THE SERVICE LIFE PREDICTION FOR BRAKE PADS OF FREIGHT WAGONS

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Resume

The analysis of the statistical values of wear of brake pads in operation, based on which a wear model was developed, is presented in this paper. This model can be used for predicting the remaining service life of brake pads according to the wagon mileage.

The distribution function of wear on the upper and lower parts of the pad was determined, which made it possible to find the main qualitative characteristics, namely, the wear intensity, the γ -percentage wear, and the average pad wear at a specified wagon mileage.

The results of the study can be factored for solving complex engineering problems of excessive wear of composite brake pads used for freight rolling stock; they could also help to extend the guaranteed overhaul period and improve the railway traffic safety.

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1 Introduction

Nowadays, Ukrainian Railways (Ukrzaliznytsia) is suffering deterioration of the technical condition of the mechanical brake system of rail wagons, which is the key element of the train traffic safety. The analysis of the traffic safety of the rolling stock has demonstrated that the excessive wear of pads can cause many failures in operation [1]. The reason for this is an imperfect design of the brake leverage system of the bogie, which has not been modernized for a long time.

The results of the study have revealed that excessive wear of pads is caused by the design features of the brake leverage system, which decreases the braking efficiency of wagons due to a smaller contact area in the brake pad/wheel tribotechnical pair (Figure 1). Therefore, this leads to frequent repairs of freight rolling stock, additional energy costs of train traction; and less efficient technical and economic performance of railway transport enterprises.

In recent years, leading wagon manufacturers have successfully modernized elements of a typical brake leverage system, which have extended the guaranteed overhaul periods for brake pads and improved the reliability, durability and maintainability of the brake system [2-5].

2 Analysis of recent research and publications

Based on preliminary observations over wagons, conducted under the operational conditions, it was found that the dual wedge-shaped wear of pads depends on the design and state of the brake system of a wagon bogie. If the wagon mileage reaches 75,000 km, the excessively worn composite brake pads with a residual working mass of 39 % are replaced; it implies excessive operating costs, which, however, can be avoided by modernizing the brake leverage system for wagons used as railway and industrial transport means. This will extend overhaul periods and increase the wagon mileage, providing that the service life of brake pads is predicted [6].

The service life of composite brake pads with mesh and wire frame, which is now in full-scale production and used in the wagon brake system, is from 90,000 to 200,000 km, according to [7]. Based on the results of the study, the average mileage per 1 mm of the pad thickness is 3,500 km on average. However, due to

Figure 1 *Unserviceable brake pads with a large residual working body*

the use of innovative materials, special designs, and improvements in the brake leverage system, the service life of a pad can be significantly increased.

In work [8], the authors proposed an approach to the statistical study. Thus, they evaluated the force with which the brake pad presses the wheel, the hardness of the pad material, etc., when determining the brake distance depending on the speed, the track gradient, and the curve radius during the rolling stock braking. The critical slope values of the brake distance, with full-service braking of the rolling stock, were statistically established. However, the authors did not discuss the case when the contact area between the excessively worn pad and the wheel decreases, therefore, the braking efficiency of the train cannot be positively assessed.

The research described in [9] deals with development of a regression friction model of the pad and wheel of industrial transport locomotives under conditions of structural uncertainty; it was the result of a great number of input parameter variables in the models, i.e., the friction coefficient was included. It is difficult to exclude unstable solutions in such a multi-parameter model, although the author suggested his vision of the problem. However, the model did not include the main parameter - the pad wear by thickness - which restricts the use of all types of brake pads (in terms of safety) under the conditions of scheduled preventive maintenance.

Author of article [10] describes the research into the cause of harmful wedge-shaped wear of pads and the possibility to eliminate it. Such a wear can result in the premature replacement of the brake pads with residual working mass within the scheduled overhaul periods. In this study, a statistical approach was used to plan experiments during the trial operation of wagons with standard and modernized brake leverage gears, included in one train. However, the task of predicting their service life was not set.

Another approach is proposed in [11], where, on the example of excessive wear of brake pads, the authors considered the problem of uneven wear of the pad/wheel friction pairs of one wagon; their dynamic processes were described by a complex model. The work deals with cases in which the values of random parameter variables under consideration follow to the normal distribution law.

Study [12] presents the analyses of some typical block brakes, which are advisable for the rolling stock of the Chinese subway. Some of them are advantageously flexible in operation, fast responding and structurally compact. In some countries, block brakes are used in wagon bogies to provide more efficient braking and extend the service life of pads. However, the use of brake blocks in wagon bogies significantly increases the weight, air consumption for braking, time for maintenance and complexity of repair.

In work [13] the authors analyzed the thermally stressed state of the pad using SolidWorks and, based on the results, propose to improve the material of pads, which will reduce their wear intensity and increase the service life.

Study [14] highlights the results of various friction brake devices that increase the braking efficiency. The authors believe that the mechanisms, which use brake pads have a negative impact on both the track and the wheel's rolling surface due to high temperatures in the pad/wheel friction zone, therefore, the disc brakes are preferable.

