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CAUSE AND EFFECT RELATIONSHIPS OF FAILURES IN THE FUNCTIONING OF STRUCTURAL COMPONENTS OF RAILWAY ROLLING STOCK

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ПРИЧИННО-НАСЛІДКОВІ ЗВ'ЯЗКИ ВИНИКНЕННЯ ВІДМОВ ФУНКЦІОНУВАННЯ КОНСТРУКТИВНИХ СКЛАДОВИХ РУХОМОГО СКЛАДУ ЗАЛІЗНИЧНОГО ТРАНСПОРТУ

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The article reveals the peculiarities of the importance of research work on determining the cause and effect relationships of failures of the functioning of structural components of railway rolling stock can hardly be overestimated due to their multifaceted role in ensuring the safety, efficiency and economy of railway transportation. These studies are critical to improving traffic safety, as failures of structural elements can lead to catastrophic consequences, including human casualties and significant material damage. Cause-and-effect analysis allows for the development of effective methods to prevent such failures, minimising the risk of accidents. From the perspective of operational efficiency, research into the causes of failures helps to optimise maintenance and repair processes, reducing downtime and increasing the reliability of rolling stock, which in turn contributes to the smooth movement of goods and passengers, increasing the economic efficiency of rail transport. Particular attention is paid to the analysis of physical and mechanical factors related to the metal manufacturing process and operational factors, such as corrosion damage.

In addition, research and development plays a key role in reducing operating costs, as predicting and preventing failures reduces the amount of repair work and overall maintenance costs. Research also contributes to extending the service life of rolling stock by identifying weaknesses in design and materials, which allows for the development of measures to strengthen and improve them. An important aspect is the introduction of new technologies, such as remote monitoring systems and non-destructive diagnostics, which allow potential failures to be detected at an early stage, increasing safety and efficiency. Finally, research into the causes of failures helps to reduce the risk of environmental disasters, especially when transporting hazardous goods, ensuring the environmental safety of rail transport. It is proved that research and development is an integral part of ensuring the safety, efficiency and economy of railway transport.

***Keywords**: Transport, freight transportation, automation, reliability, rolling stock, traffic safety, cause and effect relationships.*

Introduction. Ukraine's railway industry accounts for 75% of the country's total cargo turnover. According to operational data, in 2024, Ukrzaliznytsia transported 174.93 million tons of cargo, which is 17.9% more than in 2023, and in 2021 - 314 million tons. The fleet of freight cars used for transportation includes more than 120 thousand cars. At the same time, the average level of depreciation of Ukrzaliznytsia's fleet remains critical at 90%. In particular, 73.3 thousand railcars (70%) have exceeded their standard service life, 18.4 thousand have served one and a half years of their standard service life, and, accordingly, the wear and tear on their bodies and running gear means an increase in accidents and traffic safety requirements, and they should be written off. By 2026, 40 thousand railcars, or one in three, are to be written off. At the same time, experts estimate that the number of new railcars needed is almost 145 thousand units. That is, there is a huge shortage of freight cars, which is partially covered by cars from non-state-owned operating companies or foreign cars. This state of the railcar fleet requires its renewal. Renewal of the fleet is critically needed - currently, only 1 railcar out of 6 meets modern requirements [1].

It is known [2] that the strength of structures is due to the joint action of the following factors: metallurgical (reflects the properties of the material - strength, corrosion resistance, weldability, fracture toughness, etc.), structural (takes into account the peculiarities of the formula of parts), technological (takes into account the peculiarities of the manufacturing technology), operational (reflects the operating conditions). Methods of studying structural strength based on an integrated approach allow taking into account the main parameters characterizing the metal state, manufacturing technology, and operating conditions to the fullest extent possible. The most effective methodology for these purposes is the systematic approach.

It is difficult to overestimate the cause-and-effect relationships of failures of structural components of railway rolling stock due to their multifaceted role in ensuring the safety, efficiency and economy of railway transportation. These studies are critical to improving traffic safety, since failures of structural elements can lead to catastrophic consequences, including human casualties and significant material damage. [3].

