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TRIBOLOGICAL CHARACTERISTICS OF FRICTION PAIRS OF VEHICLES BRAKING MECHANISMS

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Abstract. In this paper by using the example of combined braking control of passenger vehicle of the segment C the estimation of influence of tribological characteristics of friction pairs of braking mechanisms to the braking process is performed. The obtained results enable to make a conclusion that at “cold” and “after cooling” braking mechanisms of the vehicle values of mathematical expectation of friction coefficient and dispersion of its values are approximately equal. The performed calculation indicates that when the friction coefficient changes by 8–20% the change of braking moment by 20–30% takes place. Thus, the difference between the largest and the smallest braking moments may be 50%, that may change the output characteristics and behavior of the investigated vehicle.

Keywords. Tribological characteristics, disc brakes, drum brakes, friction pairs, coefficient of friction.

INTRODUCTION

Currently in passenger vehicles of segments A, B, C combinations of various types of braking mechanisms (BM) may be used. Large quantities of these segments BM production defined the use of combined braking control [1]. Depending on a number of reasons disk braking mechanisms (DBM) or drum braking mechanisms (DRBM) may be used on all wheels, or DBM may be mounted on the front wheels and DRBM may be mounted on the rear wheels. Frequent use of combined braking control on such models is explained by the fact that 85% of vehicle kinetic energy is dissipated by the BM of the front axis, as well as that it enables to obtain simple and at the same time effective BM during parking with connection to the braking elements of the rear BM. This system of BM found widest use in vehicles with full mass up to 1500 kg and maximum travel speed 40–50 meters per second.

Unequal distribution of braking forces between the axes of the vehicle during the use of this type of BM leads to different power and thermal loadings of the front and rear BM axes. This especially is observed when moving on long roads going down the hills and in the city conditions. Heating up to different temperatures of the front and rear BM friction pairs surfaces of the leads to the changes of tribological characteristics of the vehicle BM and influences its behavior in the process of braking.

Braking qualities of the vehicles to a large extent are defined by the tribological characteristics (coefficient of friction) of frictional pairs of the vehicle. Reduction of the coefficient of friction leads not only to lower effectiveness of vehicle braking, but also to the effect of non-uniformity of braking forces on the sides of the vehicle, which leads to a change of behavior of the vehicle in the process of motion.

The investigations performed earlier [2, 3] indicated, that the greatest influence on the violation of behavior of the vehicle takes place because of the changes of BM tribological characteristics. Currently in passenger vehicles on the front wheels DBM of open type is mounted. Thus, the investigation of tribological characteristics of the friction pair “brake disk – brake pad” is of interest.

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The purpose of the paper is the estimation of the influence of the change of tribological characteristics of braking mechanisms friction pairs to the process of passenger vehicles braking.

ESTIMATION OF THE INFLUENCE OF THE CHANGE OF TRIBOLOGICAL CHARACTERISTICS OF BM TO THE BEHAVIOUR OF PASSENGER VEHICLES

Currently in the market of passenger vehicles spare parts producers of brake pads and braking disks of indicated segments of different companies from many countries are represented. In the publication [4] results of investigation of tribo-technical characteristics of brake pads of vehicles of segment C produced by 17 different companies are presented. Results of the indicated investigation are presented in the Table 1.

Table 1. Coefficients of friction of braking frictional pairs [4].

Manufacturing company	**Braking from the speed of 100 km/h ("cold BM")**	**Braking from the speed of 100 km/h ("heated up to 250 °C BM")**	**Last braking of the "mountain" cycle (*t* °C of the block)**	**Braking from the speed of 100 km/h after cooling of the BM**
ATE	0.58	0.47	0.43 (260)	0.48
ATE with the disk ATE	0.49	0.32	0.39 (180)	0.37
Best	0.41	0.37	0.40 (250)	0.46
Bosch	0.48	0.28	0.36 (260)	0.46
Dafmi	0.44	0.31	0.30 (280)	0.44
Ferodo	0.44	0.30	0.29 (280)	0.35
AP Lockhead	0.27	0.23	discontinued experiments	discontinued experiments
AP Lockhead with the AP disk	0.23	discontinued experiments	discontinued experiments	discontinued experiments
Lucas	0.51	0.32	0.30 (280)	0.45
Lucas with the disk Lucas	0.53	0.30	0.35 (280)	0.45
QH	0.63	0.33	0.42 (290)	0.57
QH with the disk QH	0.59	0.39	0.43 (270)	0.65
Railunds	0.55	0.44	0.41 (220)	0.48
Rona	0.45	0.45	0.44 (230)	0.52
Samko	0.60	0.22	0.36 (260)	0.60
STS	0.48	0.41	0.38 (230)	0.47
Trans Master	0.41	0.37	0.38 (260)	0.45
VATI	0.35	0.37	0.40 (230)	0.47
EZATI	0.45	0.35	0.33 (200)	0.46
Polyhedr	0.41	discontinued experiments	discontinued experiments	discontinued experiments
TIIR	0.39	0.33	0.27 (270)	0.38

