THE INFLUENCE OF THE COOLING ON THE DISC BRAKES TEMPERATURE INCREMENT FROM THE ASPECT OF TRAFFIC SAFETY

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Vehicle exploitation in different traffic conditions and on different terrains often requires use of the brake system, which further influences the increment of the temperature of executive organs, as well as the brake system efficiency decrement and violation of traffic safety. This paper is based exactly on this subject, and the research was conducted in the laboratory on the test rig, which simulates the quarter of the vehicle. Three different investigations were conducted for one vehicle, during which the vehicle speed and braking pressure were the same, and only variable was air flow speed (0 km·h^{-1}, 7 km·h^{-1}, and 10 km·h^{-1}) around the disc brake, with the aim to maintain as the lowest possible temperature in the contact of brake disc and brake pads. The obtained results show that the increment of the airflow speed causes a longer braking distance. The conclusions made on the basis of the reviewed literature from the subject field, and their comparison with obtained results, indicate on the fact that the forced cooling is not necessary, because it was not overpassed the working temperature of disk brakes, used in this research.This paper gives insight into how the air flow speed around the brake disc, has an inconvenient influence on the stopping distance, and also gives directions for the improvement of the traffic safety and reliability of the brake system during vehicle exploitation.

Key words*: disc brake, experimental investigations, cooling, air flow speed, braking distance*

1. Introduction

During the braking process, the contact between the brake disc and brake pads occurs friction which is necessary for the braking, but the undesirable phenomenom of friction, also appears heating of brake elements [1]. The brake disc must be made as such, to absorb the highest possible amount of heat in a shortest possible time interval. After that, the absorbed heat must be dissipated into the environment [2], because the high temperatures can cause braking noise, intensive wearing, and in some cases for brakes failure [3], and besides that, this can also disturb the correct work of the suspension [4].

In some cases, the heating of brakes is not an undesirable phenomena, because the increment of the temperature of the friction couple, up to some level, increases the friction coefficient, which leads to the decrement of the stopping time. This is very convenient from the aspect of traffic safety. That is, it can be said, that from the aspect of the value of the friction coefficient, it exists the optimal temperature, which elements of the brake system should have. More accurately, the friction coefficient will rise until some value of the temperature is achieved, and after this value of the temperature is achieved, the friction coefficient will start to decrease with further temperature increment, this phenomenon in the literature is known as „brake fade“ [5]. This primarily depends from the thermal sensitivity of the brake [6].

In the case of the normal exploitation conditions of the vehicle, when only a periodical braking (the adjustment of the speed to the traffic conditions, or stopping because of traffic signs or due to the unpredicted situation) the friction couple will not achieve a critical temperature, because during the acceleration, the friction couple will cool down [7]. On the cooling intensity of the friction couple, the strong influence has the geometry of the brake disc, the geometry of the blades of the brake disc, holes and slots on the contact surface of the brake disc, the applied materials, the mass of the vehicle and the exploitation conditions [8-12]. Besides that, the contact surface of brake pads dictates the heating value of the friction pair. By design of the contact surface of brake pads, it can be achieved the evenness of the temperature in contact, and this will further reduce the thermal stresses [13]. Further with the reduction of thermal stresses, will be prolonged the lifetime of the executive organs of the brake system. In the case of the vehicle driving on long downhills or in the case of often stops, it can come to the achievement of critical temperature, after which the friction coefficient will start to decrease [14, 15]. The high temperatures which appear in such exploitation conditions, do not affect only on the friction coefficient, but also affect the thermal instability of the friction couple, as well as on the material properties, which further affect on the braking efficiency [16]. Also, in the case of a vehicle with the hydraulic brake system, where the brake fluid plays a very important role in the transfer of the braking force, from the command to the executive organs, the braking fluid can affect the response time of the brake system [17]. The quality of the braking fluid is characterized by boil point, because it is a functional element in the brake system, and as such it must satisfy all demands.