From the point of view of traffic safety, studies[4] have been conducted that focus on the important problem of risk prediction in the diagnosis of freight car axle assemblies, which is of great importance for improving the safety of rail transportation. However, it is necessary to describe in more detail the algorithms and methods used in the predictive model, as well as to validate the model on a large amount of data. Also, in particular, insufficient attention has been paid to improving structural reliability. Publication in a reputable publication increases the credibility of the model, but more information is needed for a full analysis.

Study [5] focuses on the important problem of the dynamic interaction of a freight car and a three-component bogie with increasing axle load, which is of great practical importance for improving the safety and efficiency of freight transportation. However, it is necessary to investigate more deeply the influence of different types of cargo and operating conditions on dynamic characteristics, as well as to validate numerical models with experimental data. In particular, insufficient attention has been paid to analyzing issues related to improving structural reliability.

Studies [6,7] focus on the important problem of detecting and classifying damage to railway gondola cars, which is of great practical importance for improving the safety and efficiency of freight transportation, gondola cars make up a significant part of the freight car fleet, they are used most intensively Fig. 1. However, it is necessary to investigate more deeply the influence of various factors that affect traffic safety, for a full analysis it is necessary to analyze the cause and effect relationships

Preventing railcar derailments depends on the quality of maintenance, compliance with operating rules and prompt response in emergency situations. It is important to continuously improve monitoring systems and staff training.

Purpose of the article and summary of the main material

The article presents the features and results of the analysis of the cause-and-effect relationship of failures of the functioning of structural components of railway rolling stock that affect train traffic safety. Based on the analysis, an empirical Pareto diagram was constructed on the basis of the development of Ishikawa diagrams in terms of traffic safety.

Based on the analysis [6-8], a traffic safety rating for technical equipment failures is developed, as well as a rating for traffic safety indicators.

For 2024, the risk rating of violations by traffic safety indicators according to [8] improved and amounted to 1.0, compared to 2023 - it was 1.14 (Fig. 1-2.) Based on the above ratings, the Ishikawa cause-and-effect diagram will be further constructed. events related to violations of vehicle safety.

It should be noted that the Ishikawa diagram is not constructed in the classical form, and only three types of factors affecting train safety were studied (Fig. 3).

Analyzing the root causes according to the Kaura Ishikawa diagram in Fig. 3, it is clear that in 2024 the main reasons affecting the number of technical equipment failures are

- train inspection technology;
- failure to comply with the technology for testing brakes from stationary installations, corrosion wear and tear, and breakage of load-bearing systems
- Inconsistency in the discharge of work;
- poor staff skills.

