the factors that contribute to a problem are shown with arrows that deflect to the right from the main arrow, while those that neutralize the problem are shown with arrows that deflect to the left. The neutralizing factors include the elements of the fire safety system (FSS): fire alarm installations (FAI), fire-extinguishing installations (FEI), extinguishing agents (EA). Thus, we can see that the occurrence of fire in traction rolling stock can be contributed by both individual indicators, and sets of indicators of various factors. The Ishikawa diagram (Figure 4) highlights the indicators of factors that in most cases caused fires in the engines of the 2TE10M, 2TE116, 2TE10B and 3TE10MK series.

As in most cases fires affect engines of specific series, let us examine which units and components of such engines are the most fire-hazardous. Figure 5 shows the analysis of fires in the engines of the 2TE10M, 2TE116, 2TE10B and 3TE10MK series over the considered time period per units and components affected by fire.

The Pareto diagram in Figure 5 shows that the bulk of the fire hazard (80 percent) for these series of engines is associated with the following set of units: electrical control circuits, electrical power circuits, traction electric motor, oil system, fuel system, turbo-charger, diesel motor, exhaust system, auxiliary electric machine. I.e. at this stage of analysis one may talk about the development of a sample of fire-hazardous units, of which the fire hazard evaluation will characterize the main body of TRS fire safety in general.

Each of the fire-hazardous units has a set of components that initiate fire. Thus, for example, in the case of electrical circuits that is the insulation and the cores. For the traction electrical motors the list is longer, from the armature to the feeder cables. Fire initiation conditions are also associated with fire-hazardous events that cause fire in a unit's component. Let us examine them in detail. The research of diesel engine fires investigation materials shows that the most frequent event is a short circuit that produces sparks with subsequent inflammation of cable cores and wires. The list of fire-hazardous events for diesel engines is as follows: electrical arc, sparks, short circuit sparks due to short-circuiting of wires, to frame, short circuit sparks due to turn-to-turn short circuit, flashover, burning of flammable materials, heating, incandescent gas, etc. As the described diesel engine characteristics that affect its fire safety are not numeric, according to the algorithm of data analysis method selection (Figure 1) further analysis of such data should be based on the cluster method.

Cluster analysis of non-numeric statistical data

Based on the investigation materials and data from automated fire safety systems, classifiers of fire-hazardous events and fire-hazardous units were developed. As the result of fire data analysis, using the events and units classifiers, chains of fire-hazardous events were constructed. Each of them corresponded to specific units.

Further analysis covers the construction of generic chains of events. A chain of events is understood as a sequence of finite or enumerable infinite number of events, of which the characteristic property is that, non-strictly speaking, the condition that occurs before or after TRS operation corresponds to a specific set of parameters that do not depend on the engine's condition before the event chaining.

The object of analysis is the chain of events, a partially ordered set. *The aim of analysis* is to develop the search rules for common features in the chains of events and construction of chains with the common feature of generic event scenarios. Achieving that goal will involve the evaluation of the proximity of chains of events by means of cluster analysis.

Let us formalize a number of concepts:

Z, a partially ordered set of all chains of events.

A_i, a partially ordered subset (POS) of the Z set of i^{th} type.

B_j, POS of the set Z.

Each subset B_j can be replaced with a universal set that characterizes the i^{th} type set (A_i subset).

The distance between two subsets B_k and B_l, that characterizes the proximity of the subsets, is calculated using the formula (1.1):

$$d_{lk} = \sum_{i=1}^{5} r_i \quad (1.1)$$

Where

$$r_i = \begin{cases} 0, x_{ki} = x_{li} \\ 1, x_{ki} \neq x_{li} \end{cases}$$

x_{ki} is an event at the i^{th} position in subset B_k;

x_{li} is an event at the i^{th} position in subset B_l.

By combining the subsets B_j based on feature d_{lk} we obtain a cluster. Table 2 shows the correspondence between the value of feature d_{lk} and commonality level.

Table 2. Spacing of subsets and level of commonality

	d				
	1	**2**	**3**	**4**	**5**
Level of commonality	High	Significant	Insignificant	Low	No

When clustering standard event scenarios, subsets with commonality levels «high» and «significant» were chosen.

The result of event clustering is shown in Table 3. Cluster power is the number of constituent and common chains of events. FHE is a fire-hazardous event.

