Article

Experimental study of the correlation between the wear and the braking system efficiency of an auto-vehicle

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Abstract: The vehicles number continuously growing lead to increasingly intense and congested traffic and it will additionally demand the braking system, and drivers behave more aggressively and as result is required that the braking system to be durable and efficient. For this is necessary the study the braking system behavior in conditions of intense and moderate traffic to increase the safety of traffic participants, respectively to demonstrate the need for more frequent replacement of some braking system elements. Thus, on a vehicle were performed a series of successive tests, through which the degree of wear of the brake pads and discs was monitored periodically and as a result the efficiency evolution of the braking system. The tests were carried out both in laboratory (on dynamometer) and in traffic to establish the efficiency of the braking system according to some parameters considered essential. The experimental tests showed that the recommendations regarding the frequency of replacement of brake pads and disks are inconsistent with their actual wear. Therefore, the aim of this paper is the establishment of the braking system efficiency of an auto-vehicle, subject to testing depending on the auto-vehicle mass, travel speed, distance driven, and braking time, based on experimental on stand and in-traffic tests, according the road safety regulations.

Keywords: Auto vehicle; Braking system efficiency; Brake pads and disc wear; Road safety; Efficiency parameters

1. Introduction

The traffic safety of an auto-vehicle depends on the braking system parameters. Braking is the auto-vehicle's ability to decelerate quickly and come to a complete stop at a minimum distance. The key auto-vehicle braking parameters are breaking force and deceleration, however, in practice; braking time and braking distance are mostly used. The adhesion parameters of the auto-vehicle could be modified, depending on the diversity of the road surfaces, their degree of wear, as well as the variation of the weight

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of the auto-vehicle. According to the laws of physics, the braking factor does not change if the load on the tire varies [1].

The auto-vehicle kinetic energy changes into thermal energy during braking and the temperature from the interface between the pads and brake disk, as well as the change in speed, has a significant impact on the coefficient of friction because it decreases with growing sliding speed and temperature. Brake wear is a phenomenon that occurs for any braking system when the friction coefficient decreases significantly depending on the temperature [2,3]. High-temperature values during braking cause brake degradation, premature wear, vaporization of brake fluid bearing failure, thermal cracking, and thermal vibrations. The ideal brake pads must ensure uniform and stable friction in all working conditions, without generating brake degradation, regardless of temperature. To achieve the desired braking performance, brake materials must have the appropriate composition, including stable friction coefficients, wear and noise generation reduced, in different (a wide range) braking conditions.

Mathematical models are frequently used which are intended for the analysis of auto-vehicle braking parameters [4]. However, the values of deceleration and braking distance parameters are random values in practice [5].

During operation, the braking system components have a dominant effect on friction coefficient and brake wear, because generally dependent on load, speed and sliding time, temperature, lubricant, and additives. Numerous studies have demonstrated the dependence of the friction coefficient on temperature, braking force, and speed [6-9]. In most studies, the friction coefficient is inversely proportional to the travel speed, while it shows a mixed trend depending on the auto-vehicle mass [10].

In steady-state based on some experimental tests has been proposed an analytical formulation very simple, that establishes the dependence of the thermal effects following the increase of friction materials temperature, pressure, sliding speed, friction temperature, and wear in the contact area between the disk and the brake pads [5,10,11]. Current braking systems allow a braking process optimization, considering the dynamic factors of grip, longitudinal and lateral accelerations, the semi-trailer/trailer presence, etc. from the brake pedal action to the final braking phase. The braking is estimated not only depending on the race or the brake pedal position but to perform emergency braking [12,13] and on its acceleration speed. Most studies and research analyze the friction process between two materials in detail, by friction coefficient variation for different pairs of materials in different test conditions [14, 15]. Other studies and research is limited to wear process effects [16], to identify its causes with the aim of increasing durability. Zhang et al. [17] recognize that the wear phenomena study is in the empirical stage, as well as some aspects present that are not yet fully understood. Most of the time, brake disks and pads mounted on used auto-vehicle s do not have the same properties as the original ones, thus leading to faster wear [13].

Also, Kchaou et al. [16] analyzed the variations of friction coefficient, temperature, and strain through simulations using finite element analysis. These analyses provide quite conclusive values, as advantages, but also present disadvantages, because it requires in complex situations some simplistic assumptions [18].