In order to maintain safety on the roads at the greatest possible level, it is very important for the vehicle to be technically correct, and in the case of come accidental situation to have as shortest possible braking distance. Also, it is important in these situations to avoid violations of traffic safety. On the market exists a great number of brake pads manufacturers, and each brake pad is different by its properties and price. The brake pads which the owner of the vehicle will use, will be chosen or by recommendation of the manufacturer or by price. One such research was conducted for more brake pads with different prices, and the best was shown the most expensive brake pad [18]. In the case when the cheapest brake pads and brake discs which exist on the market, it can come to the reduction of the efficiency of the brake system, in the cases of intensive or long-term braking [19].

The previous review of the literature from the subject field, which was the starting point, as well as the motivation for this research, is shown in Tab. 1. It can be seen that the temperature is one of the main causes of the decrement brake efficiency. Also, the temperature increases with the increment of a number of braking repetitions. Exactly these two phenomena will be investigated in this paper. That is, it will be investigated how the number of consecutive braking, affects on the temperature increment and brake efficiency decrement.

Table 1. The review of conclusions and disadvantages found from the research that are related with the subject of this paper

References	Conclusions	Disadvantages
[1-3]	The brake disc must to absorb as highest possible heat amount and to release it to environment.	High temperatures influence the noise, wear, and even failure.
[4]		Disturbance of the correct work of the suspension.
[5, 6]	Overheating of the brake system effects on the fading of braking characteristics.	Violation of traffic safety.
[7, 14-16]	The number of braking influences the evolution, temperature, speed, specific power, and friction coefficient.	Increment of a number of braking it reduces the efficiency.
[8-12]	The cooling efficiency influences the brake disc geometry (is it a vented brake disc or not, the ribs shape) and brake pads, the existence of holes and slots on the contact surface of the brake disc, and applied materials.	The appearance of cracks around the slots and holes. The compatibility of materials of parts which are in contact. Different thermal expansion.
[13]	If the brake pad achieves the contact with brake disc with a complete contact surface, the temperature will be more even.	Higher price of brake pads.
[17-19]	It is necessary to mount replacement parts according to the manufacturer's recommendation, as well as the maintenance of the same.	The existence of moisture in brake fluid in the case of the hydraulic braking installation. Price.

According to the data of the World Health Organization, every year in the traffic life lose 1.3 million people, while between 20 and 50 million of people are not life endangered. More than half of all which died because the traffic accidents, belong to the group of vulnerable traffic participants [20]. The reason because of most often comes to traffic accident is the human mistake, such is the too fast drive, on which directly influences has the hurry, or non-adjusted speed to the traffic conditions, traffic participants which often change lanes, frequent use of sirens, and similar [21-23]. All this affects the often activation/use of brakes, what during time affects brakes efficiency decrement. One more regime which can affect the brake efficiency decrement is the drive on long downhills, where the brakes are used constantly. Besides that, it has an influence, and if the driver is distracted in some way, during the drive, for example, if he uses the cellphone [24]. In the case, when the driver is distracted, he needs more time to stop the vehicle, than in the case when happens something unexpected [25].

The aim of this paper is to determine how the cooling of the disc brake will influence the temperature of disc brake elements. Also, the aim is to determine how the cooling intensity will influence the braking distance, all with the aim to prevent violations the traffic safety.

2. Stopping distance

The stopping distance is the distance which the vehicle passes from the moment when the driver reacts on the accidental situation, until the vehicle stops. The stopping distance consists from three parts [26]:

- Thinking Distance
- Reaction Time
- Braking Distance

The determination of the stopping distance can be conducted as in the case of its determination in the case of some traffic accident [27], eq. (1).

