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WEAR OF BRAKE SYSTEM COMPONENTS IN VARIOUS OPERATING CONDITIONS OF VEHICLE IN THE TRANSPORT COMPANY

PRZEBIEG ZUŻYCIA ELEMENTÓW UKŁADU HAMULCOWEGO W ZRÓŻNICOWANYCH WARUNKACH EKSPLOATACJI SAMOCHODU W PRZEDSIĘBIORSTWIE TRANSPORTOWYM*

Effective fleet management is related to the care for their rational use and proper diagnostics. Early detection of potential irregularities enables to prevent failures and carry out transport processes in an undisturbed way. One of the most important components, from the safety point of view, is the braking system. Laboratory tests can be used to determine the durability characteristics of individual components. Individual indications referring to operating conditions would be most desirable. The article, based on a two-year period of testing of a group of Renault vehicles fitted with disc brakes, presents measurement of wearing and tearing the system components (brake discs and brake friction insert) in a function of selected factors, depending on the time and environment in which the transport was carried out. Nonparametric statistical tests were used to analyze the results. Mann-Whitney and Kruskal-Wallis tests were used to verify the hypothesis on the insignificance of differences. Their results were compared with the results of ANOVA variance analysis. The significance of factors influencing the degree of brakes wear was checked. Possible directions of using the results of brake wear measurement for rationalization of transport processes were also indicated. Presented method may also be applied to the evaluation of other components (assemblies, subassemblies, systems) of motor vehicles.

Keywords: *car exploitation, wear of brake system components, influence of usage conditions.*

Efektywne zarządzanie flotą pojazdów związane jest z dbałością o ich racjonalne użytkowanie i właściwą diagnostykę. Wczesne wykrywanie potencjalnych nieprawidłowości pozwala zapobiegać awariom i realizować procesy transportowe w sposób niezakłócony. Jednym z ważniejszych podzespołów, z punktu widzenia bezpieczeństwa użytkowania pojazdu, jest układ hamulcowy. Na podstawie badań laboratoryjnych można wyznaczyć charakterystyki trwałości poszczególnych jego elementów. Najbardziej pożądane są indywidualne wskazania, odwołujące się do warunków eksploatacji. W niniejszym artykule, na przykładzie badań grupy pojazdów marki Renault, wyposażonych w tarczowe mechanizmy hamulcowe, przeprowadzonych w okresie dwóch lat, dokonano pomiarów zużycia elementów układu (tarcze i klocki hamulcowe) w funkcji wybranych czynników, zależnych od czasu i środowiska, w którym realizowane były przewozy. Do analizy wyników wykorzystano nieparametryczne testy statystyczne. Celem weryfikacji hipotezy o nieistotności różnic zastosowano testy Manna-Whitney'a, oraz Kruskala-Wallisa. Ich wyniki porównano z wynikami analizy wariancji ANOVA. Sprawdzono istotność czynników wpływających na stopień zużycia hamulców. Wskazano również możliwe kierunki wykorzystania wyników pomiaru zużycia hamulców do racjonalizacji procesów transportowych. Zaprezentowana metoda może znaleźć zastosowanie także do oceny innych elementów (zespołów, podzespołów, układów) pojazdów samochodowych.

Słowa kluczowe: *eksploatacja samochodów, zużycie elementów układów hamulcowych, wpływ warunków użytkowania.*

1. Introduction

Hitherto, the optimization of transport systems has been primarily focused on the economic issues [2, 6, 24]. In recent years, the trend of planning activities based on decision-making models, taking into account the negative impact of transport on the environment (e.g. pollutants emission [17], noise [5] or road safety [12]) is noticeable. Customer satisfaction and proper quality of services are also emphasized [4]. It is ensured by maintaining high readiness [20] and reliability of the entire transport system [18, 19], as well as its individual compo-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** nents, e.g. the engine [14]. Simulation models are also being developed, enabling to analyze systems which are different in scale and functions, as well as taking into account in them the sensitivity [16] and flexibility issues [1, 9]. As a result, the number of disturbances in the system is lower (adverse effects caused by, for example, defect of the transport means) and lower costs of its operation. The concept of risk is also underlined. The suitability of vehicles in the aspect of their basic safety systems, such as the brake system, reduces the likelihood of hazards that may interrupt the operation of the transport system. Also in this respect, the interest of scientists and practitioners is noticeable [26].

The analysis of the impact of various factors on the wear of brake system components presented in the literature is generally referred to the results of laboratory tests (bench tests). It most often concerns the materials from which the discs were made [25], brake pads [21], as well as the mutual interaction of the friction pair in various operating conditions [8, 23]. For example, the article [10] presents the results of experiments aimed at examining the impact of model ambient conditions on the friction coefficient of a friction pair of a disc brake. The influence of various operating conditions (brake disc rotational speed, number of braking cycles) and external factors (appearance of water and brake fluid in the friction area) was analyzed confirming their significance, while the research work [7] was the influence on friction elements of the vehicle brakes, of the factors stemming from their working environment (humidity and temperature), resulting in a change in the braking force. Also in the article [15] a significant influence of the temperature of the friction pair on the friction coefficient was demonstrated.

