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Working Capacity of Track Structure and Failure Simulation of its Components

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ABSTRACT

The safety and reliability of rail transportation is a relevant theoretical and practical problem of modern engineering. This study is devoted to the problems of permanent way operation. The permanent way is a key component of the rail infrastructure that takes and transfers the axial load from the rolling stock wheels, directs its movement, guarantees smoothness, and largely limits the maximum permissible speed and tonnage. The review section covers the main design trends and current promising designs of the permanent way. Complex and non-homogenous operating conditions, reaching the engineering limit of strength improvement for the tracks, using high-tonnage and high-speed rolling stock – these are the main aspects that determine and direct the efforts aimed at improving and increasing the reliability of the permanent way. This paper offers an alternative approach to evaluating the reliability of the permanent way construction, and developed and tested mathematical models of component failures. The assumption is that by creating a single public universal database of such failures, which are based on standard characteristics and parameters of their reliability and durability, it is possible to conduct an additional evaluation of fail-safety and operability of permanent way components at the design stage, as well as to find new ways to improve said components.

KEYWORDS
Rail transport, permanent way, track panel, reliability indicators, distribution function

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Introduction

Rail transport is a key link in the transport system, which provides continuous transfer of passengers and freight in various directions. Railways affect economic growth and the development of industry, and stimulate scientific progress. According to statistics, the railway is the safest way of land transportation – 0.2 lethal cases per 1.5 billion km of running. This is 400 times safer than a motorcycle, which is considered the most dangerous transport, and 20 times safer than a car.

The density of freight and passenger traffic for rail transport is high. For instance, the freight turnover in the USA, which has a total of 231 thousand km

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of tracks and a network density of 14 km per 1000 km2, is about 2500 billion tkm; in Russia and China – about 2000 billion tkm with 85 and 61 thousand km of tracks and 5 and 6 km per 1000 km2, respectively; in Kazakhstan – 170 billion tkm with 15 thousand km of tracks and a density of 6 km per 1000 km2; in Germany – about 90 billion tkm with 35 thousand km of tracks and a density of 56 km per 1000 km2. Railways are the third most frequently used transport in the structure of the freight and passenger traffic worldwide (Voskresensky, Voskresenskaya & Nikolayeva, 2015). Thus, the abundance, popularity, and relative cheapness of rail transport determine the relevance of improving the security and fail-safety of this transport.

The railroad is a complex of engineering constructions, the main purpose of which is to handle trains at a set speed. The permanent way is of special interest to engineers and researchers, since it plays a key role in taking and transferring to the subgrade the dynamic load from rolling stock wheels and in directing the movement of the rolling stock. The components of the permanent way include the rail-tracks, clamps, rail bases and rail support, as well as the base of the rail support, switches, flat crossings, and a number of devices, such as anchors, lay-outs, bridles, and other small parts (Lysyuk, Sazonov & Bashkatova, 2003; Chernyayeva, 2008).

The permanent way is a system that consists of several elements and has a probabilistic nature, since its state in any given time of operation is difficult to predict accurately and precisely. Furthermore, the permanent way operates in difficult and non-homogenous conditions; it is exposed to mechanical wear, corrosion, deformation, fatigue failure, etc. Thus, the performance of its functions (taking and transferring the load from rolling stock wheels) requires meeting a number of crucial requirements. These include high durability and reliability of the construction, resistance to deformation and mutual bracing of components, service life, maintainability, and standardization for mass manufacturing (Lysyuk, Sazonov & Bashkatova, 2003). This determines the operability and reliability of the rail-tracks, which is evaluated by numerical indices of its fail-safety, service life, and maintainability.