In the current environmental conditions (pollution) another aspect of great importance is the formation of material particles and their size classification which analyzes air quality in a closed space, by measuring and testing [15], considering the big number of auto-vehicles in circulation. Related to the air quality with implications on life quality, there are papers much that noise experimentally studies the (sound pollution) at braking using for the brake pads different materials and constructive variants. The noise produced at braking is in particular influenced by the friction conditions (type of material, contact surface, normal force, sliding speed, temperature, etc.) [18].

The braking systems' performance is also given by the constructive variant choice, the focus being on the grouping of the benefits and disadvantages of some variants of braking systems, the most common are disk or drum brakes and drive unit liquid or with air [12]. Some research highlights the advantages of disk brakes, compared to those of drum brakes [18]. Modern auto-vehicles are equipped on the front wheels with ventilated disk brakes while on the rear wheels either unventilated disks or drums and high-performance auto-vehicles always have disc brakes both on the front and rear.

Thus, Yin et al. [19] analyzing the braking process and test methods identified five main parameters to determine the braking performance of a auto-vehicle, namely: friction coefficient between the road surface and the tire, auto-vehicle mass, driver physical effort, drive system, the friction coefficient between disk and the brake pads, during braking. Then, Rashid [20] and Sharip [21] investigated in extreme conditions the braking performance of the brake disks. For this, they claim that brake disks must have more efficient heat transfer, so good thermal conductivity, good mechanical strength, friction high resistance, thermal shock, and good friction characteristics. Moreover, regarding wear, lightweight, and convenient adjustment [23], there must not be significant differences, and all these are depending on the constructive variant choice. Therefore, the regulations imposed, which must be fulfilled by braking systems change continuously and the performance requirements are constantly increasing show Hutchinson et al. [22]. Thus, numerous studies and research were undertaken [18, 23], to improve the reliability and performance of braking systems.

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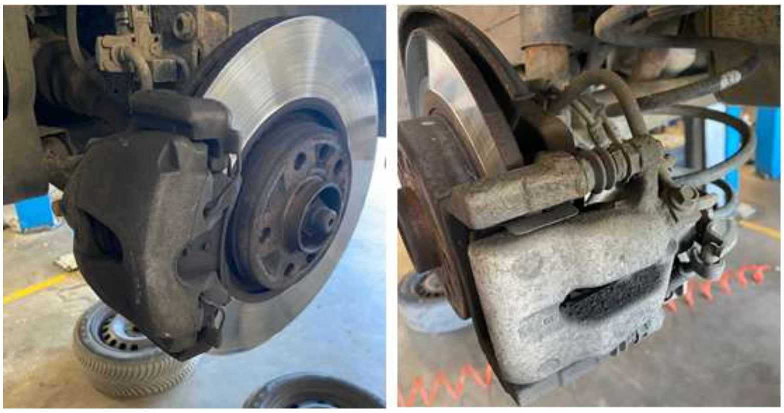
Considering all these aspects, the paper aims to study the behavior of the braking system in conditions of intense and moderate traffic, by analyzing some important parameters, both theoretically and experimentally to increase the safety of traffic participants. To determine the braking system tribological behavior in conditions of intense and moderate traffic, several successive tests were carried out on the vehicle, through which the wear tendency of the brake pads, even of the brake discs, was followed, as well as the efficiency evolution of the system braking. For this, it was necessary to carry out tests on the dynamometer stand, as well as in traffic (off-road), with the purpose to determine the efficiency of the braking system depending on the auto-vehicle mass, travel speed, braking distance, and time. Also, the degree of wear of the brake pads was periodically monitored.

2. Materials and research method

For the experimental determination of the efficiency of the braking system, an auto-vehicle was used in conditions of intense traffic, in an urban area, where the braking system was heavily stressed, and the brake pedal was operated frequently, following the replacement of the brake pads

Also, the auto-vehicle under test was also used in extra-urban areas, at constant speeds, where the braking system was not used intensively, but moderately

The auto-vehicle chosen for the experiments has a disk and pad braking system, both on the front axle and as well as the rear one. On the front axle, the auto-vehicle has ventilated discs (Figure 1a), while on the rear axle, it is equipped with solid (non-ventilated) discs (Figure 1b).



(a) (b)

Figure 1. Brake disc; ventilated brake disc (a); non-ventilated brake disc (b)

The auto-vehicle's technical specifications are presented in Table 1.

