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Influence of Travel Speed, Time, and Distance of Braking on the Efficiency of a Car's Braking System

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Abstract: The importance of utilizing an optimal and efficient braking system is emphasized in this study. Braking system optimization and efficiency were practically determined through successive tests on the brake dynamometer, according to road safety regulations. Subsequently, the results were correlated with practical tests involving consecutive braking at different speeds, tracking both the time and distance of braking. The coefficient of friction (COF) was established for each braking instance by utilizing the braking force measured on the brake dynamometer. This paper aims to highlight the genuine impact of the braking system by measuring and establishing its braking efficiency depending on the car's speed, time, and distance of braking.

Keywords: braking efficiency; braking distance; braking time; coefficient of friction; car braking system

1. Introduction

The braking system of a car has a pivotal role in ensuring road safety. The capacity of a vehicle to swiftly decelerate and come to a complete halt within a certain distance is realized by the braking system. However, the braking force and deceleration are the main braking parameters of a car. Practical, the parameters most commonly utilized are braking time and distance, through their values. Factors, like the height of the center of mass, load distribution across axles, and the contact area between the road surface and the tires, can be influenced by variations in the car's load. It's important to note that changes in tire load do not alter the braking factors, a principle given by the fundamental laws of physics [1].

The friction coefficient (COF) when braking is significantly influenced by changes in velocity and the temperature of the brake disc-pads interface (decreases with temperature and sliding speed). Any vehicle with a friction-based braking system exhibits wear of the disc-brake pads system when the COF noticeably decreases as a result of temperature variations [2–4]. In other words, the factor affecting braking system (brake disc-pads) wear is the tribological state of the braking parts when they are in operation. A number of variables, such as the load, speed, temperature, sliding time, and materials composition in contact affect the tribological properties of the contact surfaces (here brake disc-pads). There is verified evidence that the COF, force, and speed of braking, temperature are all in direct relation. Also, was proven that the COF varies depending on the car mass and is inversely proportional to travel speed [5]. Vehicle braking parameters are routinely evaluated using mathematical models. However, in real-world situations, the braking and deceleration parameter values are always unpredictable [6].

Yin et al. [7] after analyzing the braking process and using testing methods have identified five main parameters (COFs between the discs and the brake pads, and also between the tire and road surface, braking command and control system, driver physical effort, car mass) that have influenced the braking process. The braking ability of the brake discs was then studied under harsh circumstances by Rashid [8] and Sharip [9] and they contend that brake discs need to transfer heat more effectively (superior thermal conductivity), with friction good properties, friction high

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resistance, low weight, and mechanical, and at thermal shock strength [10], and all of these depend on the constructive variant selected. Therefore, the regulations that must be adhered to by braking systems vary continuously, and their performance criteria and dependability continue to improve [10], together with the materials used, by simulations and tests over time, and in the field.

As more vehicles share the same road space, traffic congestion becomes a common occurrence, especially in urban areas. This situation often leads to frequent braking due to the need for maintaining safe following distances, navigating through congested traffic, and adhering to traffic signals and road signs. The frequent use of the braking system in such congested environments poses significant challenges to the overall efficiency and performance of a vehicle's braking system.

Continuous stop-and-go movements result in increased wear and tear on the brake components, potentially leading to decreased braking efficiency in a shorter period of time. This underscores the necessity for vehicles to be equipped with robust and responsive braking systems that can handle the demands of urban traffic and frequent braking scenarios.

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Also, continue to improve the materials used, redesign the braking system assembly (with all components), simulations regarding the behavior of the braking system over time, field testing, as well as studies and research to improve the braking systems performance of motor vehicles [1, 2, and 13].

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Therefore, the wear of the brake pads and discs was monitored to evaluate the efficiency of the braking system, through a series of successive tests on a motor vehicle, both on the brake dynamometer stand and in traffic. At the same time, the braking distance and time were measured to be able to evaluate and establish the efficiency of the braking system depending on the travel speed,

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time, and distance of braking. Thus, the COF has been determined with the following mathematical relationship:

$$\mu = COF = \frac{Breaking\ Force\ (F)}{Normal\ Force\ (N)}, \tag{1}$$

and the braking force had been measured by testing the vehicle on the dynamometer, while the normal force is determined by the following equation/relation:

$$N = m \times g \tag{2}$$

where: m - vehicle mass (kg); g – gravitational acceleration (9.81 m/s²).

