STATISTICAL RESEARCH ON BRAKING MALFUNCTIONS OF PASSENGER ROLLING STOCK IN OPERATION

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Resume

In this article are highlighted the results of the research on braking malfunctions of passenger rolling stock identified during the car maintenance. Based on the collected statistical material, the key factors that cause braking malfunctions in operation are highlighted. The main brake equipment units that account for the largest number of malfunctions in operation are determined. The data on the malfunctions of air distributors used in passenger rolling stock was systematized using the STATISTIKA software package. To ensure continuous monitoring and timely detection of defects in the brake system of passenger trains, it is critical to use modern diagnostic tools to predict the technical malfunctions of pneumatic and electropneumatic brake system units of passenger cars. Moreover, this would ensure compliance with the requirements for overhaul periods for passenger cars in accordance with the current standards and technical documents and would guarantee the traffic safety on Ukrainian railways.

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1 Introduction

The operation of Ukrainian Railways (Ukrzaliznytsia, UZ) can be optimized and the high quality of passenger transportation can be ensured by implementing advanced technological solutions aimed at improving the traffic safety [1-6]. One of the research priorities in this regard is to improve the braking system of passenger cars, which plays a key role in the safe operation of rolling stock.

In practice, considerable attention is paid to the system of maintenance and repair of passenger cars, which is aimed at minimizing risks of forced train stops. That requires the systematic detection and elimination of malfunctions at passenger car maintenance depots. A significant amount of rolling stock constantly passes through the rail sections equipped with such maintenance depots at which maintenance staff performs the required technical inspection of railcars and identifies faulty and defective units. This can lead to significant delays in trains or even their stoppage on the rail hauls. Among the critical units that require special attention are brakes.

The brake equipment for passenger cars is a key element in ensuring safety and comfort during the rail transportation. It provides effective braking of the train at different operating modes, including both standard and non-standard traffic conditions. The proper operation and regular maintenance of the brake system is the foundation of reliable passenger car operation, which guarantees the safety of life and health of passengers and staff.

High reliability of the brake system during the operation of passenger trains is defined as one of the key priorities in car maintenance and repair. Potential malfunctions can be predicted by means of an integrated diagnostic system for passenger cars. It would allow monitoring the technical condition of the main elements of the brake system, such as air distributors or electric air distributors of the train in operation. Timely detection and elimination of any defects in these units would help to provide the trouble-free operation of the brake system and reduce the time required to eliminate faults, which in turn, significantly improve the safety of rail transportation.

Modern brake diagnostic systems for cars are usually labour-intensive and not always highly reliable regarding individual brake units [7]. This poses significant challenges for the railway train traffic safety. Accordingly, there is a growing need to improve diagnostic technologies to optimize maintenance and repair processes and increase the overall reliability of brake systems.

Diagnostic systems can be improved through the development of more efficient monitoring methods that can quickly and accurately identify potential malfunctions and predict potential failures. This approach will not only reduce the time for diagnostics and repairs, but significantly reduce the risks associated with the operation of passenger cars, as well, thereby ensuring a significant level of passenger transportation safety.

Analysis of recent publications. The efficient operation of rolling stock and railway transport equipment is critical for increasing the capacity and safety of rail transportation [8-9]. These aspects are fundamental for all UZ structural divisions. The optimized operation of the rolling stock and railway equipment implies not only maintenance and modernization, but the continual updating of management strategies aimed at improving the operational characteristics of the transportation system, as well.

Many studies have been devoted to analysing the operation of brake systems on railway rolling stock and improving their operating efficiency. Thus, in studies [10-11] are highlighted the peculiarities of the use of vacuum, pneumatic, mechanical, electrodynamic and magnetic rail brakes for railway transport. Their advantages and disadvantages, together with promising application methods to be implemented for any rail vehicle, are considered. However, authors of these studies did not pay attention to the diagnostics of brake equipment units of passenger cars on the train's route.

In study [12] is dealt with the methodology for computational and experimental research into the braking efficiency of passenger cars using mathematical models and computer modelling. However, the authors of the study, which was aimed at improving braking efficiency and train safety, did not pay attention to diagnosing the pneumatic units of railcars that ensure the performance of the whole braking system and the train's route speed.

Authors of study [13] described the operation of the UIC pneumatic brake system used for freight wagons. They emphasized that if a train consists of 10-15 wagons, the air brakes are difficult to control due to the complexity of the air distribution system and its operation processes, which affects the longitudinal forces in the train. The operation of the air distributor at different operational modes was analysed. However, the authors did not address the issues of controlling the pneumatic and electrical parts of the brake equipment along the train's route.

In [14], the authors emphasized that a higher train speed means that the production costs of railcar units that account for the reliable operation of the vehicle will be higher. The requirements for the development of new types of brakes for railway rolling stock with improved performance characteristics are presented. However, the authors did not pay attention to the on-board technical diagnostic tools on passenger rolling stock, the use of which would significantly increase the train speed and ensure railway traffic safety.

In study [15] is described the operation of the pneumatic brake system of rolling stock during rail freight transportation. The authors investigated the complex pneumatic processes in the train braking system. It is determined that a significant amount of compressed air leaks into the atmosphere through the loose brake connections. It is established that the modelling of dynamic processes in a pneumatic network depends on the loading of a vehicle. However, the authors did not consider the diagnostic tools that can better control the technical condition of the brake system when the train is moving.