The complex structure of the permanent way causes frequent failures of its components, which ultimately incapacitates the entire system (Chernyayeva, 2008). In both the reliability theory and the operation of the rail-track, incapacitation, i.e. failure of structural elements, includes both complete (for instance, rail breakage) and partial (for instance, reduction of the set rolling stock speed on a section) failures. Since failure handing is one of the most expensive activities in railway management, railway companies should focus on preventing failures, rather than handling them (Khanina, 2014). Reliability and service life indicators are the quantitative characteristics of component properties, which is why the structural life may be presented by dimensional or dimensionless values. Prediction of the reliability and operability of the system is an important element of maintenance. Modeling construction element failures is an informative technique (Gishvarov & Timashev, 2012). This technique does not require additional investments. However, with a right choice of initial operating conditions, taking into consideration the features of a specific track section, changes in its condition with tonnage run, etc., this technique objectively and accurately determines the areas that should be optimized during design and operation.

Literature Review

According to statistics, the main causes of transport incidents and events, besides the human and environmental factors, are rolling stock derailment (70% of all events), contact fatigue of wheel pairs and rail-tracks, and increased rate of wheel and rail-track wear. It is also worth keeping in mind that the extreme limit state of the tracks is determined by the wear, fatigue, and ageing of other construction elements, too (2015).

The operability of railroads in general and that of the permanent way in particular is determined by both its maintenance and the design and putting into operation of its improved components. Both the maintenance and design inventions are always aimed at improving the interaction between the tracks and the rolling stock, reducing the amplitude of horizontal and vertical impacts, correcting rail-track warps, correct canting, etc., which slows down the accumulation of permanent deformations and damage (Bigus et al., 2015).

The modern reality and pace of life demand a constantly growing speed and rate of passenger and freight transportation, which, in turn, increases the axial load on sleepers, the vibration of the rail-tracks, and reduces the mean time between failures of construction elements (Bachmann & Huesmann, 2007; Huesemann, 2005). The combination of these factors increases the rate of planned and forced repairs, necessitates improved methods of evaluation and monitoring of the track state, and generally makes maintenance more expensive (Voskresensky, Voskresenskaya & Nikolayeva, 2015). Thus, improving the reliability of rail-tracks is always relevant and may be done in two ways – by increasing the durability of tracks and by finding new design solutions.

The implementation of any new technical and technological solutions requires considerable time, resource, and financial investments during design and operational tests (Bayan et al., 2016). However, such solutions often tend to be more cost-and resource-efficient in the long run, compared to the maintenance and repairs of existing outdated constructions. All of the above also applies to railway management. Economically developed countries are actively looking for alternative engineering solutions for the permanent way (Voskresensky, Voskresenskaya & Nikolayeva, 2015).

The investigation of latest trends and projects found that engineers are looking for ways to improve the operability of the permanent way by expanding the scope of applicability of continuous welded rail-tracks, and designing differentiated and dual constructions for high-speed and heavyweight movement, as well as constructions for different climatic zones (Chernyayeva, 2008). Studies in this field use functional and cost analysis of the rail-track construction and its components, correct the standards of track design and maintenance, and develop new efficient repair and maintenance technologies.

Nowadays, the construction of railroads traditionally includes sleepers on a ballast section made of crushed stone of varying durability (Bikbau, 2010). One of the promising techniques of railroad construction is the use of reinforced concrete structures that consist of precast slabs, beams, frames or sills (Bachmann & Huesmann, 2007; Huesemann, 2005). At present, solid (block) reinforced-concrete structures are mostly used to construct tracks on bridges and in tunnels or as the support of tram tracks. However, researchers continue to look for other solutions.

For instance, scientists in Japan, Germany, France, China, and several other countries focus on looking for the optimal ballast less permanent way (Dieleman et al., 2008; Kaewunruen et al., 2014; Kaewunruen & Remennikov, 2010) due to the operation of high-speed rolling stock. The current leader in terms of speed and length of high-speed tracks is China, where the speed of the rolling stock at certain parts of the tracks goes up to 430 km/h. Despite the doubtless stability of ballast less tracks, which maintain their geometric parameters throughout the entire service life, the cost of their construction is 5-6 times higher than that of the conventional track panel supported by a ballast section (Kaewunruen & Remennikov, 2010; Dieleman et al., 2008). Furthermore, these systems are more rigid. Numerous studies are devoted to the reduction of this rigidity.