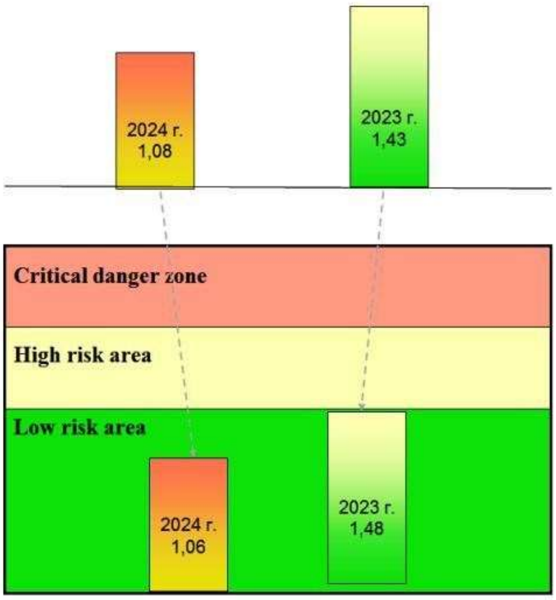

Fig. 1. Traffic safety ranking by failures of technical means

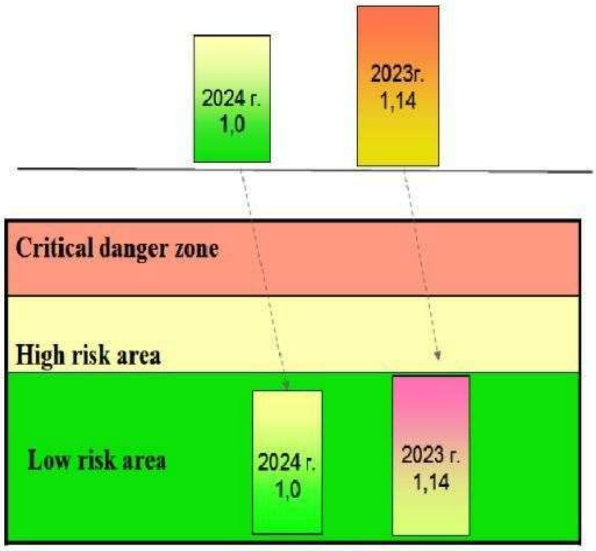

Fig. 2. Traffic safety ranking by performance

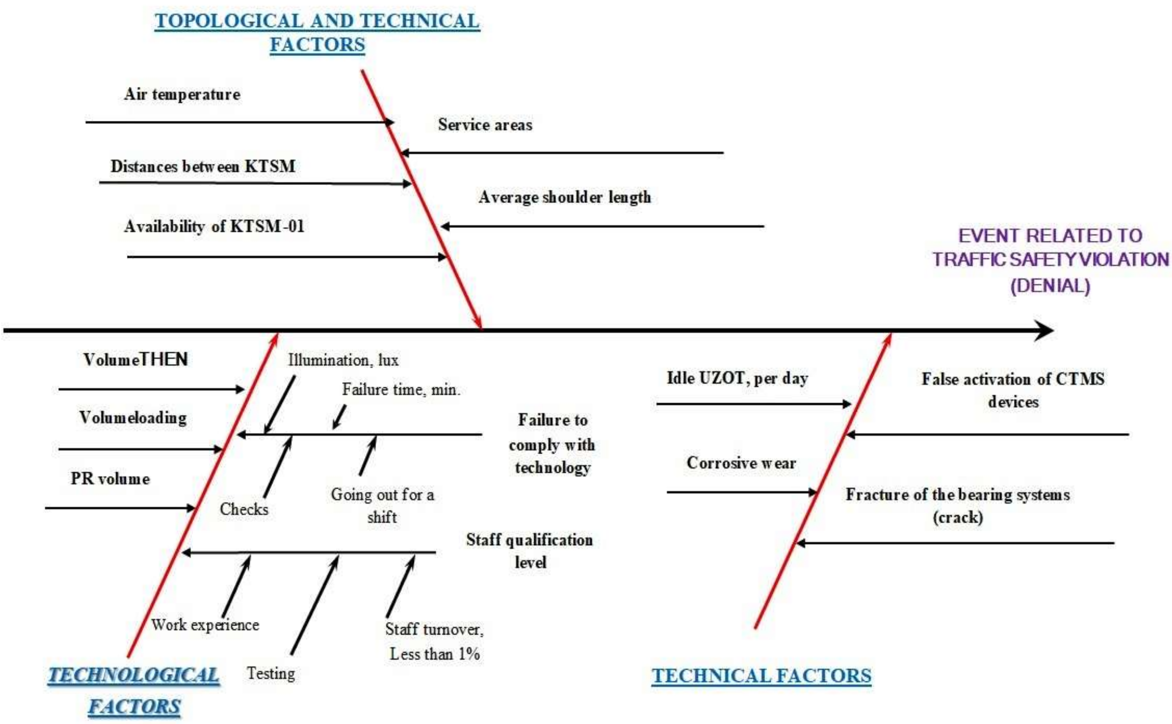

Fig. 3. Cause and effect diagram of Ishikawa events (technical equipment failure) related to traffic safety violations