Or, $$COF = \mu = d/g = -\ a/g, \tag{3}$$

with d = - a is deceleration is equal with braking acceleration, a, in m/s²; g – gravitational acceleration, g = 9.81 in m/s² ≈ 10 in m/s², but $a = v/t$, v – initial speed at braking, in m/s, and t – braking time, in s.

Then, the vehicle braking system efficiency, η is defined as the ratio between the braking force, F and the weight, G of the vehicle, expressed in percentages and given by the relation/equation [11]:

$$Braking\ efficiency\ (\eta,\ \%) = \frac{\text{Braking force (F)}}{\text{Weight (G)}} \times 100. \tag{4}$$

Through successive replacements, considering that the car's initial kinetic energy, $E = (m \cdot v^2)/\ 2$ (v - initial braking speed) must be equal to the mechanical work, $W = F \cdot S$, done from the moment of braking, until the movement complete stop (vehicle final velocity, $v_f = 0$ and S - braking distance) by the vehicle's braking system, the equation/relation (3) becomes:

$$\eta,\ \%) = \frac{\text{v}^2\ \text{(m/s)}}{2 \cdot \text{g}\ \{\text{m/s}^2) \cdot \text{S (m)}} \text{ x } 100, \tag{5}$$

where: v - initial braking speed, in (m/s); g – gravitational acceleration, in (m/s²); S – braking distance, in (m).

It can be seen that in equation/relation (4), the measured parameters appear (in braking distance, $S = v \cdot t - (d \cdot t^2)/2$, in (m), with t - stopping/braking time, in (s), and d - vehicle deceleration, in (m/s²). Thus, measuring the braking time and distance depending on travel speed, and the friction coefficient made it possible to the verification/evaluation and validation of the braking system efficiency of the tested vehicle (car).

2. Materials and Methods

To measure the parameters necessary to establish the braking efficiency, both on the brake dynamometer and in the field (in urban traffic conditions), a real car was used, when the brake pedal is operated frequently, and the braking system is heavily stressed. Brake systems can be tested in a simulated environment using a brake dynamometer. Brake dynamometers can be used at any time to measure the performance of a brake system over the course of its lifetime [12].

Brake dynamometers can replicate the forces that a vehicle would face in addition to measuring performance. The wheels are rotated and stopped by the brake dynamometer to simulate driving situations. This is done with an electric motor with 75 to 200 CP. The motor is managed by a computer that can simulate various vehicle inputs.

The motor generates torque that causes the wheel to turn, simulating the kinetic energy of a moving object. In other words, it causes the brake system to rotate at the required speed, or at an interval of "n" rot/min (rpm) [12]

The vehicle put through testing was driven in urban locations with heavy traffic, subjecting the braking system to severe stress and requiring frequent use of the brake pedal, also it was driven at constant speeds in rural locations, with little bit or no use of the braking system.

It is mentioned as when is creating or reverse engineering an application, manufacturers of brake pads for the aftermarket, frequently avoid testing on a real car. It costs money and takes time to do this kind of testing. Results can also be affected by human factors.

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The tested car (provided with braking assisting devices) has a disc and pad braking system, both on the front (ventilated discs) and rear (unventilated discs) axle.

To establish the car braking system efficiency, along with the braking force was used the Nussbaum VISIO brake dynamometer, version 2.0.1.4 STD, equipped with a BT110/410 model roller set (3.5 kW, 6.0 kN, 5.0 km/h) [13], to measure the braking system parameters of the tested car and simplified it is illustrated in Figure 1.

