Automation of failure forecasting on the subsystems of the railway transport complex in order to optimize the transportation process as a whole

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Abstract. The existing technology of working with railway rolling stock belonging to various operators should improve the safety of the transportation process. This is one of the priority issues of the operation of the railway transport complex and is aimed at improving the safety of the goods transported, reducing the cost of repairing losses associated with loss or damage to cargo, reducing the non-productive costs of eliminating various types of traffic safety violations. At the same time, the majority of "new" operators providing services do not set out to ensure the safety of the transportation process. The main condition for them is to get the maximum amount of income and profit. These reasons have led to significant changes in the pattern of relations between cargo owners, carrier, rolling stock operator companies and require the speedy automation of most production cycles in order to ensure full control of the situation on the smooth organization of the transportation process. The article assesses the safety of the railway transport complex and constructs a mathematical model of the impact of specific indicators of the violation types on the overall safety level. The described system of mathematical predictive regression-type models can be used in the future to predict the level of security in the selected areas of activity. The factors that have the most significant impact on the safety of technical means by using the developed program complex of failure forecasting have been identified. The proposed program will enable structural managers to make reasoned decisions to improve the safety of the transportation process in both freight and passenger transport.

1. Introduction
Throughout the modern history of Russia's development as a state, as well as in the foreseeable future, the railways of the Russian Federation retain the role of the system-forming dominant element of the general transport complex. They provide about 80% of the freight turnover, bring service to about 80 large and small regions, more than 70,000 enterprises of various industries, while providing more than 50% of export-import freight transportation. In addition to the role of the national transport integrator, railway transport is providing employment for more than 1.5 million people throughout the country. It plays a huge social role, while at the same time being an important component for ensuring Russia's defense capability and mobilization readiness [1, 2]. Biggest role belongs to infrastructure works [3-7] and to arranging the optimization transport process.
The third stage of the reforms being carried out in the railway transport complex was characterized by a reduction in the share of the inventory fleet railcars in connection with the creation of a series of separate freight transport companies and the transfer to operational management of part of the rolling stock fixed assets – the inventory fleet railcars. After that, these companies moved into the category of "private" that formed a competitive sector of the transport market in the industry. The existing technology for working with rolling stock belonging to various operators in fact should ensure an increase in safety of the transportation process. This is one of the priority issues of the functioning of the railway transport complex in any conditions and is aimed at: increasing the safety of transported goods, reducing costs for compensation for losses associated with loss or damage to cargo, as well as reducing the non-productive costs of the industry aimed at eliminating various kinds of traffic safety violations.

At the same time, the long period of railway transport in these conditions shows that a significant part of the «new» operators providing services does not set their task to ensure the safety of the transportation process. The main condition for them is to get the maximum amount of income and profit. These reasons have led to significant changes in the relationship patterns between cargo owners, carrier, and rolling stock operator companies.

The safety of the functioning of the railway transport complex includes the following main elements: safety of the transportation process; environmental safety; safety of transported goods, rolling stock and infrastructure; personal safety of staff and users. Ensuring safety and minimizing risks in the operation of all components of the complex depends on a number of factors:

- studying and obtaining timely, adequate information about the conditions of operation;
- working with the staff of operator companies;
- implementation of the transport process only in the conditions of serviceable vehicles and infrastructure;
- careful planning of the rolling stock operation.

The role of the above factors is multiplied when the cargo is transported, weighting down the consequences of a possible failure. Implementation of these areas of development, aimed primarily at retaining existing customer bases and creating new ones, is impossible without the speedy automation of most production cycles in order to ensure full control of the situation on the smooth organization of the transportation process. This is particularly the case with regard to the acceptance of cargo in transport, since it is this production cycle, with the existing technology of handling rolling stock that belongs to different operators, is the most labour-intensive and has a greater impact on the safety of the transportation process at all its stages [8].

2. Use of a system of mathematical predictive models to forecast the level of security in the designated areas of operation

At the current stage of development, the industry regularly increases the volume of traffic in all areas of activity, as well as the quality of services provided, on the premise of the safety of trains and the production of maneuvering, the preservation of material values, nature and other components of the system and its subsystems. Since rail transport is a multi-industry economy, representing a transfer conveyor of huge length, its uninterrupted and accident-free work depends on the operation of each individual part of its components - subsystems. The problem is to identify the factors that affect the safety level of the railway transport complex and its subsystems, taking into account the degree of this influence [9-12]. The solution to the problem involves the decomposition of the object of research, considered as a complex system.