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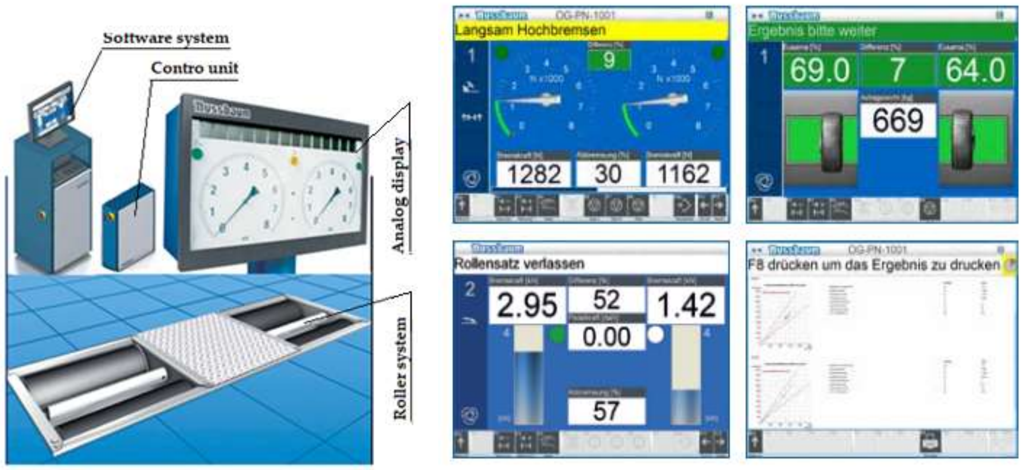
Table 1. Auto-vehicle technical specifications

Parameter	Values
Engine power	88 kW
Engine capacity	1,910 cm³
Maximum allowed weight	1,865 kg
Weight of the auto-vehicle in service	1,375 kg

The Nussbaum VISIO dynamometer (ATT Nussbaum Prüftechnik GmbH, Kehl-Auenheim, Germany) was used to measure the brake system efficiency parameters of the auto-vehicle under test, with a BT110/410 roller set (3.5 kW, 6.0 kN, 5.0 km/h), and is presented in Figure 2.



(a) (b)

Figure 2. Nussbaum VISIO dynamometer (adapted after [23]) (a); parameter monitoring by a software application (b)

This dynamometer model is used for testing the braking system for auto-vehicles and light commercial auto-vehicles and equipped with an analog display that indicates the braking force on a circular scale with a diameter of 350 mm (see Figure 2a). A brake force excessive imbalance is indicated by warning lamps [23]. The analog display has the advantage of clearly and quickly indicating the results and a computer can graphically display values and results, to be presented and stored in a data base.

Braking force values are quickly and easily read on the 350 mm circular scale of the analog display (see Figure 2a). Warning lamps light up when the braking slip limit values and maximum braking force difference are exceeding, values that can be adjusted. Values such as the mass on the axle and braking efficiency are shown on the 14-digit LCD (see Figure 2b).

The modern software system (see Figures 2a and b) offers many possibilities and is essentially simple and intuitive to use on a interface with two levels. According to your

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own requirements, the software can be configured so that the display of the braking force can be represented in analog or graphical form. The graphic display of braking force can be represented analogically or in columns. The test can be started by the displacement the auto-vehicle on the test strip. Two or more sequences can be configured, and subsequently, the test procedure that best suits the requirements can be selected [23].

After the dynamometer rollers (Figures 3a and 3b) have been put into operation, with the help of an electric motor, the test stand recognizes if all auto-vehicle wheels are correct position on the dynamometer rollers. Otherwise, it automatically changes the test sequence to irregular rolling left-right [23].

(a) (b) (c)

Figure 3. Dynamometer rollers with the front wheels (a); the rear wheels (b) of the auto-vehicle and the sensor for evaluation of the brake pedal pressing force (c)

The brake pedal force sensor (Figure 3c) is another important accessory of the dynamometer, whose signal can be read from a distance or sent via wire. This will allow the calculation of the difference between the braking forces using the brake pedal force. The difference in braking force can be printed on the test report protocol or viewed on the LCD display.

Most countries use testing the braking system effectiveness at a braking force in the range of 0 to a maximum of 8 kN and the speed of 5 km/h, while dynamometer rollers are loaded usually.

The dynamometer rollers are made of plastic corundum or in welded construction, and both have adhesion coefficients that fulfill international requirements.

