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A SYSTEMIC APPROACH TO FORMALIZED DESCRIPTION OF FACTORS AFFECTING THE BRAKE

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Resume

The article highlights the results of the traffic safety analysis conducted in the wagon industry of Ukrainian Railways. Based on this study, it was found that the largest number of transport accidents are caused by the braking equipment of wagons. The study is based on the statistical data on malfunctions of the mechanical part of the brake equipment of bogies, in particular, those caused by the wear of wagon brake pads. The results obtained were arranged and processed in the data analysis and visualization program STATISTIKA.

Using a systemic approach, the structural, technological and operational factors that affect the reliability and efficiency of the brake system of bogies and the wagon safety were classified.

The research could contribute to increase the efficiency of the railway transport operation and maintenance of its position in the spectrum of the transportation process.

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1 Introduction

The development of Ukraine's transport system requires a comprehensive solution for increasing the operational efficiency of railway rolling stock and ensuring the safety of trains [1-2]. Whereas an increased volume of the freight transported by Ukrainian Railways (UZ) requires greater weight and higher speeds of freight trains [3-5]. All of these can be achieved by reliable operation of the automatic wagon brakes. However, the analysis of the rail transport accidents has proved that the technical condition of the brake equipment has significantly deteriorated in recent years. The largest number of damages has occurred to the mechanical part of brakes, which is the key element of the train traffic safety. The inspections of the brake systems of bogies, belonging to the UZ's inventory wagon fleet and industrial enterprises, have shown that most of the devices for the parallel retraction of brake shoes are in an unsatisfactory condition. One of the reasons is the imperfect design of the brake lever transmission (BLT) of bogies.

A typical break beam used in bogies has a balanced suspension. However, this condition is violated after the BLT elements are attached. Under the influence of forces, generated by the weight of the attached elements, the brake beams incline and come closer to the wheels while the upper ends of the pads press the wheels. When the wagon moves without braking, the upper ends of the pads rub against the wheels. As a result, the upper parts of the brake pad area are subjected to intense abrasion, which causes abnormal wear. During the braking, a harmful abrasion of the pads adds unwanted contact friction, which reduces the braking performance of trains and increases the risk of train derailments. It also creates conditions for the high-temperature surface damage to the wheels. Therefore, most wagons are running with loud tapping wheels, which increases the resistance to movement and leads to unnecessary energy consumption for train traction. In addition, this circumstance may contribute to the occurrence of rail transport accidents. In this regard, the issue of identifying the factors affecting the reliability of the wagon brake system is urgent.

Given the acute urgency of the problem of ensuring the train safety, experts and scientists from different countries have carried out numerous studies, based on which various devices and brake lever transmission mechanisms have been developed to eliminate or slow down the intensive wear of pads, for example, such as the dual wedge-shaped wear. Thus, in [6] the authors proposed a brake pad retraction device for wagon bogies with automatic correction of the relative position of the brake pads with respect to the rolling surfaces of wheels. However, such a device complicates the BLT and requires periodic labour-intensive adjustments in operation, thus making it impractical.

The issue of improving the efficiency of the pneumatic brake on the hopper wagon is covered in [7], where the authors proposed the modernisation of the BLT design and substantiate it using Solid Edge Siemens PLM Software. However, it is not quite clear how the maintenance and repair of the functionally configurated levers can be carried out. In addition, it should be noted that the calculations did not take into account the final forces acting on the pads for which such a BLT was designed.

Over the past decade, experts from many countries have been studying the specifics of the braking process in rail vehicles so that to improve the efficiency and reliable operation of BLT. For example, in study [8] is described the calculations of the braking force of a vehicle equipped with a UIC pneumatic brake designed for passenger trains, while in study [9] is presented an attempt to integrate this idea into the wagon fleet, which would improve the braking efficiency and, consequently, traffic safety.

The peculiarities of ensuring the stable friction properties of brakes used for railway rolling stock are given in [10]. A new approach to achieve a stable friction coefficient during different train brake modes is proposed. Various designs were used to modernise the elements of the brake pad/wheel tribotechnical pair and their mechanical characteristics; the results were experimentally confirmed. However, these studies were made for the disc brake.

In study [11] the analysis is highlighted of some typical block brakes rationally used on Chinese subway vehicles. Among their advantages are flexible operation, quick response and compact structure. In some countries block brakes are used on wagon bogies for more efficient braking and uniform wear of brake pads. However, their use in wagon bogies will increase the weight, air consumption for braking, repair time and complexity of wagon maintenance.

A scientific approach to assessing the efficiency of the wagon brake system is presented in study [12]. An information model for describing the wagon braking is proposed. The study also presents mathematical models with the main characteristics of the braking system, which allows estimating the braking efficiency of the train. However, the calculations of braking processes do not include the coefficient of abnormal wear of brake pads, which can significantly affect the wagon braking distance.

An analysis of the quality performance of cast-iron and composite pads used on different vehicles is highlighted in [13]. Some negative factors of the brake pad operation are given, their impact on the environment and processes that cause damage to the rolling surface of wheels of the rolling stock are described.