In accordance with the accepted structure of the organization of the railway transport complex and the degrees of influence on the transportation process safety indicators, it is advisable to distinguish the following subsystems:

- traffic department;
- traction directorate;
- service of railcar facilities;
• track service;
• automation service;
• passenger service;
• freight and commercial operation service;
• electrification service.

A generalized characteristic of the level of safety of the railway transport complex at the federal and regional levels will be the vector of \( y = (y_1, y_8) \), components of which are the number of defects in the activities of the allocated subsystems, occurred for a variety of reasons \( (x_1 – x_{42}) \). Let us introduce designations that characterize defects in work that occurred for the following reasons:

- \( x_1 \) – departure for an occupied station-to-station block;
- \( x_2 \) – derailment of railcars;
- \( x_3 \) – defects of the railcar fleet;
- \( x_4 \) – damage to the locomotive fleet;
- \( x_5 \) – break of the automatic coupling
- \( x_6 \) – train delay of more than one hour due to locomotive malfunctions;
- \( x_7 \) – uncoupling of railcars in transit due to malfunction of roller axle-boxes;
- \( x_8 \) – uncoupling of railcars in transit due to other technical faults;
- \( x_9 \) – train delay of more than one hour due to technical faults of the railcars;
- \( x_{10} \) – train derailment;
- \( x_{11} \) – rail breakage;
- \( x_{12} \) – train delay of more than one hour due to technical failures of the track;
- \( x_{13} \) – train departs for an unprepared route.
- \( x_{14} \) – blocking of the signal, which caused the running a red light at the station;
- \( x_{15} \) – malfunction of alarm, centralization and locking devices with train delays of more than one hour;
- \( x_{16} \) – uncoupling of the passenger railcars for technical faults;
- \( x_{17} \) – malfunction of the wheel sets;
- \( x_{18} \) – wreck of the cargo in transit;
- \( x_{19} \) – uncoupling of railcars due to the violation of the technical conditions for the placement and fastening of cargo and cargo loading;
- \( x_{20} \) – contact network malfunction;
- \( x_{21} \) – auto-locking malfunction;
- \( x_{22} \) – malfunction of the rolling stock inspection systems;
- \( x_{23} \) – low quality and violation of the rolling stock depot maintenance and overhaul technology;
- \( x_{24} \) – decrease in the quality of trains inspection;
- \( x_{25} \) – high physical wear and ageing of fixed assets;
- \( x_{26} \) – lack of and low quality of spare parts and necessary materials;
- \( x_{27} \) – reduction in the number of employees.
- \( x_{28} \) – increase in the guaranteed haul distances of mileage of loaded and empty railcars;
- \( x_{29} \) – imperfection of the technical means and technologies of preventing defects cases;
- \( x_{30} \) – violation of the splitting-up and braking mode of the cuts on the gravity sorting yards;
- \( x_{31} \) – non-compliance with the requirements of instructions on the maintenance of inclined tracks and sorting tracks, arrangement of gravity sorting yards;
- \( x_{32} \) – descent and collision in shunting operations;
- \( x_{33} \) – drop of the parts of the rolling stock and cargo on the track;
- \( x_{34} \) – non-fencing of the places of trackwork by stop signals.
- \( x_{35} \) – technical condition of the body elements of freight railcars;
- \( x_{36} \) – inconsistency in the actions of third-party organizations and transport companies;
- \( x_{37} \) – low labor and technological discipline, insufficient staff level, poor knowledge and non-compliance with regulatory documentation;
- \( x_{38} \) – theft of fixed assets;
х₃⁹ – violation of the established work and rest schedule of the workers;
х₄₀ – loading of railcars in excess of the established standards;
х₄₁ – lack of proper control by rail workers in the reception of cargo for transportation.
х₄₂ – other reasons for the unspecified nature.

The level of security of each subsystem is estimated by one indicator - the number of defects within the range of the service.

Based on the results of the East Siberian Railways, the Russian Railways branch has built a mathematical model of the impact of specific indicators of the types of violations \( x_i, i=1\text{–}42 \), on the general state of the level of safety of the regional railway transport complex with its decomposition on subsystems \( y_j, j=1\text{–}8 \) [13-15].

The following criteria are used to assess the adequacy of models:

\( R \) – of multiple determination;
\( t \) – Student’s;
\( F \) – Fischer’s;
\( DW \) – Darbin-Watson’s;
\( E \) – average relative approximation error.

To build each regression model for \( y_j, j=1\text{–}8 \), several hundred (depending on the nature of the data) of its alternatives, followed by a choice of the best of them, were built based on their vector criterion of adequacy. With that, the algorithm described in work [2, 16-17], was used.