The test stand is equipped also with an optional weighing device, which measures the mass of the auto-vehicle under test [23] mounted under the dynamometer rollers for the braking efficiency calculation. In Table 2, the parameters that influence the braking system efficiency, determined by tests on the test stand, are presented. Both the auto-vehicle mass and the wheel and axle static mass were determined on the test stand, with the help of the specialized scale with which the stand is provided.

Table 2. Parameters of the auto-vehicle under test

Parametru	Axa 1	Axa 2
Static mass of the wheel on the left, kg	473	267

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Static mass of the wheel on the right, kg	473	267
Axle mass, kg	946	534
Total mass of the auto-vehicle, kg	1,566	
Mileage, km	115,477	

To determine the service and parking brake parameters, further tests were performed. Thus, the auto-vehicle wheels on the front and rear axle were placed on the set of rollers of the test stand. The electric motor of the test stand sets the rollers in motion, which rotate the wheels of the auto-vehicle with a number of rotations equivalent to a 5 km/h travel.

To test the service brake, the operator operates the brake pedal which is connected to a sensor measuring the pedal pressure. With this device, the test stand software can determine the difference in braking force.

By pressing the brake pedal, the brake pads press against the disc, thus stopping its rotational movement. Thus, with the help of the sensors mounted on the test stand, the software can determine and calculate the important parameters of the service braking system. The pedal is operated repeatedly, in order to determine the most accurate results. Instead, for testing the parking brake, after the operator actuates, the brake pads press on the disc via the caliper and stop the rotational movement of the brake disc, but with a much lower braking force than the service brake. And in this case, the sensors and the test stand software determine the important parameters of the parking brake system. The following devices were used for field tests: timer, roulette, mobile radar, and reference points for actuating the brake pedal.

The results of the experimental tests are discussed, analyzed, and presented tabled and graphically, in what follows.

3. Experimental results and discussions

Intense traffic places a faster deterioration on the auto-vehicle's braking system, leading to premature wear of the brake disc and pads. Moreover, limit situations, such as sudden and strong braking contributes frequently to the destruction of the braking system.

Studies have shown that, on average, the lifespan of brake pads is between 40,000 and 100,000 km. The range is relative, considering the fact that the life of the brake pads is influenced by the of shareholders number of brake pedal. Drivers who drive in urban areas are recommended to change their brake pads every 40,000 km, while drivers who drive outside urban areas every 100,000 km.

After installing a new set of pads, the auto-vehicle was subjected to a set of tests on the brake system test stand. Along with changing the pads, the brake fluid was also replaced, so that the efficiency of the braking system is as high as possible. It is important to mention that the brake discs showed signs of wear, such as scratches on the contact surface, but also rust.

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In Figure 4(a), the scratches on the brake disk surface are shown. Traces of wear caused by the use of defective brake pads can be observed, which leads to the destruction of the brake disc.

(a) (b)

Figure 4. Scratches and wear traces present on the brake disk surface (a); brake disk with traces of rust (b)

In Figure 4(b), is can see the degradation of the brake disc caused by the presence of rust. After removing the brake pads, the degree of wear can be observed, compared to a set of new brake pads, as well as the signs of wear and detachment of the friction material. These aspects are presented in Figures 5 and 6.

(a) (b)

Figure 5. The degree of wear of the brake pads: -view of the right-left pads (a); enlarged view - right plate (b)

(a) (b)

Figure 6. Comparison between the new and used brake pads: side view (a); top view (b)

To determine the degree of wear of the pads on the front axle, a special thickness measuring system was used, Figure 7. The thickness of the friction material of a new pad was 13 mm (see Figure 7(a)), and after the brake pad has been worn, the system indicated a thickness of 10 mm (see Figure 7(b)), thus resulting in wear of 3 mm after 18,664 km traveled.

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(a)

(b)

Figure 7. Brake pad wears measurement (a) from the front axle; (b) from the rear axle

Figure 8. Visualization of the measured system: parameters of the braking system on analog display

For rear axle brake pads, the friction material thickness of a new pad was 10 mm, and after they have been used, the measurement system indicated a thickness of 7 mm, thus resulting in wear of 3 mm after the 18,664 km traveled (see Figure 7(b)). Thus, the disks and pads were replaced with new ones, the brake fluid was also replaced, and respectively the brakes were aired out, in order to obtain optimal pressure in the braking system. Following the replacement of the pads, a series of tests of the braking system were carried out, to determine its efficiency, the braking force, as well as other parameters concerning the entire braking system.

