METHOD FOR DETERMINING THE FACTOR OF DUAL WEDGE-SHAPED WEAR OF COMPOSITE BRAKE PADS FOR FREIGHT WAGONS

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Resume

The work highlights the results of a study into the dual wedge-shaped wear of composite brake pads for freight wagons. It has been found that the over-normative wear makes the area of a composite brake pad larger in the lower part up to a value directly proportional to the wagon mileage and smaller in the upper part. To assess the braking efficiency of a rail vehicle, a graphical analytical method has been developed; it allows determining the factor of dual wedge-shaped wear of pads depending on the wagon mileage. The results of calculation were verified by comparing two samplings obtained by mathematical and computer modelling. The results of calculation have proven that the hypothesis on the adequacy is not rejected.
The results of the study conducted will allow more accurate assessment of the braking efficiency of freight rolling stock to be made, as well as contribute to improving the safety of train traffic.

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1 Introduction

The statistical data of recent years on the traffic safety released by the Wagon Department of Ukrzaliznytsia have shown that the mechanical equipment of brake systems of wagons has become too vulnerable due to higher speeds and greater volumes of freight transportation.

One of the factors negatively affecting the braking efficiency of rail transport vehicles is the dual wedge-shaped wear (Figure 1).

Currently, considerable effort is being made to solve the problem of dual wedge-shaped wear of composite brake pads of the freight wagon bogies used for the 1520-mm mainline rail network [1]. This problem is the result of design features of the brake leverage. It is this deviation from the normative wear established for composite brake pads that is associated with lower braking efficiency of the rail vehicle due to a smaller contact area between the pad and the wheel. This may cause increased maintenance and repair expenditures, as well as extra energy costs for the train traction. Therefore, there is a need to develop measures for eliminating the dual wedge-shaped wear of composite brake pads used for the rolling stock [2].

2 Analysis of recent research and publications

In the mechanical braking system of the running gears of freight wagons, the triangles, when the force is transmitted to them through a system of rods and levers from the brake cylinder during braking, work in a way that the brake shoes are pressed against the wheels simultaneously and with an equal force. However, due to the dynamic processes during the movement of a wagon and the interaction of a wheel with a track irregularity, this balance is disturbed, the pads touch the upper edges

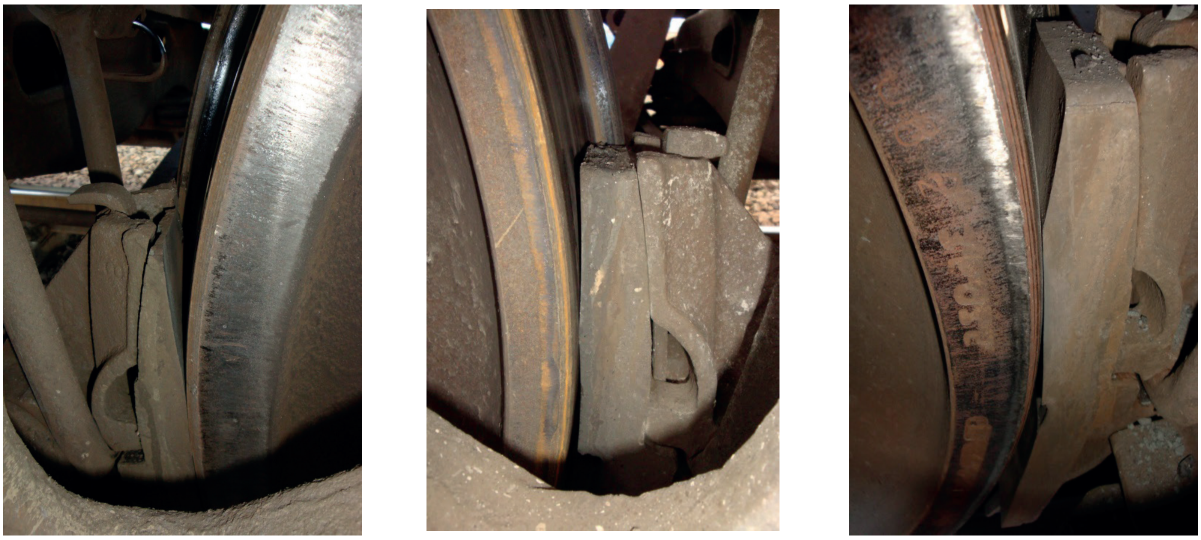

Figure 1 *Wagon pads with wedge-dual wear*

of the wheels, and this causes their dual wedge-shaped wear [3].