Traffic department \( y₁ = 2.47 + 1.3x₁ + 1.48x₂ + 1.48x₃, \)

\( R = 0.975, F = 59.26, DW = 2.83, E = 7.85\%, \)

Traction Directorate \( y₂ = -77.78 + 0.98x₄ + 5.67\sqrt{x₅} + 17.24\sqrt{x₆}, \)

\( R = 0.993, F = 214.87, DW = 1.63, E = 0.76\%, \)

Service of Railcar Facilities \( y₃ = 9.4 + 7.54\cdot10^{-5}\cdot x₇^3 + 8.42\sqrt{x₈} + 10.57\sqrt{x₉}, \)

\( R = 0.991, F = 168.34, DW = 1.93, E = 0.69\%, \)

Track Service \( y₄ = 12.87 + 4.6\sqrt{x_{10}} + 0.28x_{11}^2 + 12.87\sqrt{x_{12}}, \)

\( R = 0.986, F = 106.8, DW = 3.02, E = 1.20\%, \)

Automation Service \( y₅ = 0.93 + 0.68x₁₃ + 0.45x₁₄^{1.5} + 0.68x₁₅^{1.5}, \)

\( R = 0.926, F = 18.76, DW = 1.12, E = 5.08\%, \)

Passenger Service \( y₆ = 0.56 + 0.75x₁₆ + 0.95x₁₇, \)

\( R = 0.981, F = 92.51, DW = 1.74, E = 8.19\%, \)

Freight and Commercial Service \( y₇ = 1.52 + 0.64x₁₈^{1.5} + 0.31x₁₉^{1.5}, \)

\( R = 0.983, F = 133.18, DW = 1.59, E = 6.71\%, \)

Electrification Service \( y₈ = 1.28 + 0.9x₂₀ + 1.15x₂₁ + 0.92x₂₂, \)

\( R = 0.993, F = 212.35, DW = 1.71, E = 1.26\%. \)

Here, under the parameters of the models in brackets, there are the values of \( t \) - the Student’s criterion.

An analysis of these adequacy criteria for each of the eight models shows that they all have high values that far exceed critical boundaries. Exception, in some cases, is Darbin-Watson's criterion \( (DW) \), indicating the presence of autocorrelation in some models \( (y₁, y₂, y₄, y₅) \). This only means that model data should only be used to address short-term forecasting tasks.
This system of mathematical predictive models of regression type is later used for medium-term forecasting of the level of safety of the East Siberian Railways of the Russian Railways OAO branch in the designated areas of operation. The results of the analysis are presented in Table 1.

### Table 1. Failure rating for subsystems.

| No. | Service                          | Failures                                                                 |
|-----|----------------------------------|--------------------------------------------------------------------------|
| 1   | Traffic department               | 1. Car derailments                                                      |
|     |                                  | 2. Other defects                                                        |
|     |                                  | 3. Departure to an occupied station-to-station block                     |
| 2   | Traction directorate            | 1. Locomotive malfunction                                               |
|     |                                  | 2. Damage to locomotives                                                |
|     |                                  | 3. The break of the automatic coupling                                  |
|     |                                  | 1. Train delays of more than 1 hour due to technical faults of railcars |
| 3   | Service of railcar facilities   | 2. The uncouplings of railcars in transit due to the malfunction of roller axle boxes |
|     |                                  | 3. The uncouplings of railcars in transit due to other technical faults  |
|     |                                  | 1. Rail breakage                                                        |
| 4   | Track service                   | 2. Train delays of more than 1 hour due to technical track malfunctions  |
|     |                                  | 3. Train derailments                                                    |
|     |                                  | 1. Signal blocking, which caused the red light running at the station    |
| 5   | Automation service              | 2. Signaling devices malfunction with train delay of more than 1 hour   |
|     |                                  | 3. Departure of the train for an unprepared route                        |
|     |                                  | 1. Faulty wheel sets                                                    |
| 6   | Passenger service               | 2. The uncoupling of the railcars for other technical reasons            |
|     | Freight and commercial          | 1. Uncoupling of railcars from the train due to violation of the          |
|     | operation service               | 2. Technical conditions for loading cargo                               |
|     |                                  | 1. Overhead system malfunction                                          |
| 7   | Electrification service         | 2. The collapse of the cargo in transit                                 |
|     |                                  | 1. Automatic blocking malfunction                                       |
|     |                                  | 3. Malfunction of special self-propelled railway equipment             |

3. **Automation of the procedure for forecasting failures for the subsystems of the railway transport complex**

In order to automate the procedure for predicting failures on the subsystems of the railway transport complex, a corresponding software package has been developed in the Delphi programming environment, using the example of the East Siberian Railways of the Russian Railways OAO branch. From the start, it includes the initial failure statistics for 2010-2019, as well as a regression model for each subsystem that allows you to make a prediction of the occurrence of a risk in any of the subsystems. The feature of the package is that when new data for the reporting period, the user in automatic mode can easily and conveniently rebuild any model and get new forecast values in all areas of the transportation process.