The authors of the analyzed publications described their achievements mainly in relation to the results of laboratory tests (e.g. laboratory analyzes of the friction pair temperature). They did not present outcomes of the research carried out under real operating conditions, taking into account the natural environment of vehicle operation, impact of the traffic in which they operate, or the impact of the calendar month, on the wear of the brake system components. A gap was found in terms of the research on the impact of the season (which in the analyzed climate is subject to cyclical changes in the form of seasons characterized by relatively constant weather conditions), as well as the impact of urban traffic (due to greater driving dynamics) on the wear of brake system elements. One can only assume that high values of ambient temperature are conducive to the increase of the operating temperature of the elements. Determining by the manufacturer acceptable consumption standards does not take into account their individual operating conditions and does not suggest how to shape them, whereas such information is important for both the vehicle user and the manufacturer providing the guarantee.

The purpose of this work was to evaluate the impact of the operating conditions on the wear of the brake system components in the process of car operation by a transport company.

2. Test method

The research covered a homogeneous group of vehicles performing similar transport tasks in two different traffic environments (urban and extra-urban). The vehicles' tires were of the same type. The items tested were original in all vehicles. The data made available related to the wear measurements of the selected brake system elements and allowed only to perform analyzes regarding the impact of traffic type and calendar month, omitting other factors, such as exact vehicle load, driving style or usage intensity expressed in kilometres. The rationale for the omission of the influence of these factors is the fact that the research concerned a fleet of new vehicles, purchased at the same time, with constant output parameters.

The data collected concerned two years of operation. They were registered from May 2016 till April 2018, on a monthly basis. The research group consisted of 20 Renault Kangoo vehicles. Half conducted transport work in urban traffic (vehicles 1-10), the others operated outside the city (vehicles no. 11-20). The measurements were made using an external analogue micrometer with a measuring range from 0.1 mm to 25 mm and a reading accuracy of 0.01 mm. The thickness of the four essential components of the brake system was measured: front and rear brake discs and front and rear brake pads. For each element, 4-5 measurements were made, the thickness of the tested elements was determined as arithmetic means from several measurements and then the average value of wear was calculated. The procedure, using brake discs as an example, is presented in Table 1. Each line of the table applies to an individual vehicle. All studies were conducted using Statistica program.

The resulting sheets were converted by arranging numerical values for all vehicles in two traffic types (urban and extra-urban). A

Table 1. Results of brake discs measurement and calculated wear

Calendar month	Measurement of element's thickness [mm]	Element's wear [mm]
5	24	
6	23.9	0.10
7	23.79	0.11
8	23.64	0.15
9	23.48	0.16
10	23.29	0.19
11	23.11	0.18
12	23.06	0.05
1	22.98	0.08
2	22.91	0.07
3	22.84	0.07

Table 2. Measurement data after conversion

Calendar month	Element's wear in urban traffic [mm]	Vehicle no.
6	0.38	1
6	0.32	2
6	0.47	3
6	0.42	4
6	0.4	5
6	0.52	6
6	0.55	7
6	0.43	8
6	0.53	9
6	0.5	10
7	0.39	1
7	0.39	2
7	0.39	3
7	0.48	4
7	0.48	5
7	0.67	6
7	0.67	7
7	0.48	8

fragment of the created measurement sets (for the friction pad of the front brakes) is shown in Tab. 2.

3. Test results

3.1. Initial analysis

In order to present the collected data and determine basic measures of the descriptive statistics, allowing to summarize the data set and to draw basic conclusions and generalizations about the collected sample, a statistical analysis was performed of the measured data collected on the Renault Kangoo brake systems. The results obtained are given in Tab. 3.

Table 3. Basic descriptive statistics of tested components wear

Element	Descriptive statistics									
	Traffic type	Number of observations	Mean [mm]	Median [mm]	Min. [mm]	Maks. [mm]	Std. Dev. [mm]	Var -co. [%]	Skew-ness	Kurtosis
Front brake friction pads	urban	220	0.47	0.47	0.27	0.69	0.08	16.10	0.39	0.36
Front brake friction pads	extra-urban	230	0.40	0.41	0.18	0.69	0.10	25.78	-0.09	-0.43
Rear brake friction pads	urban	230	0.12	0.10	0.01	0.25	0.05	38.94	0.62	-0.49
Rear brake friction pads	extra-urban	230	0.08	0.06	0.03	0.25	0.05	55.46	0.70	-0.73
Front brake discs	urban	220	0.13	0.11	0.02	0.25	0.05	39.38	0.66	-0.46
Front brake discs	extra-urban	230	0.09	0.07	0.04	0.18	0.04	39.50	0.64	-0.92
Rear brake discs	urban	230	0.05	0.05	0.02	0.11	0.02	38.04	0.65	-0.67
Rear brake discs	extra-urban	230	0.04	0.03	0.01	0.08	0.02	43.83	0.56	-0.43