An analysis of braking devices in the shoe/wheel tribotechnical pair is given in [14]. The negative consequences of using shoe brakes are also given. The recommendations for the use of disc brakes with conventional tribotechnical pairs are provided [15].

Authors of [16] have dealt with the effect of brake pad material (composite rubber compound) on the rolling surfaces of wheels under operating conditions. The study also gives a review of literature sources covering similar research. It is established that the causes of wheel malfunctions are affected by the thermal conditions mainly during braking. The authors prove that the temperature on the rolling surfaces of wheels during braking with composite-rubber-compound pads can reach values of more than 900 °C. The main reason for this is the relatively low thermal conductivity of composite-rubber-compound pads in comparison with the thermal conductivity of cast-iron pads. However, the studies described do not take into account the fact that in most wagons, more than 90% of composite brake pads have dual wedge-shaped wear. Therefore, such pads have a smaller brake area if compared to new pads, which negatively affects both the braking efficiency and the appearance of surface high-temperature defects on the wheels in operation.

Authors of studies [17-19] emphasize that the overheating of tribotechnical pairs can cause malfunctions of the brake system and adversely affect the traffic safety. Thus, theoretical studies were carried out regarding the possibility of increasing the heating temperature of tribotechnical pairs during braking for different speeds and brake disk designs.

The results presented in [20-22] confirm the predominant influence of thermal loads over the mechanical ones, as well as the residual stresses caused by the high thermal loads in the all-metal wheel with a block brake.

The analysis of literature sources has made it possible to conclude that the issues of better rail traffic safety by improving the operating conditions of brake systems are quite relevant. At the same time, these issues require further research.

The purpose of the study is to formally describe the factors affecting the functioning of the BLT elements using a systemic approach. To achieve this purpose, the following tasks were defined:

- to analyse the state of the problem of train safety; and
- to classify the factors affecting the reliability

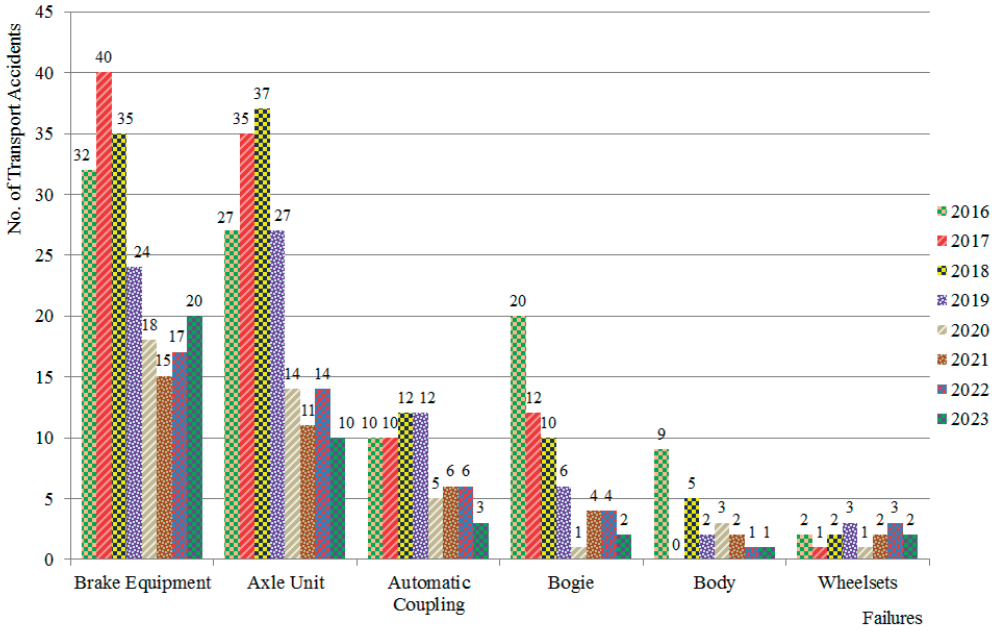

Figure 1 *The comparative bar chart of transport accidents in the wagon industry by type of wagon component failures*

and efficiency of the wagon brake system using a systemic approach.

2 Materials and methods

The main causes of railway accidents, due to wagon malfunctions caused by the fault of wagon repair enterprises, are:

- faulty wagon components due to low-quality repairs;
- poor organisation of train maintenance;
- lack of equipment, instruments, tools, means of diagnosis and flaw detection, spare parts for quality repair and maintenance in accordance with the requirements given in regulatory and technical documentation;
- poor-quality repair and testing of brake equipment units;
- violation of the regulatory and technical requirements during scheduled repairs and maintenance; and
- unsatisfactory technical training provided for maintenance and operating personnel.

The quality of work of the wagon industry can be assessed by the number of transport accidents, failures and malfunctions of technical means over a certain time period. For UZ the main condition of traffic safety is ensuring the reliability of the brake equipment of wagons, which is the backbone of traffic safety. For modern rolling stock it can be improved by means of proper identification of causes of malfunctions of the brake equipment [23].

The analysis of traffic safety for the UZ wagon fleet over a period from 2016 to 2023 was based on the number of failures in wagon units, as shown in the comparative bar chart (Figure 1).