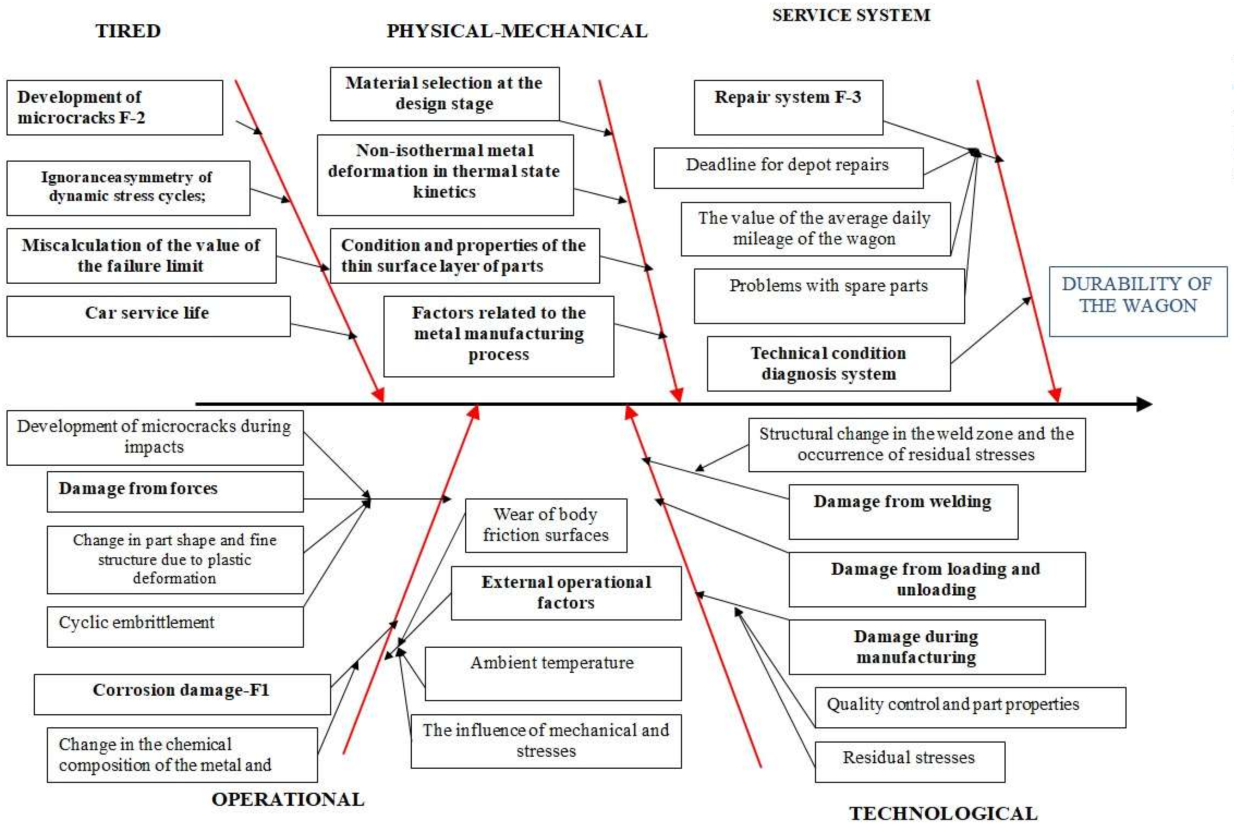

Fig. 4. Cause and effect relationships between railcar performance and operational damage, 5-parameter Ishikawa diagram

Fig. 4 shows the Ishikawa diagram with cause and effect relationships, which shows the impact of various factors and events that affect the level of gondola car performance.

At the stage of accidental operational factors, the diagram identifies power; external and corrosion effects.

First of all, it should be noted that there is no strict, generally accepted definition of the term “accidental operational factors”.