The number of observations included in the analysis, due to the removal of negative values resulting from the replacement of an element with a new one, is different for individual elements. Central tendency measures are similar. The analysis of distribution variability was carried out without considering the impact of the calendar month, therefore the values obtained are large (e.g. the variation coefficient for the rear brake friction pads element is $V = 56\%$). This shows that the impact of the season on the wear process can be significant. The wear distribution of friction pads of the front brake in extra-urban traffic is characterized by left-sided asymmetry (negative skewness). Thus, the majority of observations take values below the mean. In the remaining distributions (positive skewness coefficient), the asymmetry is right-handed: the majority of observations are above average. Positive value of the front brake friction pad wear distribution kurtosis indicates that it is more concentrated than the normal distribution (leptokurtic distribution). The negative value of the kurtosis of remaining brake system elements distribution means that the measurement results are less concentrated compared to the normal one (platykurtic distribution).

The homogeneity of the sample was evaluated by the significance analysis of the 'Vehicle' factor. Due to the lack of compliance with the assumptions for the ANOVA analysis, the Mann-Whitney test was used for all vehicles' pairs . Most of the *p-values* obtained were higher than the assumed level of significance $\alpha = 0,05$, therefore no significant differences were found between the wear of elements of the brake system in the individual vehicles. Selected results of the analysis conducted are presented in Tab. 4.

Similar level of the brake system elements wear in the sample of cars for a given type of traffic is confirmed by the example charts. Fig. 1 shows the wear of the front brake discs in the urban traffic, while in Fig. 2 – rear friction pads in extra-urban traffic.

Table 4. Results of Mann-Whitney test for a component of rear brake discs in vehicles in urban traffic

Vehicle No.	2	3	4	5	6	7	8	9	10
	p-value for the Mann-Whitney test								
1	0.0679	0.6476	1.0000	0.8278	0.7940	0.9653	0.9480	0.8790	0.6953
2		0.2560	0.0526	0.2127	0.1679	0.3049	0.2749	0.3049	0.1422
3			0.5420	0.9826	0.7441	1.0000	0.8962	1.0000	0.6476
4				0.6633	0.9480	0.8448	0.8618	0.7773	0.8790
5					0.8109	1.0000	0.8278	1.0000	0.6013
6						0.7773	0.9653	0.8278	0.6953
7							0.6476	0.9307	0.5420
8								0.6953	0.7441
9									0.5713

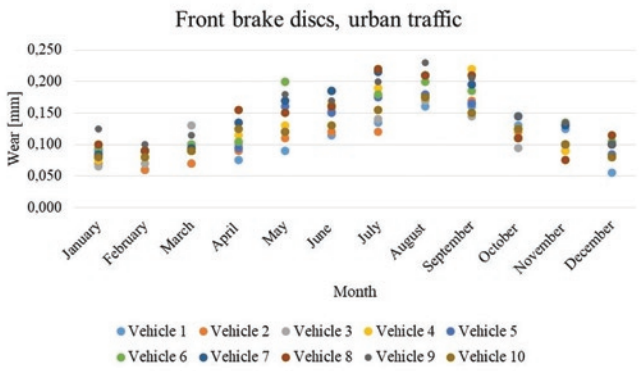

Fig. 1. Wear of the front brake discs in urban traffic for 1-10 vehicles

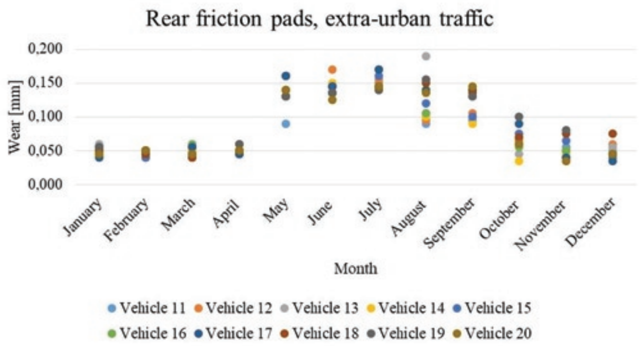

Fig. 2. Wear of the rear friction inserts in non-urban traffic for 11-20 vehicles

The research hypothesis assumes that the wear of the brake system elements depends on the type of traffic (environment) in which the vehicle operated (urban, extra-urban) and the calendar month (season). It was assumed that the impact of these variables is important. The verification allows the ANOVA variance analysis. Its implementation is possible after meeting the requirements, which include the normality of distributions in all *k* sets, and the equality of their variances [22].