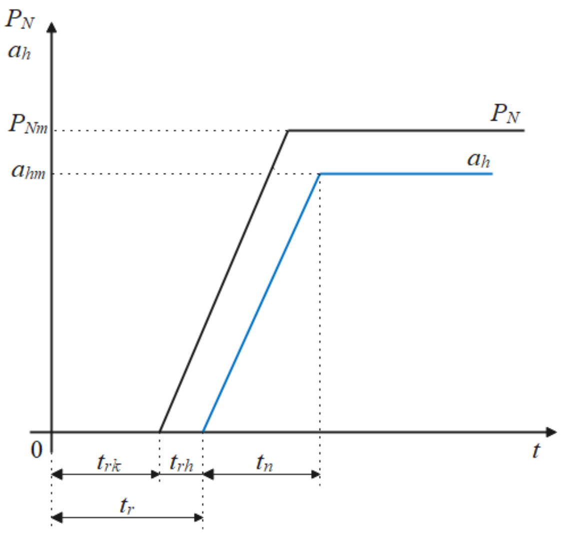


Figure 1. The simplified diagram of the straight-line braking [26]

$$S_z = V_0 \cdot \left(t_r + \frac{t_n}{2} \right) + \frac{V_0^2}{2 \cdot \mu \cdot g} \quad (1)$$

The advantage of such determination of the stopping distance is that it includes all components of the system human-vehicle-road. Fig. 1 presents the braking of the vehicle on the straight horizontal road in the case of all wheels braking. Common for the equation (1) and Fig. 1, are times which are of high importance for stopping distance, and there are the driver reaction time and system response time (t_r) and time necessary for the braking pressure to achieve its maximal value (t_n).

In the case of a traffic accident, the speed of the vehicle during the braking is not known. Different form this, during the brake testing in laboratory conditions, the speed is known. So, the braking distance, for the laboratory investigations, can be determined by the application of eq. (2).

$$s = \int_{t_1}^{t_2} V(t)\,dt \tag{2}$$

According to eq. (2), it can be concluded that in this case will be calculated the braking distance, where are not included the driver's thinking and reaction, only the braking from the moment of brake activation, on the basis of speed change.

3. Experimental installation

The experimental work was conducted on the test rig BRAKE DYNO 2020, shown on Fig. 2. The test rig is designed as such to simulate the kinetic energy of the quarter of the vehicle mass. That is, how during the braking process, the kinetic energy of the vehicle is stopping, more accurately, the brakes must consume the kinetic energy of the vehicle, in order to stop it. So, by adjusting the rotational speed of the flywheel mass (5), it can be simulated the kinetic energy of the quarter of the vehicle mass, by equalizing the rotational kinetic energy of the flywheel mass (5), with the desired translational kinetic energy of the quarter of the vehicle. In order to simulate the kinetic energy, the test rig consists of the drive part (electric motor (1), and frequency regulator (13) which is necessary to adjust the rotational speed of the electric motor (1), and by that the rotational speed of the flywheel mass (5)). The flywheel mass (5) is connected with the electric motor (1), through the electromagnetic clutch (2). The braking performs by activation of the hydraulic brake installation (brake cylinder (12) and pipes (26)). The activation of the hydraulic installation performs by pneumatic installation (compressor (10), pipes (25), and pneumatic components (9) which besides the brake activation, also serve and for braking pressure adjustment). The temperature of brake pads measured by four thermal sensors mounted in brake pads at 2 mm from contact surfaces, while the temperature of the brake disc is followed by a thermal imager (8). The ventilator (30) serves to simulate the air flow through the disc brake. All data collected from sensors on the PC (11), on which is installed special software for the test rig automatic control, as well as for the data collection from sensors. An important parameter is the rotational speed of the flywheel (5) and thereby also the rotational speed of the ventilated brake disc (6). For the measurementof this parameters, inductive sensor (14), is used, which gives possibility of vehicle speed calculation at each moment of measurement. In order to follow are necessary parameters, were used several crucial sensors, whose characteristics are given in Tab. 2.