The pneumatic braking systems of freight trains that guarantee the safe rail transportation are described in [16]. An algorithm is proposed for determining diagnostic features for advanced diagnostic systems to detect malfunctions of pneumatic brakes. It is recommended to accumulate diagnostic values using a laboratory car acting as an experimental platform. The authors used the method that allows detecting maximum values in combination with a first-order difference function to divide and classify time series of air pressure into the phases of braking and lapping. Several algorithms of the modified machine learning method are investigated. This makes it possible to achieve an accuracy of about 99% when detecting faults in the brake line of a rail car, and more than 94% when diagnosing faults in brake equipment units. However, the algorithms of the modified machine learning method proposed in this paper are applicable only to pneumatic brake systems of freight rolling stock.

In study [17] was examined the pneumatic brake system of freight trains used on Chinese Railways. A model of the brake system is analysed based on the equation of gas flow and the equation of air flow rate through the calibration holes in the brake units. The proposed model was tested in experimental conditions on 150 pilot rail vehicles. The tests were conducted at different braking modes: step-by-step braking, full braking and emergency braking. The pressure and the time of filling the brake cylinders, spare tanks, and the time response for air distributors of a freight train were studied. In addition, the switching times of the air distributor elements under the simulation conditions were determined.

The analysis of literature [8-17] has made it possible to establish that the issues of diagnosing inoperative brake systems and their elements on passenger rolling stock are quite relevant and require further development and study.

Purpose and main objectives of the article. The purpose of the article is to highlight the peculiarities of statistical research into malfunctions of brake units of passenger rolling stock in operation.

To achieve this purpose, the following objectives have to be set:

- to analyse the collected statistical data on malfunctions of brake equipment units of passenger cars;
- to systematize the data on malfunctions of brake equipment units using STATISTIKA; and
- to propose a technical diagnostic system to improve the efficiency of braking equipment units of passenger cars.

2 Materials and methods

The study of the technical condition of the brake systems of passenger cars included a comprehensive analysis of braking malfunctions at various operating modes, namely charge and release, service braking, overlapping, full-service braking, and emergency braking [18]. The key brake system components, such as electric air distributors (No. 305), air distributors (No. 292), brake lines with fittings, electric lines, brake cylinders and spare tanks, were given special attention. This technical inspection was carried out in accordance with the requirements of the current regulatory documents [19-22].

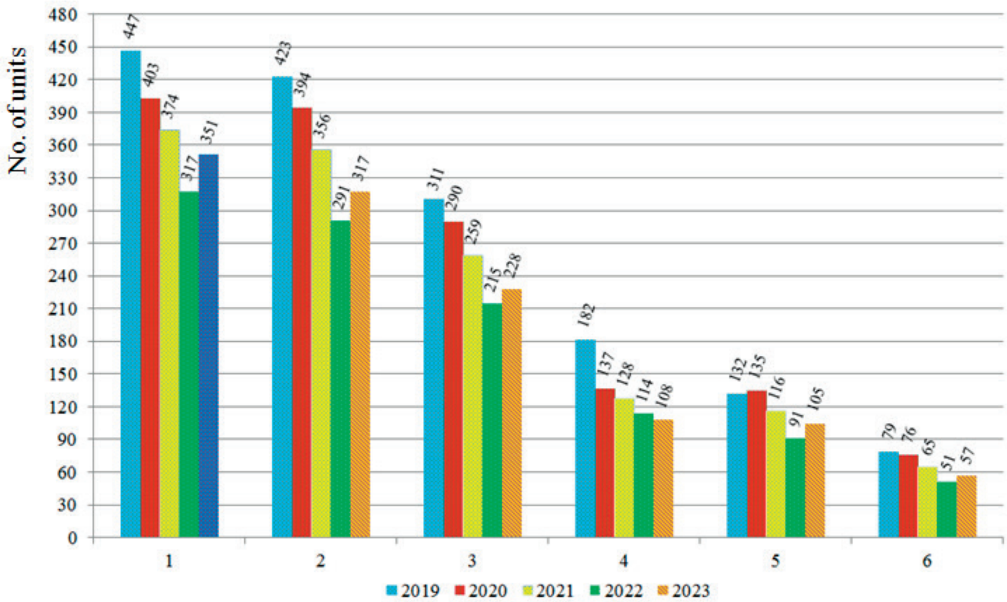
Based on the analysis of statistical data, collected during the maintenance of brake equipment of passenger cars, a histogram was constructed (Figure 1). It presents the distribution of malfunctions in the basic units and elements of pneumatic and electrical part of brake equipment collected between 2019 and 2023.

The analysis of this histogram demonstrates that in 2023 the number of malfunctions in the main units of brake systems of passenger cars decreased if compared to 2019. This is due to the decommissioning of many passenger cars that did not meet the technical requirements and the service life of which expired. Those measures helped to improve the overall reliability and efficiency of rolling stock.