Table 5. Results of the Shapiro-Wilk test for rear brake friction insert component

No.	Month	Shapiro-Wilk Statistics	p-value
1.	January	W = 0.9105	p = 0.0039
2.	February	W = 0.8663	p = 0.0002
3.	March	W = 0.9444	p = 0.0488
4.	April	W = 0.9496	p = 0.0733
5.	May	W = 0.9395	p = 0.2349
6.	June	W = 0.9687	p = 0.3262
7.	July	W = 0.9643	p = 0.2334
8.	August	W = 0.9829	p = 0.7968
9.	September	W = 0.9815	p = 0.7455
10.	October	W = 0.9618	p = 0.1932
11.	November	W = 0.8981	p = 0.0017
12.	December	W = 0.9389	p = 0.0317

In the analyzed sample there are groups defined by the grouping variables: 'Traffic' and 'Month'. The analysis of the normality of distributions for the grouping variable 'Traffic' using Shapiro-Wilk test showed that the zero hypothesis H0 assuming their normality should be rejected. All obtained *p-value* results were lower than the assumed level of significance $\alpha = 0{,}05$. For the grouping variable 'Month', only a few did not meet this assumption. Sample results of the Shapiro-Wilk test, for the rear friction brake pads, are shown in Tab. 5.

The homogeneity of the variance was verified by means of the Levene test and the Brown-Forsythe test, which assume in the H_0 hypothesis the homogeneity of the variance between the tested samples. According to the results for urban and extra-urban traffic (Tab. 6), only for the rear brake friction pads the uniformity of variance between the tested samples was confirmed, while for the remaining parts of the vehicle a rejection of H_0 is necessary.

The same analysis was carried out for groups defined by calendar months. Selected results for the front brake discs are presented in Tab. 7.

For each of the four examined elements, the collected data violates the analysis of variance ANOVA requirements (both assuming normality of residual distribution and homogeneity of variance). For this reason, it was decided to perform nonparametric tests, for each factor separately and without taking into account mutual interactions, which are well defined only in the variance analysis. For this purpose, alternative tests were used, which did not require meeting a number of requirements for parametric tests. In order to verify the hypothesis about the irrelevance of differences between two independent groups, the Mann-Whitney test was used, while for the factor of at least three levels, the Kruskal-Wallis test was used. The null hypotheses in both cases assume that the samples come from one population, which amounts to verifying the irrelevance of differences between average ranks for compared groups (sometimes simplified to medians).

Because the ANOVA variance analysis is somewhat resistant to violation of its assumptions, and the probability of making type I and type II errors is smaller, it was decided to conduct this study in parallel, for purposes of comparison, being aware that the obtained results should be treated as indications and rely on the results of non-parametric tests. The analyzes performed were presented separately for the front elements of the brake system (discs and friction pads of the front brake) and rear ones (discs and friction pads of the rear brake).

3.2. Testing front components of the brake system

According to the above considerations, non-parametric tests were carried out for the defined groups. Mann-Whitney test was used for the division by the type of traffic participated in (urban, extra-urban) and the Kruskal-Wallis test for groups resulting from particular months. The results obtained are presented in the Tables below. The Tab. 8 compiles calculations for front brake discs and friction pads.

The results obtained indicate that the influence of all the distinguished factors on the degree of wear, both of the discs and friction pads of the front brake, is significant. The *p-values* obtained testify that for the 'Traffic' factor which, in the Mann-Whitney test for both elements of the system, reached the *p-value* < 0.001. The relationship for the front brake discs is confirmed by the frame graph (Figure 3) and the wear median values, which are 0.11 mm and 0.07 mm respectively for urban and extra-urban traffic.

The degree of wear of the front friction pads is also dependent on the environment in which the driving is taking place – Fig. 4. The consumption medians in the urban and extra-urban traffic amounted to 0.47 mm and 0.41 mm, respectively.

The *p-values* < 0.001 obtained in the Kruskal-Wallis test for the analysis of the 'Month' factor (Tab. 8), confirm its significance in the wearing process of both front discs and friction pads. This level is changing over the next months. For front brake discs, wear is

Table 6. Results of the Levene and Brown-Forsythe tests for urban and non-urban traffic

Variable	Average urban	Average extra-urban	Levene'a F(1.df)	df Levene'a	p Levene'a	Brn-Fors F(1.df)	df Brn-Fors	p Brn-Fors
Front friction pads	0.47	0.40	27.97	448	0.0000	25.20	448	0.0000
Rear friction pads	0.12	0.08	2.59	458	0.1081	0.37	458	0.5418
Front discs	0.13	0.09	22.39	448	0.0000	14.57	448	0.0002
Rear discs	0.05	0.04	12.38	458	0.0005	5.16	458	0.0236

Table 7. Results of the Levene and Brown-Forsythe tests for chosen month for front brake discs

	January		February	
Test/ p-value	Levene'a	Browna-Forsythe'a	Levene'a	Browna- Forsythe'a
January	-	-	0.5958	0.7625
February	0.5958	0.7625	-	-
March	0.2986	0.2526	0.1229	0.1361
April	0.0093	0.0215	0.0022	0.0088
May	0.0780	0.1039	0.0259	0.0468
June	0.0002	0.0014	0.0000	0.0006
July	0.0000	0.0001	0.0000	0.0000
August	0.0000	0.0000	0.0000	0.0000
September	0.0018	0.0013	0.0004	0.0004
October	0.0000	0.0042	0.0000	0.0018
November	0.0002	0.0024	0.0000	0.0008
December	0.3674	0.4920	0.1441	0.3033

