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RELIABILITY IMPROVEMENT OF TRACK INFRASTRUCTURE IN OPEN-PIT RAIL TRANSPORT

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Abstract. The article presents the results of experimental studies on the operational reliability of the track infrastructure in industrial open-pit railway transport, evaluated by the criterion of track gauge variation due to the accumulation of residual deformations in the structure of intermediate and joint rail fastenings in jointed track, and side wear of the rail head caused by increasing axle loads and train speeds. The experiments were conducted under real operating conditions of open-pit railway systems.

The study aims to identify potential causes of sudden failures and service life reduction in the track infrastructure by monitoring the change in track gauge in response to cumulative tonnage and train speed.

The obtained patterns describe the formation of both progressive and sudden failures in the intermediate and joint fastenings of the track infrastructure in industrial open-pit railway transport. The study also establishes the probability and duration of uninterrupted operation of technical components and systems, in accordance with the specified reliability level and reliability margin, based on track gauge variation as a key parameter and depending on the service life and operational period.

It was found that the maximum deviations in track gauge ranged from minus 20 mm (1500 mm) to plus 30 mm (1550 mm), which is a fivefold increase in both narrowing and widening compared to the standard tolerance range of minus 4 mm to plus 6 mm.

The study identified regularities in the intensity of maximum gauge variation in relation to the volume of traffic and train speed. Specifically, the rate of gauge change was 10.4 mm per 1 million gross tons at train speeds of 4–12 km/h and 13.5 mm per 1 million gross tons at 12–24 km/h – an increase by a factor of 1.3.

According to the study, the time to failure for track infrastructure of a new design based on the gauge deviation criterion is as follows: for intermediate rail fastenings with reinforced concrete sleepers and spike fixings – up to 2 years at a cumulative load of 1 million gross tons, with a probability of failure-free operation ≤ 0.8; for structures with pre-stressed concrete sleepers and screw/bolt/anchor fastenings – 15 years at 50 million gross tons, with a probability of failure-free operation ≥ 0.95 and a reliability index of 1.0.

Keywords: reliability, track gauge, industrial open-pit railway transport, track infrastructure.

1. Introduction

This research addresses the operational condition of the track infrastructure of railway transport at industrial enterprises in accordance with the requirements of the Rules for Technical Operation of Railway Transport at Industrial Enterprises [1]. The test sections included both straight and curved track segments with radii exceeding 350 m. The track infrastructure consisted of obsolete reinforced concrete sleepers decommissioned from the mainline railway network of JSC "Ukrzaliznytsia", equipped with KB-type intermediate rail fastenings. The standard track gauge is 1520 mm. Permissible deviations in track gauge that do not require corrective maintenance on straight sections and curves with a radius over 350 m should not exceed +6 mm for widening and –4 mm for narrowing, according to regulatory requirements for industrial railway transport [1].

All existing structural components of the industrial open-pit railway track infrastructure are operated under conditions that lead to the accumulation of contact-induced residual deformations and other types of damage in virtually all elements – in the upper part of the rail head; in pads between rails, baseplates, and sleepers; in the ballast layer; as well as in the upper zone of the subgrade. In addition, operational use leads to geometrical track irregularities in plan, profile, and gauge. The rate of devel-

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opment of all these phenomena increases with higher traffic loads and axle loads over time, especially after capital repairs of the track infrastructure elements [2–5].

One of the most important performance indicators for the track infrastructure of industrial open-pit railway systems is reliability. Significant parameters in this context include: track gauge (distance between the inner sides of the rail heads); alignment and gradients of the rail track; curve radii; train speeds along track segments; throughput capacity; freight flow and cumulative transported tonnage; the type, mass, and axle load of rolling stock; availability of technical equipment; condition of technical inspections; and the level of scientific, technical, and production support.

The reliability of the track infrastructure in industrial open-pit rail systems has a critical impact on the technical and economic performance of mining transport, on operational safety, and on the labor productivity of personnel in the mining sector. The need to improve infrastructure reliability becomes particularly acute when axle loads from traction units and dump cars reach 350–450 kN, while the bearing capacity of the current track structure is limited to 240–270 kN [5–9]. Additional factors affecting reliability include:

– changes in the state of the geological environment in mining regions [10];

– the specifics of equipment and transport used in ore extraction technologies [11];

– the transformation of soil strata properties due to rock mass displacement [12];

– the methods of constructing internal dumps for transport communications [13];

– the impact of mining and industrial activities on the performance of track infrastructure in open-pit transport systems [14];

– the rate of deformation development in rock masses based on geodetic monitoring data [15];

– the evaluation of risks associated with the operation of technological solutions [16].