Thus, disc brakes are in the focus of many specialists; they calculate the thermally stressed state of the brake elements, observe their operation, and thoroughly investigate the temperature modes for some elements of the rolling stock brake system [15-16]. During the braking, the thermal energy develops in the contact zone of the brake pad/wheel tribotechnical pair. This energy gets dissipated by forced convection, conduction and radiation from the exposed surfaces of the brake. Some authors note that the overheating of tribotechnical pairs can cause failure in the brake gears in operation, which may threaten the train traffic safety [17-18]. From this

Table 1 *Numerical characteristics of the wear measured on the composite brake pads X_1 and X_2*

Pad wear measured	Estimated values of characteristics			
	$\overline{x}$	s^2	As^2	Es
Top X_1	31.69	238.38	0.002	2.01
Bottom X_2	31.86	237.51	0.001	2.01

point of view, considerable theoretical work is being done to study the temperature characteristics of composite brake pads used in wagons under different operating conditions at various speeds [19-20].

The above analysis of literature sources has demonstrated that the problems of excessive wear of pads and ways to increase their service life under the normal operating conditions for brake leverage gears in wagons are yet to be studied. Therefore, it is advisable to introduce measures aimed at improving the performance of brake leverage systems with modernized elements; it reduce the operating costs and ensure the train traffic safety, as well.

The purpose of the study is to predict the service life of brake pads used in freight wagons.

To achieve this purpose, the following tasks have been assigned:

- to formulate a wear model of the brake pad on the basis of the statistical values obtained, so that to predict the remaining working body depending on the wagon mileage;
- to study the wear distribution function for different parts of the pad and, based on it, to determine the wear characteristics for a specified wagon mileage; and
- to research into the wear characteristics of the pad, according to the mileage of a wagon with modernized brake leverage systems, the pads of which are worn-out.

3 Creating the model to predict the brake pads wear and the wear distribution

The information collected in the course of the research on the change in the geometric parameters of brake pads depending on the wagon mileage is subject to careful processing. The thickness of the brake pads was checked during the inspection of freight wagons in the arrival park of the sorting station. With help of a measuring tool, the thickness of the pads in the upper and lower parts, as well as their wear, were determined. The results of the measurements were recorded in the developed report for controlling the geometric parameters of the pads, modernized brake lever gears of the bogies. In this regard, the methods of mathematical statistics were used to analyze the brake systems of the freight wagons. Therefore, creating the favorable conditions for the further serial introduction of updated brake lever transmission designs into production at wagon-building plants, or their modernization at wagon repair enterprises of the joint-stock company "Ukrzaliznytsia".

The statistical estimation method was used to predict the wear of pads of the 2TR-11 type used in wagons with modernized gears. The chemical composition of the 2TR-11 type composite pad contains: 20% of rubber, 47.5% of baride, 15% of carbon black, 2.5% of vulcanizing composition, 15% of other substances. The wear values on the top and bottom of the pad in operation at the wagon mileages from 0 to 197,800 km were found; the number of tests that formed the sample size was n =106. The optimal number of intervals is adopted from the studies highlighted in the work [21]. With a sample size of n =106, the number l = 5 is taken. This meets the requirements for modern statistical research [22]. Such an approach should be considered, if the results of using the Sturges formula are taken into account. In this case, it is $l = 1 + 3.3221gn \approx 5$. That is, the samples of working hours per service life should be divided into 5 intervals, if the total number of observations exceeds 100 units.

In order To determine the wear on the top X_1 and bottom X_2 of the brake pad, the numerical characteristics were found; they included average value $\overline{x}$, corrected variance s^2, squared asymmetry coefficient As^2, and excess coefficient Es - for the random variables X_1 and X_2. The results are shown in Table 1.

A model of wear of the geometric dimensions of brake pads and estimation of their parameters, based on the results of operation of modernized devices for parallel retraction of brake shoes, has been formulated. The model of wear of the geometric dimensions of wagon brake pads was applied as a statistical function. In this case, the density function $f(x)$, for random wear values of x pads, was determined as follows [6, 23-25]:

$$f(x) = \begin{cases} 0, & x \notin (b,c), \\ \dfrac{1+k}{c-b}\left[1-\left(\dfrac{x-a}{b-a}\right)^{\frac{1}{k}}\right], & x \in [b,a], \\ \dfrac{1+k}{c-b}\left[1-\left(\dfrac{x-a}{c-a}\right)^{\frac{1}{k}}\right], & x \in (a,c], \end{cases} \tag{1}$$

where a is the modal value;
b, c are the lower and upper pad wear limits, respectively;
k is the parameter of the pad wear shape.

Equation (1) is determined with $k > 0$ and $k < -1$, where $b < a < c$ and $b \geq 0$. For Equation (1), the distribution function has the form [23-24]:

$$F(x)=\begin{cases}0, & x\le b\\ \left\{x-b+k(x-a)\times\left[1-\left(\frac{x-a}{b-a}\right)^{\frac{1}{k}}\right]\right\}/(c-b), & b<x\le a\\ \left\{x-b+k(x-a)\times\left[1-\left(\frac{x-a}{c-a}\right)^{\frac{1}{k}}\right]\right\}/(c-b), & a<x\le c\\ 1, & x>c.\end{cases} \quad (2)$$

Here, the lower wear limit is $b = 0$, and the upper wear limit is $c = 65$ mm. With these parameters, the mathematical expectation is as follows:

$$M(X)=\frac{(55+55k+165kq+55q)}{2(2k+1)(1+q)}. \quad (3)$$

where q is dimensionless parameter.