Table 8. Results of the factors significance for brake discs and rear friction insert component

Factor	Front brake discs		Front friction pads	
	ANOVA p-value	MW/KW test p-value	ANOVA p-value	MW/KW test p-value
Traffic	< 0.001	< 0.001	< 0.001	< 0.001
Month	< 0.001	< 0.001	< 0.001	< 0.001
Vehicle (Traffic) Vehicle	< 0.001	< 0.001	0.066	< 0.001
Month x Traffic	< 0.001	–	0.010	–

higher from May to September and decreases from October to April (Figure 5).

Similar, though less varied, results were obtained for the front friction pads. Their monthly consumption is also the highest from May to September, which confirms the significant impact of the calendar month (Figure 6).

The level of wear of the front elements of the brake system, both discs and pads, is therefore significantly conditioned by the environment in which the transport is conducted. Higher indications were obtained for urban traffic compared to driving outside the city.

The graphs show observations that could be considered unusual, but due to a small sample, they could not be unambiguously analyzed, which is why they took part in the test.

The calculated significance of the interaction between the factors: 'Month' and 'Traffic' (Tab. 8) indicates that their combined effect is not the same as the sum of the impacts of each individually. A multiplied impact on the wear of the tested elements in the vehicles travelling in the city traffic during the summer months should be expected. This is confirmed by the graph of average wear of the front brake discs, depending on the type of traffic and the month, shown in Fig 7 .

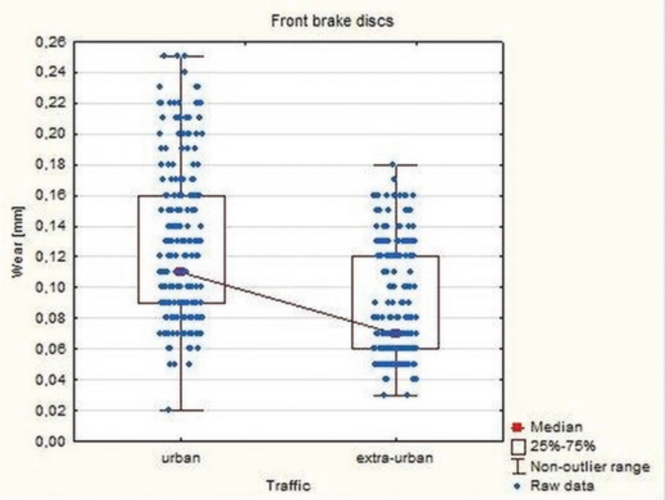

Fig. 3. Wear of the front brake discs component depending on the type of traffic

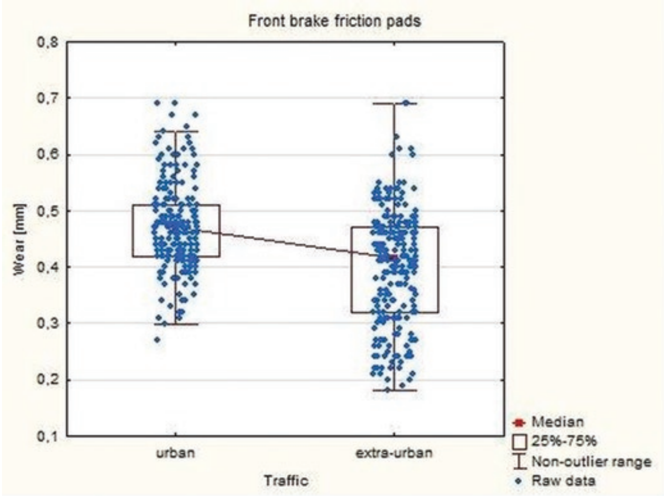

Fig. 4. Wear of the front brake friction insert component depending on the type of traffic