Study [4] describes some structural changes in the elements of the brake system of the freight wagon bogie, which were designed to eliminate the dual wedge-shaped wear of composite brake pads. However, the authors did not consider the wear of composite brake pads that could exceed the normative values according to [5] because this wear had not been sufficiently studied regarding the brake leverage of the bogie intended for the 1520-mm track.

Ukrainian and foreign specialists and scientists in the field have tried to change the difficult situation in the railway industry regarding frequent replacement of worn composite brake pads by designing special devices to eliminate their wear. Thus, some tests were carried out on full-scale samples of rail vehicles for the reliability of brake systems of bogies during which the wear and temperature values were measured [6-7].

Study [8] presents an analysis of performance indicators of cast iron and composite brake pads used for various types of the rolling stock. Some negative characteristics of composite brake pads that can damage the rolling surface of wheels of the rolling stock and lead to higher costs of freight transportation were analysed. Moreover, the authors described negative environmental effects of composite pads.

The study of the design features of innovative brake systems of modern rolling stock is given in [9]. The main factors impacting the efficiency of brake systems were identified. The temperature load on the components of tribotechnical pairs "brake pad-wheel" during braking of the rail vehicle was calculated. However, the study did not take into account the dual wedge-shaped wear of composite brake pads, which is frequent in the brake system of a bogie, and its negative impact on the braking efficiency in the freight train consisted of loaded and empty wagons.

Study [10] presents some modifications that can eliminate angular displacements of the brake cylinder rod at its maximum extension out of the body and restrict these displacements. The optimal parameters of the safety element of the brake cylinder rod of the wagon at the permissible moment of resistance were also chosen. The strength of the brake cylinder was calculated using the finite element method, which made it possible to prove that the strength requirement was satisfied. However, it should be noted that an equally important factor affecting the braking efficiency is the brake leverage, which is a determining factor of the train traffic safety. However, the authors did not consider how and whether the extension value of the brake cylinder rod actually changes, if the brake pad is worn, especially when this wear is dual wedge-shaped.

Article [11] presents the study into the performance indicators of various types of brake pads used for the rolling stock. The main advantages of cast iron brake pads, as well as disadvantages of composite ones are given. The price of composite pads depends on the compositions and production technology. The authors present the quality requirements for the manufacture of brake pads and measures to improve the specifications, standards and other documentation. Different types of composite brake pads should be evaluated not only by coefficient of friction and wear resistance, but also by the performance indicators that affect the rolling surface of the wheel and cause various defects due to high temperatures. Among such defects are hollows, slides, cracks, metal tearing all of which cause extra expenditures for repairs of wheels through turning their rims [12].

Study [13] presents a review of publications and an analysis of the quality performance of cast iron and composite pads. The disadvantages of composite brake pads are also given, among them, for example, low thermal conductivity on the rolling surfaces of

***Table 1** The statistical data obtained through in-service inspection of pads*

Average mileage of a wagon, km	Wear value of pads, mm				Total length of the pad with its dual wedge-shaped wear (AB), mm	Length of the slot, (*CD*), mm	Working area according to the mileage (*KP*), mm
	At the upper part	Along the plane delimitation line	At the lower part	Length of harmful abrasion			
7,200	3.5	2.5	1	44	296	40	30
14,400	8	4	3	50	290	40	22
26,400	13	9	4	56	284	40	19
36,000	20	16	8	64	276	38	12
42,300	26	21	9	67	269	37	11
48,000	30	24	11	70	265	37	10
54,600	37	29	12	75	265	37	9
62,400	42	35	13	81	259	37	8
68,300	49	44	14	83	257	36	7
74,400	56	50	15	90	250	36	6

wagon wheels, which can cause numerous thermal malfunctions. This can require additional expenditures for repairs of wagon wheelsets. Another significant drawback is insufficient information in the manuals for production of composite pads and other regulatory documents regarding the rubber mixture ingredients used as well as their chemical composition. This contradicts the current legislation of Ukraine and makes it impossible to control these substances. However, the authors did not present the operating costs of brake pads with dual wedge-shaped wear that mainly occurs when the train moves without braking.

At present it is almost impossible to solve the problem the dual wedge-shaped wear of composite brake pads for freight wagons in operation. Therefore, while designing innovative brake systems for freight wagons, it is necessary to develop measures aimed at eliminating the over-normative wear of the pads when the train moves without braking. This will ensure the train traffic safety and significantly increase the speed of modern freight trains.