The value of parameter q is determined if q of the expression is determined $q = 65q/(1+q)$.

The dispersion is determined using the formula [20, 22]:

$$D(X)=\frac{(c-b)^2(k+1)\begin{pmatrix}2k^2q+7k^2+7k^2q^2+\\+(4k+1)(q+1)^2\end{pmatrix}}{12(2k+1)^2(1+q)^2(3k+1)}. \quad (4)$$

For this model, the squared asymmetry is a function of the two variables, and has the following form [6, 21]: $\beta_1^2=\mu_3^2/\mu_2^3$, where μ_k is the central moment of the k-th order,

$$\begin{aligned}\beta_1^2 &= 108(4k^2q^2-4k^2+4k^2q^3-4k^2q^3-4k^2q+\\&+3kq^3+7kq^2-3k-7kq-1-q+q^2+q^3)^2\times\\&\times k^4(3k+1)/((k+1)(2k^2q+7k^2+7k^2q^2+\\&+4k+8kq+4kq^2+1+2q+q^2)^3(4k+1)^2).\end{aligned} \quad (5)$$

The excess is determined by the expression $\beta_2=\mu_4/\mu_2^2$ [24- 25]; it is equal to:

$$\begin{aligned}\beta_2 &= 9(3k+1)(1+90kq^2+60kq+1184k^3q^3+\\&+368k^2q+1011k^5+572k^6+813k^44q^3+366k^3+\\&+6q^2+102k^2+q^4+532k^2q^2+1184k^3q+\\&+1636k^3q^2+1932k^4q+1932k^4q^3+2958k^4q^2+\\&+102k^2q^4+1684k^5q^4+60kq^3+368k^2q^3+\\&+1684k^5q^3+2546k^5q^2+872k^6q^2+4q+15k+\\&+15kq^4)/(5(2k^2q+7k^2+7k^2q^2+4k+8kq+\\&+4kq^2+1+2q+q^2)^5(4k+1)(5k+1)(k+1)).\end{aligned} \quad (6)$$

To estimate the dimensionless parameters k and q, the method of moments was used [24-25]; it included the equating of the theoretical characteristics in Equations (5), (6) and empirical numerical characteristics (Table 1), the coefficient of squared asymmetry and a kurtosis coefficient.

The solution of this system of equations produced the following parameter values of Equation (1): a) for the top $k = 0.32$, $q = 0.78$, $a = 28.33$; b) for the bottom $k = 0.32$, $q = 0.82$, $a = 29,2$.

The parameter values obtained were used to construct the density distribution graphs for the random pad wear values (Figures 2 and 3) and the pad wear distribution function (Figures 4 and 5).

Consider the sensitive characteristics of the distribution law of a random variable and their operational estimates of the pad wear. Since the correlation is not the adequacy of a probable model, consider the functional characteristics of random variables that are sensitive to distribution models. Their form was established according to experimental data and is one of the essential grounds for proximity, which is close to adequacy of the formulated model. One of these characteristics in the reliability theory is the failure rate, hereinafter called the λ-characteristics. The theoretical λ-characteristics is widely used in practice; it is determined using the formula

$$\lambda(x)=\frac{f(x)}{1-F(x)}. \quad (7)$$

The formula looks like:

$$\lambda(x_{(i)})=\frac{n(x_{(i)})}{\left[n-\sum_{j=1}^{i-1}n(x_{(i)})\right](x_{(i)}-x_{(i-1)})}, \quad (8)$$

where $n(x_{(j)})$ - the frequency of the pad thickness x occurrence in the interval $(x_{(i)}, x_{(i-1)})$.

Based on the measurements of the wear rate for 106 composite brake pads of wagons with modernized devices, the empirical and theoretical λ-characteristics with obtained distribution parameters in Equation (1), was constructed (Figure 6). The points of empirical λ-characteristics practically coincide with the points of theoretical λ-characteristics, which indicates the possibility of using Equation (1) for a random size value of the top and bottom wear of composite brake pads of wagons.

Figure 6 shows the λ-characteristics and the empirical estimates of wear on the top and bottom of the brake pads of wagons [6].

Figure 6, a and b, demonstrates that this characteristics has a virtually linear increasing dependency in the range from 0 to 45 mm. Since the empirical estimates of the λ-characteristics are quite close to the theoretical curve of the λ-characteristics, the pad wear model in Equation (1) can be used for research in this area.

The estimate of the μ-characteristics of the average residual service life [6, 23-24, 26] has significantly lower random fluctuations than the estimate of the μ-characteristics calculated using the same parameters.