The diagram shows the most significant factors affecting the durability of a gondola car. In accordance with the diagram, five areas of research should be organized and work should be organized in each area according to the classification by level 3 factors. If necessary, each of the factors in the Ishikawa diagram can be subjected, in turn, to a cause-and-effect analysis, which greatly expands the capabilities of this diagram.

Based on the results of the above cause-and-effect relationships, five groups of factors are distinguished that reduce the performance of the studied elements of gondola bodies arising at each stage of their life cycle. Each group of factors leads to a mismatch in the durability of a particular structural component.

When analyzing causality, an impact may have a number of causal factors that can be grouped into different categories. The causal factors are often identified through a brainstorming exercise and are presented in a tree structure (causal tree). A systematic approach to identifying hazards, as a rule, guarantees the identification of most hazards. To apply the systematic approach, we propose to use factor analysis, which is developed based on the analysis of events and data from the BP.

The Pareto distribution for a random variable X with parameters x_m (minimum value, $x_m>0$) and k (shape parameter, k>0) is given by the following probability distribution function:

Distribution Function (CDF)

$$F_X(x) = P(X \le x) = \begin{cases} 1 - \left(\frac{x_m}{x}\right)^k, & \text{if } x \ge x_m, \\ 0, & \text{if } x < x_m. \end{cases} \quad (1)$$

Probability density function

The derivative of CDF gives the density:

$$\boldsymbol{f_X(x) = \begin{cases} \frac{k \cdot x_m^k}{x^{k+1}}, & \text{if } x \ge x_m, \\ 0, & \text{if } x < x_m. \end{cases}} \quad (2)$$

The moments of a random variable having a Pareto distribution are given by the formula:

$$E[X] = \begin{cases} \frac{k \cdot x_m}{k-1}, & \text{if } k > 1, \\ \infty, & \text{if } k \le 1. \end{cases} \quad (3)$$

Dispersion:

$$D(X) = \begin{cases} \frac{k \cdot x_m^2}{(k-1)^2(k-2)}, & \text{if } k > 2, \\ \infty, & \text{if } k \le 2. \end{cases} \quad (4)$$

The variance is finite only at $k > 2$.
Median:

$$M(X) = x_m \cdot 2^{1/k}.$$

A Pareto diagram allows you to distribute efforts to solve emerging problems and identify the main factors that need to be addressed to overcome emerging problems. There are two types of Pareto diagrams: by results and by causes. In a generalized sense, Pareto's law leads to the self-similarity of the ABC curve and can be a starting point for building a multinomial factor analysis model. (Fig. 5) shows an empirical Pareto diagram based on the 5-parameter Ishikawa diagram

Fig. 5 shows that in this case, the priority measures should be aimed at detecting and eliminating faults in systems F1, F_2 and F_3.

F_1-Structural factors 40%, influence (*materials of construction*: steel (carbon/low alloy),aluminium alloys, composite *frame and body construction*: stiffness and load distribution, quality of welded joints, *corrosion protection*: hot-dip galvanizing, polymer coatings, cathodic protection (for tanks).

F_2-Operational factors 30%, (*operating mode*:intensity of use, weight loads (overloads), *operating conditions:*

climatic effects (temperature, humidity), aggressive environments (sea air, chemicals), *quality of maintenance:*timeliness of repairs, compliance with maintenance schedules).

F_3-. External influences 15% (*dynamic loads*:vibrations and shocks, aerodynamic forces (for high-speed wagons), *corrosion processes:*atmospheric corrosion, electrochemical corrosion).

F_4-Technological factors 10% (*manufacturing quality:*assembly accuracy, weld inspection (defectoscopy), *monitoring systems:* condition monitoring sensor, diagnostic systems (predictive mainte)).

F_5-Regulatory requirements 4,6 % (*compliance with standards, requirements for*: strength of construction stabilit, safety).