3 The aim and main objectives of the article

The purpose of the study was to determine the factor of dual wedge-shaped wear of composite brake pads used for freight wagons.

To achieve this purpose, the following tasks were assigned:

- to determine the braking area of the composite pad taking into account the dual wedge-shaped wear;
- to design a graphic analytical method for determining the factor of dual wedge-shaped wear of composite brake pads relative to the freight wagon mileage; and
- to verify the results of the factor of dual wedge-shaped wear of composite brake pads by comparing samplings obtained by analytical and computer modelling.

4 Features of the detection of factor of dual wedge-shaped wear of composite brake pads

In operation the train speed is regulated by means of brakes when the brake pad is pressed to the rolling surface of a wheel. When the train mileage increases, the wear of the composite brake pad is gradually becoming worse. Moreover, due to the imperfect design, the upper part of the brake pad *AK* (Figure 1) suffers the dual wedge-shaped wear; it reduces the total length of the pad *AB*, the nominal dimensions of which is $AB = a_v = 340$ mm. Therefore, when the length *AK* decreases, the area Q_{ef} at the top of the pad also decreases (Table 1). The similar reduction can be seen for the angle α_{bp} formed between the centre of mass of the pad and its both ends.

So that to determine the area Q_{ef} of the working area of the pad depending on the wagon mileage, the design diagram shown in Figure 2 was drawn up. The calculation was made on the example of a composite brake shoe type 2TR-11.

AB is the total length of the pad; *AK* is the length of the top of the pad; *KB* is the length of the bottom of the pad; *CD* is the length of the air slot of the pad; α_{bp} is the angle formed between the centre and both ends of the pad; β_n is the angle formed between the centre and both ends of the air slot of the pad; R_{bp} is the radius of the working (braking) area of the pad.

To determine the total area Q_{ef} of the brake pad, determine the length of the arc $\smile l_{AB} = l_{ba} = l_{ba\,v}$ by the formula:

$$l_{ba\,v} = \frac{\alpha_v}{180^\circ} \cdot \pi R_{bp} \,. \tag{1}$$

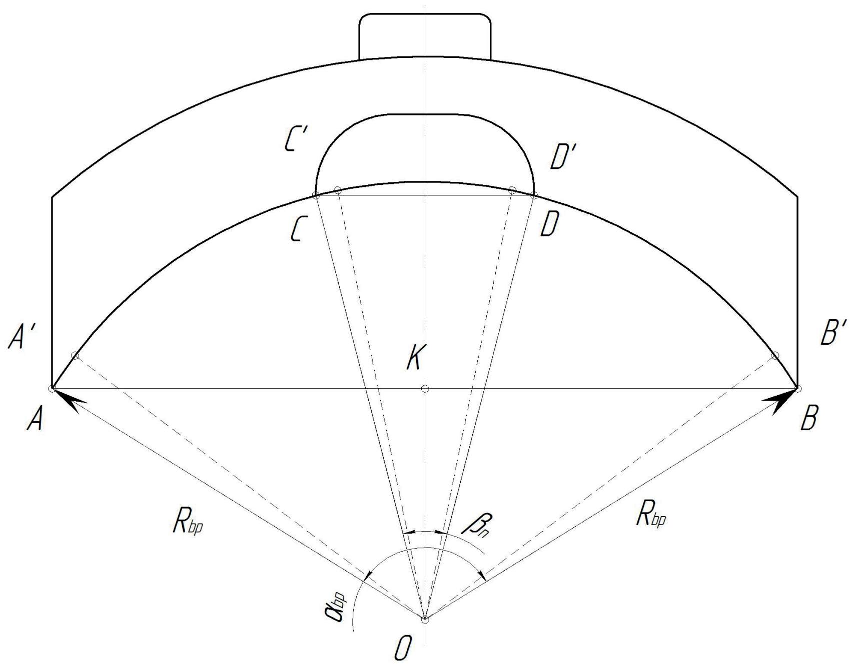

Figure 2 *The design diagram of a composite brake pad type 2TR-11*

From the triangle AOB determine the angle α_{bp} formed between the centre of mass of the pad and its both ends; this angle changes with an increase of the wagon mileage, therefore $\alpha_{bp} = \alpha_v$:

$$\cos\alpha_v = \frac{R_{bp}^2 + R_{bp}^2 - a_v^2}{2R_{bp}^2} = 1 - \frac{a_v^2}{2R_{bp}^2} = = 1 - \frac{a_v^2}{5202}. \quad (2)$$