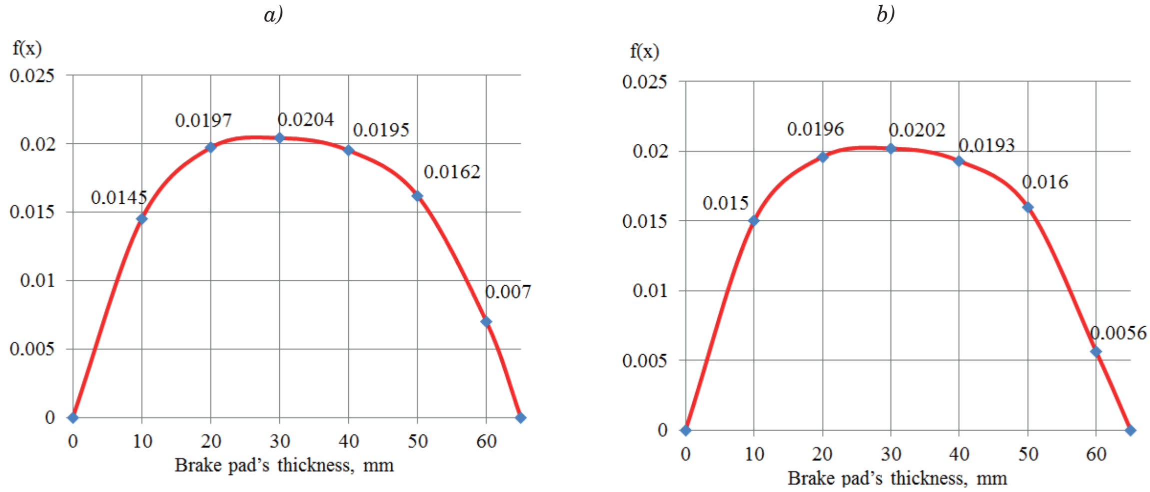

Figure 2 *The theoretical curve of the wear distribution density on top (a) and bottom (b) of the pad with parameter estimates obtained by the method of moments*

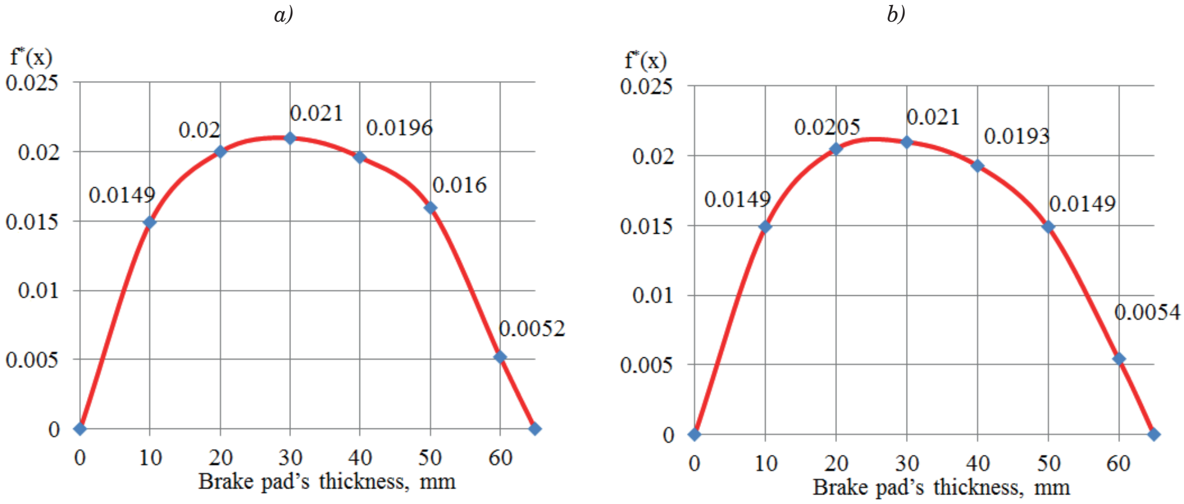

Figure 3 *The empirical curve of wear distribution density on top (a) and bottom (b) of the pad in operation*

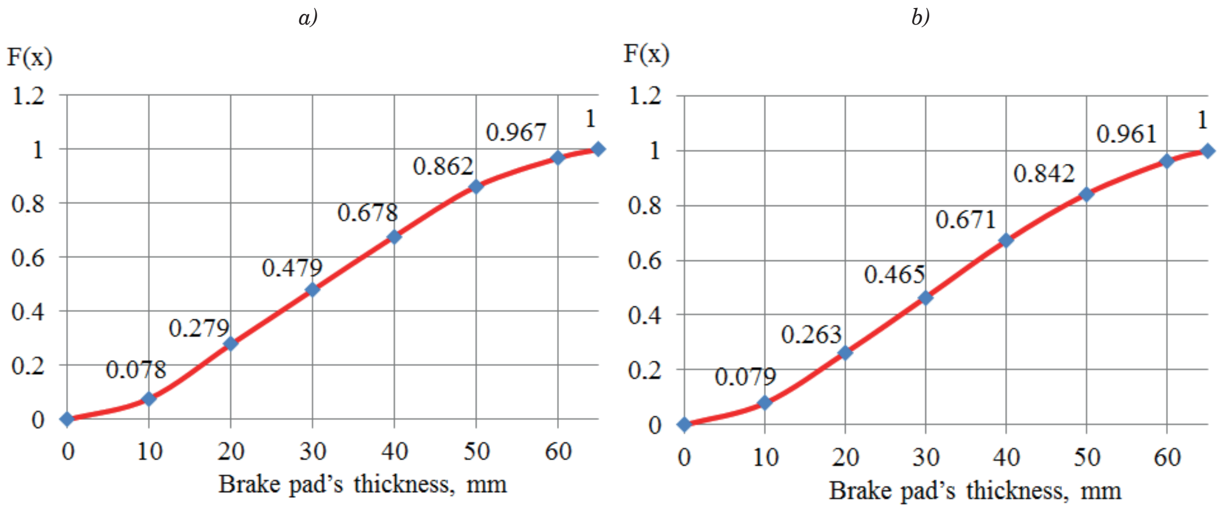

Figure 4 *The theoretical curve of the wear distribution function on top (a) and bottom (b) of the pad with parameter estimates obtained by the method of moments*