Figure 1 shows that in recent years, the wagon brake equipment has become one of the most vulnerable elements under modern operating conditions and for most wagons it is in a poor state. It can also be seen that the number of transport accidents with wagons has been steadily declining over the past few years. The main cause is the reduction in the UZ inventory wagons fleet. It can also be seen that the number of wagons repaired at depots or repair enterprises has been steadily declining recently. Therefore, the reduction dynamics regarding the number of transport accidents in relation to the number of wagons repaired in recent years has amounted to 0.23%. This indicates that the reduction in transport accidents in the wagon industry invariably depends on the number of repaired wagons, however the traffic safety is not improving [24].

Based on the analysis (Figure 1), it was found that the largest number of transport accidents in the wagon industry between 2016 and 2023, caused by unsatisfactory operation of brake equipment, occurred in 2017 and amounted to 40 accidents. Therefore, it was decided to pay more careful attention to the quantitative assessment of failures in braking equipment that had led to transport accidents on the Ukrainian railways.

Such a qualitative analysis of brake equipment failures between 2002 and 2023 was based on the regulatory and technical documentation. Based on the results, a bar chart was constructed (Figure 2), which shows that the largest number of transport accidents due to brake equipment failures, 113 accidents in 2003, occurred due to poor quality repairs provided by UZ wagon repair enterprises. It can also be seen that the number of transport accidents due to brake equipment failures had been constantly changing by year. This has proved once again that Ukrainian wagon repair

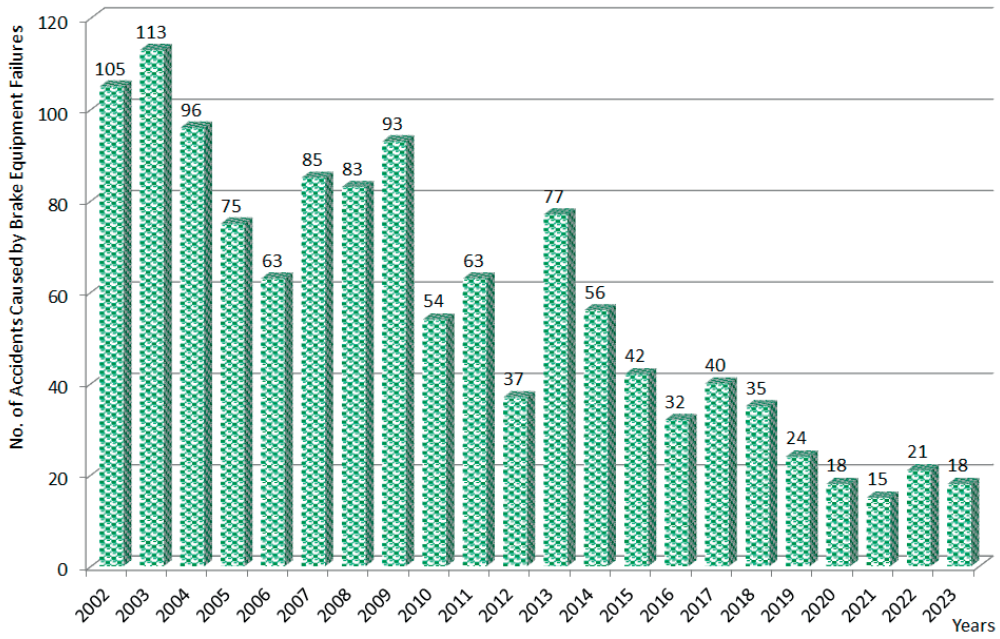

Figure 2 *The bar chart of the distribution of failures in the wagon brake equipment that led to transport accidents*

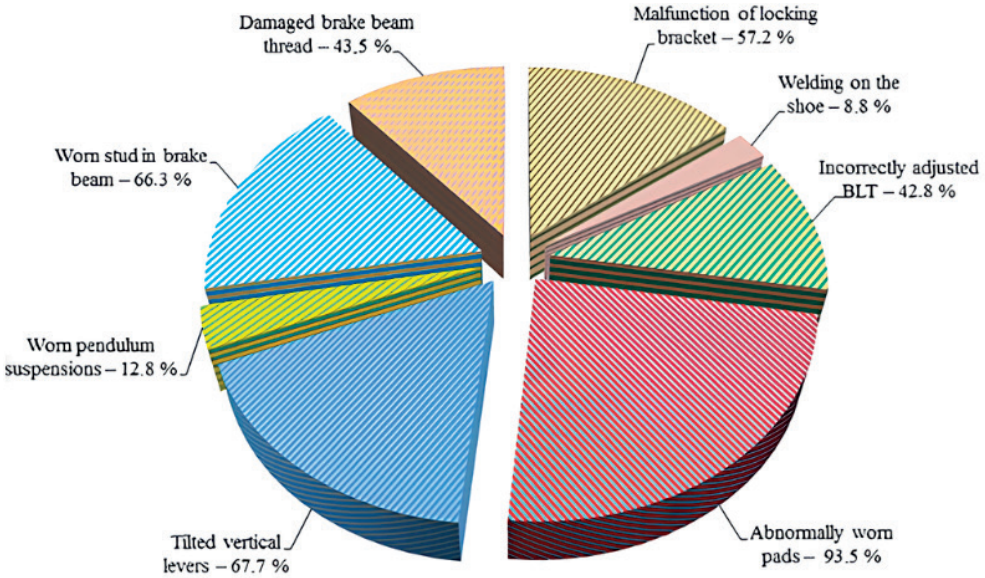

Figure 3 *The distribution diagram of malfunctions in the mechanical part of the brake equipment of wagon bogies*