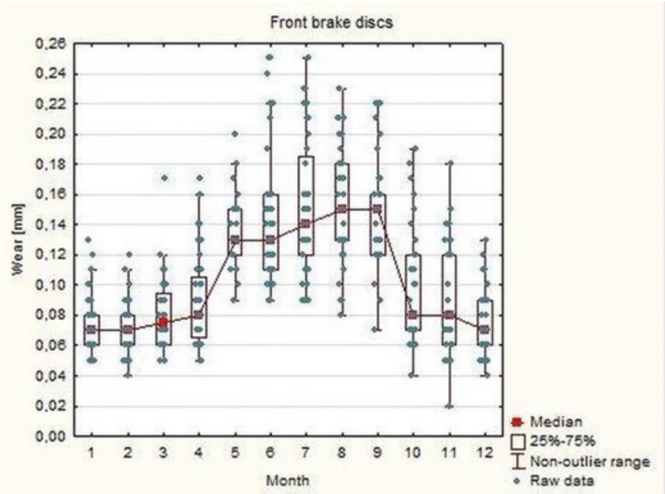

Fig. 5. Wear of the front brake discs component depending on the month

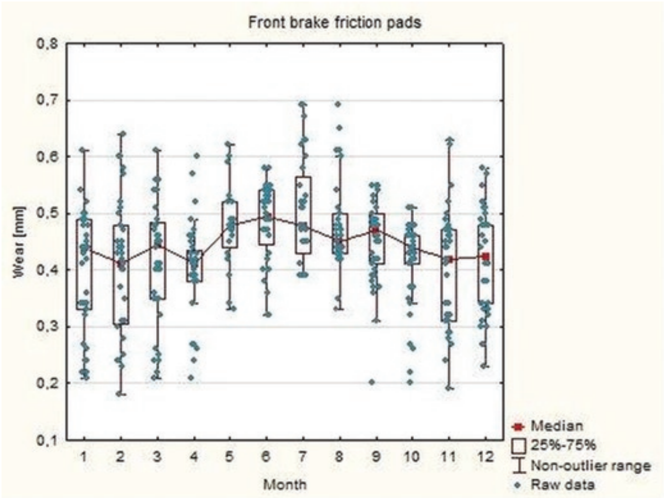

Fig. 6. Wear of the front brake friction insert component depending on the month

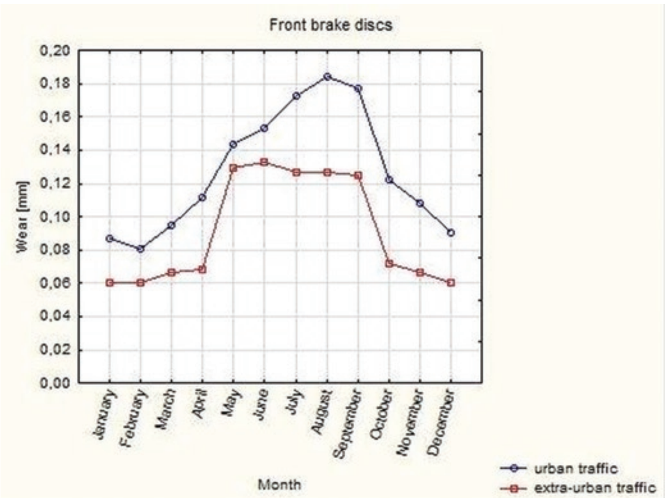

Fig. 7. Average wear of the front brake discs component depending on the type of traffic and month

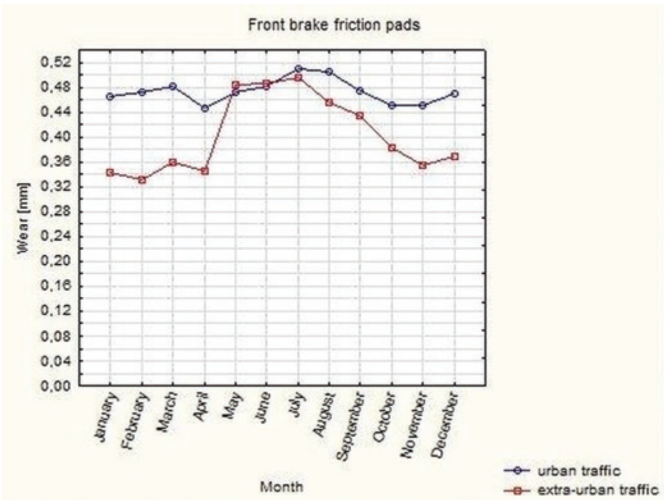

Fig. 8. Average wear of the front brake friction insert component depending on the type of traffic and month

Similarly, on the graph of average wear of the front friction pads, depending on the type of traffic and month (Fig. 8), a clear interaction is visible. Its absence would result in equidistant pairs of points for the same month.

3.3. Testing of the rear components of the brake system.

The conclusions from the analysis of the rear components of the brake system are similar to those for the front components. The results of the conducted statistical tests obtained also indicate the existing dependence of their wear on the examined factors. The results of significance tests for individual factors, with respect to wear, are presented in Tab. 9.

Table 9. Results of the factors significance for brake discs and rear friction insert component

Factor	Front brake discs		Front friction pads	
	ANOVA p-value	MW/KW test p-value	ANOVA p-value	MW/KW test p-value
Traffic	< 0.001	< 0.001	< 0.001	< 0.001
Month	< 0.001	< 0.001	< 0.001	< 0.001
Vehicle (Traffic) Vehicle	0.005	< 0.001	0.089	< 0.001
Month x Traffic	0.001	-	< 0.001	-

The obtained *p-value* < 0.001 in the Mann-Whitney test means a significant influence of the 'Traffic' factor, which is confirmed by the frame graph of the rear brake discs wear, for which the wear medians in the urban and extra-urban traffic are 0.05 mm and 0.03 mm respectively (Fig. 9).