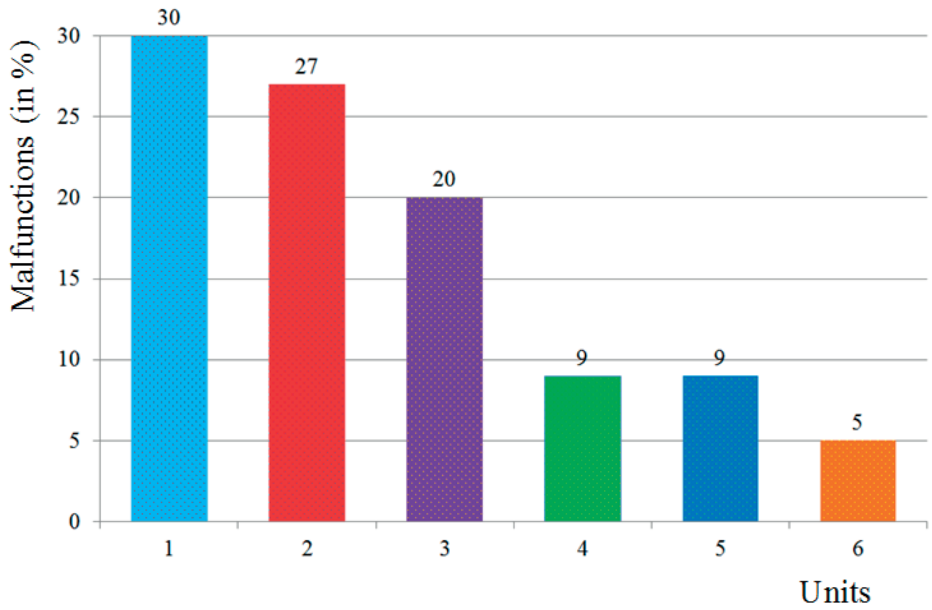
The histogram also shows that in recent years, units and elements of the pneumatic and electrical parts of the brake equipment of passenger cars fail in operation primarily due to their inoperable state. Therefore, there exist critical problems that require urgent solutions on how to improve the performance of brake systems and ensure the train safety [23].

Over 2023 the condition of brake equipment was assessed through the systematic technical inspections carried out in the operational and repair depots of the passenger facility. Based on the collected statistical data, the histogram was constructed (Figure 2). It illustrates the distribution of malfunctions of brake equipment units in 2023 by visualizing problematic aspects and their dynamics over the specified period.

The inspection conducted revealed 1,166 malfunctions of pneumatic brake equipment of passenger cars. As seen from the histogram above, electric air distributor malfunctions rank first, among which are inoperable braking and releasing valves, pneumatic relay malfunctions, clogged throttle openings, damaged

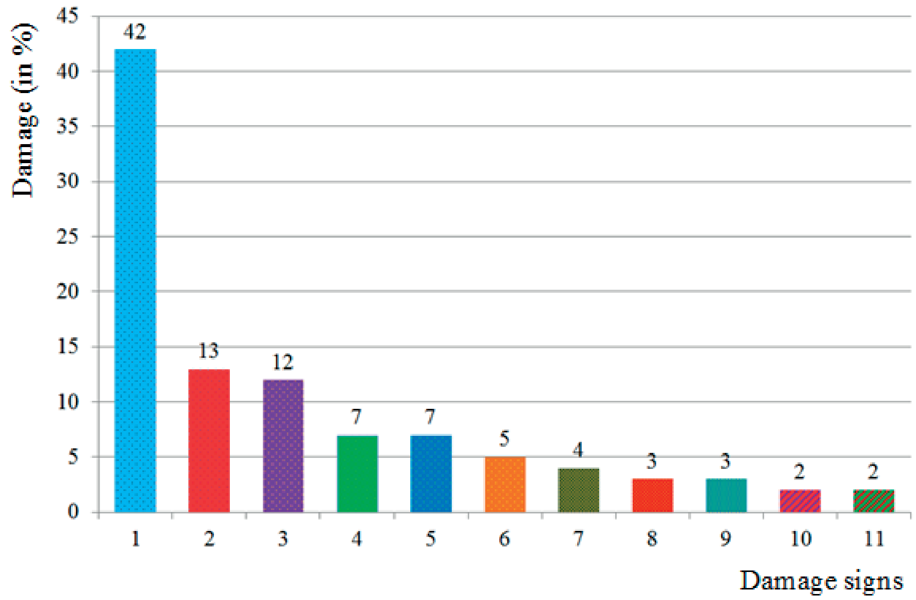


1 - electric air distributor No. 305; 2 - air distributor No. 292;
3 - brake line with fittings; 4 - electric line; 5 - brake cylinder; 6 - spare tank
Figure 1 *Distribution of malfunctions in passenger car brake equipment*



1 - electric air distributor No. 305; 2 - air distributor No. 292; 3 - brake line with fittings; 4 - electric line; 5 - brake cylinder; 6 - spare tank

Figure 2 *Distribution of malfunctions in passenger car brake equipment*



1 - air leakage due to a loose connection of the hoses; 2 - air leakage due to damage to the connecting hose; 3 - air leakage due to a loose threaded connection of the air line; 4 - malfunction of the elements of the end valve; 5 - breakage of the brake line; 6 - malfunction of the elements of the connecting valve; 7 - disconnection of the pipe leading to the air distributor; 8 - rupture of the connecting hoses; 9 - malfunction of the pipe leading to the reserve tank; 10 - malfunction of the stop valve; 11 - other malfunctions of the brake line

Figure 3 *Distribution of malfunctions in the brake line and fittings*

(broken) diodes, lack of electrical contact, etc. They were detected in electric air distributor No. 353 and amounted to 30% of the total number of malfunctions.

The air distributor malfunctions rank second; they include clogged throttle openings and filters, wear of the main and cut-off spools, wear of bushings and the main piston, etc. The inspection revealed them in 317 air distributors, which is 27% of the total number of faults.

Malfunctions of the brake line and valves rank third; they include damaged main and supply pipes, loss of density at coupling joints, inoperable end cranes, stop cranes, disconnecting cranes, etc. As a rule, such malfunctions cause air leakage from the pneumatic part into the atmosphere at all brake operating modes. In addition, the brake can spontaneously activate while the train is moving. These malfunctions were detected in 228 cars, which is 20% of the total number of units inspected.

