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Technique to Determine Integral Distribution of Forces Acting on the Railway Track

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ABSTRACT

A comprehensive assessment of the effectiveness of heavy-haul traffic is a prerequisite for its implementation in world railway sector. The assessment should include the study of the effect of increased axial loads on degradation of the elements of the track's superstructure, deformation parameters of the ballast layer and the track's substructure, and of measures intended to reinforce the railway infrastructure accordingly. It is necessary to consider rather accurately the force factors acting on the track and generated by different types of rolling stock with various axial loads. The distribution of force factors for a specific section of a railway track is a multifactorial process, the quantitative parameters of which depend on the structure of the train traffic flow, the type of rolling stock and its share in the total daily train traffic passing through this section, speed limits set for the section, track profile (straight line, curve), technical conditions of rolling stock and elements of the track superstructure.

The objective of the work was to develop a technique for determining the integral law of distribution of vertical and lateral forces affecting the track and caused by wheels of different types of rolling stock, depending on the share of the operation of the respective types of rolling stock in the daily train traffic flow. Methods of mathematical statistics were used.

In the process of experimental studies of the effects of various types of rolling stock, the statistical distributions of vertical and lateral forces have been determined. The histograms of vertical and lateral forces have been approximated by theoretical laws. Kolmogorov–Smirnov fit criterion has been used to confirm goodness of chosen approximation functions. A technique has been developed for mixed freight and passenger railway traffic that allows to consider the contribution of the share of each type of rolling stock in the force impact on the track when calculating the total impact. The technique is based on real, experimentally established distributions of vertical and lateral forces, traffic speed at the considered section of the track with regard to seasonality (winter, summer), and can be used for the sections where heavyhaul traffic is being implemented.

Keywords: railway, heavy-haul traffic, rolling stock, high axle loading, vertical and lateral forces, distribution law, impact, track.

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Introduction. The implementation of heavy-haul traffic has for many years been the pole of attention of world's railways as a tool to improve the efficiency of rail freight transportation. The activities of the non-governmental International Heavy Haul Association[1] include the objective to conduct research aimed at solving technological problems associated with development of rolling stock and infrastructure.

Research related to various aspects of introduction of heavy traffic is conducted in many countries. Particularly, the [1] studied the dynamic response of a railway track to longitudinal forces arising in heavy-haul trains in braking modes and the influence of vertical forces on longitudinal loads in rails.

The [2] studied the sleeper deflection (vertical displacement), influence of pressures of unsupported sleepers on ballast depending on their position during movement of heavy-haul trains. The pressure on ballast and acceleration of sleepers were determined depending on their vertical position for the cases when geogrids were used and the cases when they were not used. The [3] used the 3D model of a heavy-haul train to study the dynamic interaction of rolling stock and track with the account for longitudinal forces in the train. A technique to increase the efficiency of calculations for complex systems «heavy-haul train–track» has been developed, and the basic principles for increasing accuracy of calculations have been determined. The [4] contains technical specifications developed for elements of the track superstructure for operating conditions of heavy-haul traffic in the desert of Saudi Arabia, considering maximum temperatures, a wide range of temperature fluctuations, ultraviolet radiation, and significant movement of sand due to wind impact.

The study [5] develops the methodology for calculating the service life of elements of the track superstructure of a given design for heavy-haul traffic considering degradation and total track deformations on a coal railway in the Republic of South Africa. The predicted life resource is calculated during operation of rolling stock with a load of 26 ton/axle for a period of 40 years with a total processed tonnage of 4000 million tons gross and a safety factor varying from 2,4 to 6,0.

The research, presented in [6], developed a method for monitoring workloads of the existing rolling stock on the track structure that is based on measuring accelerations of the rails in the vertical and horizontal transverse directions. The comparative analysis of the statistical parameters of the stress of the rails and of acceleration during passing of the shunting locomotive and gondola cars showed satisfactory results in determining the pressure from wheels on rails.