Hence,

$$\alpha_v = \arccos\left(1 - \frac{a_v^2}{2R_{bp}^2}\right). \quad (3)$$

By substituting α_v in Equation (1) with Equation (3) we get:

$$l_{ba\,v} = \frac{\arccos\left(1 - \frac{a_v^2}{2R_{bp}^2}\right)}{180^\circ} \cdot 3.14 \cdot 51 = = 0.89 \cdot \arccos\left(1 - \frac{a_v^2}{2R_{bp}^2}\right). \quad (4)$$

Determine the length of the small arc of the slot in the pad $\smile l_{CD} = l_{sa} = l_{sa\,v} = l_n$, which changes during braking along with the angle β_n formed between the centre of mass of the pad and the ends of the air slot, therefore the angle $\beta_n = \beta_v$.

The length of the slot $CD = b_v = 40\,mm$.

$$l_{sa\,v} = \frac{\beta}{180^\circ} \cdot \pi R_{bp}. \quad (5)$$

From the triangle COD find the angle β_v formed between the centre and the ends of the air slot of the pad:

$$\cos\beta_v = \frac{R_{bp}^2 + R_{bp}^2 - b_v^2}{2R_{bp}^2} = 1 - \frac{b_v^2}{2R_{bp}^2} = = 1 - \frac{b_v^2}{5202}. \quad (6)$$

Hence,

$$\beta_v = \arccos\left(1 - \frac{b_v^2}{5202}\right). \quad (7)$$

By substituting β_v in Equation (5) with Equation (7) we get:

$$l_{sa\,v} = \frac{\arccos\left(1 - \frac{b_v^2}{2R_{bp}^2}\right)}{180^\circ} \cdot \pi R_{bp}^2. \quad (8)$$

It follows from here that:

$$l_{sa\,v} = \frac{\arccos\left(1 - \frac{b_v^2}{5202}\right)}{180^\circ} \cdot 3.14 \cdot 51 = = 0.89 \cdot \arccos\left(1 - \frac{b_v^2}{2R_{bp}^2}\right). \quad (9)$$

Find the total length of the composite brake pad

$$l = l_{AB} - l_{CD}. \quad (10)$$

All braking levers of freight wagons from wagon manufacturers and after car repair works must be operable [14-15]. Therefore, the width *MK* of a new composite pad with the appropriate profile (Figure 2) will gradually be increased to *MF* depending on the wagon mileage; this can be explained by a decrease

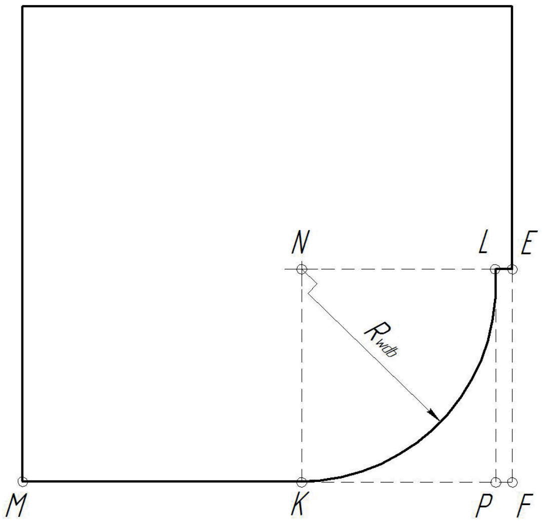

Figure 3 *The cross-section of a composite brake pad*

in the radius R_{wdb}, which also increases the area Q_{ef}. However, due to low mileage of freight wagons, the device for the parallel retraction of brake shoes can become inoperable, thus it does not retain the shoes at a distance from the rolling surfaces of wheels. Therefore, composite brake pads will have the dual wedge-shaped wear in the upper parts [16]. In addition, due to the dual wedge-shaped wear of the pads, their area Q_{ef} will increase in the lower part to a certain extent directly proportional to the wagon mileage, and in the upper part this area will be decreased. For example (Figure 3), determine the working area of the pad by implementing the above method that takes into account the average wear for:

a) pads with nominal dimensions when the device for the parallel retraction of brake shoes is operable and the wagon mileage is zero;

b) pads when the device for the parallel retraction of brake shoes is operable and the wagon mileage is 74,100 km;