Key indicators for assessing the reliability of industrial open-pit railway track infrastructure may include:

– track gauge in key cross-sections of the track grid and its relative variation from the nominal design parameter of 1520 mm, taking into account permitted tolerances for widening and narrowing as per regulatory requirements [1];

– wear and accumulation of residual deformations at rail joints and in the base of intermediate fastenings;

– degradation of vibration isolation performance at rail joints and under-rail supports under prolonged cyclic loading [17, 18];

– damage to elements and components of intermediate fastenings under dynamic wheel loads;

– exceedance of permissible wheel loads relative to the bearing capacity of the infrastructure, including recurring derailments [6; 19].

The described deformations and critical variations in design parameters caused by dynamic loading from rolling stock create the basis for evaluating the functional state of the track infrastructure in open-pit rail transport systems [6].

Current research and literature on the reliability of track infrastructure in industrial open-pit railway transport remain insufficiently developed Available works by domestic researchers such as M.A. Frishman, V.A. Lazarian, V.V. Rybkin, E.I. Danilenko, O.M. Patlasov, O.M. Darenskyi, M.P. Nastechyk, R.V. Markul, M.D. Kostiuk, V.D. Danovych, M.I. Karpov, O.O. Shekhovtsov, V.V. Kuznetsov, V.M. Tverdomed, K.V. Moiseienko, A.F. Bulat, M.S. Chetveryk, K.V. Babii [2; 7–9; 10–23], among others – present theoretical and experimental studies aimed at improving the technical and economic performance of 1520 mm gauge railway infrastructure, as well as the development and assessment of intermediate rail fastenings and their technical characteristics. However, these studies primarily focus on railway infrastructure in general or for mainline railway transport. Research specifically addressing reliability indicators of track infrastructure under the conditions of industrial open-pit railway transport remains largely absent from the technical literature.

The aim of this research is to improve the reliability of industrial open-pit railway track infrastructure by enhancing the stability and consistency of the track gauge under the loads exerted by mining rolling stock.

The research objectives required to achieve this goal are:

– to determine the relationship between cumulative gauge variation and changes in transported tonnage and train speed;

– to develop a failure mechanism scheme for sudden reliability degradation in the track infrastructure of industrial open-pit railway systems;

– to define key reliability indicators for the track infrastructure in industrial open-pit railway transport.

2. Methods

This study outlines the methodology for experimental testing and statistical data analysis. The approach includes a systematic series of experiments under real operating conditions to assess the accumulation of residual deformations in track gauge – measured between the inner faces of the rail heads – and the wear on the side surfaces of the rail heads as a function of the cumulative tonnage and varying train speeds over the observation period.

Track gauge measurements were carried out using calibrated track templates with a measurement accuracy of 1.0 mm. Measurements were taken along base sections of the track at 1-meter intervals from a reference point. In the joint zones of the jointed track, measurements were performed within a 3-meter segment on both sides from the center of the joint.

The results of the track gauge measurements under different operational characteristics of the railway track and rolling stock were processed using mathematical statistics and probability theory to identify mean, minimum, and maximum values.

3. Theoretical and experimental parts

According to the stated objectives and research methodology, the primary parameter used to characterize the condition of the rail track was the overall track gauge measured at key cross-sections and its relative variation compared to the nominal standard design value [1]. The total gauge variation at each cross-section reflects the accumulation of residual deformations in the elements of the intermediate rail fastenings, wear of the working surfaces on the rail head sides, and structural damage to fastening components under dynamic loads from rolling stock – often exceeding the allowable normative limits. These changes were induced by cumulative technological freight loads.

The experimental studies of gauge variation were conducted under industrial operational conditions by systematically surveying designated track sections throughout the service life of the open-pit railway infrastructure.