The work [7] presents study of the problem of modelling of stochastically distributed rail imperfections on the surface of the rail head. The two-layer model described in this paper allows to consider mechanical properties of construction elements of rail track and to analyze interactions between rails and sleepers. The response of the rail track to the passing train was shown for linear and deterministic models.

Thus, the implementation of heavy-haul traffic is preceded by extensive studies on the effects of rolling stock on the track.

In Russia, the General Scheme for Development of Railways Network of JSC Russian Railways for the period up to 2020 and 2025 [8] provides for development of heavy-haul transportation at heavy traffic sections of the network to master forecast cargo flows and to reduce transport costs. At the same time, in accordance with the Strategy for the Development of Railway Transport in the Russian Federation until 2030 [9], the task was set to ensure the compliance of technical and technological condition of the infrastructure, as well as of its maintenance, with the best world standards. The organization of heavy-haul traffic by using cars with increased axial load contributes to technological efficiency by increasing throughput of the given network sections, and results in grown capacity to transport additional volume of bulk cargo.

However, the process of introducing rolling stock with an increased axial load requires additional studies to assess the effect of increased axial loads on degradation of the elements of the track superstructure, deformation parameters of the ballast layer and of the substructure. While

[1] [Electronic resource]: https://ihha.net/.

developing the comprehensive assessment of the effectiveness of heavy-haul traffic, it is necessary to consider measures, necessary to reinforce the railway infrastructure, which in turn requires accurately considering force factors acting on the track and generated by different types of rolling stock with diversified axial loads.

The distribution of force factors for a specific section of a railway track is a multifactorial process, the quantitative parameters of which depend on the structure of the train traffic flow, the type of rolling stock and its share in the total daily train traffic passing through the section, speed limits set for the section, track profile (straight line, curve), technical conditions of rolling stock and elements of the track superstructure.

The study's *objective* is to develop an algorithm for determining the law of integral distribution of vertical and lateral forces generated by various types of rolling stocks at a random section of rail track.

Theoretical foundations were based on the *methods* of mathematical statistics and probability theory [10, 11]. Differently to the approach contained in the Methodology [12], where the impact is determined by calculation, to obtain quantitative parameters of the integral distribution of vertical and lateral forces, it is proposed to use the results of experimental studies on the impact of various types of rolling stock on the track, comprising effects of cargo trains formed with cars with axle loads of 23,3, 25, 27 tf (tonne-force), of passenger, rapid trains, multiple unit trains, etc., obtained by the researchers of VNIKTI and of VNIIZhT [Russian Railway Research Institute] and presented in the works [13–18].

Results

Algorithm of determining integral law of distribution of vertical forces

The following assumptions are made:

• The daily set of trains as well as their technical condition are assumed to be similar for a long time;

• Climatic conditions are divided among two components, namely winter and summer periods, determining accordingly difference in force action due to changed rigidity of track.

Under the assumptions made, integral distribution of vertical forces can be determined in the following sequence.

Following multiple experimental researches on the impact of freight, passenger, high-speed, multiple unit trains on the track it was established that according to the Kolmogorov–Smirnov test (goodness of fit criterion), the distribution of vertical forces generated due to the action of the trains formed with uniform cars with axial loads with close values, locomotive engines, and multiple unit trains is quite correctly approximated by the normal (Gaussian) distribution law.

Vertical force distribution probability density is defined by the normal law:

$$f(F_i) = \frac{1}{\sigma_{F_i}\sqrt{2\pi}} e^{-\frac{(F_i - \overline{m}_{F_i})}{2\sigma_{F_i}^2}},$$

where F_i is current value of vertical force;

$\overline{m}_{F_i}$ is expected value (mathematical expectation) of the set of vertical forces;

σ_{F_i} is root-mean-square deviation (RMSD, or root-mean-square error, RMSE) of the set of vertical forces.