c) pads when the device for parallel retraction of brake shoes is inoperable and the pads have dual wedge-shaped wear after the wagon mileage 7.200 km. According to the measurements, such a pad has the following averaged values of the dual wedge-shaped wear: thickness at the top $b_U = 3.5$ mm; thickness along the plane delimitation line $b_{BL} = 2.5$ mm; thickness at the bottom $b_B = 1$ mm; and length of harmful abrasion at the top of the pad $l_H = 44$ mm;

d) pads when the device for the parallel retraction of brake shoes is inoperable and the pads have the dual wedge-shaped wear after the wagon mileage 74,400 km. According to the measurements, such a pad has the following averaged values of dual wedge-shaped wear: thickness at the top $b_U = 56$ mm; thickness along the plane delimitation line $b_{BL} = 50$ mm; thickness at the bottom $b_B = 15$ mm; and length of harmful abrasion at the top of the pad $l_H = 90$ mm.

MF is the width of the working (braking) area of the pad.

Determine the width of the pad m_v:

$$m_v = MK = MF - KF,$$
$$KF = KP + PF, \tag{11}$$
$$MF = 80\,mm;\ NK = NL = KP = R_{wdb} = 35\,mm;$$
$$LE = PF = 3\,mm.$$

According to the calculation, the following working (braking) areas Q_{ef} of the pad were obtained:

a) for a pad with the nominal parameters at zero wagon mileage Q_{ef} = 12891.27 mm^2;
b) for a wagon mileage of 74,100 km Q_{ef} = 20683.86 mm^2;
c) for a wagon mileage of 7,200 km and a pad with the dual wedge-shaped wear Q_{ef} = 12335.23 mm^2;
d) for a wagon mileage of 74,400 km and a pad with the dual wedge-shaped wear Q_{ef} = 15096.76 mm^2.

The averaged statistical experimental data for determining the factor of dual wedge-shaped wear that depends on the harmful wear of brake pads were obtained during control measurements of the geometric parameters of pads after different wagon mileage.

The optimal number of statistical data was determined by formula [17]

$$n = \frac{t^2 \cdot \sigma^2}{\delta^2}, \tag{12}$$

where t is the Student's test value for a given sampling;
σ is the root mean square deviation of a random variable under study;
δ^2 is the absolute error of the measurement.

It was found that at the mathematical expectation 14784.65, the root mean square deviation 3865.728 and the Student's coefficient 2.3, the number of experiments was sufficient.

On the basis of the calculations, the graphical dependence between the working (braking) area of