In Fig. 1 histogram of distribution of friction coefficient of the pair "brake pad – brake disk" obtained for the case of testing of "cold" vehicles (Table 1) is presented. Investigation of the histogram indicates that the highest number of friction pairs has the coefficient of friction at cold BM in the interval $\mu_x = 0.4–0.5$.

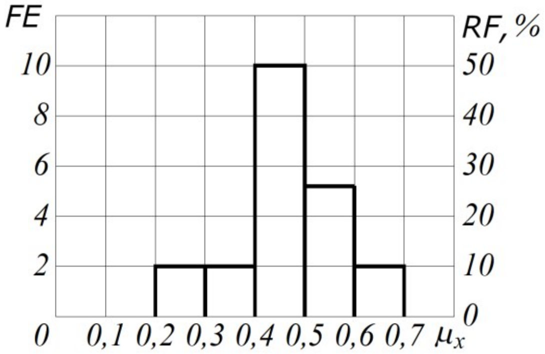
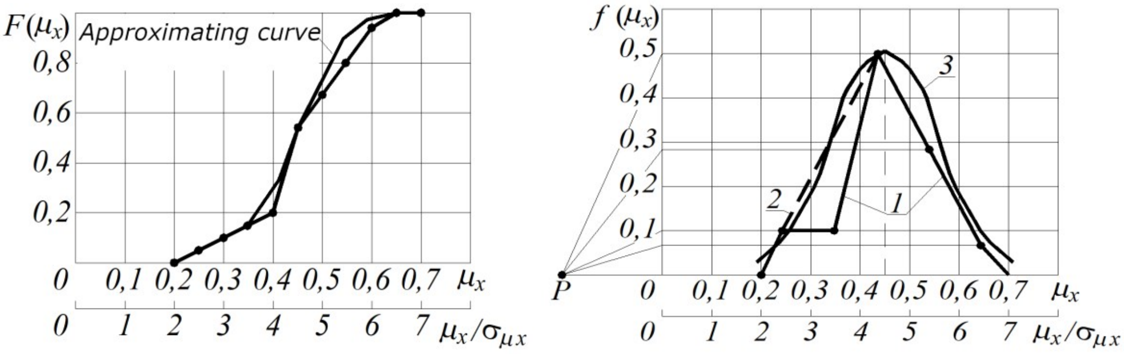


Figure 1. Dependence of frequency of events (*FE*) and relative frequency of events (*RF*) of being of the friction coefficient μ_x (when the brakes are "cold") in a given interval of values.

Mathematical expectation of the coefficient of friction, dispersion of its random quantity, medium quadratic deviation, and coefficient of variation of the coefficient of friction at "cold" BM are $\mu_{\mu X}$=0.46, $D_{\mu X}$=0.0106, $\sigma_{\mu X}$=±0.10, $\upsilon_{\mu X}$=±0.220.

In Fig. 2a function of distribution of friction coefficient μ_x when the brakes are "cold", obtained based on the histogram (Fig. 1) is presented.



a) b)

Figure 2. Function of distribution (a) and density of distribution (b) of friction coefficient μ_x: 1 – broken line obtained by performing graphical differentiation, 2 – improvement of precision of the obtained broken line, 3 – approximating curve of the normal law of distribution.

After performing of the graphical differentiation of the curve $F(\mu_x)$, the broken line is obtained and denoted as 1 (Fig. 2 b). Gently sloping branch formed in the area μ_x≈0.25–0.35, is determined by the fact that the volume of samples in this interval is small (totally two blocks). Thus, it can be deleted (line 2, Fig. 2 b). From the graphical relationship represented by the broken line 1 it is seen that we have normal distribution of the random quantity μ_x.