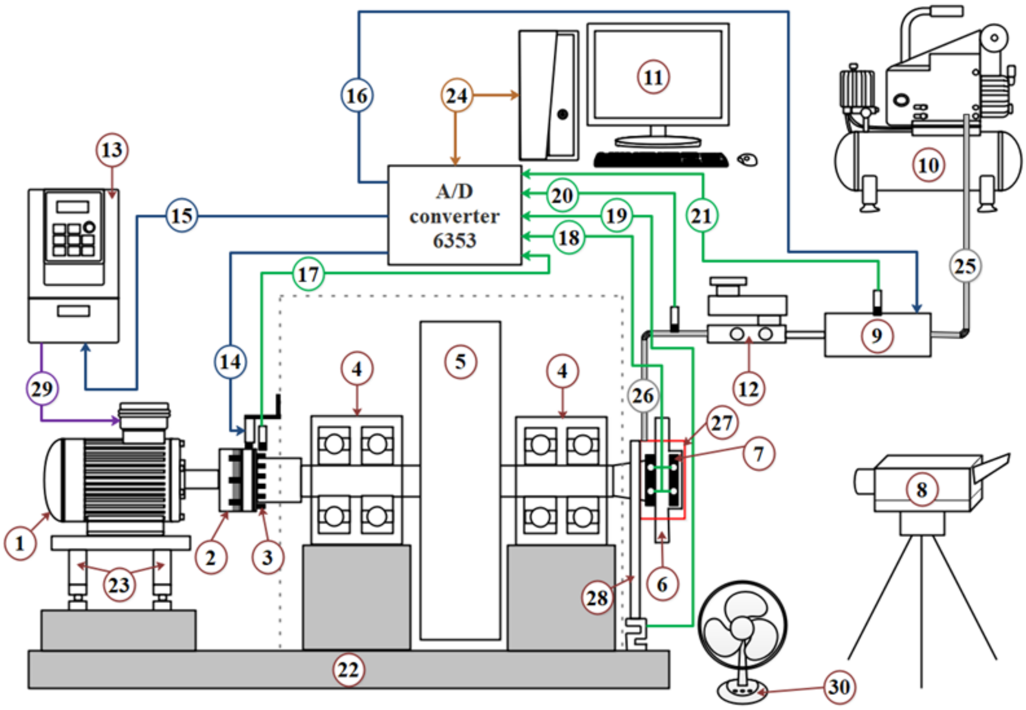


Figure 2. The scheme of the experimental installation installation

Table 2. Type and characteristics of used sensors

Parameter	Name of used sensor	Type	Measuring range	Error
Disc brake revolutions number	BCT1204PZ-YB	Inductive sensor	0 ÷ 10.000 min^{-1}	-
Braking pressure	WPM-131D	Resistive sensor	0 ÷ 25 MPa	0.2%
Braking torque	CZL312 5t	Resistive sensor	to 5 t	0.03%
Brake pads temperature	Pt100	Resistive sensor	0 ÷ 250 °C	0.1%
Brake disc temperature	Testo 868	Thermal imager	0 ÷ 650 °C	± 2%

4. Experimental plan

The investigation of the cooling influence, that is, the speed of the air flow around the brake disc and brake pads (Fig. 3) during the investigation, will be conducted for two different air flow speeds and for one investigation in a peaceful environment, that is, when don't exist the forced air flow around the disc brake. The brake disc is made from cast iron, while brake pads are made from frictional materials. The characteristics of materials of the friction pair are given in Tab. 3. The initial conditions are the same for all three investigations (Tab. 4), the difference is only in the speed of the air flow around the brake disc. The BC is the abbreviation for the brake cooling, while the number along BC represents the number of tests. The 0 is the first test where the airflow speed around the brake was 0 $km \cdot h^{-1}$, 1 is the second test where the airflow speed around the brake was 7 $km \cdot h^{-1}$ and the 2 is the third test where the airflow speed around the brake was 10 $km \cdot h^{-1}$. It will be conducted a ten consecutive repetitions of acceleration and braking until the stop, Fig. 4. Each test consists of the standstill, acceleration, achievement of the desired speed, and braking. The standstill actually represents the period characteristic for real exploitation conditions, during which the driver puts the vehicle in first gear and releases the clutch, and after this, the vehicle starts from standstill to accelerate. The next period is acceleration, during which the vehicle needs some time to achieve the desired speed, and after the desired speed achievement, the driver starts braking until the vehicle stops.

The explained procedure will be repeated ten times consecutive. During all ten tests, will be investigated the influence of the cooling intensity (v_v) on the generated temperatures of the brake disc and brake pads, as well as, will be determined the braking distance for each test.