enterprises provide poor quality repairs of wagon brake components due to the use of outdated equipment. Despite the fact that the number of failures has been decreasing rapidly in recent years, the safe operation of wagons it not guaranteed.

Based on the results of the analysis of transport accidents in the wagon industry, it was found that the wagon braking equipment ranked first in terms of failures and malfunctions occurred in operation. Therefore, the technical condition of the mechanical part of wagon brake elements was studied at wagon repair enterprises through 2023. The BLT of wagons was inspected at wagon repair enterprises specializing in brake beams. During those inspections, all the dimensions of the BLT components were checked using measuring tools and templates; then the components were divided into the following groups:

- components that can be used without repair;
- components that need repairing according to the technological process;
- components that cannot be repaired but can be used for other purposes at the wagon repair enterprise; and
- components that cannot be repaired and should be sent for scrap.

While dividing the BLT components into these groups, their defects were thoroughly recorded and further used in the research. A total of 5,702 BLT

components were inspected, and the following diagram was drawn based on the results of the statistical data obtained (Figure 3).

Based on the observation results, the following main types of malfunctions were identified:

- abnormal brake pad wear formed due to failures of the device for the parallel retraction of the brake shoes - 93.5% (Figure 4, a);
- malfunctions of brackets and locks (devices for parallel retraction of the brake shoes), i.e., incomplete retraction of brake pads from the rolling surface of wheels in operation due to the inoperability of standard devices - 57.2% (Figure 4, b);
- wear of the brake beam stud due to its interaction with the bracket - 66.3% (Figure 4, c);
- increased tilt angles of vertical two-arm levers, especially the internal levers of the BLT of bogies in the braked state with full-size and maximally worn composite brake pads due to a relatively large thickness of pads reinforced to 65 mm, which negatively affects the braking efficiency of wagons - 67.7% (Figure 4, d);
- damage to the threaded part of the brake beam head for connecting the crown nut, which forces the shoe with a pad to slip behind the outer edge of the wheel thread and causes the ridge wear of the pad in operation - 43.5% (Figure 4, e);
- misalignment of the BLT due to the incorrectly selected locations for the pivot pins in rods and links - 42.8%;