4. Results and discussion

Figures 1 and 2 show the distribution density characteristics of track gauge deviations for selected groups of rail track measurements. The presented histograms display the average, maximum, and minimum values of the measured parameters, which correspond to a normal distribution.

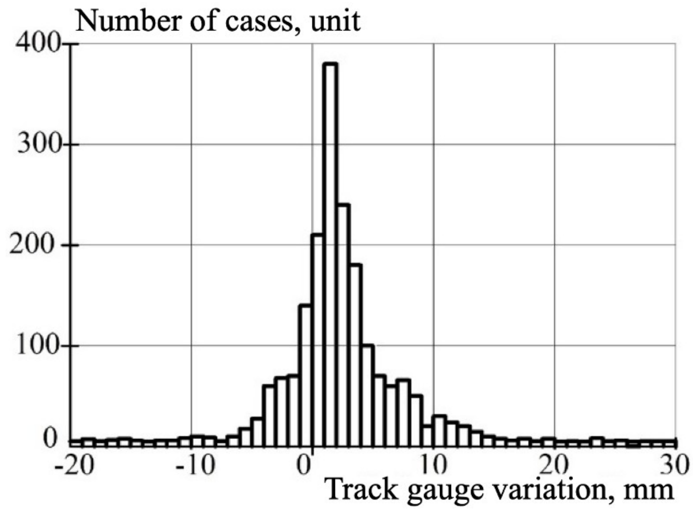

Figure 1 – Histogram of track gauge variation for the first test section of the open-pit enterprise “Central Mining and Processing Plant” (Kryvyi Rih)

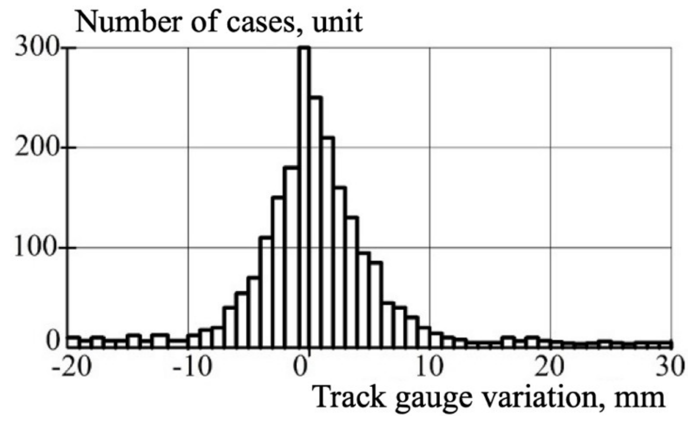

Figure 2 – Histogram of track gauge variation for the second test section of the open-pit enterprise “Central Mining and Processing Plant” (Kryvyi Rih)

These histograms were constructed for different operating conditions and loading regimes at stabilized train speeds and cumulative freight volumes ranging from 2 to 50 million gross tons during the period of operation.

From the histograms in Figures 1 and 2, it is evident that under actual operating conditions, the track gauge varied from –20 mm to +30 mm, whereas the normative values range from –4 mm to +6 mm. Thus, both gauge widening and narrowing exceed the permissible limits by a factor of five compared to the regulatory requirements [1]. The histograms, classified by train speed, rolling stock type, and mining-technical conditions, were used to derive dependencies between the histogram characteristics and the cumulative freight volume.

Figures 3 and 4 present specific data sets showing track gauge variation parameters for groups of surveyed track segments. The figures include maximum (1), average (2), and minimum (3) gauge values for train speeds in the range of V = 4–12 km/h, and similarly (4, 5, 6) for speeds of V = 12–24 km/h.

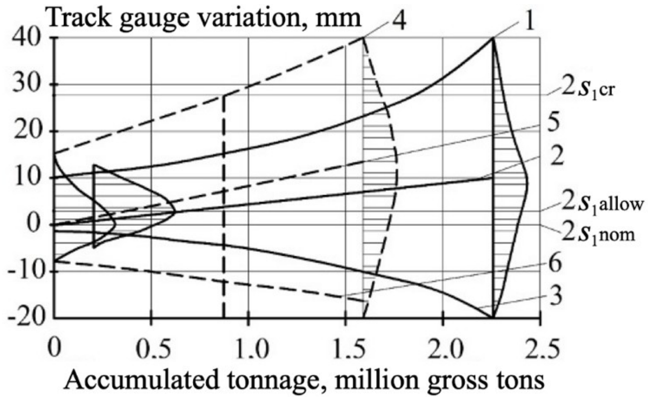

Figure 3 – Dependence of rail track gauge variation on accumulated tonnage for the first test section of the open-pit enterprise “Central Mining and Processing Plant” (Kryvyi Rih)