Electrical line malfunctions rank fourth; they include damage to the contacts of the electrical part of the connecting hoses, breakdown of the electrical wire to the body, damage or reduction of the insulation resistance of the wires, lack of contact in the terminal boxes, damage or breakage of the wires, etc. Such malfunctions were detected in 108 cars, which is 9% of the total number of malfunctions.

Brake cylinder malfunctions rank fifth and include worn cuffs, weakened or broken return springs, rod wear or bending, loss of seal density between the body and the cover, etc. Those malfunctions lead to a decrease in the efficiency of train braking, they were detected in 105 brake cylinders, which is 9% of the total number of those inspected.

Malfunctions of spare tanks rank sixth and include local abrasions, corrosion and mechanical damage, overdue testing, etc. According to the inspection results, such malfunctions were found in 57 spare tanks, which is 5% of their total number.

Based on the results of the malfunctions found during the car maintenance at the servicing depot, as well as on the route, the distribution of malfunctions in the brake line and valve was obtained (Figure 3).

Based on the results of the diagram analysis, the following main malfunctions in the brake line and fittings were identified (in %):

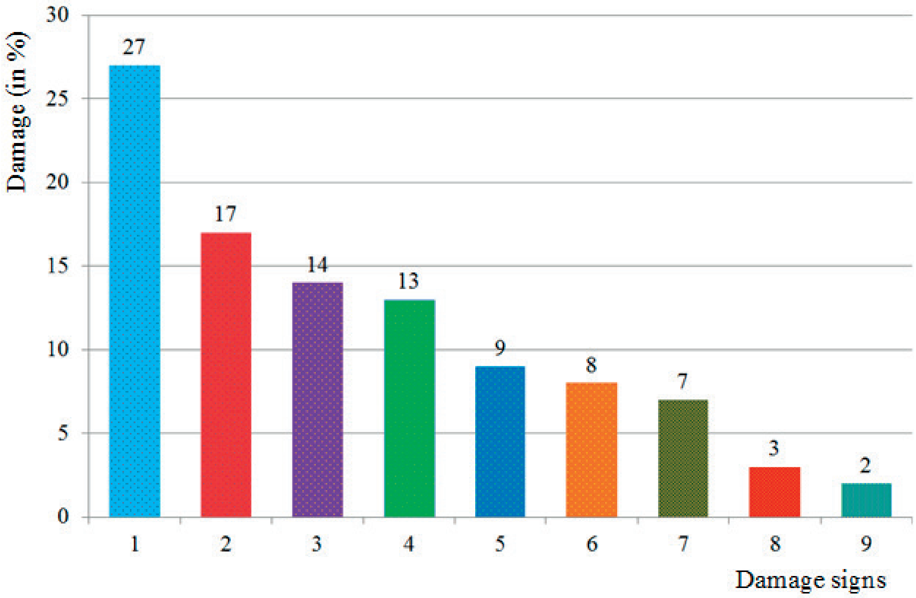
- air leakage due to lose connection of sleeves 369A (Figure 3, item 1) as a result of damage or wear of the sealing rings, wear of the profile of connecting heads, etc. (42%);
- air leakage due to a damaged connecting hose (Figure 3, item 2) as a result of deficiencies in the operation of individual elements, such as wear of the sealing ring, malfunctions of the tube and connections, etc. (13%);
- air leakage through the loose threaded connection of the air duct (Figure 3, item 3) due to damage or wear of the threaded connection, unsuitable mounting seal, etc. (12%);
- malfunctioning of the end valve elements (Figure 3, item 4) due to cracks in the body, poor installation, thread damage, broken or missing handle, etc. (7%);
- breakage of the brake line (Figure 3, item 5) due to damage or wear of the threaded connection, poor installation of the seal, fastening faults, etc. (7%);
- malfunctioning of the connecting valve elements (Figure 3, item 6) due to damaged threads, broken or missing switching handle, air leakage from the body, poor quality installation of the seal, etc. (5%);
- disconnection of the pipe supplied to the air distributor (Figure 3, item 7) due to defects in the operation of individual elements, such as wear of the threaded connection, damage to the threaded fasteners, poor-quality installation of the seal on the pipeline, etc. (4%);
- rupture of the connecting hoses (Figure 3, item 8) due to damage to the tube, wear of the hose head and ferrule thread, poor-quality installation of the seal, deformation of the clamp fastening, etc. (3%);
- malfunctions of the pipe leading to the spare tank (Figure 3, item 9) due to wear or damage to the threaded connection, poor quality of the seal, deformation or damage to their fastenings, etc. (3%);
- malfunction of the stop valve (Figure 3, item 10) due to poor installation of the seal, damaged threads, broken or missing switching handles, cracks in the body, etc. (2%);
- other malfunctions of the brake line (Figure 3, item 11) due to defects in the operation of individual elements; these defects include damage or breakage of threads, abrasions, corrosion and mechanical damage, air leakage through the threaded connections, poor installation of the seal, etc. (2%).

Of special attention is the fact that the largest number of malfunctions identified during the car maintenance was in the elements of electric and pneumatic air distributors. This is due to the complexity of their structural elements manufactured with high precision, and a significant number of calibration holes in spools and bushings [18].

Based on the statistical material collected during the maintenance of passenger cars carried out at the service depot, as well as on the route, the distribution histogram of malfunctions of air distributor No. 292 was drawn (Figure 4).