The brake dynamometer rollers set the auto-vehicle's wheels in motion at a speed of 5 km/h. At the same time, the test stand software collects data regarding the braking system parameters (Figure 8), obtained by successive actuation of the braking system by the operator, so that at the end this generates a report with the exact results.

The results according to the auto-vehicle mass and the number of driven kilometers are presented in Table 3 and graphically in Figure 9.

Table 3. Braking system parameters according to the variation of the auto-vehicle's mass and driven km

	Auto-vehicle mass/mileage: 1566 kg/ 115477 km		**Auto-vehicle mass/mileage: 1462 kg/ 134141 km**		**Auto-vehicle mass/mileage: 1480kg/ 134141 km**		**Auto-vehicle mass/mileage: 1526kg/ 134141 km**	
Parameter/Axis	**Axis 1**	**Axis 2**	**Axis 1**	**Axis 2**	**Axis 1**	**Axis 2**	**Axis 1**	**Axis 2**
Braking force on the left wheel, kN	2.99	1.7	2.68	1.57	2.93	1.84	2.88	1.6
Braking force on the right wheel, kN	2.84	1.61	3.17	1.63	3.54	1.75	2.74	1.66
Braking force on the axis, kN	5.83	3.31	5.85	3.2	6.47	3.59	5.62	3.26

Difference between braking forces, %	5	5	15	4	17	5	5	4
Axle ratio, %	73	74	63	62	69	68	58	60

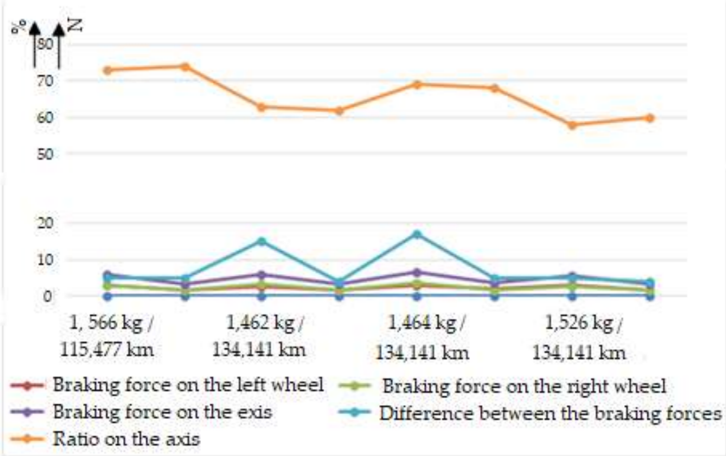

Figure 9. Variation of the braking system parameters depending on the mass (4 values) and driven km (2 values) of the auto-vehicle

Also, in Table 4 and Figure 10, the evolution of the efficiency of the braking system is presented, as well as the measured braking force, depending on the mass of the auto-vehicle and the number of kilometers driven.

Table 4. Braking system efficiency according to the mass variation, for two values of the driven km of the auto-vehicle

	Auto-vehicle mass 1,566kg/ 115,477 km	**Auto-vehicle mass 1,462 kg/ 134,141 km**	**Auto-vehicle mass 1,484kg/ 134,141 km**	**Auto-vehicle mass 1,526kg/ 134,141 km**
Braking difference of the service brake, m	5	15	17	5
Service brake efficiency, related to the auto-vehicle total mass, %	73	69	63	59
The efficiency of the parking brake, related to the auto-vehicle total mass, %	16	16	16	19