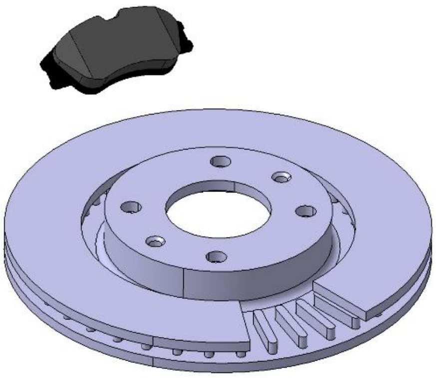


Figure 3. The look of the ventilated brake disc and the brake pads

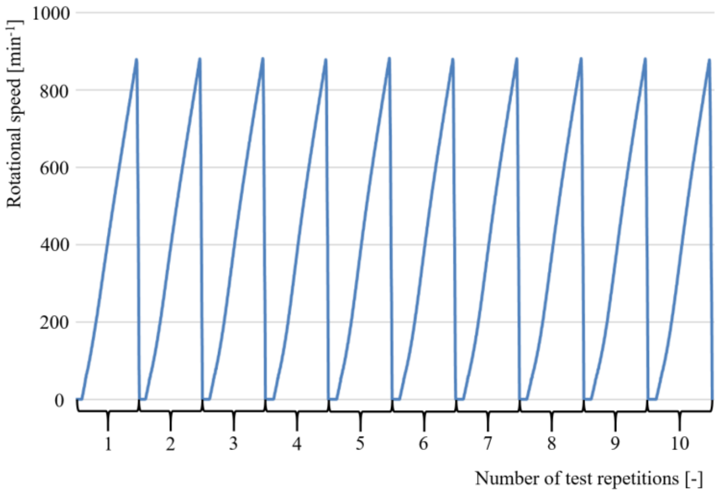


Figure 4. The diagram representation of the repetition test for ten consecutive cycles (standstill-acceleration-braking until stop)

Table 3. Material characteristics of the brake disc and brake pads

	Brake disc	Brake pad
Density [kg·m^{-3}]	7100	2300
Elastic modulus [GPa]	118	20
Poisson ratio [–]	0.32	0.3
Thermal conductivity [W·m^{-1}°·C^{-1}]	53.3	3
Specific heat [J·kg^{-1}·°C^{-1}]	490	1200
Thermal expansions [°C^{-1}]	$10.85 \cdot 10^{-6}$	$10 \cdot 10^{-6}$

The investigation was conducted in the laboratory conditions. On the basis of the scheme of the test rig (Fig. 2) can be noticed that doesn't exist the wheel connected to the brake disc. This means, that there is no part which will contribute to the heat conduction, which represents one disadvantage in respect to the case when are is a tested disc brake in the assembly with the wheel. The wheel in this case is not mounted, in order to follow the temperature of the contact surface of the brake disc. Another disadvantage is the non-existence of other vehicle systems, which exist in the case of real vehicle and which can affect the vehicle stopping. One more disadvantage is the non-existence of contact between the wheel and the road, which can be successfully simulated during the test on a dynamometer. In this case, when existing contact between the wheel and the road, due to the rolling resistance, the stopping time of the vehicle will be shorter.

Table 4. The control parameters of tests with variable cooling of the disc brake

Test name	Input data	
Test BC0	$T_p = 25\ °C$	$v_v = 0\ \text{km}\cdot\text{h}^{-1}$
Test BC1	$m = 300\ \text{kg}$ $p = 5\ \text{MPa}$	$v_v = 7\ \text{km}\cdot\text{h}^{-1}$
Test BC2	$v = 100\ \text{km}\cdot\text{h}^{-1}$	$v_v = 10\ \text{km}\cdot\text{h}^{-1}$

On the basis of the defined tests, it was defined and the investigation procedure, Fig. 5. All investigations were conducted for the same initial conditions, the initial temperature of the brake disc was 25,5 °C ± 0,5 °C, while the temperature of the environment during all tests was 21 °C ± 1 °C. This was necessary for the later comparison of tests/results. Before the measurement starts, it is chosen the test according to which will be conducted the investigation. After that, the output parameters were defined (data which will be recorded during the experimental work). The next step is the start of the test rig. After some time, the brake disc achieves the desired rotational speed which corresponds to the desired speed of the vehicle. When the desired speed is achieved, the brake activates. The output data are saved on the memory of PC. The measurement, as well as the data saving lasts until are finished all ten cycles of standstill, acceleration, and braking until stop. The next step is data processing, analyzing, and discussion of the results, as well as the conclusions make on the basis of the conducted analysis.