The density of distribution of vertical forces appearing due to the action of freight trains formed with different cars with various axial load (empty, low-loaded and full-loaded cars), considering also the vertical impact forces, can be more exactly described by the log-normal distribution law.

Distribution density of probability of random variable, whose logarithm is distributed by the normal law, is described by the following ratio:

$$f(F_1) = \frac{1}{\sigma_{F_i} F_i \sqrt{2\pi}} exp\left\{-\frac{ln\left(F_i - \overline{m}_{F_i}\right)}{2\sigma_{F_i}^2}\right\},$$

where F_i is current value of vertical force;

σ_{F_i} is root-mean-square deviation of vertical forces;

$\overline{m}_{F_i}$ is expected value of vertical forces.

If there are *loaded and empty cars* in the trains, the distribution is a *superposition of the laws of distribution of probability of vertical and lateral forces determined with experimental* *statistical data,* with relevant *expected values and root-mean-square deviations.*

Expression for integral relative frequency of vertical force F_i generated due to different types of rolling stock k_1, k_2, ..., k_j which participate in forming the frequency distribution law for forces F_i can be written as follows:

$$F_1 \to P_1^{\Sigma} = \gamma_{k_1} P_{F_1}^{k_1} + \gamma_{k_2} P_{F_1}^{k_2} + \ldots + \gamma_{k_j} P_{F_1}^{k_j};$$

$$F_2 \to P_2^{\Sigma} = \gamma_{k_1} P_{F_2}^{k_1} + \gamma_{k_2} P_{F_2}^{k_2} + \ldots + \gamma_{k_j} P_{F_2}^{k_j};$$

$$F_i \to P_i^{\Sigma} = \gamma_{k_j} P_{F_i}^{k_1} + \gamma_{k_2} P_{F_i}^{k_2} + \ldots \gamma_{k_j} P_{F_i}^{k_j},$$

where $P_1^{\Sigma}, P_2^{\Sigma}, \ldots, P_i^{\Sigma}$ are respective integral relative frequencies of vertical forces F_1, F_2, ..., F_i generated by the daily set of trains;

$P_{F_1}^{k_1}, P_{F_1}^{k_2}, \ldots, P_{F_1}^{k_j}$ are relative frequencies of vertical forces F_i generated due to different types of rolling stock k_1, k_2, ..., k_j (statistical features of relative frequencies of vertical forces should be experimentally identified separately for each type of rolling stock);

k_j is the type of rolling stock running on this section (k_1 is intended for locomotive engines);

k_2 designates freight trains with full-loaded cars under load of up to 23,5 tf/axle with bogies of type 18–100[2];

k_3 designates freight trains with low-loaded cars with bogies of type 18–100;

k_4 designates freight trains with innovative cars with axial load of 25 tf/axle;

k_5 designates freight trains with innovative cars with axial load of 27 tf/axle;

k_6 designates passenger trains;

k_7 designates rapid passenger trains (*Nevsky express train*, etc.);

k_8 designates trains with higher speed (*Sapsan [peregrin falcon] train*);

k_9 designates multiple unit trains;

$\gamma_{k_1}, \gamma_{k_2}, \ldots, \gamma_{k_j}$ are shares of rolling stock of k_j type running within the daily set of trains, $\gamma_{k_1} + \gamma_{k_2} + \ldots + \gamma_{k_j} = 1$;

F_1, F_2, ..., F_i are vertical forces in the statistic partition of vertical forces with increment of ΔF_i.

To define an integral distribution law, allowance should be made for authorized running speed and climatic operation conditions.

In case if the authorized train speed (velocity) is within the intermediate interval between the velocity V_{min} and the velocity V_{max} for which the statistic parameters of distribution laws are defined, it is necessary to additionally calculate $\bar{m}_{F_a}$ and $\bar{\sigma}_{F_a}$ for currently authorized speed V_a.