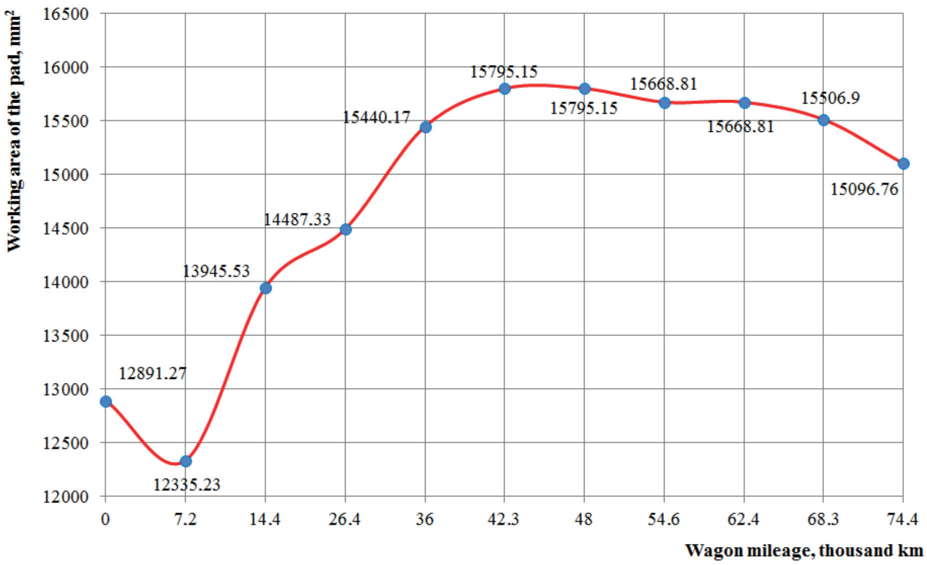

***Figure 4** Dependence of the working (braking) area of the pad with dual wedge-shaped wear on the wagon mileage*

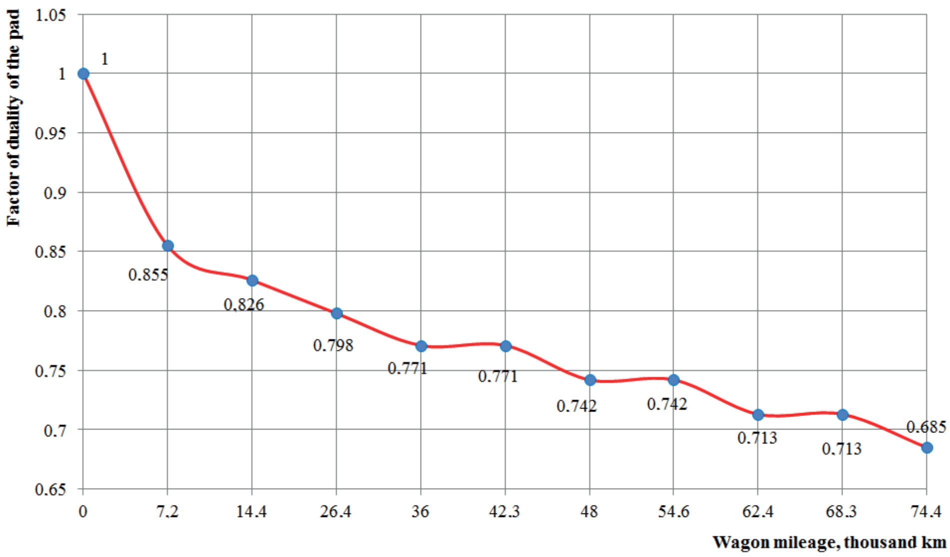

***Figure 5** Dependence of the factor of duality of the pad on the wagon mileage*

the pad with dual wedge-shaped wear (Figure 4) and the factor of duality (Figure 5) was built, these characteristics depend on the wagon mileage.

Thus, on the basis of the braking efficiency of freight trains with composite brake pads, the empirical values and the graphical dependence of the factor of dual wedge-shaped wear, which is directly proportional to the wagon mileage, a graphic analytical method has been developed. It will help to determine the factor of dual wedge-shaped wear for the given mileage of a freight wagon. The factor of dual wedge-shaped wear shows which part of the working surface of the pad is used for braking. In operation, its numerical value can range from 1.0 (no harmful abrasion and the whole useful working area of the pad is used for braking) to less than 0.685 (abrasion in the top of the pad, it approaches the centre). Such cases were observed during production tests; they may lead to the breakage of composite brake pads when used for freight wagons.

It is important to notice, that the temperature factors were not taken into account when carrying out the calculations, because these pads are all-season.

The results obtained were verified with appropriate calculations using an F-test. The verification was carried out by comparing two samplings (Table 2) obtained analytically and with computer modelling. The area of the pad was determined using the spatial model of the pad created in SolidWorks [18-22]. In this case, the nominal parameters of the 2TR-11 brake pad were taken into account, i.e. a 3-D model of the pad was created

***Table 2** Dependence of the working area of the composite brake pad on the freight wagon mileage*

Average mileage of a freight wagon, km	Surface area of the pad, mm²	
	Analytical calculation	Computer calculation
7,200	12,335.23	112,498.2
14,400	13,945.53	13,029.09
26,400	14,487.33	13,576.79
36,000	15,440.17	14,055.32
42,300	15,795.15	14,190.95
48,000	15,795.15	14,430.69
54,600	15,668.81	14,160.63
62,400	15,668.81	14,485.31
68,300	15,506.9	14,935.79
74,400	15,096.76	14,731.45

***Table 3** Basic properties of the 2TR-11 brake pad material*

Indicator name	Value
Brinell hardness, HB	1.2 - 3.0
Modulus of elasticity, Pa	5,000
Poisson's ratio	0.37
Mass density, kg/m³	2.2
Compressive strength, MPa	15
Thermal expansion coefficient, K⁻¹	$4.1 \cdot 10^{-6}$
Friction coefficient	0.1

based on its drawing dimensions. The main parameters of the material of this pad are listed in Table 3. Then this model was imported to Solid Edge, where, with the built-in options the area was determined (Figure 6).

The design value of the factor according to the F-test was determined by [20]

$$F_p = \frac{S_{ad}^2}{S_y^2}, \tag{13}$$

where S_{ad}^2 is the adequacy variance;
S_y^2 is the error mean square.

The adequacy variance was found according to the formula:

$$S_{ad}^2 = \frac{\sum_{i=1}^{n}(y_i - y_i^p)}{f_i}, \tag{14}$$

where y_i^p is the design value obtained by modelling;
f_i is the number of degrees of freedom.