Based on the results of the histogram analysis, the following main types of air distributor malfunctions were identified (in %):

- slow charging of the reserve tank (Figure 4, item 1) due to clogged calibration holes and filters, slow movement of the main piston and spools as a result of increased resistance in the charging position, contamination or increased viscosity of the lubricant, etc. (27%, the largest number);
- air distributor does not work during the service braking (Figure 4, item 2) due to a slow movement of the main piston and spools as a result of increased resistance in the braking position, contamination or increased viscosity of the lubricant, etc. (17%);
- reduced pressure of the brake cylinder in the Lap position (Figure 4, item 3), which leads to air leakage from the pneumatic cylinder due to damaged threaded connections, poor seals and wear of the cuffs (14%);
- increased pressure of the brake cylinder in the Lap position (Figure 4, item 4), accompanied by a slow movement of the main piston and air distributor spools in the braking mode (13 %);
- the accelerator does not trigger at emergency braking (Figure 4, item 5) due to insufficient pressure in the accelerator chamber, failure to connect the accelerator chamber to the brake cylinder, and in the accelerator-off mode (9%);
- the accelerator is triggered at service braking (Figure 4, item 6) due to a slight moving effort of the main piston and air distributor spools as a result of triggering or weakening of the buffer spring (8%);



1 - slow charging of the reserve tank; 2 - air distributor does not operate at service braking; 3 - lower pressure in the brake cylinder in the Lap position; 4 - higher pressure in the brake cylinder in the Lap position; 5 - accelerator does not operate at emergency braking; 6 - accelerator operates at service braking; 7 - malfunction of an emergency braking accelerator; 8 - brakes are released unauthorizedly in the Lap position; 9 - brakes are released unauthorizedly after emergency braking

Figure 4 *Distribution of malfunctions of air distributor No. 292*

- malfunction of the emergency brake accelerator (Figure 4, item 7) is the cause of its actuating during the charging of the brake line due to a small moving force of the accelerator piston (7%);
- unauthorized release of brakes in the Lap position (Figure 4, item 8) caused by air leakage from the brake cylinder as a result of poor-quality installation of threaded connection seals or damaged release valve (3%);
- unauthorized release of brakes after emergency braking of the train (Figure 4, item 9) due to significant air leakage from the brake cylinder caused by damaged release valve of the reserve tank (2 %).

3 Results

The collected statistical data on the detected malfunctions of air distributors No. 292, for different passenger car mileages during their maintenance, are shown in Table 1.

The optimal number of experimental data n, required to verify that the sampling-normal distribution is consistent, can be determined by the ratio of the mean value of the modulus of deviation of the random variable x_i from its sample mean $\bar{x}$ to the standard deviation σ [24-25].

Provided that the following inequality is satisfied:

$$\left|\frac{\left|\sum|x_i-\bar{x}|\right|}{\sigma}-\sqrt{\frac{2}{\pi}}\right|<\frac{0.4}{\sqrt{n}}, \tag{1}$$

the sample size is considered sufficient for further research. The number $\sqrt{2/\pi}$ defines this ratio for a normally distributed random variable.

The average mileage of a passenger car after the maintenance service (MS-3) was 78,600 km, and after depot repair (DR) it was 146,900 km [26].

The data analysis was based on mathematical statistics methods for determining the variance of the population and the standard deviation, which is an estimate of the standard deviation based on the unbiased estimate of the variance [27]. The key statistical indicators were calculated using the following formulae:

- average sample value of a random variable

$$\bar{x}=\frac{\sum_{i=1}^{n}x_i}{n}; \tag{2}$$

- variance σ^2 of a random variable calculated by the formula

$$\sigma^2=\frac{\sum_{i=1}^{n}(x_i-\bar{x})}{n-1}, \tag{3}$$

where n is the size of a given sample; x_i is the i-th sample element. It was found, that $\bar{x}=31.655$, and σ^2 = 31.107.

The experimental dependence of the frequency of malfunctions in air distributor No. 292, detected during the maintenance service and on the route of passenger cars, relates to the number of observations. At the same time, the distribution function of this random variable $F(x)$ of the sample is unknown [26].

The H_0 hypothesis is formulated by the following definition: the distribution function of a random variable is described by the normal distribution law $F_0(x)$

Table 1 *Statistical data on the total number of malfunctions in air distributor No. 292*

Month of observation	No. of malfunctions	Average car mileage interval after MS-3, N, km	Average car mileage interval after DR, N, km	Month of observation	No. of malfunctions	Average car mileage interval after MS-3, N, km	Average car mileage interval after DR, N, km	Month of observation	No. of malfunctions	Average car mileage interval after MS-3, N, km	Average car mileage interval after DR, N, km
1	30	77.530	47.790	29	24	104.710	208.530	57	34	63.490	145.610
2	29	72.420	156.750	30	26	71.320	123.50	58	36	89.840	223.160
3	25	45.260	104.750	31	27	97.950	138.380	59	39	88.160	243.100
4	26	98.870	165.540	32	28	39.100	56.460	60	41	32.760	201.840
5	25	94.130	119.870	33	29	102.360	179.170	61	42	97.130	74.870
6	23	116.410	93.760	34	31	120.180	243.750	62	39	71.150	53.590
7	22	99.560	178.940	35	32	52.480	170.180	63	37	95.140	207.890
8	24	81.090	84.990	36	33	120.460	177.430	64	36	33.170	49.270
9	23	99.300	176.140	37	36	117.370	146.510	65	34	79.280	195.020
10	27	98.260	64.710	38	34	33.550	201.030	66	31	112.830	171.940
11	28	117.000	194.430	39	33	70.930	196.060	67	33	109.410	174.100
12	30	41.020	77.570	40	32	69.640	59.120	68	34	106.220	170.990
13	27	66.480	246.140	41	30	67.120	144.960	69	35	104.390	230.160
14	26	98.350	54.690	42	29	69.640	77.540	70	36	58.250	120.220
15	25	77.260	129.930	43	30	116.90	244.490	71	39	62.790	120.610
16	23	65.790	45.450	44	31	33.760	60.990	72	41	62.610	175.010
17	23	38.330	90.700	45	32	33.460	152.310	73	43	41.570	86.710
18	22	99.680	206.060	46	34	100.230	127.280	74	42	115.500	136.860
19	21	71.610	151.430	47	36	30.100	115.880	75	40	69.390	241.690
20	23	36.370	118.330	48	37	96.530	157.550	76	39	76.340	107.770
21	24	48.540	135.300	49	40	51.840	110.750	77	35	51.750	85.250
22	25	47.450	149.230	50	36	115.030	127.360	78	31	37.650	224.540
23	25	88.960	198.500	51	35	34.260	240.840	79	32	66.250	66.490
24	28	87.290	180.340	52	34	100.260	213.840	80	36	117.830	178.920
25	33	110.860	114.630	53	32	71.940	185.620	81	34	63.070	154.760
26	31	74.410	231.540	54	31	52.170	186.620	82	37	88.180	185.070
27	30	83.040	142.150	55	32	87.950	235.740	83	39	121.840	137.100
28	29	83.760	44.250	56	33	94.450	142.280	84	40	111.880	49.180