In the same way parameters of distribution, distribution functions and distribution densities of friction coefficients for "hot" BM μ_h; for "mountain" cycle of experiments μ_m and BM after cooling up to normal temperature μ_c were obtained. Parameters of distribution of friction coefficient for "hot" BM: $m_{\mu h}$=0.34, $D_{\mu h}$=0.0047, $\sigma_{\mu h}$=±0.068, $\upsilon_{\mu h}$=0.200; when braking is of "mountain" cycle: $m_{\mu m}$=0.37, $D_{\mu m}$=0.0028, $\sigma_{\mu m}$=±0.053, $\upsilon_{\mu m}$=0.143; for cooled BM: $m_{\mu c}$=0.47, $D_{\mu c}$=0.0057, $\sigma_{\mu c}$=±0.075, $\upsilon_{\mu c}$=0.160.

When the brakes are heated to more than 200 °C reduction of the coefficient of friction of frictional pairs takes place, as well as reduction of frictional moments by 1.25–1.40 times takes place, this is to be considered when designing of the brake control and predicting of the behavior of passenger vehicle in the process of braking.

Also, of interest is the estimation of possible nonuniformity of braking moments to the wheels of a single axis because of the difference in the friction coefficients. This difference may take place because of mounting of braking pads of different producers as well as because of nonuniform heating of brakes of the left and right wheels.

The obtained results enable to make a conclusion that for "cold" and "cooled" BM values of mathematical expectation of friction coefficient and dispersion of its values are approximately equal. It is seen that thermal processing of friction pairs enabled to increase mathematical expectation of friction coefficient from μ_x=0.46 to μ_c=0.47 and to reduce medium quadratic deviation of friction coefficient from $|\sigma_{\mu x}|$=0.1 to $|\sigma_{\mu c}|$=0.075. For heated BM (in case of testing of "hot" BM and for "mountain" cycle of experiments) values of mathematical expectations of friction coefficient are near to each other but are much lower than for "cold" and cooled brakes ($m_{\mu h}$=0.34, $m_{\mu m}$=0.37). Values of medium quadratic deviations are also near to each other ($\sigma_{\mu h}$=±0.068, $\sigma_{\mu m}$=±0.053). One is to note that for the latter cases dispersion of the friction coefficient is smaller than for the previous cases.

In Fig. 3 histogram of distribution of the difference of friction coefficient for the same friction pair for various testing regimes is presented. Parameters of distribution: $m_{\Delta\mu}$=0.17, $D_{\Delta\mu}$=0.0064, $\sigma_{\Delta\mu}$=0.08, $\upsilon_{\Delta\mu}$=0.471. Scope of random quantities $\frac{\Delta\mu_{max}}{\Delta\mu_{min}} = \frac{0.38}{0.08}$.

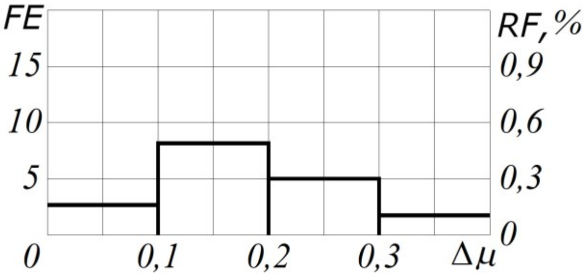


Figure 3. Dependence of frequency of events (*FE*) and relative frequency of events (*RF*) from the variation of the friction coefficient

In the publication [8] results of testing of eight samples of compositions of frictional materials for disk brakes of open type are also presented. Statistical processing of values of friction coefficients of the indicated materials enabled to obtain the parameters of the distribution: m_μ=0.389, D_μ=0.0056, σ_μ=0.075, υ_μ=0.193. Because in the process of testing of the indicated samples [12] temperature was not controlled, thus the obtained results show good correlation with the results obtained previously for "hot" BM and for BM when "mountain" cycle of experiments is performed.

DRBM in passenger vehicles currently are being installed on the rear wheels. Despite of the fact that the greatest influence on the effectiveness of braking has front BM, stability of operation of rear BM has essential influence on distribution of energy absorbed during braking between separate BM.

In the market of spare parts for passenger vehicles currently production of various companies are represented, including far away countries. Because of this, authors of the investigation [5] provide results of estimation of DRBM stability qualities of segment C passenger vehicle, when they are equipped with braking pads, produced by various companies (Table 2). Tests were performed in the laboratory [5].

In the process of braking constant supplied pressure was kept in the experimental setup according to the rules European Economic Commission of the United Nations Number 13 [5, 6]. All braking pads were processed.

When testing for heating, cycle consisting of 15 sequential breakings with equal intervals was implemented. Heating temperature for all pads (till the end of the fifteenth braking) was practically equal and had the value of 180–200 °C [5].