For the rear friction pads also, the wear is different for urban and extra-urban traffic. In this case, the medians of wear are 0.10 mm and 0.06 mm respectively (Figure 10).

The significant impact of the 'Month' factor is confirmed by the results of the Kruskal-Wallis test. For the front brake discs the *p-value* < 0.001 result received prevented the adoption of the null hypothesis (Tab. 9). The wear graph shows two different periods in the individual calendar months (Figure 11).

Similarly for the rear friction pads, the level of wear is significantly dependent on the calendar month, which is confirmed by the graph in Fig. 12. The highest values were obtained for summer months (from May to September).

The analyzes presented are complemented by the charts of average wear, taking into account the type of traffic and the calendar month. The values obtained for the rear brake

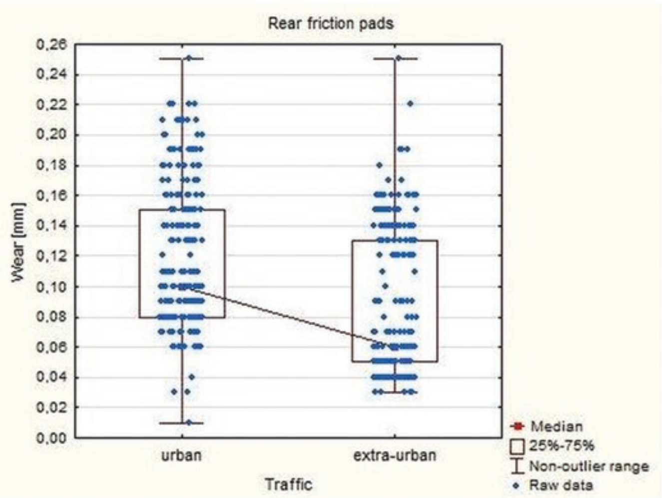

Fig. 9. Wear of the rear brake discs component depending on the type of traffic

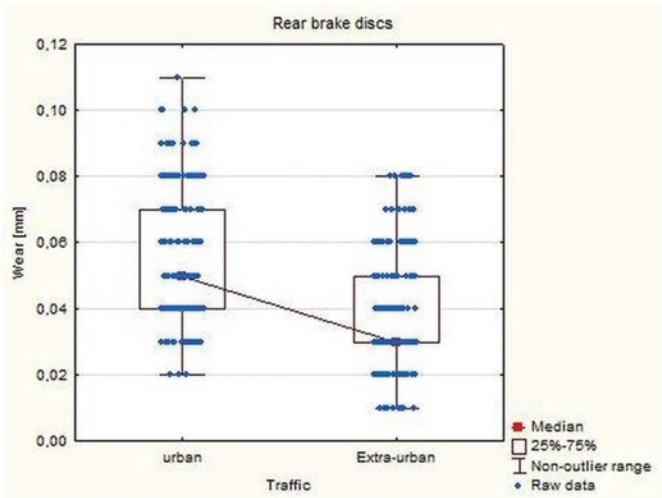

Fig.10. Wear of the rear friction insert component depending on the type of traffic