If we assume that the expected values and root-mean-square deviation values vary linearly depending on increase in speed, then the expected value of actual speed V_a will be defined as follows:

$$\bar{m}_{F_a} = m_{F_{\min}} + \Delta \bar{m}_F \bullet \frac{V_a - V_{\min}}{V_{\max} - V_{\min}},$$

where $\bar{m}_{F_a}$ is expected value of vertical forces for actual authorized speed V_a at the relevant section;

$\Delta \bar{m}_F = \bar{m}_{F_{\max}} - \bar{m}_{F_{\min}}$ is change in the expected value of vertical forces depending on increase in velocity from V_{min} to V_{max}.

The root-mean-square deviation value is defined similarly:

$$\bar{\sigma}_{Fa} = \bar{\sigma}_{F_{\min}} + \Delta \bar{\sigma}_F \bullet \frac{V_a - V_{\min}}{V_{\max} - V_{\min}},$$

where $\bar{\sigma}_{F_a}$ is root-mean-square deviation of vertical forces for actual authorized speed V_a at the relevant section;

$\Delta \bar{\sigma}_F = \bar{\sigma}_{F_{\max}} - \bar{\sigma}_{F_{\min}}$ is change in the root-mean-square deviation of vertical forces depending on increase in speed from V_{min} to V_{max}.

Considering the revised values $\bar{m}_{F_a}, \bar{\sigma}_{F_a}$ typical of the authorized speed of trains, the vertical force distribution laws are developed for each type of rolling stock involved in the daily train traffic, and vertical force integral distribution law is developed for actual speed V_a.

Integral distributions for summer and winter operating periods of a section are defined to consider the climatic conditions and the duration of summer and winter periods. Operating period of track section in

[2] Model of bogies frequently used in Russia and other countries. See, e.g., http://ukbv.ru/en/kontragentam/documentation/tracs/1932–18–100.html – *Ed. note.*

summer is taken as *s* and operating period in winter is taken as *w*:
$P_{i\,s}^{\Sigma} \rightarrow f(F_i),\ P_{i\,w}^{\Sigma} \rightarrow f(F_i).$

Then for a specific value of vertical force F_i the integral relative frequency is defined as $F_i \rightarrow P_{i\,s+w}^{\Sigma} = \alpha P_{i\,s}^{\Sigma} + \beta P_{i\,w}^{\Sigma}$,

where $P_{i\,s+w}^{\Sigma}$ is integral relative frequency for all types of rolling stock running on the relevant section during the year considering the authorized speed and climatic «winter–summer» conditions.

Algorithm of integral distribution of lateral forces

To define the lateral force distribution law, we shall apply methodological approaches which have been used for defining the vertical force distribution law.

Rail loading (stress) condition for curved sections of rail track is defined by radius of curves, speed and values of canting of outer rail (its superelevation over the inner one), and those features should be considered when defining the distribution law.

Integral relative frequency for different types of rolling stock k_j, for example, for lateral force $H_{b\theta}$ considering the quantity *j* of types of rolling stock which impact the integral relative frequency of lateral force is defined as:

$$H_{b\theta} \rightarrow P_{H_{b\theta}}^{\Sigma} = \sum_{j=1}^{k_j} \gamma_{k_j} \cdot P_{H_{b\theta}}^{k_j},$$

or, in expanded form as:

$$H_{b1} \rightarrow P_{H_{b1}}^{\Sigma} = \gamma_{k_1} \cdot P_{H_{b1}}^{k_1} + \gamma_{k_2} \cdot P_{H_{b1}}^{k_2} \ldots + \gamma_{k_j} \cdot P_{H_{b1}}^{k_j};$$
$$H_{b2} \rightarrow P_{H_{b2}}^{\Sigma} = \gamma_{k_1} \cdot P_{H_{b2}}^{k_1} + \gamma_{k_2} \cdot P_{H_{b2}}^{k_2} \ldots + \gamma_{k_j} \cdot P_{H_{b2}}^{k_j};$$
$$H_{b\theta} \rightarrow P_{H_{b\theta}}^{\Sigma} = \gamma_{k_1} \cdot P_{H_{b\theta}}^{k_1} + \gamma_{k_2} \cdot P_{H_{b\theta}}^{k_2} \ldots + \gamma_{k_j} \cdot P_{H_{b\theta}}^{k_j},$$

where γ_j^{kj} is share of types of rolling stock of k_j type involved in the daily train traffic;

k_j is type of rolling stock;