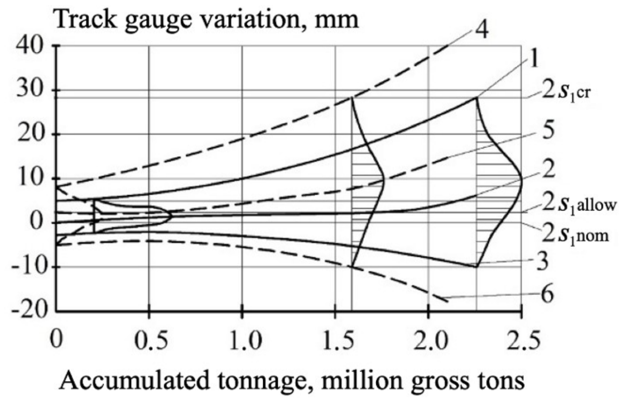

Figure 4 – Dependence of rail track gauge variation on accumulated tonnage for the second test section of the open-pit enterprise “Central Mining and Processing Plant” (Kryvyi Rih)

Based on the general analysis of the grouped graphs shown in Figures 3 and 4, lines 1 and 4 illustrate consistent patterns in the rate of track gauge change as a function of cumulative tonnage. It was established that the maximum track gauge variation reached 10.4 mm per 1 million gross tons at train speeds of 4–12 km/h, while at speeds of 12–24 km/h, the variation increased to 13.5 mm per 1 million gross tons. This indicates that the rate of gauge expansion increases by a factor of 1.3 with higher train speeds. The rate of gauge narrowing due to increased cumulative load was also determined for minimum values (lines 3 and 6 in Figures 3 and 4), amounting to 4.7 mm and 7.8 mm per 1 million gross tons, respectively.

Based on the obtained track gauge variation values relative to cumulative freight tonnage, a hypothesis was formulated regarding the tendency of gauge widening as a function of accumulated tonnage. This relationship is approximated by the following equation derived from curve fitting of the graphs shown in Figures 3 and 4:

$$2s_1 = A_i + \sum c_i G_1 + \sum u_i G_2 \,, \qquad (1)$$

where $2s_1$ – track gauge, mm; A_i – parameter reflecting initial gauge values determined by construction or repair quality, mm; c_i, u_i – approximation coefficients characterizing the intensity of variation in the output parameter (track gauge, mm) depending on cumulative freight flow, gross tons; G_1, G_2 – cumulative freight flow values, gross tons; i – conditional parameter defined by the approximation model.

Figures 3 and 4 illustrate the model of progressive gauge change accumulation. Gauge variation results from the gradual build-up of residual deformations in the elements of intermediate fastenings and wear of contact surfaces in the following interacting components: wheel–rail; rail–fastening; spikes/screws/bolts–sleepers, etc.

The intensity of residual deformation accumulation and track gauge variation depends on the loading regimes, which are determined by rolling stock mass, train speed, and accumulated freight tonnage. As seen in Figures 3 and 4, the intensity of track gauge variation at a train speed of V = 12–24 km/h is 1.4 to 1.7 times greater than at 4–12 km/h. This is due to increased dynamic loading from faster and heavier mining trains, which in turn elevates stress on the track infrastructure.

The relationship between cumulative freight tonnage and track gauge variation is nonlinear: both the maximum and minimum deviations increase more sharply than the average values. Extreme values correspond to sections where structural elements of the track exhibit inadequate bearing capacity relative to the increased load from rolling stock.