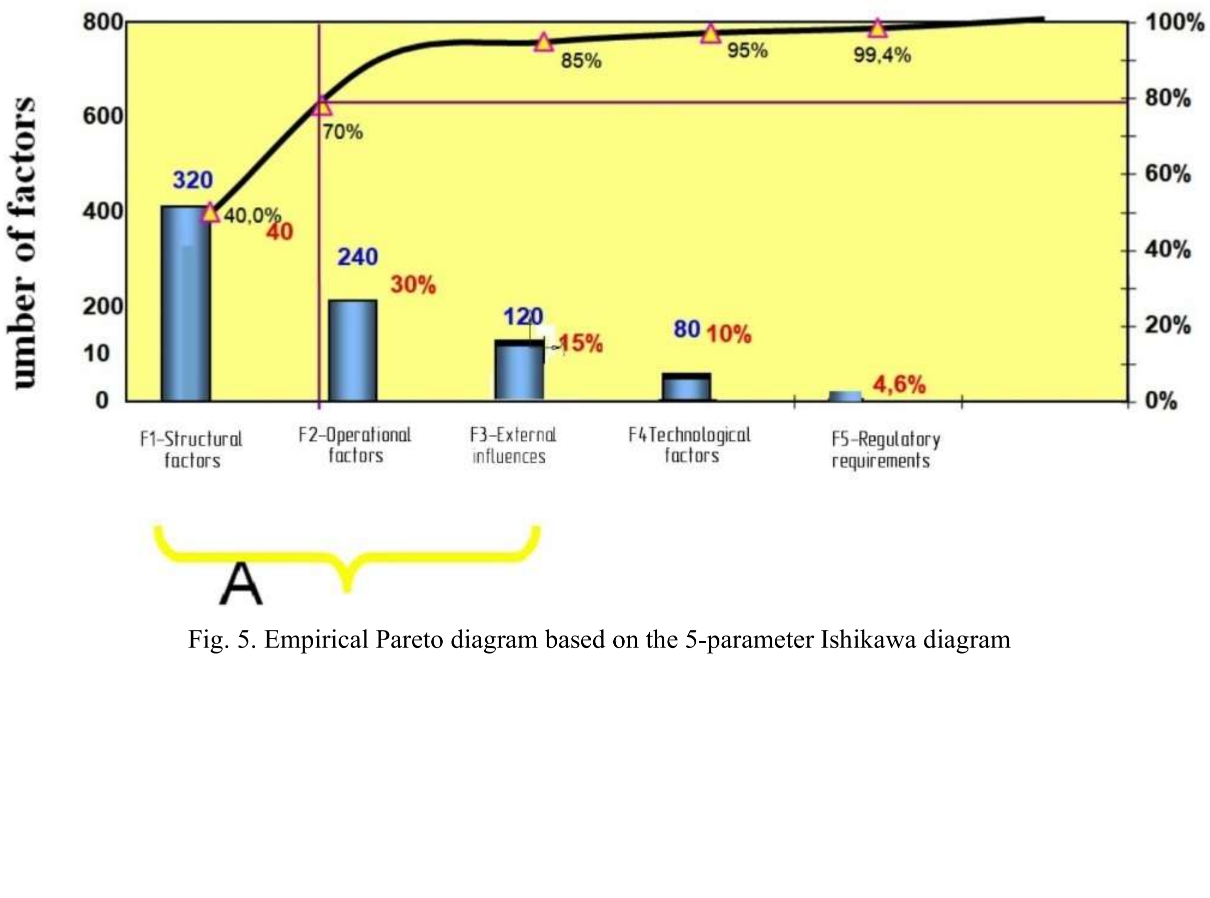

Fig. 5. Empirical Pareto diagram based on the 5-parameter Ishikawa diagram

Conclusions:

Research into the cause and effect of rolling stock failures is a strategic area for ensuring the competitiveness of rail transport, reducing accidents and moving to a preventive maintenance model. They integrate knowledge from mechanics, materials science, cybernetics and ecology, making them interdisciplinary and innovative.