The ballast less permanent way with point-fixed tracks, mostly manufactured by such German companies as Rheda, Züblin, and Stedef, are tracks on a slab foundation (Kolos & Kozlov, 2016). The main design feature of this type of permanent way is its reduced level of vibration induced by the rolling stock, which gave it the name Low Vibration Track (LVT). The construction comprises of a layer of concrete, reinforced-concrete pocket that is similar to tunnel lining, and special reinforced-concrete sleepers embedded in concrete with P65 rails on Vossloh clamps. The sleepers are embedded in a solid slab in rubber seats. A similar Japanese project – the Shinkansen construction – is a track that consists of multiple 4.93 x 2.34 x 0.19 m assembly concrete slabs, connected with asphalt concrete grout that is placed between the slabs, and a “cylindrical cork”. The weight of each slab is 5 tons (Dieleman et al., 2008).

Similar works on the implementation of this type of permanent way are also done in Russia. A section of the experimental line of the Railway Research Institute (Moscow, Shcherbinka station) comprises of P65 rails, Vossloh 300-1 W intermediate tension clamps, dual-block reinforced-concrete sleepers that are solidly embedded into the load-bearing reinforced-concrete slab 0.3 m thick made of B40 concrete, and transverse and longitudinal reinforcement 20 mm in diameter. The load-bearing reinforced-concrete slab rests on a 0.3 m thick hydraulically bound load-bearing layer made of B15 lean concrete. A protection layer of crushed-stone-sand-gravel mixture 0.4 m thick is located under the lean concrete. The ballast bed is a subgrade 2 m high (Sultangazinov, 2008; Kolos & Kozlov, 2016).

Another designed and tested variant of a ballastless permanent way is a construction with continuous rail support. The structure of ERC (Embedded Rail Construction), manufactured in the Netherlands, provides for continuous rail support along the entire length of tracks (Dieleman et al., 2008; Kolos & Kozlov, 2016). The construction has good reliability and durability indexes, but is difficult to build and requires special equipment and considerable expenditures. Nowadays, this design is used for the most part to optimize and mechanize construction, rather than to look for engineering solutions of railroad-related problems.

Thus, the use of ballastless variants showed that they maintained their geometric characteristics, including the vertical plane, and remained unchanged under the effect of normal operational loads (Bachmann & Huesmann, 2007; Huesemann, 2005; Kozlov, 2016). This is why ballastless permanent ways are actively implemented and expanded worldwide. However, the improvement of the existing track construction remains a relevant issue for developing countries that use high-speed and heavyweight rolling stock but are not able to implement such projects.

In view of this, Russian railways have started using modern track machines with better productivity and reliability, improved methods of evaluation and monitoring of the track state that predict the residual operation life. This includes track recording cars, in-process control machines, track displacement detection systems, and other equipment. All this is aimed at optimizing the cost of the service life of the railroad construction and guaranteeing movement security (Cooper, 2011; Kozlov, 2016).

The operational characteristics of the existing permanent way are enhanced by improving its construction. This can be achieved by increasing the bending stiffness of rails while increasing their mass per unit length, increasing the stiffness of the rail base by increasing the sleeper diagram or increasing the stiffness of the ballast by increasing the thickness of the crushed-rock ballast layer under sleepers (Bikbau, 2010). Thus, the prediction of operability and durability of the permanent way in its designed and existing optimized variants with regard to all standard requirements, operational conditions, and combination of impact factors, is a relevant issue for railway management.

The purpose of this study is to determine the promising areas and methods of improving the permanent way construction, with a view to improving its operability, and to generalize and analyze the models of failure of its components as a criterion for evaluating the efficiency of engineering solutions.

Methods

The research used field observations, statistical treatment of data, the theory of probability, and the theory of reliability of repairable technical systems to investigate and predict the operational failure rate and failsafe operability of the track construction. The research also used analytical studies and the systems approach to systematize and generalize data.

The data on the failure of permanent way components that are used in this research were collected by field observation of rails, sleepers, and other construction elements, determination of their geometric dimensions and mutual bracing, as well as by nondestructive control methods, including flaw detection.