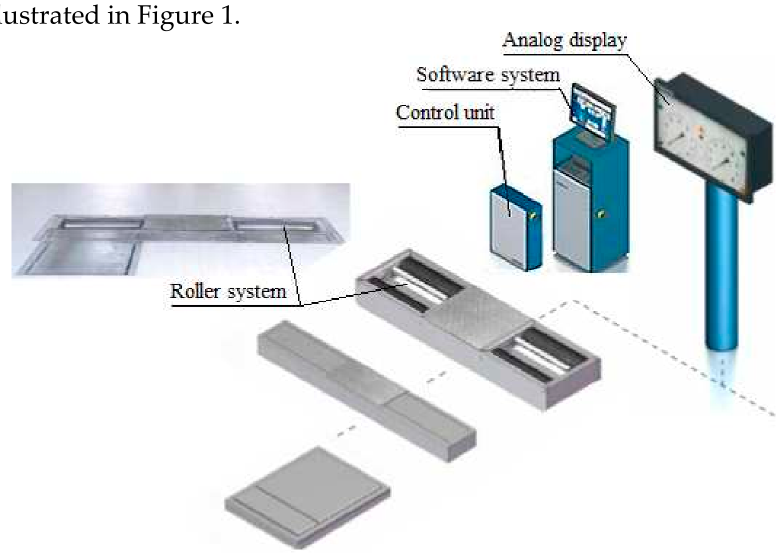

Figure 1. Nussbaum VISIO dynamometer [13].

This dynamometer type is employed for the braking system testing of cars and light commercial vehicles, with the following component parts and technical specifications: axle load of 4 tons, with a maximum braking force of 6 kN; galvanized roller set; electronic measurement system with strain gauges; start protection for braking rollers; control unit (see Figure 1); large-scale indicators for braking values (diameter 350 mm, see Figure 1 – analog display); differential indicator and automatic lamp; splash-resistant motors; roller set with premium plastic corundum coating; cable set with a length of 15 meters [13] (see and Figure 2).

The modern software system (see Figure 1 – software system) has several features and a two-tier interface that makes it typically user-friendly and simple to understand.

Users can set up the program such that the brake force graphs are displayed visually in either analog or column format. By driving the car onto the testing track of the stand, the test can start. The software's ability to configure two or more sequences makes it possible to choose the testing method that best satisfies the requirements [13]. The testing stand detects if the vehicle is correctly positioned on rollers with all wheels, when the dynamometer rollers are in motion, driven by the electric motor (Figure 2). Otherwise, it automatically switches to an erratic left-right rolling. The force sensor for the brake pedal is another crucial part of the testing stand [14]. Either a wire or remote control can be used to connect the device.

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Figure 2. Vehicle positioned on Nussbaum VISIO rollers dynamometer, in motion and with the transmission of the signal to the control unit.

A series of successive tests were conducted in the field to determine braking time and distance depending on the vehicle's velocity, in urban traffic conditions. The car had a mass of 1462 kg at the time of performing these tests. Additionally, were used for the testing also following instruments: stopwatch; tape measure; mobile radar; brake pedal activation reference points.

It is mentioned that road braking occurred before the wheels locked, and the conditions in which the experimental determinations took place on the road were generally on dry road (with a few areas of wet roads, regardless of the season). The road was made o asphalt (the usual, traffic in urban areas) with macro geometric characteristics, generally smooth (with a few areas with small slopes). The climatic conditions were corresponding to for each season because the tests were done in several series, from a day to other, both in spring, summer, autumn and winter, at temperatures from 5 to over 30 °C (depending on the season), moderate wind and relative humidity (without being measured). After each determination in similar conditions, a break of 0.5 h was made (starting from the same speed) for the friction elements to cool down. As measuring equipment for the traffic tests, the ones presented above were used, namely: the mobile radar for the travel speed with an accuracy of +/- 2 km/h, by comparison with the indicated at the car's board; digital timer for measuring braking time with a precision of 1/100 of a second; the usual 10 m ruler, for measuring the braking distance; brake pedal actuation reference points.

The friction coefficient/braking was established through calculations, using braking force measured on dynamometer, considering the mass of the vehicle, that involving determining the braking process parameters (braking distance and time, braking acceleration).

3. Results and Discussion

To ascertain the braking system parameters as closely to real values as possible, the vehicle was weighed on the testing stand equipped with a scale. The technical parameters of the tested vehicle are presented in Table 1.