$$F_0(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}. \tag{4}$$

The function $F_0(x)$ is fully defined for the given $\bar{x}$ and σ.

The alternative hypothesis H_1: the distribution function does not follow the normal distribution law.

That is, H_0: $F(x)=F_0(x)$, H_1: $F(x)\neq F_0(x)$.

Test the hypothesis H_0.

The purpose of that is to check whether the sample is consistent with the assumption that the distribution function of the aggregate is $F_0(x)$.

Further, the consistency criterion χ^2 is used and the frequency of occurrence of a random variable included in the sample in a given interval is calculated. Based on the results of car maintenance, it was found that the number of all observations was $n=84$.

Finally, the range of sample data 20-44 is divided into 12 intervals with a step equal to two (Figure 5) and the frequency of observations, with which random variable falls into each interval is determined.

Based on the analysis of statistical data on malfunctions of air distributors No. 292 of passenger cars for 2023, the information was systematized and processed in STATISTIKA.

The results of the processing are shown in Figure 5, which presents the empirical data on the faults of this unit.

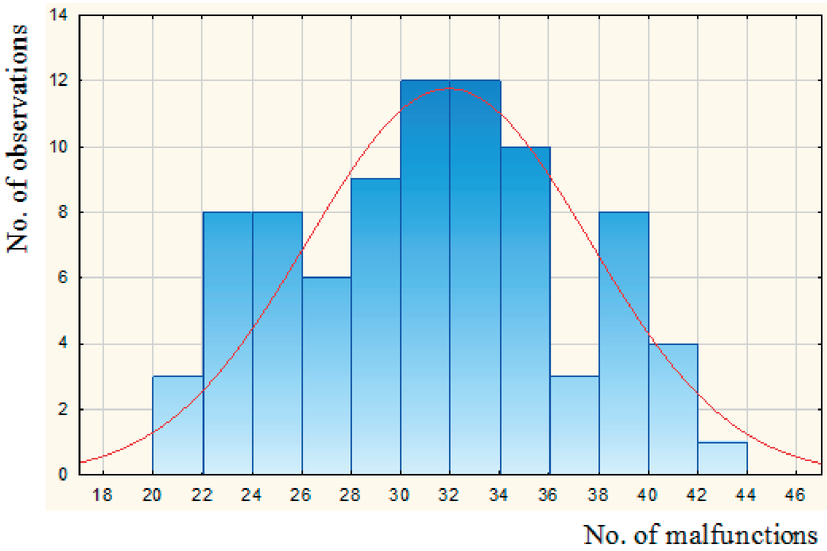


Figure 5 *Results of processing the statistical data on malfunctions of air distributor No. 292*

The solid line in Figure 5 describes the theoretical frequency of occurrence of a malfunction if the sampling distribution function follows a normal distribution law.

This statement can be confirmed or denied with the use of the χ^2 criterion (Pearson's criterion) of consistency of the distribution function *F(x)* of the sample with the normal distribution $F_0(x)$.

Pearson's theorem states that if the hypothesis H_0 is realized, then the experimental values $\chi^2(n)$ converge to the critical value χ^2_{n-1} for the *n*-1 degree of freedom.

Therefore, the new random variable χ^2 of statistics $\frac{(n_i - np_i)^2}{np_i}$ for the *i*-th interval is introduced where np_i is the corresponding value of the theoretical frequency.

Before constructing a random variable, its theoretical probability must be determined using the following formula:

$$p_i = P(x_1 \leq x_i \leq x_2) = F\left(\frac{x_2 - \bar{x}}{\sigma}\right) - F\left(\frac{x_1 - \bar{x}}{\sigma}\right), \quad (5)$$

where *F(x)* is the Laplace function;
x_1, x_2 are the left and right boundaries of the *i-th* interval.

The experimental value $\chi^2(n)$ is determined by the formula

$$\chi^2(n) = \sum_{i=1}^{m} \frac{(w_i - p_i)^2}{p_i} = \sum_{i=1}^{m} \frac{(n_i - np_i)^2}{np_i}, \quad (6)$$

where *m* is the number of intervals;
n_i is the *i-th* experimental frequency;
p_i is the theoretical probability of a random variable falling into the *i*-th interval;
w_i is the experimental probability of a random variable falling into a given interval;
np_i is the theoretical frequencies of a random variable falling into the *i*-th interval.