$H_{b1}, H_{b2}, \ldots, H_{b\theta}$ are values of lateral forces;

$P_{H_{b1}}^{k_1}, \ldots, P_{H_{b\theta}}^{k_j}$ are relative frequencies of lateral forces generated by rolling stock of k_j type;

$P_{H_{b\theta}}^{y}$ is integral relative frequency of lateral force $H_{b\theta}$ generated by different types of rolling stock of k_j type generating the lateral force $H_{b\theta}$ with the account for their quantity;

$P_j^{H_{b\theta}}$ is track impact relative frequency; it is defined from the lateral force distribution density by theoretical distribution laws using the experimentally deduced statistic parameters and basing on a share of each type of k_j rolling stock generating a lateral force $H_{b\theta}$.

When the input data get in the intermediate position in between the experimentally deduced parameters $\bar{m}_{H_b}$ and $\bar{\sigma}_{H_b}$ for speed $V_{\min}$ and speed $V_{\max}$, integral distribution relative frequencies of lateral force $H_{b\theta}$ are defined by the linear interpolation method (similarly to the case of vertical forces when defining the integral distribution of vertical forces). Here $\bar{m}_{H_b}$ and $\bar{\sigma}_{H_b}$ are expected values and root-mean-square deviations of lateral forces experimentally deduced for the curves with specific radius, authorized speed, outer and inner rails, superelevation of the outer rail, summer and winter operating conditions.

Besides, it is very important to correlate density of distribution of lateral forces throughout the outer and inner rails with the speed and superelevation.

Expression for integral relative frequencies of lateral forces can be written in expanded form as follows:

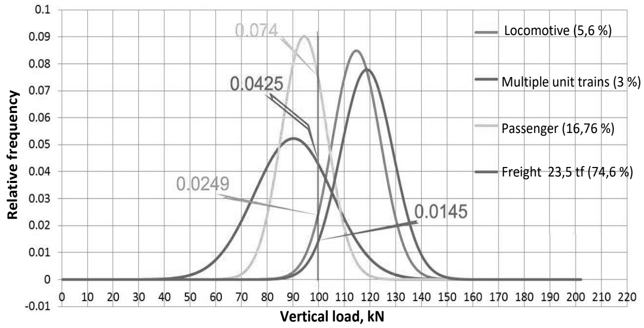
$$H_{b1} \rightarrow P_{H_{b1}}^{\Sigma};$$
$$H_{b2} \rightarrow P_{H_{b2}}^{\Sigma};$$
$$H_{b\theta} \rightarrow P_{H_{b\theta}}^{\Sigma}.$$

Then the integral densities of distribution of lateral forces generated by the daily set of trains running through this section shall be defined.

Technique to determine integral distribution of vertical and lateral forces

Based on the experimentally defined distributions of vertical and lateral forces generated by different types of rolling stock, their statistic parameters, a technique has been developed to determine an integral vertical and lateral forces distribution depending on the structure of train flow, actual speed, railway track profile and climatic conditions.

Let us by way of illustration determine an integral distribution of vertical forces within the straight station-to-station block section between Golutvin and Podlipki stations of Moscow railway [a branch of Russian Railways] for the 2nd main track. It is known



Pic. 1. Input data for calculation of integral relative frequency of vertical force F_i = 100 kN (summer period).

that at that block section the authorized speed is V_a = 80 km/h.