The main causes of failures in rolling stock structures are material fatigue, which leads to cracks and fractures under cyclic loads and vibrations, corrosion processes that significantly reduce the strength of metal parts, poor repair quality that causes repeated failures due to insufficient staff qualifications, overloading of rolling stock that accelerates wear and damage, extreme operating conditions such as temperature fluctuations, humidity and pollution that require the use of special materials, and human error.

Despite the research conducted on the corrosion problem and the design and technological measures developed on the basis of their results, corrosion is the most common type of defect in the metal power structure of a gondola car body. This is mainly due to the two circumstances described below. Firstly, the corrosion resistance characteristics of modern metals and the methods used to protect the structure from aggressive environments do not ensure a low probability of corrosion. Secondly, modern science, with a solid amount of knowledge about the types and mechanisms of corrosion damage, does not offer railcar designers acceptable methods for predicting the time of corrosion initiation and the rate of its development.

The material considered in this work is the basis for solving such important issues as:

- study of material (steel) properties of vehicle parts and processes leading to their failures;

- assessment of the effect of overloading on crack growth;

- determination of critical dimensions, shape and position of defects.

- Corrosion prevention by design measures such as: avoiding water stagnation (drainage holes, inclined surfaces), sealing welds and joints, using composite steels or rubber or plastic pads in places of mechanical wear, for individual vehicle components.

- Combating post-weld deformations.

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Фомін О.В., Бурлуцький О.В., Причинно-наслідкові зв’язки виникнення відмов функціонування конструктивних складових рухомого складу залізничного транспорту

Стаття розкриває особливості важливості, науково-дослідних робіт, з визначення причинно-наслідкових зв'язків виникнення відмов функціонування конструктивних складових рухомого складу залізничного транспорту важко переоцінити через їхню багатогранну роль у забезпеченні безпеки, ефективності та економічності залізничних перевезень. Ці дослідження є критично важливими для підвищення безпеки руху, оскільки відмови конструктивних елементів можуть призвести до катастрофічних наслідків, включаючи людські *жертви та значні матеріальні збитки. Аналіз причинно-наслідкових зв'язків дозволяє розробити ефективні методи запобігання таким відмовам, мінімізуючи ризики аварійних ситуацій. З точки зору ефективності експлуатації, дослідження причин відмов допомагають оптимізувати процеси технічного обслуговування та ремонту, зменшуючи час простоїв та підвищуючи надійність рухомого складу, що в свою чергу, сприяє безперебійному руху вантажів та пасажирів, підвищуючи економічну ефективність залізничних перевезень. Особливу увагу приділено аналізу факторів фізико-механічого характеру пов'язаними з процесом виготовлення металу та експлуатаційного, таким як пошкодження від дії корозії.*

Крім того, науково-дослідні роботи відіграють ключову роль у зниженні експлуатаційних витрат, оскільки прогнозування та запобігання відмовам дозволяє зменшити обсяги ремонтних робіт та знизити загальні витрати на обслуговування. Дослідження також сприяють подовженню терміну служби рухомого складу, виявляючи слабкі місця в конструкції та матеріалах, що дозволяє розробляти заходи щодо їх посилення та покращення. Важливим аспектом є впровадження нових технологій, таких як системи дистанційного моніторингу та безрозбірна діагностика, які дозволяють виявляти потенційні відмови на ранніх стадіях, підвищуючи рівень безпеки та ефективності. Нарешті, дослідження причин відмов допомагають знизити ризик екологічних катастроф, особливо при перевезенні небезпечних вантажів, забезпечуючи екологічну безпеку залізничних перевезень. Доведено, що науково-дослідні роботи є невід'ємною частиною забезпечення безпеки, ефективності та економічності залізничного транспорту.

Ключові слова: *Транспорт, перевезення вантажів, автоматизація, надійність, рухомий склад, безпека руху, причинно-наслідкові зв'язки.*

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