For the given level of significance α (probability γ) and the known degree of freedom *k*, find the critical value of the parameter x_α.

Since the degree of freedom $k = m - 1 = 12 - 1 = 11$, for the value $k = 11$ and the significance level $\alpha = 0.05$ according to the table [23, 26], the critical value of this parameter is found, it is $x_\alpha = 19.7$.

It should be noted, that at this stage of the study, the parameter α equals to the value of 0.05 as an example. At subsequent stages of the study, it is planned to adopt this parameter at a level lower than 0.05. In this case, the same methodology will be used as described in this presented research. This will allow to compare the obtained result and to draw a conclusion about the appropriateness of using this parameter in the corresponding range.

According to the criterion χ^2, the hypothesis H_0 is accepted if the following inequality is fulfilled

$$P(\chi^2_{n-1} - x_\alpha) < 1 - \alpha, \quad (7)$$

or it is equivalent to the inequality $\chi^2(n) < x_\alpha$. Otherwise, if the parameter $\chi^2(n) \geq x_\alpha$ or inequality in Equation (7) is not satisfied, the alternative hypothesis H_1 is accepted.

The experimental value of the parameter determined by Equation (6) is $\chi^2(n) = 7.55$.

According to the results of the calculations, it was found that the inequality $P(\chi^2_{n-1} - x_\alpha) < 1 - \alpha$, written in the form $\chi^2(n) < x_\alpha$, is fulfilled, since 7.55 < 19.7.

This means that the hypothesis H_0 is accepted. Therefore, the distribution function of this sample is normal.

The technical inspection of the brake equipment units of passenger cars, conducted in 2023, demonstrated that air distributors accounted for the largest share of malfunctions (27%). These results correlate with the interim findings of the study, according to which the failure rate of air distributors No. 292 depends on seasonal temperature fluctuations. In particular, there

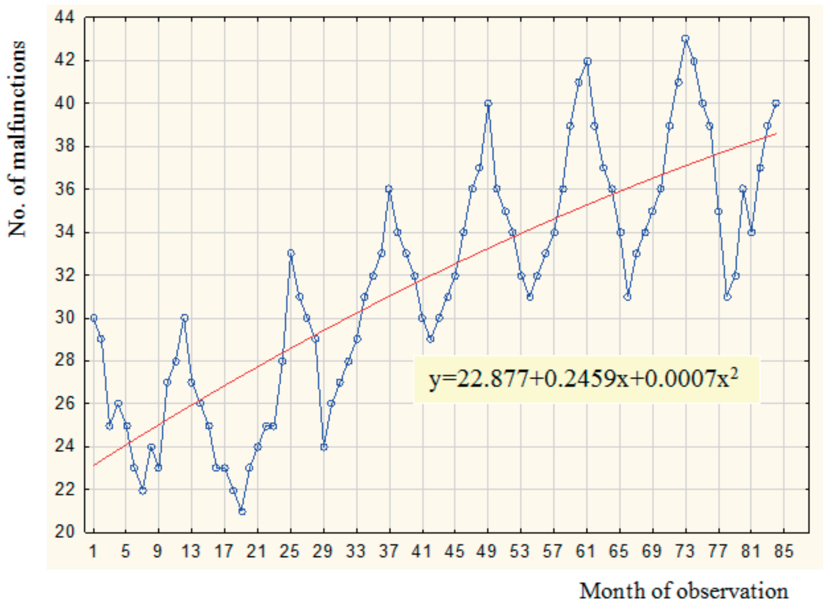


Figure 6 *Graphical distribution of malfunctions of air distributors No. 292 by month*

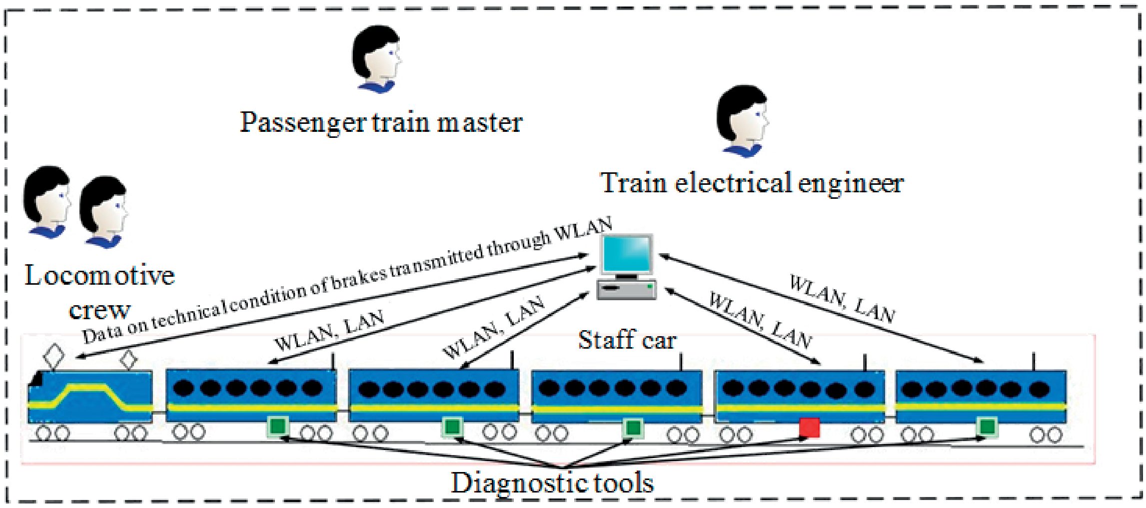


Figure 7 *The technical diagnostic system for the brake equipment of the passenger rolling stock*

is a significant increase in the number of malfunctions during the cold season (Figure 6) due to deteriorating operating conditions.