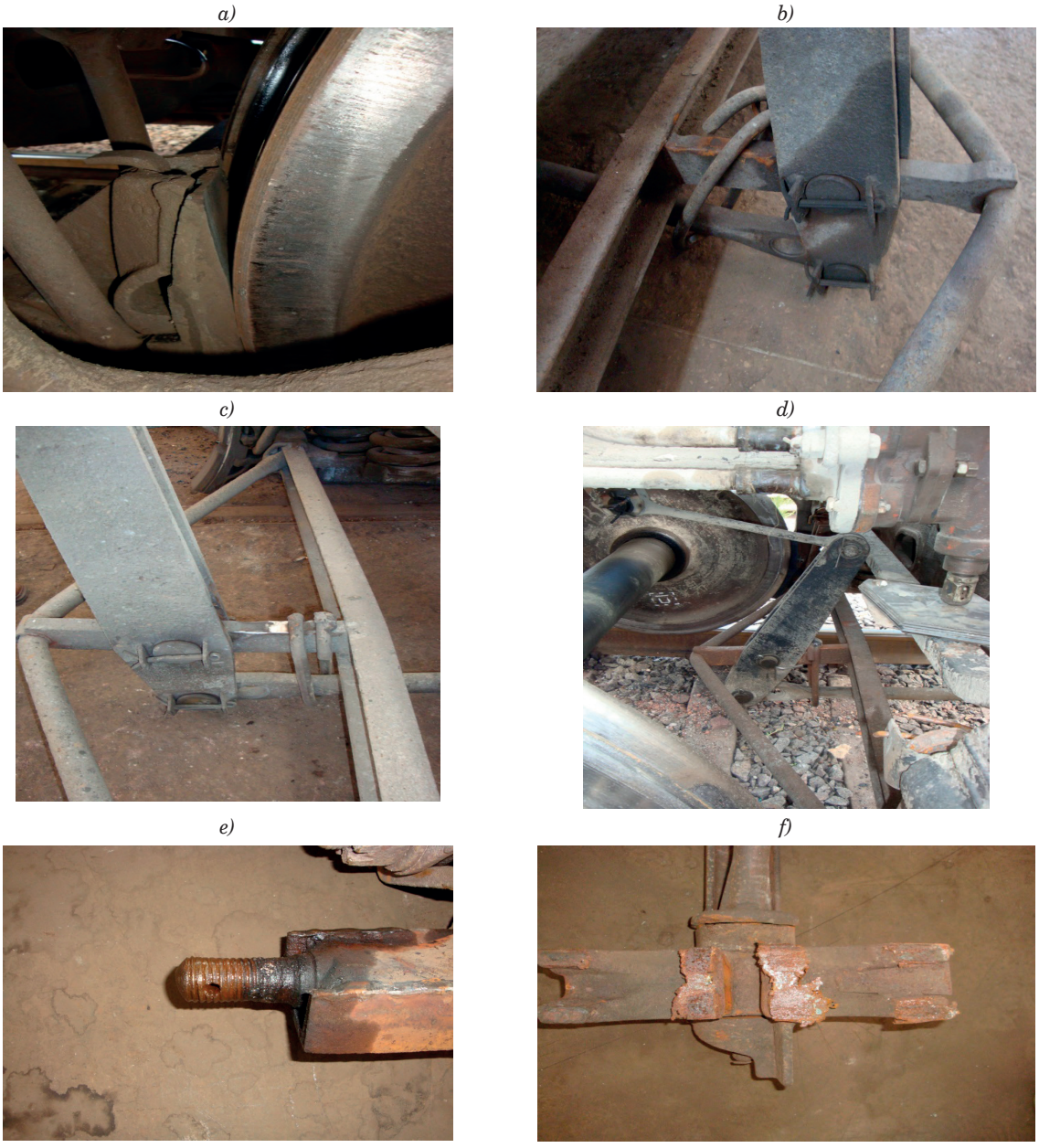

Figure 4 *Malfunctions of the mechanical part of the braking equipment in wagon bogies*
a) abnormal pad wear; b) deformation of bracket and absence of lock; c) worn brake beam stud; d) tilt of the vertical lever; e) damage to the threaded part on the brake beam head; f) welding on the shoe

- worn pendulum suspensions resulting from the local contact of their cylindrical part with the shoe - 12.8%;
- welding on the shoe due to a maximally worn pad with its subsequent destruction - 8.8% (Figure 4, f)).

In practice, the malfunction of the pad can occur in operation due to the adverse effect of forces that reduce the braking efficiency; in terms of the traffic safety, it is unacceptable. Thus, the investigation of the brake pad wear in wagons cannot be carried out without taking into account the cause - wear - effect relationship.

3 Results

The statistical data obtained by inspecting the brake pads for different wagon types made it possible to analyse the formation of dual wedge-shaped wear and assess the braking efficiency for the rolling stock.

The statistical data on the wear of wagon brake pads were arranged and processed in STATISTIKA. The results of the calculations are shown in Figure 5. The results of statistical data processing in the "STATISTIKA" software package made it possible to establish that the distribution of the wedge-dual wear of brake pads during their use in a typical brake lever transmission is not described by a normal law (red curve in Figures 5-6). At the initial stage of wagon operation, new pads wear out mostly due to the free-running and traction modes rather than the braking mode. Thus, the upper parts of the working surfaces of pads wipe (the edge vibration wear) due to the wagon dynamics; it becomes the centre of the dual wedge-shaped wear with the simultaneous tilting of the pad [25-26].

When the wagon mileage increases from 23,000 to 26,400 km (Figure 6, Position 1), the pad wears intensively forming the dual wedge-shaped wear. However, when the wagon mileage increases from 35,000 to 44,700 km, the wear in the upper part of the pad slows down (Figure 6, b, Position 2) [27].

The analysis of field surveys and analytical studies of the dual wedge-shaped wear of brake pads have made it possible for the first time to identify the negative factors associated with significant damage to the railway infrastructure and the environment.

The current development of the wagon-building and wagon-repair industry involves the search for the new scientific methods on how to design and modernize wagon assemblies. Therefore, the systemic approach is the basis for developing a classification of factors affecting the reliability and efficiency of the mechanical BLT of wagons [28]. This approach can help to consider the BLT as an integrated system of components, connections, and properties that specify the whole brake system in operation. An important step of this systemic approach is determining the BLT structure, i.e., the identification of elements, their connections and interactions. The structure of the mechanical BLT of the wagon under study can be considered for both analyzing its properties and describing it as a set of individual interconnected elements.

The systemic approach can also be used for the classification of factors contributing to the abnormal wear of the brake pads of bogies in operation; these factors can be divided into the following groups:

- structural, including the shape, size, materials of brake system components, types of their interconnections, etc.;
- technological, including specific requirements for the BLT components in production and repairs; and
- operational, ensuring the proper use of the BLT of wagons over the guaranteed inter-repair period.

Figure 7 presents a classification of structural, technological and operational factors affecting the reliability and efficiency of the braking system of wagon bogies, and train safety, based on the systemic approach.