Similarly, the generic unit groups were defined. In order to construct generic fire scenarios for diesel engines, a correspondence analysis of generic unit groups and fires from the event cluster was performed. If fires from the generic unit groups correspond with the fires from the event cluster, scenarios can be built. Frequent scenarios are built if at least 4 fires correspond. The number of corresponding fires is

Table 3. Example of clustered events

Cluster no.	Power	Years/ months		FHE1	FHE2	FHE3	FHE4	FHE5
1	8	October 2014	Cluster center	*Destruction, rupture*	*Sparking*	*Spark hits*	*0*	*Spark*
		March 2013	Cluster elements	Absence (of a part)	Sparking	Spark hits	0	Spark
		May 2013		Damage	Sparking	Spark hits	0	Spark
		April 2014		Use of nonstandard parts	Sparking	Spark hits	0	Spark
		May 2013		Use of nonstandard parts	Sparking	Spark hits	Spark hits	Spark
		March 2014		Defect	Sparking	Spark hits	0	Spark
		April 2014		Damage	Sparking	Spark hits	0	Spark
		July 2013		Destruction, rupture	Sparking	Spark hits	0	Spark

Table 4. Built scenarios of diesel engine fires with the power level of 5.

Scenario	Units	Events				Power
1	Diesel motor exhaust	Absence (of a part)	Damage	Use of nonstandard parts	Destruction, rupture	4
	Cooling system	Sparking	Spark hits			
2	Fuel system	Absence (of a part)	Incorrect installation	Damage/wear (ageing)	Rupture	4
	Exhaust system, draining system	Heating of flammable materials and substances, their contact with hot parts of the engine				
3	Electrical systems	Insulation disruption/chaffing, rupture	Short-circuiting of cables	Short circuit to frame	Heating	8

the power of the scenario. Table 4 shows examples of built scenarios of diesel engine fires.

The analysis of non-numeric data results in fire scenarios that include the units and series of events that entail fires. Fire risk evaluation based on actual condition of TRS must take into consideration those conditions that contribute to the probability of hazardous fire scenarios.

Definition of the nature of observed data

The numeric characteristics of fire TRS safety include the number of fires within the 2011 – 2015 observation period. The observation interval is one month. Before submitting the observation results to statistical processing it must be made sure that they make a truly random sample, i.e. are stochastically independent (alternatively, the observation result may be dependent on the order number, observation time, presence of cyclic or monotonous bias) [7]. For that purpose let us analyze the set of sample data using the criterion of "run up" and "run down". This criterion was chosen because of the ability to "grasp" the drift (along the sample observation) of the mean value in the periodic distribution under study. The initial sequence (number of fires per month) is associated with a sequence of pluses and minuses. At the i^{th} position in the sequence is a plus if $x_{i+1} - x_i > 0$, a minus if $x_{i+1} - x_i < 0$. If two or more consecutive observations are equal, only one of them is taken into consideration, the others are excluded from the sequence. The series criterion is based on the affirmation: if the sample is random, in the character sequence it forms the total number of series ($v(n)$) cannot be too small, while their length ($t(n)$) cannot be too large. In the quantitative form this rule is as follows:

$$v(n) > [\frac{1}{3}(2n-1) - U(\alpha)\sqrt{\frac{16n-29}{90}}$$

$$t(n) < t_0(n)$$

Value $t_0(n)$ depending on the length of sequence (n) is defined as follows: if $n \leq 26$, $t_0(n) = 5$; if $26 < n \leq 153$, $t_0(n) = 6$; if $153 < n \leq 1170$, $t_0(n) = 7$.

The analysis of time sequence of fires has shown that the sequence of the number of fires is a random sample. That means that further analysis should be made by means of applied statistics. Among other things, fire forecasting must involve the evaluation of the lower and upper limits of this probability. In [8], a detailed account is given of the special aspects of estimating the probability of fire occurrence on diesel engines of various types. They therefore will not be scrutinized in this article. The results of assessment of the probability of fire are used as a key factor in the construction of the risk assessment model.

Conclusion

The article highlights the requirement for the development of an algorithm for selection of an analysis method of raw data on a facility subject to several sources of information. The author defines the primary methods of analysis subject to the presence of numeric and non-numeric data. She demonstrates the sequential application of qualitative and semi-quantitative data analysis methods without evident connections with grouping and classification of the end results. Cluster analysis of non-numeric statistics is used for construction of generic fire scenarios.

The systems approach to the application of various types of analysis allows defining a list of TRS parameters to be taken into consideration in risk assessment, defining the measurement scale and the nature of observed values.

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About the author

Olga B. Pronevich, Head of Unit, JSC NIIAS, Moscow, Russia, tel.: +7 (495) 967 77 05, ext. 516, e-mail: O.Pronevich@vniias.ru

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