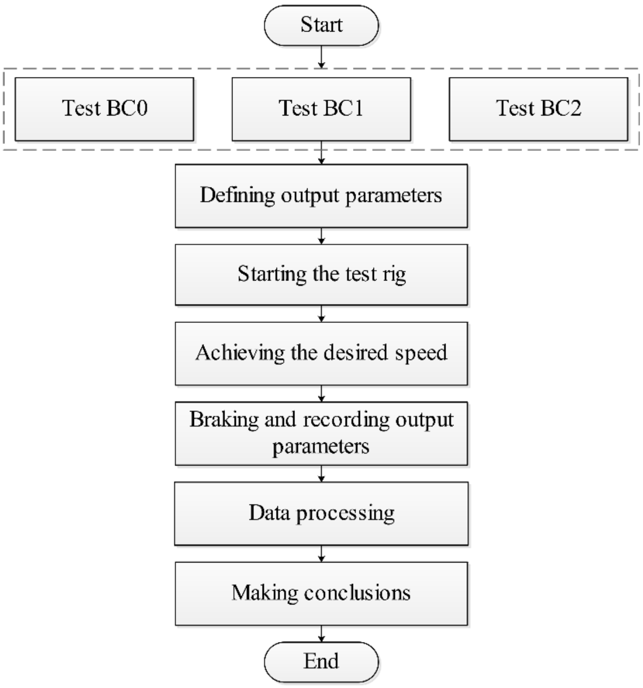


Figure 5. The algorithm of the investigation procedure

5. Results and discussion

The influence of the cooling on the braking efficiency, will be shown and evaluated for each repetition test, through the value of the braking distance. The braking behavior shown by deceleration change, can be seen in Fig. 6. The shape of the deceleration curve almost corresponds to the theoretical braking behavior from Fig. 1. The main difference is because is not include the driver reaction time, because the test rig control is automatized, and at the moment when the defined speed is achieved, the brake activates automatically. As an example, it was taken the first braking from test BC2. On the basis of the results obtained from the conducted tests (where the only difference in the experimental work was related to the cooling of the disc brake, that is, did the experimental work conducted for the case of the peaceful environment

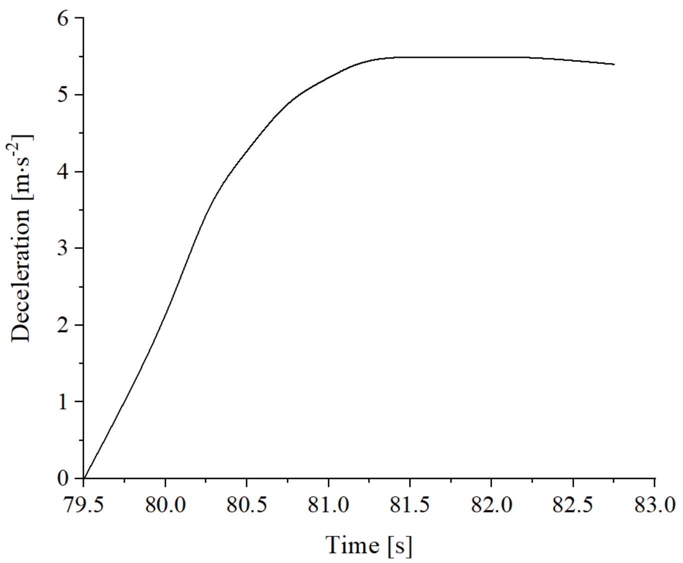
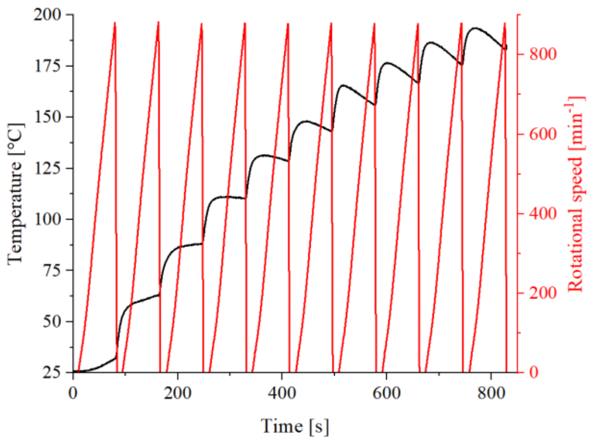