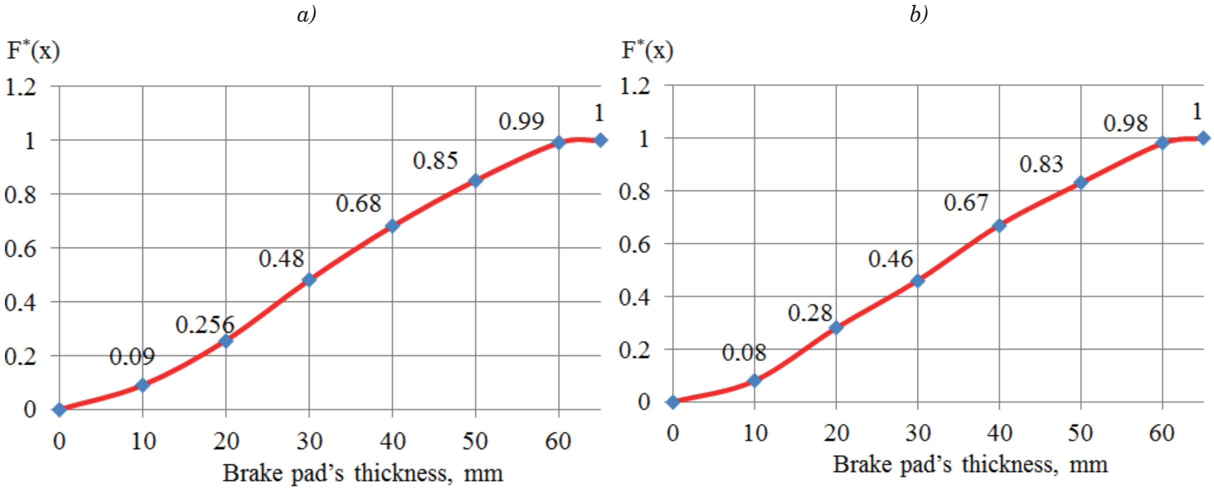

Figure 5 *The empirical curve of the wear distribution function on top (a) and bottom (b) of the pad in operation*

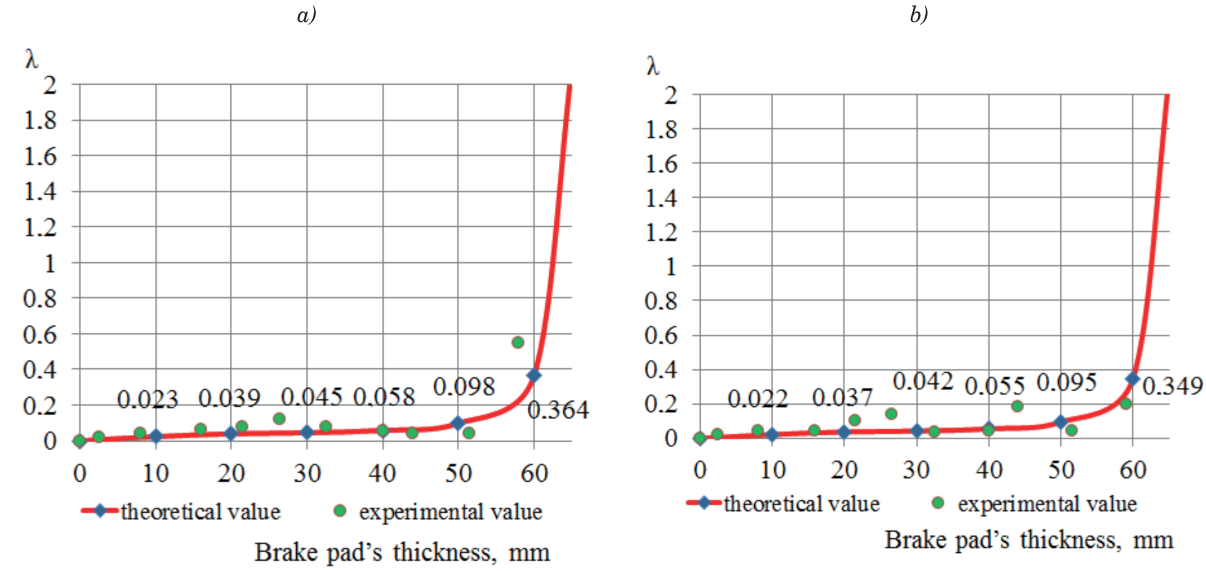

Figure 6 *The graphs of the λ- characteristics of the wear on top (a) and bottom (b) of the composite brake pad and its empirical estimates*