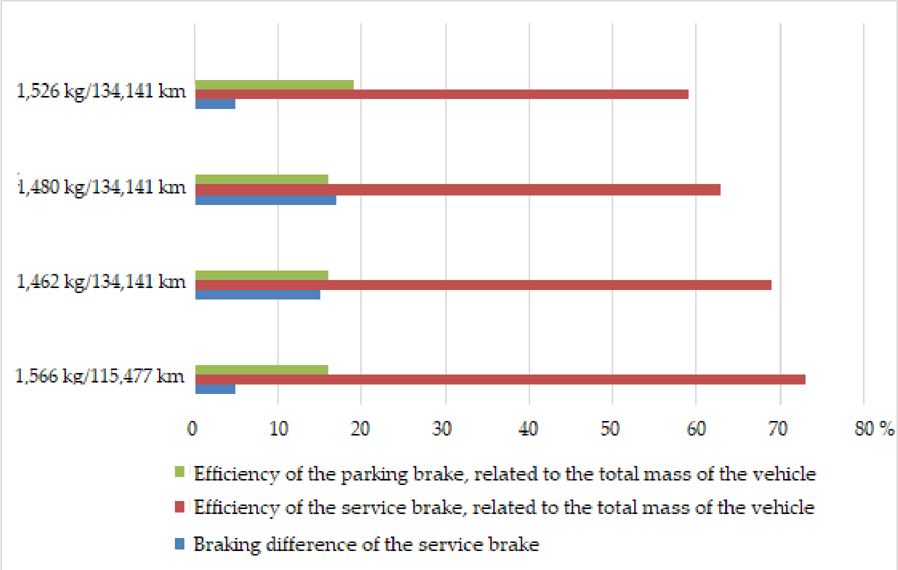

Figure 10. Evolution of the braking system efficiency depending on the variation of the mass, for two values by driven km of the auto-vehicle

From the analysis of Table 4 and Figure 10, a significant reduction in the efficiency of the braking system can be observed, namely by 16%, after 18,664 km driven. This is explained by the fact that the auto-vehicle was used in urban traffic conditions (intense and moderate), which led to brake pads and disks accelerated wear.

In Table 5 and Figure 11, the evolution of the efficiency of the braking system is presented, as well as the measured braking force, depending on the variation in the auto-vehicle mass (1,484, 1,526, and 1,566 kg) and the number of driven kilometers (115,477, 134,141, and 139,334, when the traveled distance increased by 5,193 km, from 131,141 to 139,334 km).

Table 5. Braking system efficiency of the depending on the variation of the auto-vehicle's mass and driven km

	Auto-vehicle mass 1,566 kg/ 115,477 km	**Auto-vehicle mass 1,526 kg/ 134,141 km**	**Auto-vehicle mass 1,484 kg/ 139,334 km**
Braking difference of the service brake, m	5	5	12
Service brake efficiency related to the auto-vehicle's total mass, %	71	59	72
Parking brake efficiency of the related to the auto-vehicle's total mass, %	16	19	24

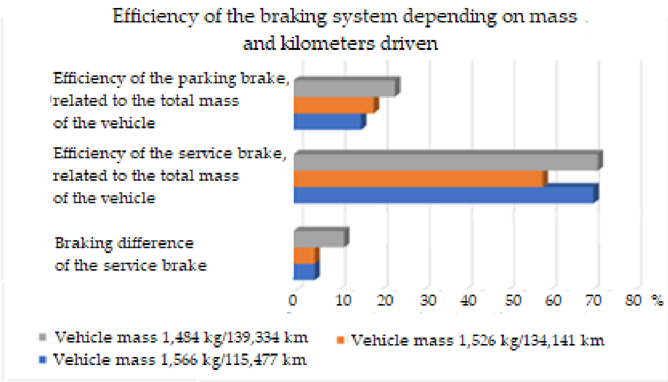

Figure 11. Braking system efficiency evolution the according to the auto-vehicle mass variation and driven km

To determine the braking time and distance, depending on the auto-vehicle speed, a successive test series were carried out in the field. At the time of the tests, the auto-vehicle had a mass of 1526 kg.

In Table 6, respectively Figure 12, the average comparative values of the auto-vehicle's braking distance and time are shown, respectively of braking system efficiency for three speeds. The braking speeds and distances were compared both on the worn braking system and on the braking system with new discs and pads.

Table 6. Average values of the braking distance and time, respectively the braking system efficiency and the auto-vehicle speed

	Braking system efficiency, %	**Minimum allowed limit for the efficiency, %**	**Auto-vehicle speed, km/h**	**Braking distance, m**	**Braking time, s**
Brake system with worn discs and pads	59	50	25	1.38	1.21
			40	4.26	1.89
			50	5.44	2.46
Brake system with new discs and pads	72	50	25	1.31	1.17
			40	3.92	1.74
			50	5.14	2.20