According to the data of the technical unit of Golutvin track maintenance division, the track is of the class I, the block section belongs to the group of extremely heavy loaded sections (group code is O [EHL]), workload is of 106,8 mln t gross, daily number of passenger trains is 46, number of freight trains is 78, number of multiple unit trains is 11.

Let's calculate the shares of types of rolling stock γ^{K_i} in proportion to the amount of wheelsets.

The total number of wheelsets has been defined following the assumptions that the weight of goods trains was of 3600...4000 tf, and the weight of loaded freight cars was of 94 tf.

The freight train weighing 4000 tf contains on average 42 cars, so the four-axle rail cars of the train have 170 wheelsets, and 78 freight trains will have 13260 wheelsets.

The total number of locomotives has been calculated by summing the numbers of freight and passenger trains Σ_l = 78 + 46 = 124. For calculation we refer to twin-unit electric locomotives with two two-axle bogies per each unit and 8 wheelsets per locomotive. Subsequently the sum of wheelsets will be calculated as 8 • 124 = 992.

The number of cars in the passenger trains is assumed to be 16. Subsequently the sum of wheelsets of passenger trains will be calculated as 46 • 16 • 4 = 2944.

The number of wheelsets of multiple unit trains is 4 • 11 • 12 = 528.

So, the total number of wheelsets running through the considered block section per day is as follows:

Σk_j = 13260 + 992 + 2944 + 528 = 17724.

The k_j set of elements is as follows:

$k_1 = 992$, $k_2 = 13260$, $k_3 = 0$, $k_4 = 0$, $k_5 = 0$, $k_6 = 2944$, $k_7 = 0$, $k_8 = 0$, $k_9 = 528$.

The share of each type of the rolling stock in the total train flow is as follows:

• share of locomotives:

$$\gamma_{11}^{k_1} = \frac{k_1}{k_1 + k_2 + k_5 + k_6 + k_9} = \frac{992}{992 + 13269 + 2944 + 528} =$$

$$= \frac{992}{17724} = 0,056;$$

• share of freight trains:

$$\gamma_{12}^{k_2} = \frac{13260}{17724} = 0,747\ ;$$

• share of passenger trains:

$$\gamma_{16}^{k_6} = \frac{2944}{17724} = 0,167\ ;$$

• share of multiple unit trains:

$$\gamma_{19}^{k_9} = \frac{528}{17724} = 0,03\ .$$

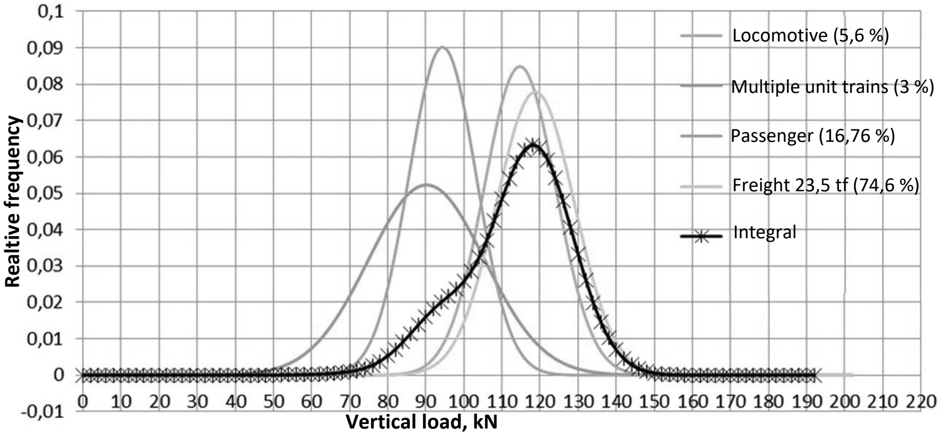
To build probability distribution and probability density function for vertical forces at this block section we determine the density distribution function for each type of rolling stock for summer and winter operating conditions:

$$P_i^{\Sigma} = \gamma^{K_1} \bullet P_{F_i}^{K_1} + \gamma^{K_2} \bullet P_{F_i}^{K_2} + \gamma^{K_6} \bullet P_{F_i}^{K_6} + \gamma^{K_9} \bullet P_{F_i}^{K_9}.$$

To build vertical forces distribution function at this block section we determine the distribution density functions considering the share of each type of rolling stock for summer and winter conditions.