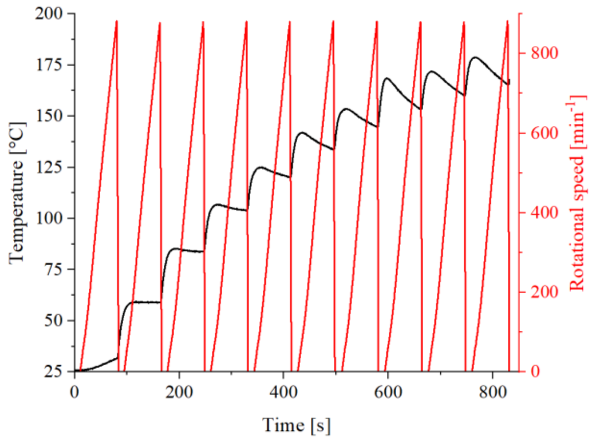
Figure 6. The behaviour of deceleration for the case of BC2 during the first braking cycle

without the forced cooling of the brake system, or for the case of the investigation with forced cooling with different air flow speed) outcome the conclusion that with greater speed of the air flow around the brake system, the temperature of brake pads will be smaller. In the case, when is not included the forced cooling (Test BC0), the generated temperature on the brake pads is the greatest, compared to the other two tests (Fig. 7).

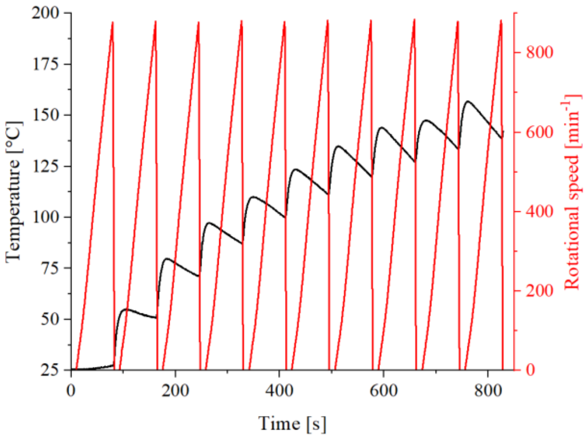
The temperature shown in Fig. 7 is the highest measured temperature of brake pads, which appears on the entering side of the outer brake pad. It can be seen that at the beginning of the acceleration, the temperatures for the case of no cooling is almost the same as the temperature when the air flow speed is 7 km/h, and this continues until the stop. After the next acceleration, the temperature on the brake pad is constant for the case when the air flow speed is 7 km/h, while for the case without cooling the temperature rises. No matter to the conducted test, the temperature on the brake pads continues to rise even after a vehicle stop. So, in the case of the 10th braking, it is not shown the maximal temperature, that is, the measurement is finished at the moment when the simulated vehicle stopped after 10th braking at each test. After 10th cycle, the lowest temperature is achieved on the brake pad when the air flow speed was 10 km/h, while the highest temperature was recorded for the case without cooling, Fig. 7. Tab. 5 gives the calculated value for the braking distance for each test, that is for each cycle. Globally, the best results from the aspect of braking distance, gave the test BC0. That is from the ten cycles, in the case of the test BC0, six times was obtained the shortest braking distance. From where comes the conclusion, that the relatively high temperature of the friction couple is not to undesirable phenomena. That is, in order to stop the vehicle at the shortest possible distance, it is necessary for the friction couple to achieve the working temperature at which the braking distance will be shortest. During these investigations, no matter to the defined conditions, the working temperature of the brake system (the temperature after which comes to the increment of the stopping distance) was not passed and it did not disturb safe stopping [28,29].