A set of brake system tests were carried out for both axles after, the vehicle's parameters were established (see Table 1). The car was placed on the brake dynamometer rollers to simulate a 5 km/h speed. For the most precise results (see Table 1), the brake was applied repeatedly. A sensor for measuring the brake pedal force and another sensor for calculating the braking force difference were also added. The results can be observed in Table 2, together with braking efficiency and COF calculated with the relation/Equation (3).

Table 1. Braking system parameters of the tested car on the brake dynamometer.

Parameter	Measure unit	Front axis	Rear axis	Front axis	Rear axis
		Test 1		Test 2	
Vehicle mass	kg	**1462**		**1524**	
Static weight of the left wheel	kg	471	260	486	276
Static weight of the right wheel	kg	471	260	486	276
Axle weight	kg	942	520	972	552
Left wheel braking force	kN	2.93	1.84	2.88	1.60
Right wheel braking force	kN	3.54	1.75	2.74	1.66
Axle braking force	kN	6.47	3.59	5.62	3.26
Difference between braking forces	%	17	5	5	4
Left wheel friction	kN	0.13	0.10	0.13	0.08
Right wheel friction	kN	0.14	0.07	0.13	0.06
Friction force on the road	kN	0.27	0.17	0.26	0.14
Dynamic wheel mass	kg	1058	592	1070	526
Maximum difference on the right	kN	2.93	1.84	2.88	1.60
Maximum difference on the left	kN	3.54	1.75	2.74	1.66
Total service brake force	**kN**	**10.06**		**8.88**	
Service brake efficiency relative to total car mass	**%**	**~ 69**		**~ 59**	
Coefficient of friction (COF)	**-**	**~ 0,68**	**~ 0.69**	**~ 0.57**	**~ 0.59**

Note: Service brake efficiency, in % = ratio of the total braking force of the service brake, of 10.06 kN = 1006 kg to the total vertical load on the axles, 1462 kg = 0.688 x 100 ≈ 69 %, because 1 kN = 100 daN and 1 daN = 9.81 kg ≈ 10 kg. The ratio values are rounded to the nearest whole value.

The experimental tests in urban traffic (of land) conditions were done at different speeds, which were varied in two ranges. The speed varied between 37 - 40 km/h, and in the end. It is mentioned that the experimental tests at these speed ranges were done after the brake pads had been used for 13,083 km, and the brake discs were reused. For a speed ranging from 37 to 40 km/h, the experimental results are presented in Table 2, and the braking time and braking distance vs. speed graphs for the speed range of 37 - 40 km/h can be found in Figure 3. At the desired speed, the braking system was acted upon when reaching brake pedal activation reference points.

Table 2. Braking time, distance, and efficiency for the speed range of 37-40 km/h.

Nr. crt.	Travel speed [km/h]	Braking time [s]	Braking distance [m]	Braking efficiency [%]	Coefficient of friction (COF)
1	37	1.56	3.81	63.16%	~ 0.65
2	38	1.93	4.30	59.03%	~ 0.54
3	37	1.80	4.20	57.67%	~ 0.57
4	38	1.96	4.36	58.22%	~ 0.53
5	40	2.34	4.50	62,50%	~ 0.47
6	39	2.20	4.36	61.32%	~ 0.49
7	40	2.36	4.66	60.35%	~ 0.47

The braking system efficiency was established in percentage, based on the relationship/equation (5) depending on the car velocity, time, and distance of braking. For example, using the relation/equation (5) the braking efficiency, η will be:

$$\eta\ [\%] = \frac{\left(\frac{37}{3.6} - 0.325 \cdot \frac{37}{3.6}\right)^2}{2 \cdot 10 \cdot 3.81} \times \mathbf{100} = \mathbf{63.16}\ \%.$$

Note: Since the initial braking speed is considered to be 30 - 35% [10,11] lower than the vehicle's moving speed (here 37 km/h = (37/3.6) m/s), the average value (32.5%) of the interval was considered in the calculation, and the gravitational acceleration, g was rounded to 10 m/s^2, and the value, η = 63.16% was obtained.