The reliability state of the permanent way was monitored by determining the resource of its main components based on the investigation results. The operational period is regarded as a scheme of work of the railroad elements, which consists of three stages: (1) initial period – the bedding-in period, rarely encountered in practice; (2) main period (with stable or monotonously changing reliability indicators); (3) period of rapid increase in the failure rate. Statistical data are gathered in data arrays by elements, depending on the cause of failure (wear, breakage, fatigue, flaw, etc.), to determine the dependency ratio for failure rate $\lambda(t)$. This includes the change rate of the failure rate during the main stage of operation, conditional failure rate at the initial stage of operation, points (time) of transfer between operation stages, the change rate of the failure rate during the initial and final periods of operation.

The obtained characteristics are the basis for the analysis of the effect of operating conditions on the reliability indicators of components or the construction, forecasting and pre-design calculations.

The reliability and resource indicators are subsequently determined according to the theory of reliability. Collected statistical data are used to determine the dependency ratio of the failure rate $\lambda(t)$ to the run life at set increments of run freight or time Δt (Methodology, 2007):

$$\lambda(t) = \frac{Q(T+\Delta t)-Q(t)}{\Delta t(1-Q(T))},$$

where $Q(t)$ is the probability of failure during the period from 0 to T.

Dependencies for other reliability indicators are subsequently determined by calculations and analytical approximation:

$$\begin{cases} \lambda(t) = at + b - k_{11}e^{-k_{12}(t-t_1)} + k_{01}e^{-k_{02}(t-t_0)}, \\ P(t) = exp\left[-\int_0^t \lambda(\tau)d\tau\right], \\ f(t) = \gamma(t)P(t), \\ F(t) = \int_0^t f(\tau)\, d\tau, t \geq 0, \\ T_{av} = \int_0^t P(\tau)\, d\tau, t \geq 0. \end{cases}$$

where $\lambda(t)$ is the failure rate, a, b, k are dependency ratios for the failure rate $\lambda(t)$, $P(t)$ is the probability of failsafe operation, $f(t)$ is the density of failure distribution, $F(t)$ is the failure distribution with run life, T_{av} is the average run life before failure.

This research will proceed to go into detail on the meaning and importance of these indicators in light of the set goal – to systematize and generalize approaches to and principles of constructing failure models for the permanent way components.

Results

The general trends in the optimization of existing track constructions have already been mentioned above. However, the main complexity of this optimization is that the projects in this field are more than 50 years old. Nowadays, most researchers believe that the sleeper base of railroads is nearing its technological limit of reliability improvement (Bikbau, 2010).

For instance, the results of theoretical studies and tests show that further increase in the mass per unit length of P65 and P75 rails over 65 kg/m is unreasonable. Active efforts in this field were made in 1950-2000. They increased the permissible mass of rails by almost two times – from 38.4 to 64.4 kg/m. This, however, increased their failure rate in terms of contact-fatigue flaws (Lysyuk, Sazonov & Bashkatova, 2003; Bikbau, 2010).

Increasing the sleeper laying density, considering that nowadays the diagram of sleepers is 1840-2000 units/km of tracks, is also inefficient, although this does increase both the permissible load of wheel pairs and the maximum speed of the rolling stock (Bachmann & Huesmann, 2007; Lysyuk, Sazonov & Bashkatova, 2003). However, this makes the construction of new tracks and the repairs of existing tracks considerably more expensive. The latest trends in technological projects and implementation of new ideas in manufacturing are based not only on modern concepts of durability and reliability of tracks, but also on economic benefits (Andreyev, 2014).

Increasing the thickness of the ballast layer, which is 50 cm thick on average, but can be 1 m thick and more at certain parts of the tracks, also does not bring significant economic benefit and is incapable of improving the quality and reliability of transportation. The same applies to the choice of the ballast sort for various types of permanent way. For instance, according to current standards, the ballast of heavy (P65) and very heavy (P75) rails with a traffic density of 25-50 million tkm per annum and more is crushed stone on a sand bed or asbestos material. Normal tracks (P50) with a traffic density of up to 25 million tkm per annum also use pit gravel or shelly ground (Cooper, 2011). Efforts are being made to look for alternative materials to construct the ballast, but the financial, labor, and resource cost of its manufacturing, if non-natural materials are involved, make this considerably more difficult.