This can be explained by the better statistical quality of the sum estimates compared to the proportion estimates. Moreover, the estimate of the μ-characteristics is sufficiently sensitive to the right-side distribution, which is required for studying the models bounded from the right. It is this characteristics, which will be considered later. Suppose that n tests are conducted, then, at specified values of x, $n \cdot P(X \geq x)$, thus, taking it into account, $n \cdot P(X \geq x+\tau)$. The ratio of these values gives the conditional probability of a value greater than τ, if all these x values have already been present. At the same time, the ordered values are considered:

$$P(X \geq \tau/x) = \frac{P(X \geq x+\tau)}{P(X \geq x)}. \tag{9}$$

The integration of Equation (9) gives $\mu(x)$:

$$\mu(x) = \int_0^{\infty} \frac{1-F(x+\tau)}{1-F(x)} d\tau = \\ = \frac{1}{1-F(x)} \int_x^{\infty} (1-F(z)) dz. \tag{10}$$

To find the empirical estimate $\tilde{\mu}(x)$, it is sufficient to arrange all the values observed in an ascending order, that is, to compile ordinal statistics $x_{(1)},\dots,x_{(n)}$. Then, the values are calculated by the expression

$\tau_0^{(j)}(x_i) = \tau_j - x_i$ for those τ_j that are not less than x_i.

If the number of such values is l, then (with a small offset)

$$\mu(x) \approx \overline{\tau}(x_i) = \frac{1}{l}\sum_{i=1}^{l} \tau_0^{(ji)}(x_i). \tag{11}$$

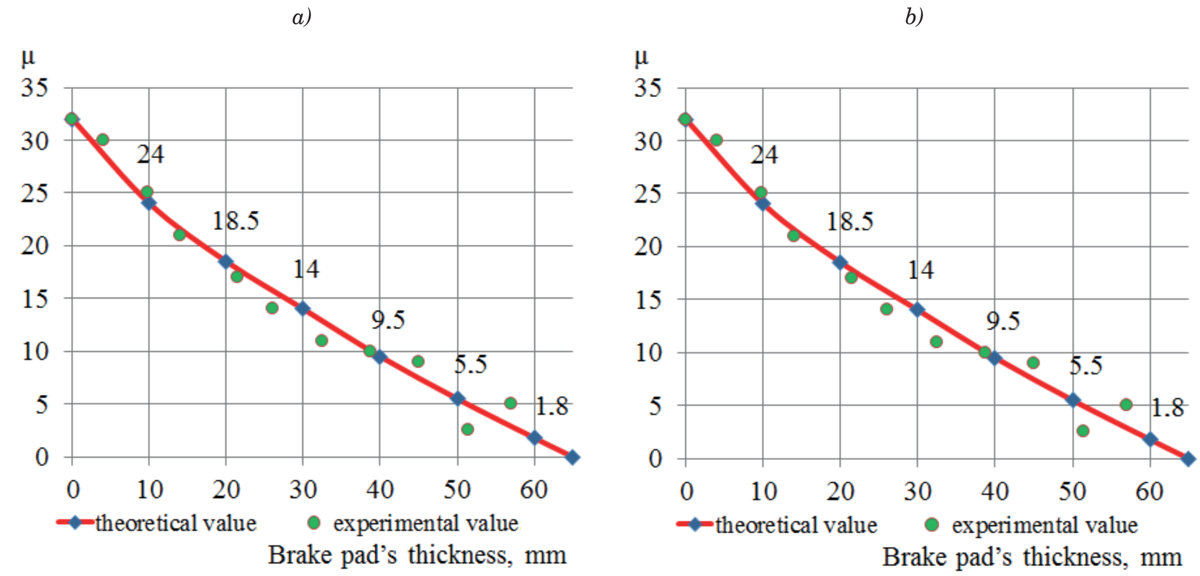

Figure 7 *The graphs of the μ-characteristics of the service life on top (a) and bottom (b) of the composite brake pad and its empirical estimates*

The estimate $\mu(x)$ can be found using the empirical estimates of the distribution function $\tilde{F}(x)$, where $\tilde{F}(x) = \frac{1}{n}\sum_{i=1}^{l} f_i$, and

$$\mu(\tilde{x}) = \frac{1}{\tilde{F}(x)}\sum_{j=1}^{l}\left(1 - \frac{\tilde{F}(x_{j+1}) + \tilde{F}(x_j)}{2}\right)\Delta x_j, \qquad (12)$$

where $x_{j+1} - x_j = \Delta x_j$.

By using Equation (10), the μ-characteristics for the pad service life on the top and bottom can be found using the calculated parameter values of Equation (1) (Figure 7, a and b) and its empirical estimates.

Figure 7 indicates that for the wear values of the wagon brake pad the empirical and theoretical μ-characteristics practically coincide and change similarly, which indicates the proximity of this model to the true model.