The structural factors include:

- offset hole in the brake beam due to the BLT design features of wagon bogies. This can lead to the brake beam disbalance and cause the dual wedge-shaped wear of pads;
- a guide mechanism for the brake lever gears is not provided in the design, therefore the pads incline to the wheels when the brakes are released in the traction and free-running modes, which causes abnormal wear of the pads; and

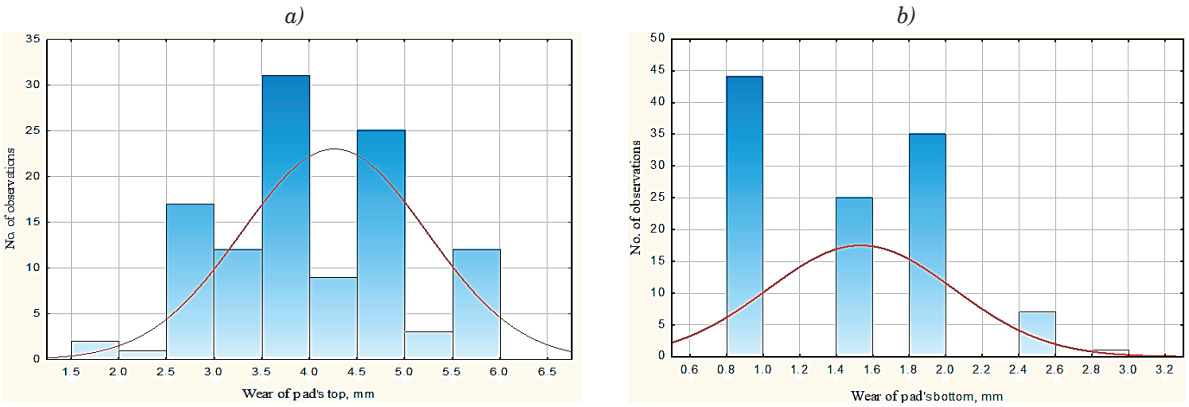

Figure 5 *The brake pad wear for the wagon mileage from 7,200 to 10,000 km a) pad's top; b) pad's bottom*

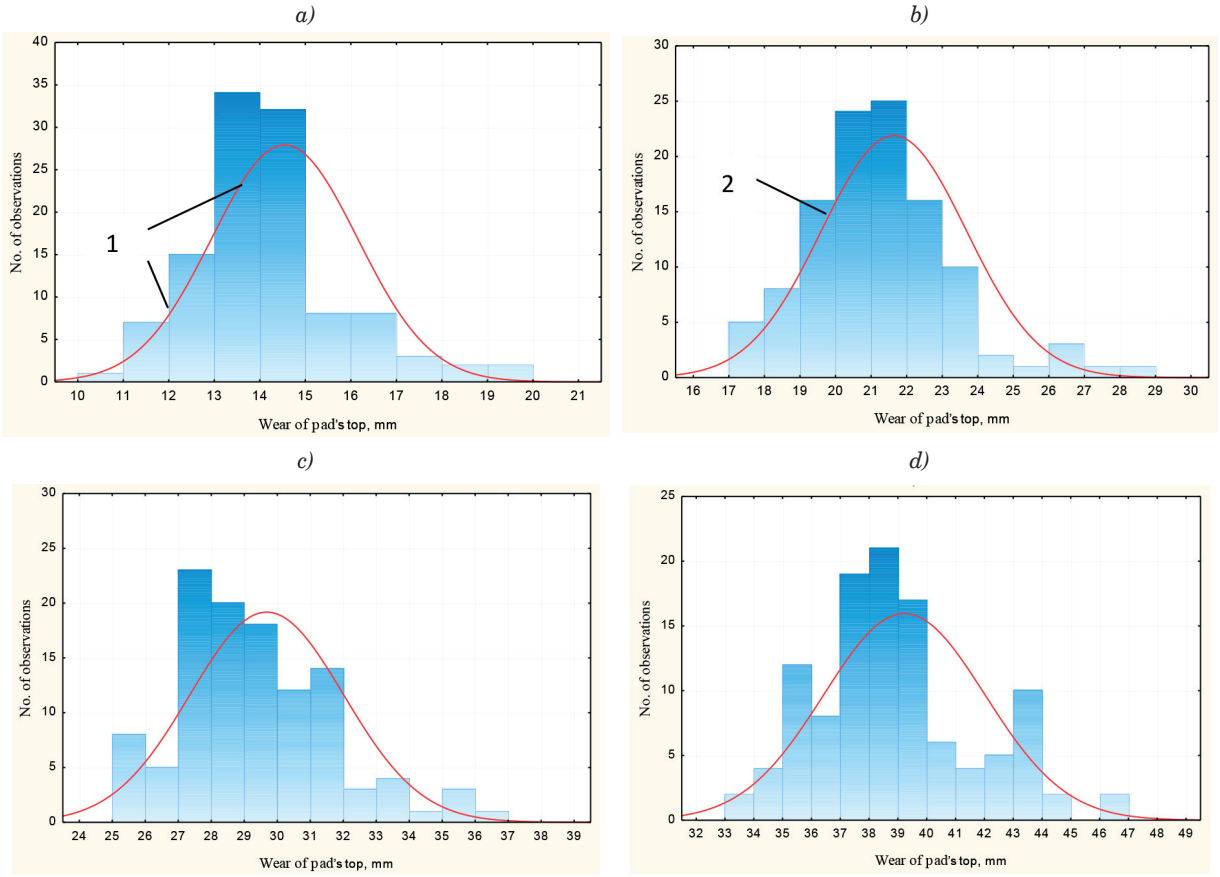

Figure 6 *The wear of the pad's top for the wagon mileages a) 23,000 - 26,340 km; b) 35,000 - 42,300 km; c) 44,700 - 48,000 km; d) 59,300 - 62,400 km*

- geometrical features of pads affect the contact area of the brake pad/wheel tribotechnical pair. Pads must have the geometric friction surfaces, which are similar to the rolling surfaces of wagon wheels. If geometric parameters of the pads change, that will negatively affect the braking efficiency of a vehicle.