The current state of the permanent way allows for axial loads of about 210-230 kN/axis, which deforms the tracks at high movement speed of trains and in difficult operating conditions. However, the necessity of organizing high-speed train movement and increasing the axial load of the rolling stock up to 300 kN/axis in the long run further aggravates the strain and deformity of all permanent way elements (Andreyev, Beltyukov & Sennikova, 2014; Kolos & Kozlov, 2013). The growth of the traffic density causes intensive accumulation of residual track deformation and complicates the maintenance of track reliability.

This creates a precedent. On the one hand, the current construction of the railroad, including the permanent way, has almost reached its technological limit, which is confirmed by theoretical estimations and operational data. On the other hand, modern requirements to the improvement of the operability of permanent way components for a more efficient use of the rolling stock and a smooth train run at set speeds require further increasing their durability, which is necessary to improve the reliability and security of rail transportation in general. The potential solution to this problem is the search for a new methodological approach, which would answer the relevant questions related to the improvement of existing railroad reliability.

This study aims to evaluate the possibility of solving this problem "by contradiction". At present, the operability and efficiency of a new project is evaluated primarily through theoretical computations and experimental testing (Bigus et al., 2014). The invention is considered worthy of implementation, manufacturing, and operation if the obtained results do not exceed the permissible values of durability as set in the current regulatory documents.

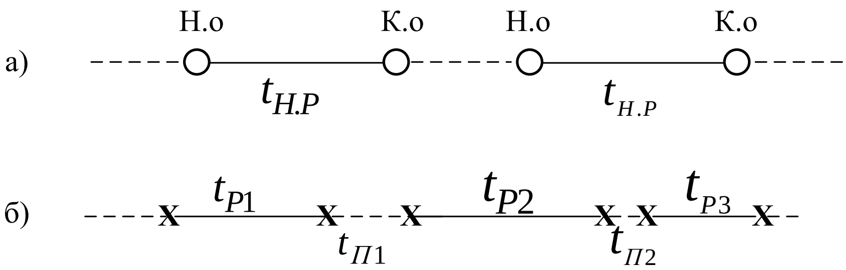
However, this approach does not solve the problem of choosing the optimal parameters of the permanent way construction; it only tells whether a specific component will operate efficiently under set operating conditions. The analysis of Russian, foreign, and the authors' previous studies found that the prediction of permanent way operability could use the existing tools, including the developed mathematical models of failures of permanent way construction elements (Sultangazinov, 2008).

The essence of the offered approach is that the fail-safety and endurance indicators of suggested constructional improvements can be evaluated with failure models for similar or prototypical elements of the permanent way construction with verified adequacy. This enables choosing a complex of upgrades without additional financial and time investments; these upgrades will improve the technical and operating characteristics of the studied track section under specific operating conditions. This approach not only evaluates durability, but also predicts the reliability of the permanent way, which essentially is an operating characteristic.

The reliability of the permanent way as an operating characteristic may be expressed in descriptive or standard (quantitative) form (Gishvarov & Timashev, 2012). The first form is the ability of the permanent way to meet operating requirements. The quantitative expression of reliability is the probability of meeting the requirements to a satisfactory level within a certain period.

As mentioned above, railway management is generally of a preventive nature. Therefore, in terms of reliability evaluation, the permanent way is regarded as an irreparable object that works until one if its components fail. This approach increases reparability and extends the repair cycle of the construction and the interval between major repairs. Thus, the evaluation of the reliability of such elements uses probabilistic characteristics of a random value – run of the object from the start of operation to the first failure.