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Also, the COF was based on the relationship/equation (3) depending on the car velocity, time, and deceleration (braking acceleration). For example, using the relation/equation (3) the COF, will be:

$$COF = \mu = (37/(3.6\cdot 1.56\cdot 10) \approx 0.65.$$

Note: The initial braking speed is considered v = 37 km/h = (37/3.6) = 10.27 m/s; braking time, t of 1.56 s (see Table 2); deceleratia, d = (10.27/1.56) = 6.58 m/s², the gravitational acceleration, g being rounded to 10 m/s², results the COF = (6.58/10) = 0.658 ≈ 0.65. Similarly, the COF shall be calculated for each vehicle speed at the moment of braking, corresponding to the braking efficiencies presented in Table 2.

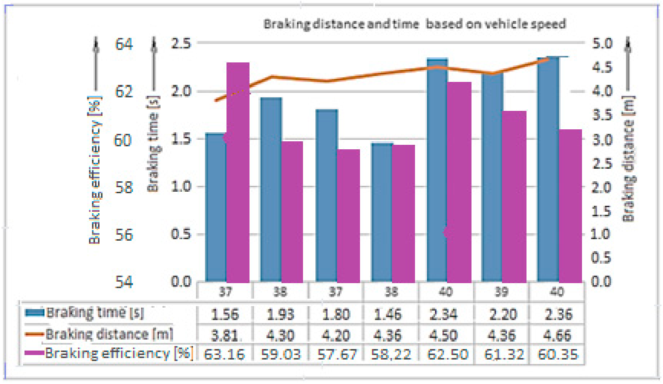

Figure 3. Braking time, distance and efficiency based on vehicle speed (37- 40 km/h).

Analyzing Table 2 and Figure 3 it can be observed that the maximum braking time and distance are reached at a velocity of 40 km/h, and the minimum braking time at a velocity of 38 km/h, while the minimum braking distance at a velocity of 37 km/h. Therefore, at the highest speed of the range considered, the longest braking time and distance result, respectively at the intermediate speed (38 km/h, and the second test series) the shortest braking time results.

The explanation would be the better adaptation of the brake pads-disc contact surface (the contact areas have increased, the possible increase in temperature or humidity on the contact surfaces, etc.). Instead, the shortest braking distance is at a velocity of 37 km/h. Hence, it can say that there is a relative correlation between travel speed, time, and braking distance. It was also observed that testing at the same travel speed and the same braking system (used brake discs-pads), the braking time and distance increased, due to the change in the stroke of the brake pedal, as a result of the wear of the brake disc-pad brake system (especially the brake pads). Then, at the same travel speed, after one or two repetitions, both the time and the braking distance differ from one test to another, with lower values in the second tests series for braking time (see 38 km/h from Table 2 and Figure 3), respectively with higher for braking distance values (see at 38 km/h in the first series of tests and 40 km/h in the second series of tests). This is due to the wear of the elements of the braking system, the environmental and traffic conditions, as well as the way the brake pedal is actuated by the driver, hence the difference between the time and distance of braking at the same velocity. For the speeds from the range of 50-51 km/h, the experimental results are presented comparatively in Table 3 and their graphs can be seen in Figure 4. A series of braking had been executed while trying to keep a steady speed and the same braking point.

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Table 3. Braking time, distance, and efficiency for the speed range of 50–51 km/h.

Nr. crt.	Travel speed [km/h]	Braking time [s]	Braking distance [m]	Braking efficiency [%]	Coefficient of friction (COF)
1	50	2.38	5.36	81.98%	~ 0.58
2	50	2.53	5.37	81,83%	~ 0.54
3	51	2.59	5.57	82.08%	~ 0.54
4	51	2.58	5.63	81.21%	~ 0.54
5	50	2.25	4.97	88.42%	~ 0.61
6	51	2.74	5.88	77.75%	~ 0.51
7	50	2.37	5.55	79.18%	~ 0.58

Note: Here, the braking efficiency was established on the same principle as the example presented in Table 2.