In the Table 3 values of mathematical expectation m_{MT} of the braking moment corresponding to the first, tenth and fifteenth breakings for all types of pads and also medium quadratic deviation σ_{MT} and variation coefficient ϑ_{M_T} obtained by us are presented. Also values of maximum absolute ΔM_{Tmax} and relative δM_{Tmax} variations of the braking moment for each type of braking blocks are presented in the Table 2.

The braking moment caused by DRBM does not have direct dependence from the friction coefficient of frictional surfaces. We will perform the estimation of variation of the friction coefficient, corresponding to the changes of braking moment given in the Table 2.

In the passenger vehicle of segment C DRBM with equal driving forces [7] is used, the braking moment of which is equal to:

$$M_T = P \cdot r_b \cdot \frac{2\mu \cdot c \cdot (a+c)}{c^2 - \mu^2 \cdot e^2} = P \cdot r_b \cdot \frac{2\mu \cdot \left(1+\frac{a}{c}\right)}{1-\mu^2 \cdot \left(\frac{e}{c}\right)^2} . \qquad (1)$$

Geometrical parameters of the investigated braking mechanism: a=93 mm, c=84 mm, e=103 mm; r_b=250 mm.

Table 2. Estimation of the value of the DRBM braking moment [5].

Manufacturing company of braking pads	**Braking moment M_T, N·m**			**ΔM_{Tmax}, N·m**	$\delta M_{T\max} = \frac{\Delta M_{T\max}}{M_{T\max}}$
	First braking	**Tenth braking**	**Fifteenth braking**		
OTA	370	240	200	170	0.459
Ferodo	320	270	240	80	0.250
Samko	540	360	320	220	0.407
Lucas	630	300	250	380	0.603
ATE	440	280	240	200	0.454
Autodetal	580	430	380	200	0.345
Saint Petersburg	600	440	350	280	0.417
Nachalo	390	330	310	80	0.205
Volzhskie	510	270	110	400	0.784
Sonatex	530	410	380	150	0.283
m_{M_T}	495	343	289	188	0.406
σ_{M_T}	±101	±76	±90	±94	0.171
ϑ_{M_T}	±0.204	±0.223	±0.310	±0.502	±0.420

After transformation (1) we will obtain the root of the quadratic equation having physical sense:

$$\mu = \sqrt{9968 \cdot \frac{p^2}{M_T^2} + 0,665} - 99,84 \cdot \frac{p}{M_T} . \qquad (2)$$

Analysis of the influence of the parameter p to the value of μ in the equation (2) showed, that real values of friction coefficient correspond to the value of the supplied pressure p=1.5 MPa.

In the Table 3 values of friction coefficient μ calculated according to the equation (2) at p=1.5 MPa for values of the braking moment indicated in the Table 2 are presented.

Table 3. Calculated values of the coefficient of friction μ.

Producer of braking blocks	**Coefficient of friction μ**		
	First braking	**Tenth braking**	**Fifteenth braking**
OTA	0.503	0.400	discontinued experiments
Ferodo	0.470	0.429	0.400
Samko	0.582	0.497	0.470
Lucas	0.610	0.454	0.410
ATE	0.541	0.438	0.400
Autodetal	0.595	0.536	0.509
Saint Petersburg	0.601	0.541	0.490

Nachalo	0.515	0.477	0.462
Volzhskie	0.571	0.429	0.223
Sonatex	0.578	0.526	0.509
Mathematical expectation μ	0.559	0.479	0.432
Medium quadratic deviation σ_μ	±0.045	±0.051	±0.088
Coefficient of variation ϑ_μ	±0.080	±0.106	±0.204

CONCLUSIONS

Pairs "brake pad – brake disk" of braking mechanisms are most unstable elements of braking control, providing absorption and dissipation of passenger vehicle energy when braking. Instability of braking moments to the wheels has substantial influence on the behavior of vehicle when braking. During the investigation as an example of DBM and DRBM it was determined that tribo-metric parameters on one axis constitute from – 0.173 to – 0.285 (DBM) and from – 0.239 to – 0.339 (DRBM).

Performed statistical analysis of tribo-metric parameters of frictional pairs (on the example of passenger vehicle of segment C) showed their wide scatter, this has essential influence on the side and axial nonuniformity of braking forces; for example, for frictional covers of DBM medium difference of friction coefficients on the left and right wheels constitutes 0.17, and medium quadratic deviation ±0,08. Difference in friction coefficients of frictional pairs in various types of braking mechanisms because of the use of frictional covers of various manufacturers may lead to the change of the distribution coefficient of braking forces in a wide range (for example for the investigated vehicles it may change in the region 0.479–0.739).

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