An in-depth understanding of complex processes in a complex system often comes from simple and easy to understand analogies. For instance, in order to understand the difference why the tracks in general are a reparable construction, but are regarded in this study as the opposite, it is possible to use a simple visualization. The schematic that can be found in the guidebook published by the Russian Railways JSC (Resource and Risk Management at Life Cycle Stages and Reliability Analysis in Rail Automatic and Telemechanic Equipment: Guide, 2012) shows the operational features of reparable and irreparable objects.



Перевод подписей к рисунку:

б) = b); $t_{H.P} = t_{C.O}$; Н.О = S.O; К.О = E.O; $t_P = t_U$; $t_П = t_D$.

Figure 1. The operation of reparable and irreparable objects over the course of time.

a) – irreparable objects, where

$t_{C.O}$ is time of continuous operation,

S.O is the start of operation,

E.O is the end of operation;

b) – reparable objects, where

t_U is the uptime,

t_D is the forced downtime.

The community of the approach and parameters during the construction of failure models is crucial for using said models to evaluate the operability and reliability of tracks. For instance, failure of permanent way components should be regarded as a random event of definite and non-random nature. The main criteria of its reliability should include parameters, their definition and interpretation in accordance with the description in fundamental scientific and practical studies (Bigus *et al.*, 2014; Gishvarov & Timashev, 2012), for instance:

- the probability of failsafe operation *P(t)* that indicates the probability of no failures occurring in set operating conditions during the set time interval. In other words, that the random value T – the run until failure – will not be less than the set t: $P(t) = P\{Tt\}$.

The indicator is calculated as a ratio of the number of objects that operated without failure until time t to the number of operating objects as of the start of operation: $P(t) = \frac{N(t)}{N}$, where *N(t)* is the number of objects that worked without failure until time t. N is the number of studied objects.

The probability of failure *Q(t)*, as an opposite characteristic of reliability, determines the probability of a failure occurring during the set run and is found depending on the probability of failsafe operation:

$Q(t) = 1 - \mathrm{P}(t)$.

- the distribution of component failures during the run *F(t)* shows the probability of failure as a probability of an object failing at T time during the set t period if it was operational at the start of operation. The indicator is an integral distribution function: $F(t) = F\{Tt\}$.
- the distribution density of component failures during the run *f(t)* is the most convenient characteristic of time distribution between neighboring failures from the end of restoration of its operating condition after failure to the occurrence of the next failure. It is a differential distribution law that is found as follows:

$$f(t) = \frac{dF(t)}{dt} = -\frac{dP(t)}{dt}.$$

- the rate of failures *λ(t)*, which shows the conditional density of the probability of object failures if no failures occurred before the studied time t, is a ratio of the density of run distribution before failure to the probability of failsafe operation:

$$\lambda(t) = \frac{f(t)}{P(t)}.$$

As a fail-safety indicator of the permanent way, this characteristic is determined only in the variant under consideration, when the construction is regarded as an irreparable object. If the permanent way is regarded as a reparable object, then the matter at hand is the flow of failures $\omega(t)$.

- the average run before the first failure T_{av}, which is the expected value of the object run before the first failure that is a ratio of the total run of studied objects before failure to the number of objects that ran without failure until time t:

$$T_{av} \cong \frac{1}{N}\sum_{i=1}^{N} t_i \ .$$

- gamma-percentile run before failure t_γ, which is a relative value that is interpreted as the run, during which the failure of the object does not occur with a probability γ. This indicator is found with the following equation:

$$1 - F(t_\gamma) = 1 - \int_0^{t_\gamma} f(t)dt = \frac{\gamma}{100}.$$

However, this study does not aim to reiterate the information regarding the reliability of railroad constructions that is presented in reference books and monographs, but only to emphasize the key moments that are important in light of the offered alternative approach to designing and putting into operation the components of the permanent way. Thus, it is only worth noting the existence of other fail-safety and reliability indicators that should also be taken into account in modeling, including operating indicators that determine the impact on the tracks. This category includes the train speed (km/h), traffic density (million tkm gross/km per annum), axial load of the rolling stock (kN/axis), train weight (t), etc.