The service life characteristics at the test points were found using the mileage of the wagon with modernized brake leverage gears. The study has shown that the relationship between the wear and mileage is close to linear. For the first approximation, take this dependence as $y = \eta(x)$, since for $x = 0$, y should be equal to zero. Using the least squares method, the slope factor η was found. For the upper wear it was $\eta_1 = 5.11$, and for lower wear it was $\eta_2 = 5.28$. By using the dependence and wear distribution in Equation (1), the distribution density of the random mileage y was determined as:

$$f(y) = \begin{cases} 0, & y \notin (\eta b, \eta c), \\ \frac{1+k}{(c-b)\eta}\left[1 - \left(\frac{y/\eta - a}{b-a}\right)^{\frac{1}{k}}\right], & y \in [\eta b, \eta a], \\ \frac{1+k}{(c-b)\eta}\left[1 - \left(\frac{y/\eta - a}{c-a}\right)^{\frac{1}{k}}\right], & y \in (\eta a, \eta c], \end{cases} \qquad (13)$$

For this model, the distribution function has the form:

$$F(y) = \begin{cases} \dfrac{-\eta(b+ka) + y(1+k) + nk(a-b)\left(\frac{y - a\eta}{\eta(a-b)}\right)^{\frac{1+k}{k}}}{\eta(c-b)}, & y \in [\eta b, \eta a), \\ \dfrac{-\eta(b+ka) + y(1+k) + nk(c-a)\left(\frac{y - a\eta}{\eta(c-a)}\right)^{\frac{1+k}{k}}}{\eta(c-b)}, & y \in [\eta a, \eta c], \end{cases} \qquad (14)$$

the next step is to find the empirical and theoretical estimates of the wear intensity and the average residual service life of brake pads taking into account the wagon mileage.

Figure 8, a and b shows the graphs of empirical and theoretical estimates of the wear intensity of brake pads with modernized brake leverage gears, taking into account the wagon mileage. Figure 9, a and b shows the graphs of the empirical and theoretical estimates of the average service life of the brake pad, taking into account the wagon mileage.

By analysing Figures 8 and 9, it can be concluded that the pad wear model, proposed in Equation (1) and obtained Equation (13), can be used to the solve major problems associated with wear of any wagon brake pad used for the rolling stock.

The designed wear model of the wagon pad and the results obtained make it possible to solve the necessary practical problems. The use of service life characteristics can help to predict the main efficiency characteristics of wagons.

The calculations have showed that the threshold of wagon mileage before the composite brake pad gets worn-out on the top is 331,880 km, and on the bottom is

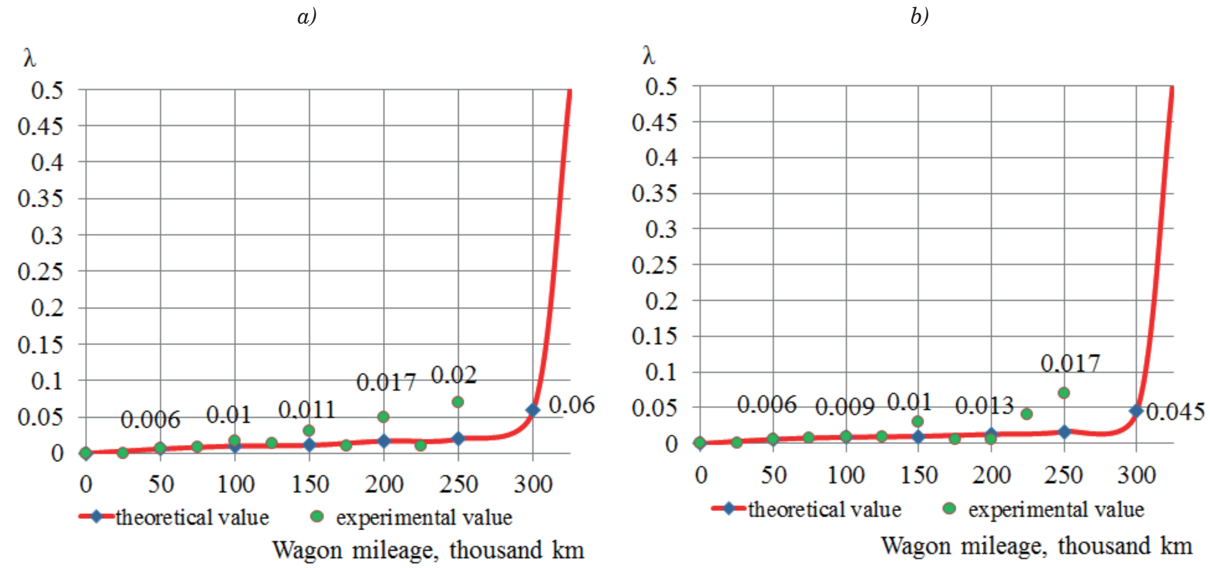

***Figure 8** The graphs of empirical and theoretical estimates of the wear intensity of the pad on top (a) and bottom (b), taking into account the wagon mileage*