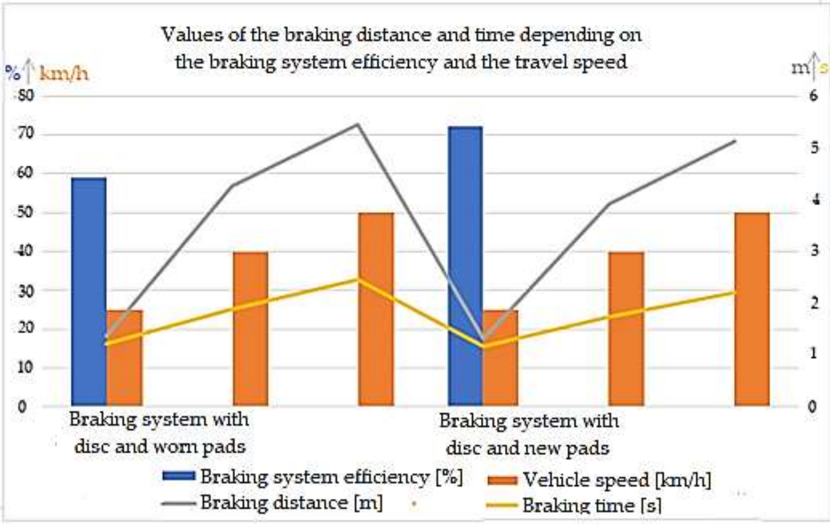

Figure 12. Comparison between the measured braking times and distance for the used braking system and the new braking system

Under normal auto-vehicle load conditions (mass of 1526 kg), an efficiency of the braking system of only 59% was observed. Considering the fact that the minimum acceptable efficiency of the braking system is 50% (see Table 6), the results are worrying, suggesting the need to replace the braking system, at a much shorter interval than the recommended one.

After the change of the worn brake disc and pads, it was found that the efficiency of the braking system increased to 72%.

Conclusions

There are many studies and research based on models that closely mimic reality, but with the exploitation data collected in real-time are still few. For this, it is necessary for the results to be validated by experimental testing methods, as close as, to operational reality or even data sampling during operation.

It applies in particular to braking systems and brakes, which should be tested and approved in accordance with prescriptions and regulations in force, related to road safety.

Following the performance of the experimental tests, a significant reduction in the efficiency of the braking system was found, after only 18,664 km driven in conditions of intense and moderate traffic in the urban environment.

Under normal auto-vehicle load conditions (mass of 1526 kg), an efficiency of the braking system of only 59% was observed. Bearing in mind that the minimum accepted point of brake system efficiency is 50%, the results are worrying, suggesting the need to replace the brake system at a much shorter interval than recommended.

Experimental tests have shown that the recommendations regarding the frequency of brake disks and pad replacement are inconsistent with the actual braking system wear.

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To estimate the wear time of a new braking system it is necessary to study its parameters. After carrying out field tests of the auto-vehicle braking system under test, it will be replaced, and the tests on the stand and in the field, resumed on the new braking system, in order to establish its efficiency.

Therefore, the research on the behavior of the braking system must continue under conditions of intense demand, to increase the safety of all traffic participants.

Based on the obtained results, a statistical calculation model will be proposed, which can be used in simulations regarding the wear tendency of the braking system.

Later, after 30,000 km is performed, in conditions of intense and moderate traffic, the theoretical results will be compared with the experimental ones.

Moreover, studies have demonstrated the psychological effect that heavy traffic has on drivers, who tend to behave more aggressively, a fact that directly demonstrates the need for an efficient braking system.

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References

1. Berjoza D., Dukulis I., Pirs V., Jurgena I. Testing Automobile Braking Parameters by Varying the Load Weight, *Proceeding of 7th International Conference on Trends in Agricultural Engineering* **2019** *(TAE 2019)*, Prague, Czech Republic, 51-58.
2. Greibe P. Braking distance, friction and behaviour. Findings, analyses and recommendations based on braking trial, *Trafitec* **2007**, Lyngby, Denmark.
3. Parczewski K. Effect of tyre inflation preassure on the vehicle dynamics, *Maintenance and Reliability* **2013**, *15(2)*, 134-139.
4. Popa M-F., Burnete N.V. Study of Brake System Parameters for Commercial Vehicles, in book *Proceedings of the 4th International Congress of Automotive and Transport Engineering (AMMA 2018)* **2019**, DOI: 10.1007/978-3-319-94409-8_80.
5. Demira A., Oz A. Evaluation of vehicle braking parameters by multiple regression method, *Scientia Iranica* **2019**, *6(26)*, 3334-3355, DOI:10.24200/sci.2019.51584.2262.
6. Yevtushenko A., Topczewska K., Kuciej M. Analytical Determination of the Brake Temperature Mode during Repetitive Short-Term Braking, *Materials* **2021**, *14*(8), 1912, https://doi.org/10.3390/ma14081912.
7. Chung J.O, Go S.R, Choi H.B, Son T.K. Temperature dependence of friction coefficient and transfer film formation in organic friction materials containing different abrasive components, *Industrial Lubrication and Tribology* **2020**, *72(4)*, https://publons.com/publon/10.1108/ILT-10-2019-0427/.
8. Ivanov P., Khudonogov A., Dulskiy E., Manuilov N., Khamnaeva A., Korsun A., Treskin S. Study of the influence of the brake shoe temperature and wheel tread on braking effectiveness, *Journal of Physics* **2020**: Conference Series 1614 012086, DOI:10.1088/1742-6596/1614/1/012086.
9. Jian Z., Changgao X. Research of the Transient Temperature Field and Friction Properties on Disc Brakes, *Proceedings of the 2012 2nd International Conference on Computer and Information Application (ICCIA 2012)*, Published by Atlantis Press, Paris, France **2014**, Project number: SBY201220101.
10. Loh W-Y, . Basch R.H, Li D., Sanders P. Dynamic Modeling of Brake Friction Coefficients, J*ournal of Passenger Car: Mechanical Systems Journal* **2001**, *110(6)*, 2627-2636, https://www.jstor.org/stable/i40199177.