The critical increase in track gauge – beyond which a hazardous state may occur (e.g., derailment) – is determined by analyzing the most unfavorable positioning of a wheelset in the track cross-section. This condition assumes that one wheel flange is pressed against the worn side surface of the rail head, while the opposite wheel rests on a critical contact surface inclined toward the track axis. This surface is formed by the tangent between the rail head's side face and the sloped section of the wheel tread, with a standard inclination of 1/10. The limiting condition is described by the following formula:

$$2\Delta s_1 = 2\, s_1^{max} - 2s_1 = a_w - c_w - r_r - \Delta_r - \sum \Delta_{ir} - h_w^{min} - P_w, \qquad (2)$$

where $2\Delta s_1$ – allowable gauge widening; $2s_1^{max}$ – maximum track gauge; $2s_1$ – nominal track gauge; α_w – wheel tread width; c_w – length of the inclined section of the wheel tread (1/10 slope); r_r – radius of the rail head side edge; Δ_r – design clearance between rail heads and wheel flanges; $\Sigma\Delta_{ir}$ – total elastic deflection of the rails and contraction of the wheelset under load; h_w^{min} – minimum allowable flange thickness; P_w – wheel mounting tolerance in the direction of narrowing.

Based on known parameter values in equation (2), the critical allowable gauge widening $2\Delta s_1$ is approximately 26 mm. By plotting this threshold onto Figures 3 and 4, one can identify the intersection with the dispersion zone of the output parameter (track gauge). When this limit is reached, the infrastructure enters a limit state – indicating the time to complete failure of the rail track infrastructure based on gauge variation.

The dependencies shown in Figures 3 and 4 allow for a model of progressive failure formation in the track infrastructure, using track gauge as a primary criterion. A generalized diagram of this progressive failure development is presented in Figure 5.

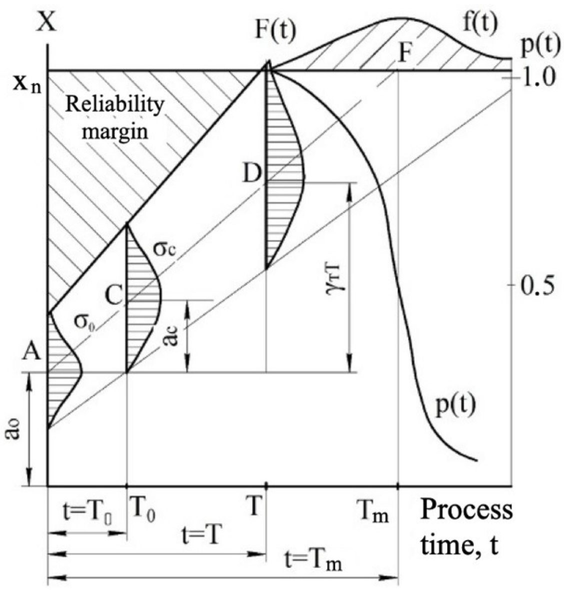

Figure 5 – Schematic diagram of progressive failure formation

According to the schematic in Figure 5 and the data in Figures 3 and 4, the initial moment of rail track installation already contains some dispersion of the output parameter (track gauge) relative to its expected mean. During operation, under the influence of service conditions, this parameter gradually shifts, forming progressive changes in track gauge. The rate of change of this parameter depends on the bearing capacity of the track structure, the intensity and duration of loading from rolling stock, rheological factors, and others.

Structural failures in rail infrastructure elements occur when the progressive change in track gauge exceeds the allowable limit $2\Delta s_1$. In the case of a linear relationship between the output parameter and operational time, the rate of change (γ_m) and mean time to failure T_m are determined by the following equation:

$$T_m = \frac{X_{max}}{\gamma_m}. \quad (3)$$

The probability of failure-free operation is calculated as:

$$P_{(t-T)} = 0.5 + \Phi' \left[\frac{S_{sr} - \alpha_0 - \gamma_m T}{\sqrt{\sigma_\alpha^2 - \sigma_y^2 T^2}} \right], \quad (4)$$

where α_0 – mathematical expectation (mean time to failure), mm; σ_α – standard deviation of the random variable, mm; Φ' – normalized Laplace function; T – service life, years.

The reliability margin K_{rel} of the rail track in terms of track gauge variation can be determined using:

$$K_{rel} = \frac{T_0(t)}{(T_0)_{min}}, \quad (5)$$

where $T_0(t)$, $(T_0)_{min}$ – minimum acceptable service life that corresponds to the target probability of failure-free operation $P(t)$, i.e., when $T_0(t) = (T_0)_{min}$.