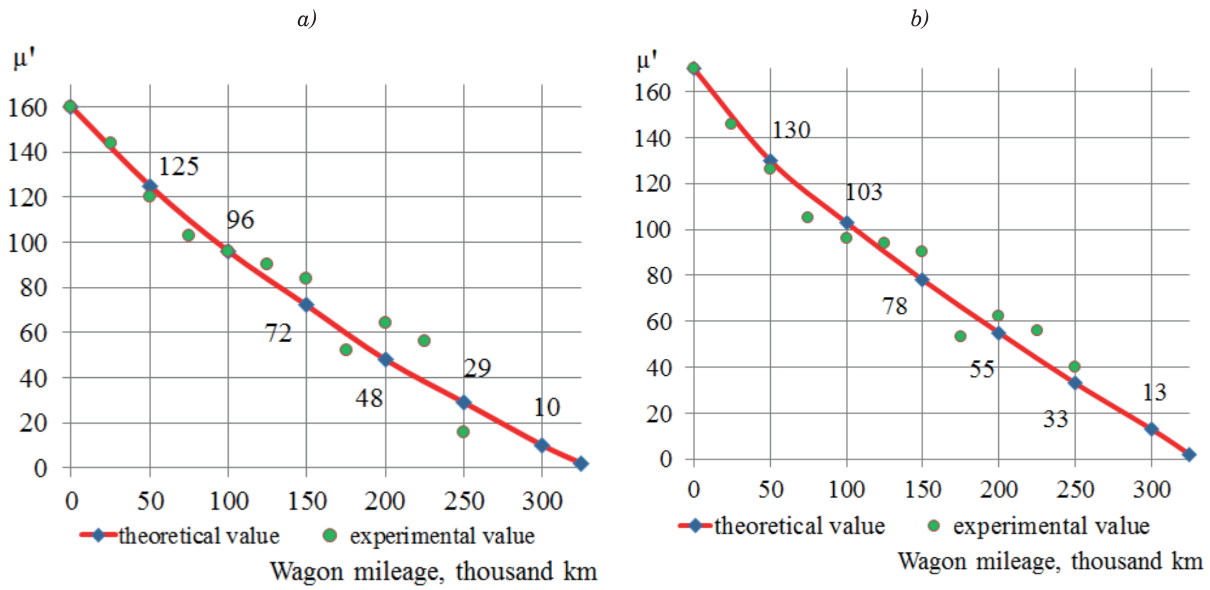

***Figure 9** The graphs of empirical and theoretical estimates of the average residual service life of the pad on top (a) and bottom (b), taking into account the wagon mileage*

343,040 km.

The values of the wear intensity of the composite brake pad of the wagon with a mileage of 250,000 km will account for λ = 0.02 on the top and λ = 0.017 on the bottom.

Given the distribution function $F(x) = P(X < x)$ and estimates of its parameters, it is possible to determine such a characteristics as the probability of the pad wear at point $x_0 - F(x_0)$, and the probability that the pad does not wear at this point $Q(x_0) = 1 - F(x_0)$. Therefore, the probability of wear on the top of the brake pads will be $F(20)$ = 0.27; $F(30)$ = 0.47 and $F(40)$ = 0.67, and on the bottom of the pads is $F(20)$ = 0.26; $F(30)$ = 0.47 and $F(40)$ = 0.67.

Another essential characteristic is the γ-percentage service life, which is determined by the expression $F(x_\gamma) = \gamma/100\%$. For example, for the upper part of the composite brake pad, if $\gamma = 95\%$, the wear is $x_\gamma = 56.79$, and if $\gamma = 90\%$, the wear is $x_\gamma = 52.93$. For the bottom part of the brake pad, if $\gamma = 95\%$, then $x_\gamma = 56.85$, and if $\gamma = 90\%$, then $x_\gamma = 53.02$.

An approximating dependence between the wear and mileage of the wagon with modernized brake leverage gears has been determined, the dependencies found take into account that the pads are worn-out.

It is determined that the average residual service life of the wagon composite brake pad with a thickness of 40 mm on the top is 9.51 mm, and on the bottom is 9.53 mm. It should be noted that if the wagon mileage is 200,000 km, the average residual service life using the slope factor on the top of the composite brake pad will be $\mu' = 50.39$ mm, and on the bottom - $\mu' = 53.13$ mm.

4 Conclusions

A model of the brake pad wear to predict the remaining service life depending on the wagon mileage was designed using the statistical values obtained. This will make it possible to accurately assess such important qualitative characteristics as the service life threshold, which can be used to predict the performance of brake pads and assess the efficiency of brake leverage gears of wagon bogies.

The wear distribution function for the pad parts has been investigated; it can be used to determine the qualitative wear characteristics (probability of pad wear-out at a specified wear; γ-percentage service life of the pad; wear intensity and average residual service life) for a specified wagon mileage. This will help to solve the practical problems for different parts of the brake pad given a known wagon mileage. The service life characteristics will help to predict the major efficiency characteristics of the wagon. The calculations have demonstrated that the wear intensity of the wagon composite brake pad at a wagon mileage of 250,000 km, on the top is $\lambda = 0.02$ and on the bottom is $\lambda = 0.017$.

An approximating dependence of the wear and mileage for the wagon with modernized brake leverage gears has been determined. It is found that the average residual resource of the wagon composite brake pad with a thickness of 40 mm is 9.51 mm on the top and 9.53 mm on the bottom.

The results obtained can be used for solving engineering problems related to excessive wear of composite brake pads used for freight rolling stock. They can be used to extend the guaranteed overhaul periods and improve the railway traffic safety, as well.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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