The technological factors include:

- violation of the production technology of the BLT of wagon bogies, which results in changes in the mechanical properties of the BLT components, increased wear and violation of nominal dimensions accompanied by operational defects;
- violation of the repair technology of the BLT of wagon bogies, which results in changes in the geometric dimensions of the components. During the welding and surfacing, the metal structure can be distorted, which changes the properties of components, creates microcracks and other defects, thus reducing the BLT reliability;
- violation of the assembly technology for the brake beam, which results in changes in the geometric dimensions of its parts. In braking, it can lead to the BLT malfunctions and displacements of pads relative to the rolling surfaces of wheels;
- violation of the BLT adjustment technology, which results in an increase or a decrease of clearances between the shoe and the wheel, provided that the M 1180.000 device is in a good working condition. If the clearances were reduced and the BLT was not adjusted properly, the pads may rub against the wheels when the brakes are released; it results in defects on the rolling surfaces of wheels as well as abnormal pad wear. The effects of increased gaps and violations of the conditions for the BLT adjustment are: 1) the braking efficiency decreases and the train safety deteriorates; 2) the probability of damage to the BLT increases and the lever gears can tilt; 3) hinge elements in the BLT can be damaged due to vibration in operation; and 4) pads are displaced relative to the rolling surfaces of wheels due to increased gaps between the pad and a wheel when braking.

The operational factors include:

- damage to the device M 1180.000 of the BLT of wagon bogies due to a malfunction of the lock and stretching of the bracket; it results in the disfunction of a device together with appearance of the standard clearances between the pad and the wheel. When the train is running without braking, the upper end of the pad rubs against the rolling surface of the wheel and causes harmful abrasion in its upper part. For the pads with dual wedge-shaped wear, the specific pressures in the upper part of the pad increases, and the friction temperature of the