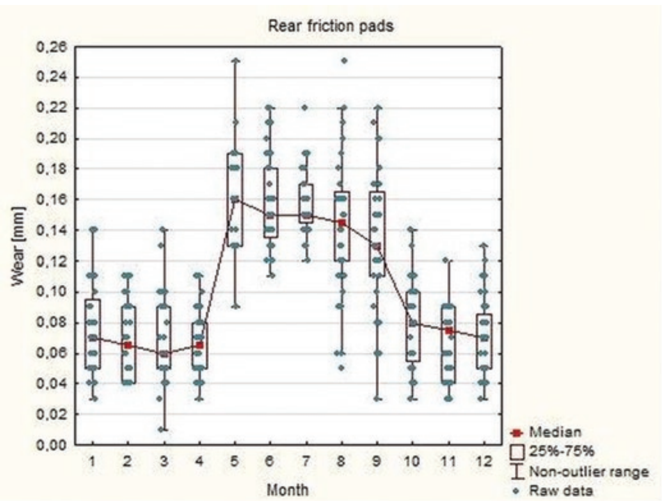

Fig. 11. Wear of the rear brake discs component depending on the month

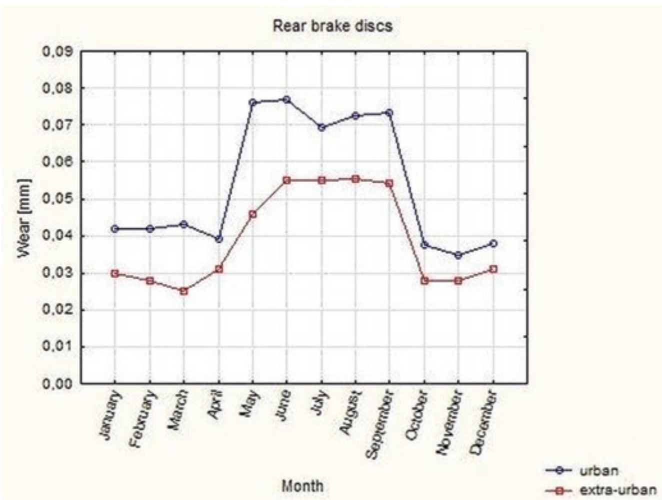

Fig. 12. Wear of the rear friction insert component depending on the month

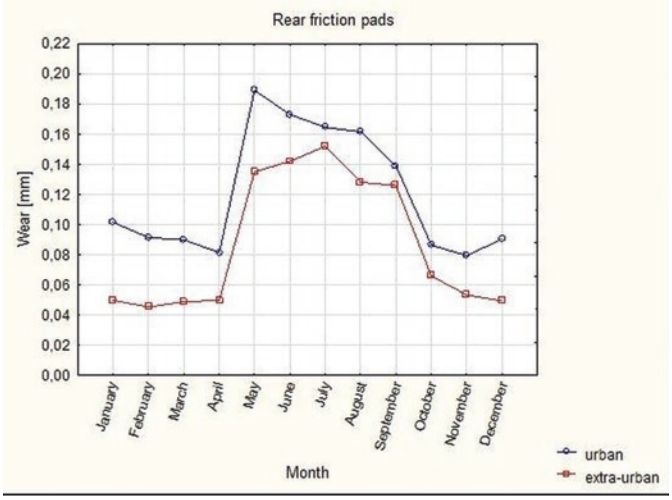

Figure 13. Average wear of the rear brake discs component depending on the type of traffic and month

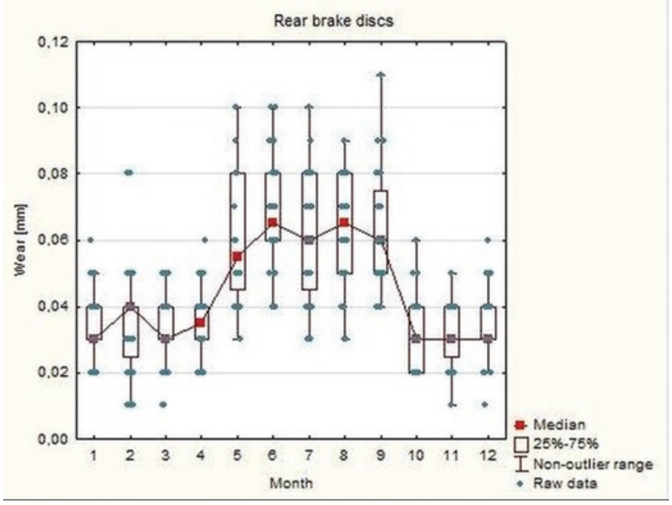

Figure 14. Average wear of the rear friction insert component depending on the type of traffic and month

Table 10. Average wear values of all tested components of the braking system

Brake system component	Traffic type	Average wear value [mm]	Difference in the wear level [%]
front friction pads	urban	0.4733	24.87
rear friction pads	urban	0.1177	
front friction pads	extra-urban	0.3998	21.19
rear friction pads	extra-urban	0.0847	
front brake discs	urban	0.1258	41.92
rear brake discs	urban	0.0527	
front brake discs	extra-urban	0.0896	43.06
rear brake discs	extra-urban	0.0386	

discs are clearly dependent on the factors studied, and their mutual interaction is also visible (Fig. 13).

The interaction between the type of traffic and the calendar month, as well as the separate impact of each factor, is also visible on the wear graph of the rear brake friction pads depending on the type of traffic and the month (Figure 14).

The difference in average wear of the elements of the front and rear brake system was also shown (Tab. 10). It results from the application of the braking force corrector in the brake system (in the newer models this function is performed by the Anti-Lock Braking System – ABS), whose role is to ensure the right balance between the front and rear vehicle axle load and the braking forces obtained on the these axles (Tab.10).

An uneven distribution of braking forces means that the wear of the front elements is greater. For the friction pads, the difference is over 20%, for brake discs more than 40%.

4. Conclusions

1) The statistical analysis carried out shows that the type of vehicle traffic as well as the calendar time of the drive (season of the year) have a significant impact on the wear of the tested elements of the brake system. Non-parametric tests conducted indicate that the impact is much higher in the summer months, when high ambient temperature is recorded, and also when transport is conducted in urban traffic.

2) The results of the parallel ANOVA variance analysis were mostly in line with the results of non-parametric tests (for all elements, the average wear was significantly higher in urban traffic than in extra-urban one).

3) The utilitarian character of the analyzes conducted allows to indicate the areas for the vehicles improvement, especially their elements (spare parts) in the context of raising the safety level.

4) Analyzes of the brake system elements wear may support transport planning optimization processes. Based on the example of the company being researched, it is worth considering cyclical changes of the type (environment) of vehicle traffic. Transport only in the city traffic, cause excessive system load, more intensive wear of components and more frequent replacements.

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