From the analysis of Table 3 and Figure 4, and in this case (car travel velocity in the range of 50-51 km/h) the findings from the previous case are valid, with the observation that in the third test (at a speed of 50 km/h), both the time and the braking distance had a sudden drop (especially the braking distance, see Figure 4). This was possible, possibly due to the increase in the friction temperature and the degree of humidity in the brake disc-pads contact area, even the degree of tire wear. Also, in each individual case, an oscillatory variation of both the braking time (but with relatively smaller amplitudes) and the braking distance (but with relatively larger amplitudes) is observed.

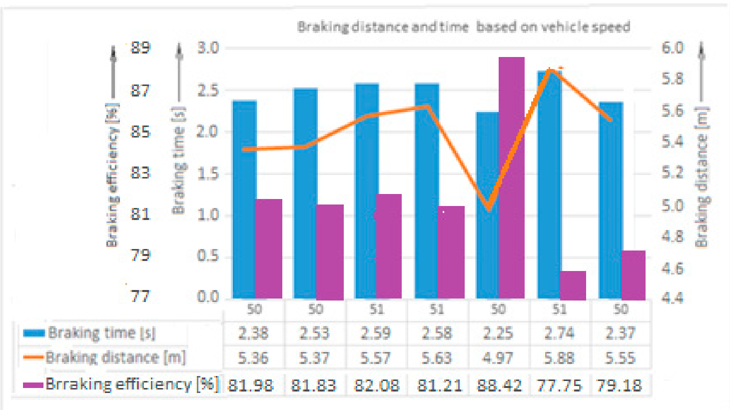

Figure 4. Braking time, distance, and efficiency based on vehicle speed (50-51 km/h).

It is observed that the efficiency of the service brake is over 43.5% (as the minimum accepted point of the efficiency of the braking system, for both travel speed ranges), under the conditions of the normal vehicle load of 1462 kg or 1524 kg (see Tables 2 and 3, as and Figures 3 and 4). This limit of 43.5% for the braking efficiency was established according to the North American Standard and with U.S.A federal regulations accepted and by European Community.

Thus, it was observed a braking system efficiency of about 60.32%, for the range of 37-40 km/h, respectively of about 81.78%, for the range of 50-51 km/h, as an average value. It is important to specify that first the experimental tests were performed in the range of speeds 50 - 51 km/h and then in the range of 37-40 km/h.

Braking efficiency results (60.32%, as the average value) show for the range 37-40 km/h, the need to replace in a much shorter time period of some braking system elements (especially the brake pads), than the recommended one. Instead, for the range 50-51 km/h, the braking efficiency being over 21% bigger, it proves that the lifetime of the braking system approaches with much to the recommended interval.

It seems that the explanation would be the experimental tests were realized after ones from the speed range of 50-51 km/h, respectively the car was used in urban/intense traffic conditions, which has led to more accelerated wear of the brake pads and even of the discs. At the same time, it seems

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that the degree of humidity, the road condition, even also the degree of tire wear, as well as the heat evacuation being slower at lower speeds led to this difference.

This is also confirmed by the evolution of the braking efficiency (through the values in Table 2, but also the graph in Figure 3). An oscillatory evolution is observed, its increase at the speed of 37 km/h, followed by a decrease at the increased speed (38 km/h), even at the same speed (of 37 km/h), in the second test. Then, with the increase in travel speed (to 40 km/h), the braking efficiency increases again (but below the first value from 37 km/h), after which it continues to decrease with the decrease in speed to 39 km/h and even to 40 km/h, on the second test. In the case of the speed interval 50 - 51 km/h, an oscillatory evolution of the braking efficiency with relatively small amplitude is also observed (see Table 3 and Figure 4), but it starts from lower values (relatively close, with small alternations, both at a velocity of 50 km/h and at a velocity of 51 km/h). After that it has a relatively sudden increase at a velocity of 50 km/h (from the third test), followed by a sudden decrease at a velocity of 51 km/h (also on the third test) and then a relatively small increase at a velocity of 50 km /h (also on the third test). These observations show the influence of the alternation of traffic conditions (the road, the degree of humidity and cooling of the braking system, the steering wheel, and the driver's mode of operation).