The described process of progressive failure formation based on track gauge variation can also be extended to other parameters, such as wear of individual rail components.

A comparative analysis of the intensity of track gauge variation for different sleeper and fastening designs shows that rail tracks with frame-type and pre-stressed reinforced concrete sleepers using spike fastenings exhibit low reliability indicators. Their mean time to sudden failure T_m is about 2 years, at a cumulative tonnage of up to 1 million gross tons, with a probability of failure-free operation $P(t) \leq 0.8$. Rail tracks with wooden sleepers and spike fastenings demonstrate a slightly better performance, with T_m of 3 years under up to 5 million gross tons, and $P(t) \leq 0.9$. Test sections equipped with pre-stressed reinforced concrete sleepers and screw, bolt, and anchor fastenings showed the best reliability performance: T_m = 15 years at up to 50 million gross tons, with $P(t) \geq 0.95$. Experimental and prototype samples of pre-stressed strand-reinforced concrete sleepers with screw, bolt, and anchor fastenings were developed by the M.S. Poliakov Institute of Geotechnical Mechanics of the NAS of Ukraine for use on mainline railway tracks [6].

During the inspection of open-pit railway transport under operating conditions, it was established that, in addition to the development of progressive structural failures, extreme cases are also possible. These include:

– emergency passage of rolling stock that has derailed,

– operation of trains at speeds exceeding the allowable limits,

– use of faulty rolling stock or violation of other operational conditions.

Such extreme cases result in excessive loading from wheelsets, which exceeds the structural bearing capacity of track components and leads to their destruction, causing sudden failures.

A schematic representation of sudden failure formation is shown in Figure 6.

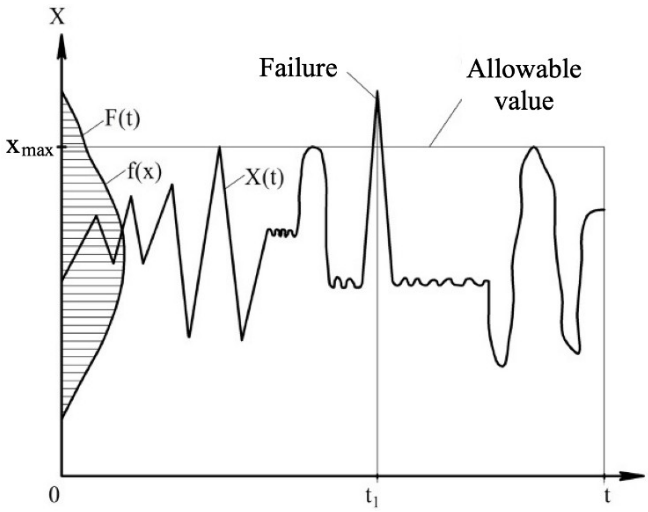

Figure 6 – Schematic diagram of sudden failure formation

In this case, the varying operational load $X(t)$ has a statistical distribution $f(x)$ over the values of the output parameter. When the actual value $X(t)$ exceeds the permissible limit, the failure of a rail track element occurs, resulting in a sudden breakdown. The zone of such events, denoted as $F(t)$, depends on the magnitude of acting vertical, lateral, and longitudinal loads, the characteristics of the rolling stock, and the maximum allowable value X_{max}, determined by the structural bearing capacity of the track. Thus, the bearing capacity of rail components defines their operational behavior and determines the reliability of the track infrastructure in open-pit railway systems.

5. Conclusions

1. Experimental studies were conducted on the reliability of industrial open-pit railway track infrastructure based on the criterion of track gauge variation caused by the accumulation of residual deformations in structural elements and side wear of the rail heads due to changes in cumulative transported tonnage and train speed along active track segments.

2. Histograms were obtained showing the intensity of track gauge variation as a function of increased tonnage and train speed, based on systematic measurements of the distance between the inner sides of the rails at 1-meter intervals along test sections of open-pit railway tracks.

3. Based on consistent and systematic measurements under actual operating conditions, it was established for the first time that the maximum track gauge reached +30 mm (1550 mm) and minimum –20 mm (1500 mm), whereas regulatory toler-

ances are from –4 mm (1516 mm) to +6 mm (1526 mm). Thus, both gauge widening and narrowing exceed the norms by a factor of five.