The error mean square was determined by the formula:

$$S_y^2 = \frac{1}{N}\sum_{i=1}^{n} S_i^2, \tag{15}$$

where S_i^2 is the variance in each line where parallel experiments were conducted.

It was assumed that the model under study was linear (Figure 7) and characterized the change in the friction area of the pad according to the wagon mileage.

The calculation demonstrated that at the error mean square S_y^2 = 585928.3 and the variance dispersion S_{ad}^2 = 1232018.8, the actual value of the factor is F_P =2.1, which is less than the tabular value F_t=3.07. Thus, the hypothesis on the adequacy of the developed model is not rejected.

It should be noted that in order to reduce wear on the friction surface of the brake pads, it is possible to introduce devices for their uniform removal from the wheel rolling surface. Such a device was developed by the authors of the article and presented in previous publications [23]. Moreover, one of the options for reducing brake pad wear is the introduction of new materials for their manufacture. The attention will be payed to these issues in subsequent research in this field.

5 Conclusions

The braking area of a composite pad with dual wedge-shaped wear was determined. It was found that the dual wedge-shaped wear makes the area of a composite brake pad Q_{ef} larger in the lower part to the value of the wear directly proportional to the wagon

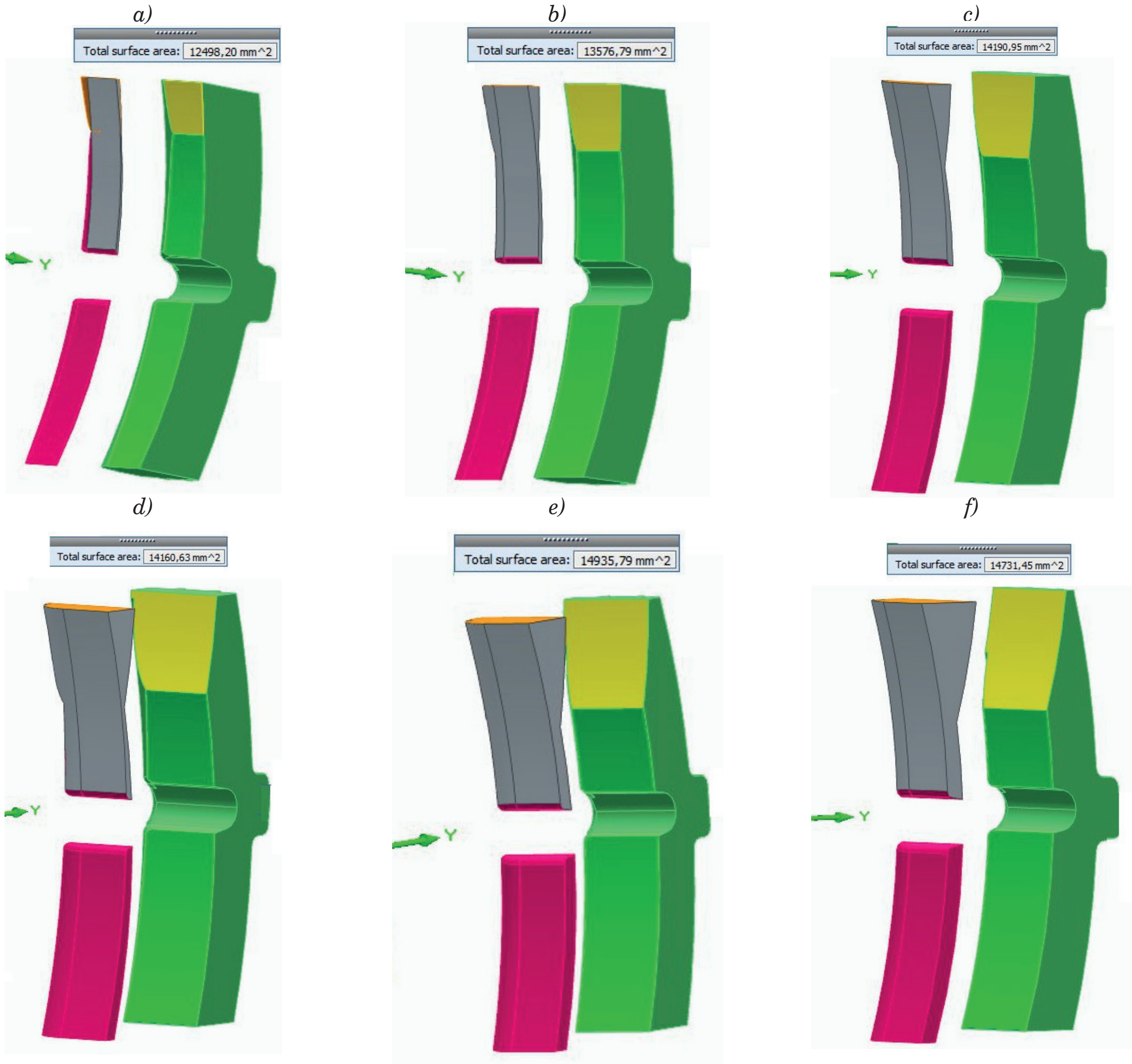

Figure 6 *Results of computer modelling for determining the area of the pad with dual wedge-shaped wear according to the freight wagon mileage a - 7,200 km; b - 26,400 km; c - 42,300 km; d - 54,600 km; e - 68,300 km; f - 74,4000 km*

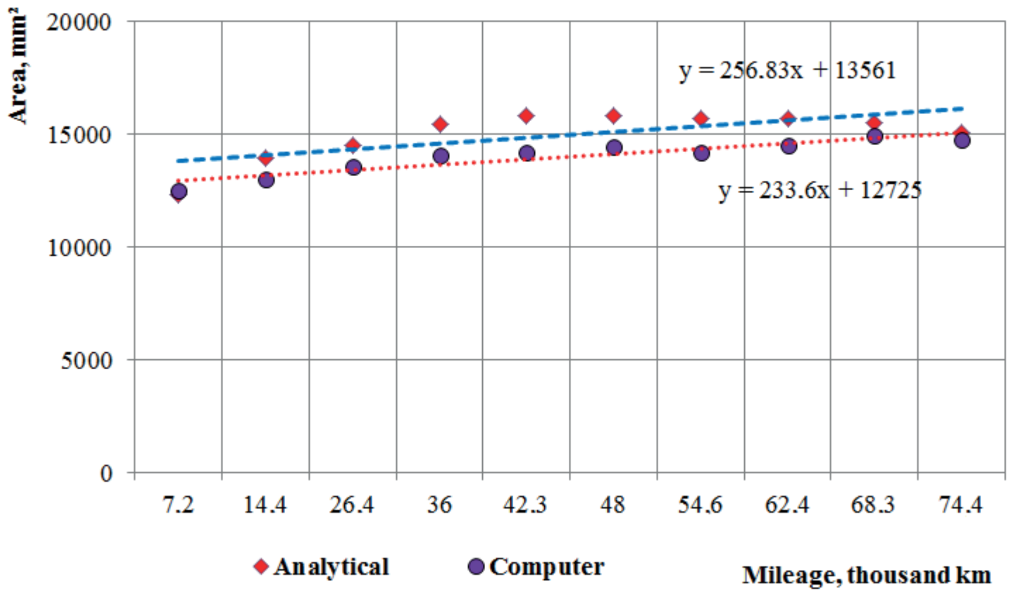