All forces and factors that affect any technical construction, including the rail-tracks, are interrelated. Thus, it is possible to determine the interrelation between the indicators of permanent way reliability through mathematical calculations. The main indicators are presented in the table 1 (Resource and Risk Management at Life Cycle Stages and Reliability Analysis in Rail Automatic and Telemechanic Equipment: Guide, 2012).

Table 1. Interrelation between reliability indicators

	P(t)	*Q(t)*	*f(t)*	*λ(t)*
P(t)	-	$1-P(t)$	$-\frac{dP(t)}{dt}$	$-\frac{1}{P(t)}\cdot\frac{dP(t)}{dt}$
Q(t)	$1-Q(t)$	-	$\frac{dQ(t)}{dt}$	$\frac{1}{1-Q(t)}\frac{dQ(t)}{dt}$
f(t)	$\int_t^\infty f(t)dt$	$\int_0^t f(t)dt$	-	$\frac{f(t)}{\int_t^\infty f(t)dt}$
λ(t)	$e^{-\int_0^t \lambda(t)dt}$	$1-e^{-\int_0^t \lambda(t)dt}$	$\lambda(t)e^{-\int_0^t \lambda(t)dt}$	-

Another important aspect that unites the component failure model into a single convenient base is the use of standard models. For instance, requirements to random value functions, schemes of failure distribution formalization, and methods of choosing failure models for specific conditions are described and approved in many international and national standards (Reliability in equipment. Failure models, 2010).

Furthermore, using tried and tested component failure models that were practically confirmed during operation allows taking into consideration the deformations caused by non-homogeneity of durability and other properties of certain elements. Thus, the implementation recommendation will include the deformations of predetermined parameters that take into consideration other types of residual deformations during structural analysis.

The detailed analysis of developed and described (Sultangazinov, 2008) tested models of permanent way component failures found the existence of numerous models for various specific cases. In addition, the authors of this paper have already described the generalized model of transport system element failures (Sultangazinov, 2008). The requirements to modern railroads necessitate further studies in this area and the creation of an essential scheme for evaluating and predicting the operability of newly designed and optimized track components.

For instance, the study of Sultangazinov S.K. (2008) described the failure probability of a component exposed to ageing under the monitoring of its technical state. The ageing of components that actually occurs at a rate of $\bar{U}_a$ is random and is a function of time or run tonnage. The failure occurs at time T_{pr}^{a} when the system reaches a certain state under critical process G_{pr}.

All permanent way components are exposed to ageing during long-term operation. With the handling of tonnage and high-speed transport, the durability and other physical and mechanical properties of rails deteriorate. The same applies to rail clamps, switches, and other metal and non-metal components. Sleepers are deformed; the ballast bed is crushed and clogged. All this generally accelerates ageing and makes the probability of failure occurrence less predictable. The relevance of the issue motivated numerous studies of the strained-deformed state of the permanent way, the dynamic of changes in the main estimated characteristics throughout long-term operation, etc.

The described study investigates cases when $\bar{U}_a$ is equal to the estimated ageing rate $\bar{U}_e$ or differs from it by ΔU. The latter may have both positive and negative values, which is confirmed by operational data.

Following the logic of model construction (Sultangazinov, 2008), the actual failure of the monitored object is possible if two conditions are met:

1) When the component reaches the state of physical failure, i.e. $G_a = G_{pr}$;
2) When the monitoring system misses the technical state of the moment when $G_a = G_{pr}$ is achieved with a set prediction.

The probability of failsafe operation of the monitored component $P_{mc}(t)$ may be presented as follows:

$$P_{mc}(t) = P_p + P_m - P_p \cdot P_m$$

where $P_{mc}(t)$ is the probability of failsafe operation of the monitored component, in other words, the probability of nonoccurrence of actual (sudden) failure; P_p is the probability of failsafe operation of an unmonitored component, i.e. the non-achievement of the state of physical failure or the $G_a = G_{pr}$ condition; P_m is the probability of failsafe operation of the technical state monitoring system, i.e. the probability of it recording the $G_a = G_{pr}$ state with a set time prediction Δt_p.