However, in both cases (the range 37-40 and 50-51 km/h), the braking system efficiency was well above the allowed limit of 43.5%, respectively it was observed that the parameters (the time and distance of braking/stopping, measured) for the braking efficiency establishment have increased with increasing car velocity (from 37 to 50 km/h). At the same time, the wear of the brake pads and discs was monitored, in relation to the initial velocity, to highlight the need for the replacement more frequent of some braking system elements, especially, in heavy traffic conditions.

Analyzing the evolution of COF with travel speed (see Tables 2 and 3) it can be seen that a very good one was obtained, located within the limits of 0.3 - 0.7 recommended by the literature, designers and manufacturers of motor vehicles and used for calculations in the design of braking systems. Negative values are purely conventional and indicate a deceleration (see relation/equation (3)). These are quite realistic values for sudden braking on dry asphalt with tires in very good condition.

Figure 5 shows the evolution of COF as a function of travel speed, which corresponds to the efficiency of the braking system, according to Tables 2 and 3.

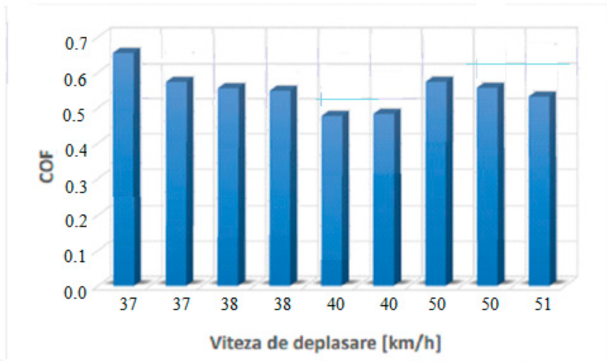

Figure 5. Evolution of the COF on a histogram depending on the speed of the vehicle**.**

It is observed that the evolution of the COF alternates, almost in the same way as the vehicle speed, decreases as an average, with the increase in speed (up to 40 km/h), after which it has an insignificant increase (to 50 km/h), followed by a slow decrease with increasing speed at 51 km/h. In addition, comparing the variation of the COFs in Tables 2 and 3, we notice that there are no significant differences, neither in terms of values nor in evolution, which proves the correctness results obtained by analytical calculation and experimental testing.

4. Conclusions

The correlation between braking efficiency and braking distance/time highlights the crucial role a functional braking system plays in mitigating potential accidents and ensuring the safety of passengers and pedestrians alike.

The experimental results have been validated by experimental methods of testing, as close as possible to operational reality, and have shown that the recommendations regarding the replacement frequency of brake pads and discs (less) are inconsistent with the braking system's actual wear. The results obtained from the analysis of braking times and distances emphasize the importance of maintaining an optimal braking system for maximum efficiency.

A high-performance braking system, well maintained and operated, can greatly reduce the risks associated with unexpected stops and collisions. It follows that continuous monitoring, maintenance, and improvement of the braking system are essential elements for improving road safety and preventing potential accidents.

Based on the experimental tests, a larger reduction in the efficiency of the braking system was found, for the velocity range of 37 - 40 km/h and with much less for the velocity range of 50 - 51 km/h in urban traffic conditions.

The braking system efficiency has been around 60%, for the range of lower speeds (37 - 40 km/h) and around 82% for the range of higher speeds, on average. By comparison with the allowed limit value (43.5%) for the braking system, these results suggest the need to replace (usually, first the brake pads,) some braking system elements, at a much shorter interval (for the lower speed range) and much longer (for the higher speed range), than the recommended one.

Because, in these conditions, it has been shown that the braking system efficiency decreases faster, it is essential, to carry out new studies to determine the braking system wear.

Therefore, it is necessary to continue research on the braking system behavior in urban traffic conditions and also at other velocity ranges, even other conditions. The results obtained will follow the braking system wear tendency by simulations, based on a statistical calculation model.

Moreover, the study has shown that heavy/urban traffic has a psychological effect on drivers, who tend to behave much more aggressively, which proves the need for an effective braking system.

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