Forecasting stages:
- the first stage is to choose a service;
- the second is to set a forecast period;
- the third is to enter the upper and lower boundary for each factor;
- the fourth is to get a forecast.

The software package allows you to get three types of forecasts: optimistic, pessimistic and neutral. The optimistic forecast shows the dynamics of failures in a better situation, i.e. all negative factors are considered to be minimal. A pessimistic forecast is when all negative factors are considered to be maximal. A neutral forecast assumes that negative factors take on average values between the maximum and the minimum ones. The results of failure forecasting are presented in Table 2.
Based on the data of the mathematical model of the software package, a failure forecasting was compiled by the example of the East Siberian Railways branch of the Russian Railways for the period of 2018-2022. [13, 14]. The results of the failure prediction are presented in Table 2. The failure forecasting based on the complexes is graphically shown in Figure 1.

![Failure forecasting for the period from 2018 to 2022.](image-url)
Table 2. Failure forecasting results with rating.

| No. | Service                        | Year | Failure forecasting | No. | Service                        | Year | Failure forecasting |
|-----|--------------------------------|------|---------------------|-----|--------------------------------|------|---------------------|
| 1   | Traffic department             | 2018 | 4.50                |     |                                | 2018 | 3.77                |
|     |                                | 2019 | 4.12                |     |                                | 2019 | 3.99                |
|     |                                | 2020 | 2.91                | 5   | Automation service             | 2020 | 4.00                |
|     |                                | 2021 | 3.02                |     |                                | 2021 | 3.52                |
|     |                                | 2022 | 4.22                |     |                                | 2022 | 4.21                |
|     |                                | 2018 | 89.50               |     |                                | 2018 | 1.89                |
|     |                                | 2019 | 90.35               |     |                                | 2019 | 2.09                |
| 2   | Traction directorate           | 2020 | 89.71               | 6   | Passenger service              | 2020 | 1.70                |
|     |                                | 2021 | 84.15               |     |                                | 2021 | 1.99                |
|     |                                | 2022 | 91.12               |     |                                | 2022 | 1.68                |
|     |                                | 2018 | 111.00              |     |                                | 2018 | 5.05                |
|     |                                | 2019 | 110.10              |     | Freight and commercial         | 2019 | 4.66                |
|     |                                | 2020 | 113.90              | 7   | operation service              | 2020 | 6.12                |
|     |                                | 2021 | 112.16              |     |                                | 2021 | 5.67                |
|     |                                | 2022 | 113.28              |     |                                | 2022 | 5.23                |
|     |                                | 2018 | 53.10               |     |                                | 2018 | 11.72               |
|     |                                | 2019 | 49.18               |     |                                | 2019 | 12.03               |
| 3   | Service of railcar facilities  | 2020 | 53.30               | 8   | Electrification service        | 2020 | 11.18               |
|     |                                | 2021 | 50.44               |     |                                | 2021 | 10.81               |
|     |                                | 2022 | 52.90               |     |                                | 2022 | 11.53               |

4. Conclusion

As the analysis of the rating of failures showed, for the transportation complex the second most important reason for failures and violations of normal operation is the lack of capacity of railway stations, i.e. the inconsistency of the level of development of the network of federal railways, the legislative framework for the organization of the process of transportation and fleets of cars moving on the network. The situation is aggravated by the lack of an effective system of centralized transportation planning, which leads to errors in the management of railcar fleets.

The transition to work with a private railcar fleet has had a negative impact on the efficiency of the entire transportation management system, the lack of proper infrastructure on the approaches to sea and river ports, the marshalling capacity of railway stations, focused on the handling of empty railcars traffic volume. It virtually eliminates the possibility of forming routes from empty railcars, creating additional load on the technical stations of the most heavy traffic areas.

As can be seen from the analysis of failures, the priority of the railway transport complex in the context of the constant increase in the volume of work is to ensure the safety of the transportation process organization. It is necessary to multilaterally consider various failures and their causes affecting the safe functioning of all subsystems. The development of probabilistic scenarios of regional growth involves continuous expansion and improvement of predictive tools.

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