 doi:10.20944/preprints202306.0215.v1

11. Zhang, S., Hao Q., **Liu Y.,** Jin L., Ma F., Sha Z., Yang D. Simulation Study on Friction and Wear Law of Brake Pad in High-Power Disc Brake, *Mathematical Problems in Engineering* **2019**, Article ID 6250694, https://doi.org/10.1155/2019/6250694.
12. Yumrak Oh Y., and Hoguen Lee,H. Characteristics of a Tire Friction and Performances of a Braking in a High Speed Driving, *Advances in Mechanical Engineering* **2014**, Article ID 260428 https://doi.org/10.1155/2014/260.
13. Wan Z., Liu X., Wang H., Shan Y. Research on the Time-Varying Properties of Brake Friction, IEEE Access **2018**, *6*, 69742-69749, DOI: 10.1109/ACCESS.2018.2878776.
14. Ilie F, Cristescu Andreea-Catalina - Tribological Behavior of Friction Materials of a Disk-Brake Pad Braking System Affected by Structural Changes—A Review, *Materials* **2022**, *15*(14), 4745, https://doi.org/10.3390/ma15144745.
15. Wahlström, J., Söderberg, A., Olander, L., Jansson, A., & Olofsson, U. A pin-on-disc simulation of airborne wear particles from disc brake, *Wear* **2010**, *268(5-6)*, 763-769, https://doi.org/10.1016/j.wear.2009.11.014.
16. Kchaou M., Sellami A., Riadh Elleuch R., Singh H. Friction characteristics of a brake friction material under different braking conditions," *Mater. Des* **2013**, *52*, 533-540, DOI: 10.1016/j.matdes.2013.05.015.
17. Zhang Y., Jin X., He M, Wang L, Wang Q., Wang L., Wu Y. The convective heat transfer characteristics on outside surface of vehicle brake disc, *International Journal of Thermal Sciences* **2017**, *120*, 366-376, DOI: 10.1016/j.ijthermalsci.2017.06.020.
18. Bao J., Liu J.,Yin Y.,Liu T. Characterization and experiments on the friction catastrophe behaviors of brake material during emergency braking, *Engineering Failure Analysis* **2015**, *55*, 55-62, https://doi.org/10.1016/j.engfailanal.2015.05.007.
19. Yin Y., Bao J., Liu J., Guo C., Liu T., Ji Y. Brake performance of a novel frictional-magnetic compound disc brake for automobiles, *The Proceedings of the Institution of Automobile Engineers, Part D: Journal of Automobile Engineering* 2018, *233(10)*, 2443-2454, https://doi.org/10.1177/0954407018791056.
20. Rashid A., Overview of Disc Brakes and Related Phenomena - a review, *International Journal of Vehicle Noise and Vibration* **2014**, 10(4), 257-301, http://dx.doi.org/10.1504/IJVNV.2014.065634.
21. Sharip S. Lightweight friction brakes for a road vehicle with regenerative braking, Thesis, School of Engineering Design and Technology, University of Bradford **2011**, DOI: 10.13140/RG.2.1.3747.4002.
22. Hutchinson B.G., Parker D. Estimated Braking Efficiencies of Different Ontario Truck Configuration., Waterloo: University of Waterloo, Department of Civil Engineering, **1995**.
23. Nussbaum, Break Test Standas, Test Lanes and Headlight Testers. *Passenger Cars and Transporters*, **2016.**