Thus, this failure model for permanent way components is sufficiently versatile. It may be used by designers and researchers as an additional evaluation criterion of the predicted ageing of the invention.

It can serve as the first link in the creation of a single public universal database of failure models, which will ultimately provide for an alternative evaluation of fail-safety and operability of permanent way components at the design stage. In addition, the "fresh" look at the reliability of railroad constructions may detect previously unstudied areas of their improvement. The creation of new constructions and the optimization of existing ones is always aimed at cutting costs and improving the technical and operational characteristics of tracks. The assumption is that the herein described approach may facilitate this process.

Discussions

The railroad in general is a complex multi-component system. Its standard service life as a major construction object is about 500 years with periodical restoration every 20-40 years. This seems to be a sufficient margin of safety for transporting passengers and freight across the world. However, the current pace of life and growing needs impose increasingly stricter requirements to the quality, speed, and reliability of transportation. Demand creates supply. This determines the relevance of the constant search for new technical and technological solutions for the construction of railroads in general.

In this context, adequately choosing the construction of the permanent way is crucial, since it plays a key role in bearing the load and impact from the rolling stock wheels and transferring it to the engineering constructions of the rail infrastructure. This, in turn, significantly affects the train movement speed and the density of freight and passenger traffic of railroads.

Depending on the operating conditions, the permanent way may have different configurations, including ballast or ballast less constructions of jointed or continuous track, jointed track on wooden or reinforced concrete sleepers, continuous track on a slab or sleeper base, etc. With regard to the category, nature, and scope of transportation, the components of the permanent way that are most important during design, construction, and operation are distinguished. For instance, the type of rails, type and diagram of sleepers, thickness and material of the ballast layer for high-speed lines, heavy traffic lines, and category 1-4 lines are determined and approved. The type of the permanent way determines the expedient combinations of its elements. However, each type requires specific new engineering solutions, improvements, and optimization. All this complicates the generalization and unification of approaches and makes it so most studies of the permanent way are devoted to specific cases and aimed at solving specific problems.

The achievement of the technical limit of durability and reliability of the existing rail-and-sleeper construction of the permanent way makes relevant the issue related to further areas and trends in this field of engineering science. This study offers a possible solution to this problem – an alternative methodological approach to choosing optimal permanent way constructions and combinations of its elements. This enables re-evaluating the effectiveness of suggested engineering solutions that aim to improve the efficiency and operability of the permanent way.

It is necessary and important to do accurate calculations for any new technical or technological solution. Nevertheless, an additional alternative evaluation and prediction of the invention reliability with tested and described, often patented, models of permanent way component failures enable making the correct choice when putting the components into operation.

In order to use this approach efficiently, it is necessary to generalize and systematize the models of permanent way components that were developed in Russian and foreign studies. Such a public database may give a new impetus to engineering projects in this area, which is necessary in the current economic situation and innovation- and technology-oriented science.

Conclusion

1. Numerous studies and experience of operation show that the existing permanent way construction with P65 and heavier rails, a sleeper laying density of 1840 units/km and more, and thickness of the crushed stone ballast about 50 cm is sufficiently durable for the normal operation of the rolling stock.

2. The improvement of the permanent way with a view to increasing the axial load of the rolling stock and its maximum permissible movement speed should take into consideration the technical capacity and economic expedience.

3. The search for new methodological approaches to creating new and improving existing permanent way components, evaluating their reliability and expedience of implementation, enables finding new directions in design.

4. Using developed and tested models of permanent way component failures as an alternative evaluation of reliability enables predicting their fail-safety and operability with less time and resources required.

5. The creation of a single public universal database of failure models, which take into account the standardized approaches and characteristics that were tested and confirmed experimentally, will enable additionally evaluating the durability and reliability of permanent way components at the design state with minimal investment costs.

Thus, considering the modern requirements to the constant increase in speeds and tonnage of the rolling stock, the problem of improving the reliability and durability of the existing permanent way construction is still relevant. This necessitates further studies and discussions of this issue.

Disclosure statement

No potential conflict of interest was reported by the authors.

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