To build integral function it is necessary to take a cross-section for each point along X-axis and to sum the values of functions shown in Pic. 1 regarding the coefficients k representing a share of respective type of rolling stock in the total train flow through this section.

Summation example for vertical forces F_i = 100 kN is shown in Pic. 1.



Pic. 2. Integral distribution of vertical forces acting on the rails due to daily set of trains with due account for summer and winter operating periods.

Let's draw a vertical line through point F_i = 100 kN and define the relative frequency of force F_i = 100 kN at the points of its intersection with graphs of distribution of vertical forces for different types of rolling stock with due account for a share of the impact of different types of rolling stocks on the track. After obtaining initial data for each type of rolling stock, we shall determine the value of integral relative frequency for the force F_i as follows:

P_S^{100} = 0,056 • 0,0249 + 0,747 • 0,0145 + 0,03 • 0,0425 + 0,167 • 0,074 = 0,0262.

Similar operations shall be done for each vertical force F_i with a selected increment (this study uses a 10 kN interval). A special software has been developed for automation of this process. Finally, the calculation results will show a set of integral relative frequencies for sequential vertical forces, which are used for building integral distribution law for the summer period.

Following the same algorithm, we can define integral vertical forces distribution probability for the winter period.

Finally, we will get a set of values for building an integral function for both summer and winter periods. As there is a difference in force impact within the «wheel–rail» system during summer and winter periods due to different stiffness of the track, we shall introduce season coefficients. It is assumed for the middle climate area [in Russia] that during the summer the track is operated for 0,6 T_y, and during the winter it is operated for 0,4 T_y, where T_y is the annual (year) period.

Consequently, previously obtained sets of values shall be summed up in compliance with season coefficients (for the summer it is equal to 0,6; for the winter it is equal to 0,4).

Total P^{Σ} = 0,6 • P_s + 0,4 • P_w; so, e.g. for F_i = 100 kN: P^{Σ} = 0,6 • P_s^{100} + 0,4 • P_w^{100} • 0,6 = 0,0262 + 0,4 • 0,025011 = 0,0257244.

The calculations result in integral distribution of vertical forces at the block section which is shown in Pic. 2.

Analysis of the obtained integral law of distribution has shown:

– obtained density of distribution of vertical forces will allow to calculate the stiffness of the elements of the elements of the track depending on the share of different types of rolling stock passing within the trains, as well as the contact fatigue wear of the rails with regard to the share of freight wagons with increased axial load;

– a similarity of final distribution with distribution calculated for the rolling stock with greatest share in the traffic can be detected (in the considered case it is a distribution for freight wagons);

– the inclusion of passenger trains and multiple unit trains into calculations results in changes in the form of distribution calculated for freight wagons, increasing the values of relative frequency for vertical forces caused by those types of rolling stock).

Brief conclusions

The developed technique allows to identify the total impact on the rails and the track considering shares of each type of rolling stock, authorised speed, climatic conditions.

Conclusions

1. A technique to determine the integral laws of distribution of vertical and lateral forces has been developed, that can be used for implementation of heavy-haul traffic and intended to more accurately consider the force impact of different types of rolling stock, including freight wagons with increased axial load, on the track.

2. The technique allows to consider impact of different types of rolling stock with regard to the design of running parts, magnitude of axial loads, speed, stiffness of the substructure due to seasonality (summer, winter), transverse railway track profile, share of each type of rolling stock in the total impact on the track.

3. Integral distributions of vertical and lateral forces calculated with the suggested technique will allow to calculate stiffness of the elements of the track superstructure under probability aspect considering share of different types of rolling stock passing by a given railway section.

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