4. Regularities in the intensity of track gauge variation depending on cumulative tonnage were identified. The maximum gauge widening rate was 10.4 mm per 1 million gross tons at train speeds of 4–12 km/h, and 13.5 mm per 1 million gross tons at 12–24 km/h, confirming a threefold increase in accumulation rate as speed increases.

5. The mechanisms of both progressive and sudden failure in intermediate and joint fastenings were identified, along with the associated probability and duration of failure-free operation under specified reliability levels and reliability margins based on track gauge variation over the service life.

6. For the first time, reliability indicators were established for the industrial open-pit railway track infrastructure in terms of sudden failure of intermediate and joint fastenings: for frame-type reinforced concrete sleepers with spike fastenings: time to failure ≤ 2 years at 1 million gross tons, with failure-free probability ≤ 0.8; for wooden sleepers with spike fastenings: time to failure ≤ 3 years at 5 million gross tons, with failure-free probability ≤ 0.9; for pre-stressed concrete sleepers with screw, bolt, and anchor fastenings: time to failure up to 15 years at 50 million gross tons, with failure-free probability ≥ 0.95. The absolute reliability index was 1.0.

Conflict of interest

Authors state no conflict of interest.

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ПІДВИЩЕННЯ НАДІЙНОСТІ КОЛІЙНОЇ ІНФРАСТРУКТУРИ КАР'ЄРНОГО РЕЙКОВОГО ТРАНСПОРТУ

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Анотація. В статті наведені результати експериментальних досліджень надійності роботи колійної інфраструктури промислового кар'єрного залізничного транспорту по критеріям зміни величини ширини колії при накопиченні залишкових деформацій в конструкції проміжних рейкових і стикових скріплень ланкової колії та зносу бічних поверхонь головок рейок від зростання пропущеного вантажу та підвищення швидкості потягів. Експериментальні дослідження виконувались в промислових умовах експлуатації кар'єрного залізничного транспорту.

Дослідження направлені на виявлення потенційних причин формування зниження надійності роботи через раптові відмови колійної інфраструктури і термінів строку її служби по вихідному параметру зміни ширини колії від сумарного пропущеного вантажу і швидкості руху потягів.

Одержані закономірності формування поступових і раптових відмов елементів проміжних і стикових скріплень колійної інфраструктури промислового кар'єрного залізничного транспорту, а також ймовірності і тривалості безперервної роботи технічних виробів і засобів відповідно до заданого рівня надійності та запасу надійності роботи рейкової колії за вихідним параметром змін ширини колії в залежності від терміна строку служби і експлуатації.

Встановлено, що максимальні значення відхилення ширини колії становлять від мінус 20 мм (1500 мм) до плюс 30 мм (1550 мм), що відповідає розширенню ширини колії в 5 разів і звуженню ширини колії в 5 разів в порівнянні з граничними відхиленнями від мінус 4 мм до плюс 6 мм.

Встановлені закономірності зміни інтенсивності збільшення максимальних значень ширини колії від величини пропущеного вантажу та збільшення швидкості руху потягів. При цьому інтенсивність зміни величини ширини колії складає 10,4 мм на 1 млн т брутто пропущеного вантажу при швидкості руху потягів в інтервалі 4–12 км/год і 13,5 мм на 1 млн т брутто пропущеного вантажу в інтервалі швидкості руху поїздів 12–24 км/год, що в 1,3 рази більше.

По результатам дослідження надійності роботи колійної інфраструктури нової конструкції встановлено, що термін строку по вихідному параметру ширини колії і напрацювання до раптової відміни складають відповідно для конструкції проміжного рейкового скріплення з каркасними залізобетонними шпалами і костильними прикріплювачами ≤ 2 років при пропущеному вантажі 1 млн т брутто та мають ймовірність безвідмовної роботи ≤ 0,8, а для конструкції з попередньо напруженими залізобетонними шпалами та шурупними, болтовими і анкерними прикріплювачами при пропущеному вантажу 50 млн т брутто мають напрацювання до відмови 15 років та ймовірність безвідмовної роботи ≥ 0,95 при абсолютному показнику надійності роботи рівному 1,0.

Ключові слова: надійність, ширина колії, промисловий кар'єрний залізничний транспорт, колійна інфраструктура.