Low temperatures negatively affect the condition of air distributor components such as valves, bushings, spools, rubber cuffs and gaskets, thus causing their premature wear. The winter temperature conditions also cause a decrease in lubricant quality, destruction of valve seats and damage to other critical components, which increases the number of malfunctions in the brake system while the train is in motion. In addition, the breach of tightness in rubber cuffs and gaskets, as well as in valve seats, increases the risk of air leakage, which further degrades the performance of the brake system of passenger cars.

Based on the malfunction data and the analytical study of the operation of air distributors No. 292 under operating conditions, a number of negative factors affecting the performance of these elements were identified. They do not only cause unstable operation of the air distributors, but they do lead to increased operating costs, longer train travel times, and reduced traffic safety, as well [7, 23, 26].

It is critical to use the modern diagnostic tools to reduce the frequency of railway transport accidents caused by malfunctions in the braking equipment of passenger cars [28-29]. This would allow for timely detection and elimination of potential malfunctions in advance and, thus, ensure traffic safety.

The technical diagnostic system is based on the processes running in the brake equipment of the passenger rolling stock (Figure 7) [28].

They are also used for determining the operability of units. Diagnostic tools are used for building and analyzing mathematical models describing the operation of the brake system of a rail car. The reliable operation of the diagnostic system would ensure the maintenance of the passenger train schedule.

The main criteria of an efficient diagnostic system are the reliability and efficiency of obtaining information on the technical condition of the brake equipment of passenger cars, the speed of processing and transmission of diagnostic information, the degree of autonomy and protection against natural and human-induced interference.

The structure of the brake system of a passenger car is characterized by quantitative parameters that represent different physical variables. Their values can be initial, permissible or boundary. During the operation structural parameters change; that leads to deterioration in the technical condition of brake equipment units of passenger cars.

The condition of the brake system a passenger train can be approximately estimated using direct and indirect characteristics (diagnostic parameters). They reflect the most probable defects associated with a decrease in performance and the occurrence of brake system malfunctions.

The requirements for the system of technical diagnostics of brake units of passenger cars are to approximate the maximum compliance with the controlled parameters. They should include the following stages:

- to determine the boundary values of the criteria by which malfunctions are graded;
- to determine the list of malfunctions of the brake system units of passenger cars that need to be diagnosed;
- to develop a diagnostic model to provide information on the degree of danger of the passenger car brake system units to be diagnosed, as well as information for maintenance personnel;
- to develop diagnostic software that, at the user interface level, should formalize the process of diagnosing the units of the passenger car brake system and provide its better functionality;
- to develop the necessary measuring devices for monitoring the brake system units of passenger cars and design a data collection system for them;
- to conduct testing and assess the reliability according to the list of malfunctions of passenger car brake system units, taking into account the statistical data on operation; and
- to develop the standard technical documents, programs and methods for diagnosing the brake system units of passenger cars, and operating documentation for diagnostic equipment.

4 Conclusions

1. A technical inspection of the brake systems of passenger cars under operating conditions was carried out; the collected statistical data were systematized. It has been established that the number of malfunctions of the main units of the brake system has decreased significantly in recent years due to has decreased significantly in recent years due to the fact that a significant number of passenger cars was decommissioned due to outdated technical conditions

A detailed analysis of the statistical data revealed that the main units of brake equipment have most of the faults. Air distributors No. 292 account for a significant number of malfunctions due to their unsatisfactory performance in operation, which is caused by the complexity of their design, strict maintenance requirements and the poor-quality repair carried out at car repair facilities. In particular, it was found that 21% of the malfunctions of air distributors No. 292 resulted from excessive brake cylinder filling time during the full-service braking, 19% was the result of excessive start-up time after full-service braking, and 15% were related to a slow increase in brake cylinder pressure in the Lap mode. These malfunctions have a significant impact on the brake system efficiency and train safety.

2. Mathematical statistical methods were used to determine the distribution of faults in air distributors No. 292 used in the brake system of passenger cars. The collected data on malfunctions were processed and systematized in STATISTIKA. The analysis showed that the distribution of malfunctions was described by a normal law.

It was found that the dynamics of changes in the malfunctions of the air distributor correlated with seasonal factors that affected their occurrence. The results of the calculations showed that χ^2=7.55. This suggests that the normal distribution of the data is adequate. The variance of malfunctions was defined as σ^2= 31.107; the arithmetic mean of the number of malfunctions was $\bar{x} = 31.655$. These results help better understand the impact of external factors on the reliability of brake systems and plan the measures for their optimization.

3. A technical diagnostic system for the brake equipment of passenger rolling stock has been proposed for improving the traffic safety. This system enables effective monitoring of key parameters of the braking system of passenger cars and controlling the air pressure in the brake line and pneumatic cylinder, which varies depending on the operating mode of the brake equipment. It will also monitor how often the pneumatic brakes are applied while the train is in motion.

The use of these diagnostic tool would accurately monitor the condition of equipment in real time, predict the service life of the equipment and optimize the overhaul periods based on the up-to-date data on the technical condition of the units. Such an approach can significantly improve the traffic safety and reduce the risk of rail accidents, thus ensuring the stable and reliable operation of the brake systems of passenger cars.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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