Figure 7 *The graphical dependence of the working area of the composite brake pad on the freight wagon mileage*

mileage, and smaller in the upper part. The area of the working part of the pad was determined using the developed method that took into account the average wear. For a pad with the nominal parameters and with zero wagon mileage Q_{ef} = 12,891.27 mm^2; with the wagon mileage 74,100 km Q_{ef} = 20,683.86 mm^2; with the wagon mileage 7,200 km and the dual wedge-shaped wear Q_{ef} = 12,335.23 mm^2; and with the wagon mileage 74,400 km and the dual wedge-shaped wear Q_{ef} = 15,096.76 mm^2. On the basis of the calculation, the graphical dependence between the working area of the pad with dual wedge-shaped wear and the wagon mileage was built.

A graphic analytical method for determining the factor of dual wedge-shaped wear of composite brake pads that depends on the freight wagon mileage was developed. This method can be used for determining the factor of dual wedge-shaped were for the given mileage of a freight wagon; using this method the braking efficiency of the freight trains with composite brake pads can be assessed.

The results of the analytical and computer modelling used for the determination of the factor of dual wedge-shaped wear were verified by means of the samplings. It was found that at the error mean square S_y^2 = 585,928,3 and the adequacy variance S_{ad}^2 = 1,232,018,8, the actual value of the factor was F_p = 2.1; this value is less than the tabular value F_t=3.07. The results of the calculation have proven that the hypothesis on the adequacy of the developed model is not rejected.

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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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