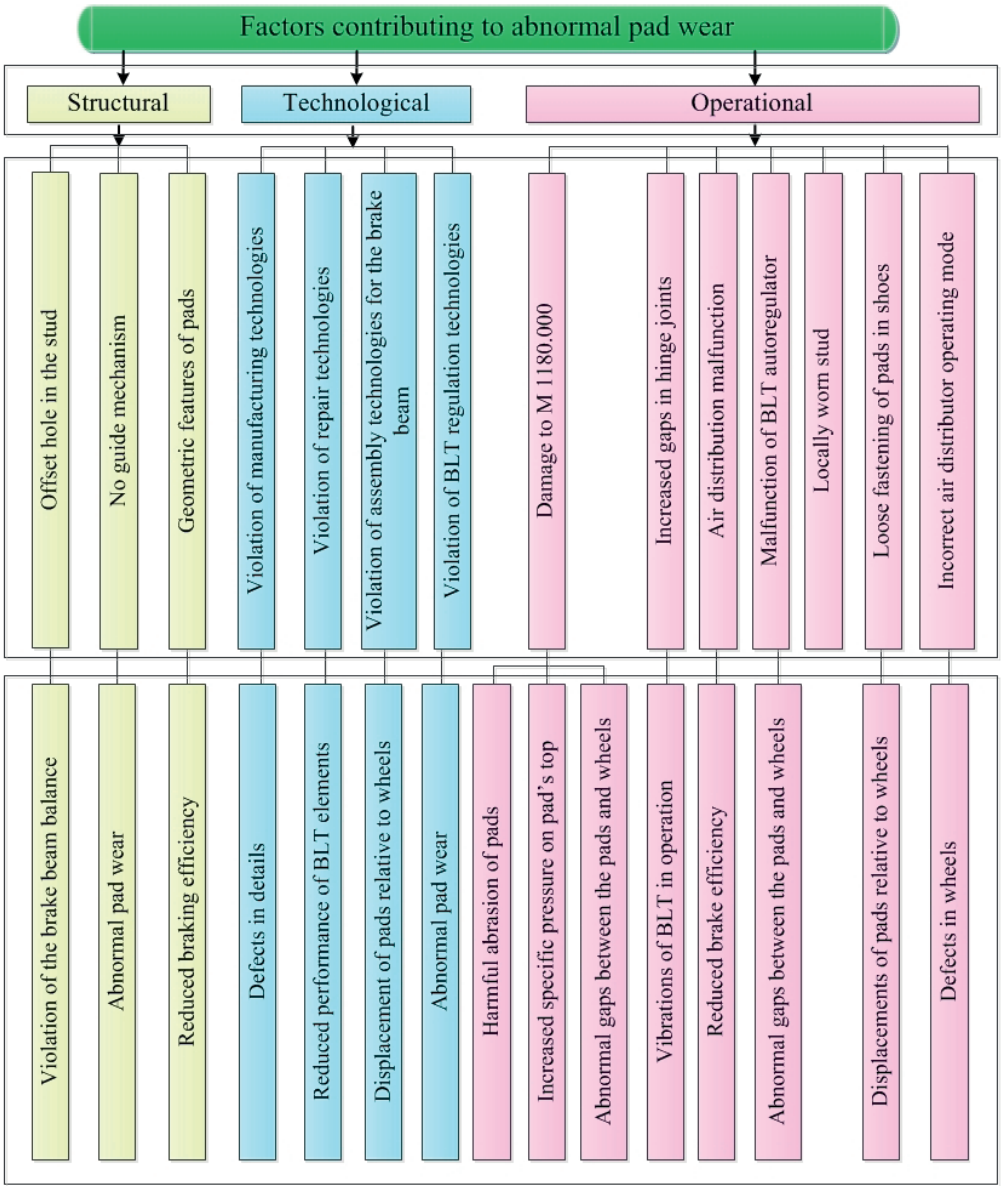

Figure 7 *The factors affecting the reliability of wagon brakes*

tribotechnical pairs increases at the point where the planes separate; it causes high-temperature damage to the rolling surface of the wheel;

- increased gaps in the hinge joints of the BLT of wagon bogies when the train is moving over a rail joint, a track irregularity or a rail switch result in increased displacements of the elements and their intensive wear due to vibrations from the BLT in operation;
- air distributor malfunctions cause slow brake release or failure to release the brake, which leads to an increase in the temperature of the brake pad/wheel tribotechnical pair, its increased wear and damage. In addition, a faulty air distributor can cause unauthorised brake release, which can lead to the wagon brake release and reducing the braking efficiency of the rolling stock, as well as impairing the traffic safety;
- malfunction of the BLT autoregulator leads to a violation of its dimensions in operation in accordance with the current regulatory and technical requirements, thus affecting the abnormal gaps between the pad and the wheel;
- local wear of the brake beam stud occurs due to its permanent contact with the bracket of the device M 1180.000 of the BLT of wagon bogies, which is caused by its failure and leads to dual wedge-shaped wear of the pads when the train is moving without braking;
- improper fastening of the pad in the brake shoe due to the application of non-standard fasteners, worn retaining keys or shoes can lead to increased gaps between the contacting surfaces and displacement of the pad relative to the wheel when braking;
- incorrect operation mode of the air distributor in the wagon causes excessive pressure of the brake

pads on the wheels, resulting in increased wear and damage, as well as the jamming of the wheelsets and leads to slides, scrapes and other defects on the rolling surfaces of wheels.

It is important to note that the negative effects of the above-mentioned classified factors can reduce the train braking efficiency, increase energy consumption needed for the train traction, reduce the service life of the pads, damage the rolling surfaces of wheels and negatively impact the environment; they also cause the significant damage to railway infrastructure and train safety. In this regard, further research will aim at developing measures for the BLT modernisation, which will increase the mileage of wagons with composite pads and extend their residual service life over the overhaul period [29-31]. This would contribute to increase the efficiency of railway transport operation and maintenance of its position in the spectrum of the transportation process [32-35].

4 Conclusions

1. The analysis of the transport accidents on Ukraine's railways has been carried out. It has shown that from 2016 to 2023, the largest number of such accidents were caused by faults in the brake equipment, which threatened the traffic safety of wagons.

The analysis of transport accidents caused by brake equipment failures in wagons, occurred from 2002 to 2023, has shown that their peak was in 2003 (113 accidents), whereas the smallest number was recorded in 2021 (15 accidents). However, these statistics are not encouraging, given that wagon fleet of Ukrzaliznytsia has been significantly reduced.

The statistical data on malfunctions of mechanical systems of the wagon bogies brake equipment was investigated. It was found that out of 5,702 brake lever transmission (BLT) elements examined, the largest percentage of failures occurred due to abnormally worn composite brake pads and amounted to 93.5%. The locking brackets of the device for the parallel retraction of brake shoes also suffer significant damage during the operation of wagons, which amounted to 57.2%, whereas the cases of worn brake beam studs amounted to 66.3%. In addition, one of the main faults in the BLT of bogies is inclined vertical levers of the brace beam, which amounted to 67.7%. All the above-mentioned faults in the BLT have a direct impact on the abnormal wear of wagon brake pads.

2. A systemic approach was used to determine the factors contributing to abnormal wear of pads in the BLT of wagons. The factors mentioned can lead to the deterioration in the braking efficiency of trains, increased energy consumption needed for train traction, shortened useful service life of the pads, damage to the rolling surfaces of wheels, and negative impact on the environment.

The proposed classification of factors affecting the BLT reliability could help to develop recommendations for the design of modern wagon brake structures. This would reduce operating costs during the freight transportation, as well as increase traffic safety of trains by modernizing the design of the mechanical part of bogie brakes.

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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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