(a)



(b)



(c)

Figure 7. The influence of the air flow speed on the value of the temperature of brake pads during the ten consecutive cycles (a) BC0, (b) BC1 and (c) BC2

Table 5. The achieved braking distance for each investigation cycle with respect to the air flow speed around the disc brake

	Braking distance [m]		
	BC0	BC1	BC2
1	55.39	53.91	53.83
2	53.15	49.97	51.52
3	47.87	49.07	45.07
4	43.09	48.69	45.66
5	47.22	47.27	53.12
6	48.10	49.64	55.64
7	46.69	51.10	55.37
8	46.41	46.01	50.73
9	46.02	47.14	51.93
10	48.64	51.86	49.44

By this, it concludes that the temperature during the first ten consecutive cycles of braking has not passed critical values, and there is no need for forced cooling. So, in practice, this can be used, by implementation of the unit which will follow the stopping distance and the temperature of the executive organs of the brake system, and at the moment when the braking distance starts to rise, the forced cooling of the disc brake, in order to maintain the working temperature of the brake system, in allowed boundaries.

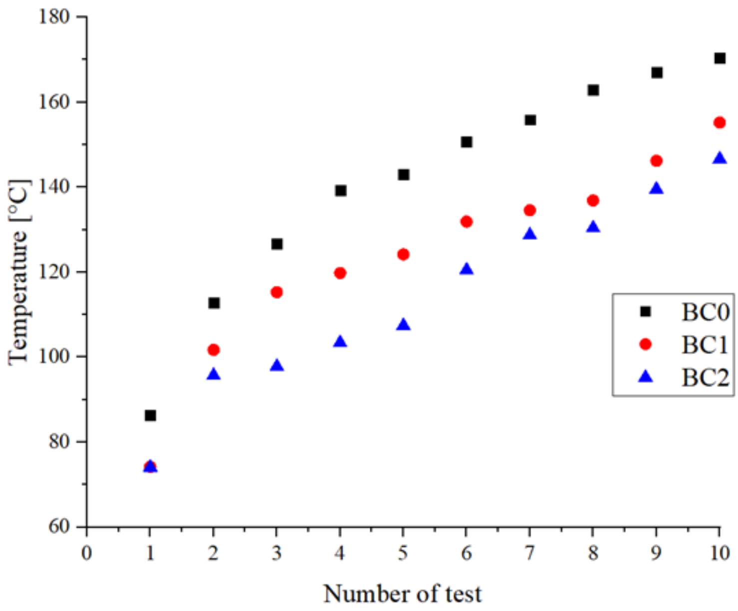


Figure 8. Maximum temperature of the brake disc for each cycle

The temperature on the contact surface of the brake disc was highest in the case without cooling, during all repetitions (Fig. 8). The lowest temperature on the contact surface of the brake disc was achieved for the case when the cooling intensity was highest, that is, during the test BC2. At the beginning, the temperature of the brake disc, for the cases BC1 and BC2, is almost the same. After that, for cycles from 2 to 5, the difference in temperature rises, at cycle 6 decreases, and for cycles 7 to 10 maintains an almost constant value. On Fig. 9 are presented the thermographic representations of the disc brake, recorded for the 10th braking cycle for all three tests. What is common for all three tests, is the same behaviour of the brake disc, that is, in all cases, on the contact surface of the brake disc formed the hot rings, which further affects the change of Young's module and material strength, and by this contributes to the deformation of brake system elements, what further cause uneven distribution of contact stress [30]. This is quite inconvenient and can cause a great damage to the brake disc, as well as the failure of the brake system [31].

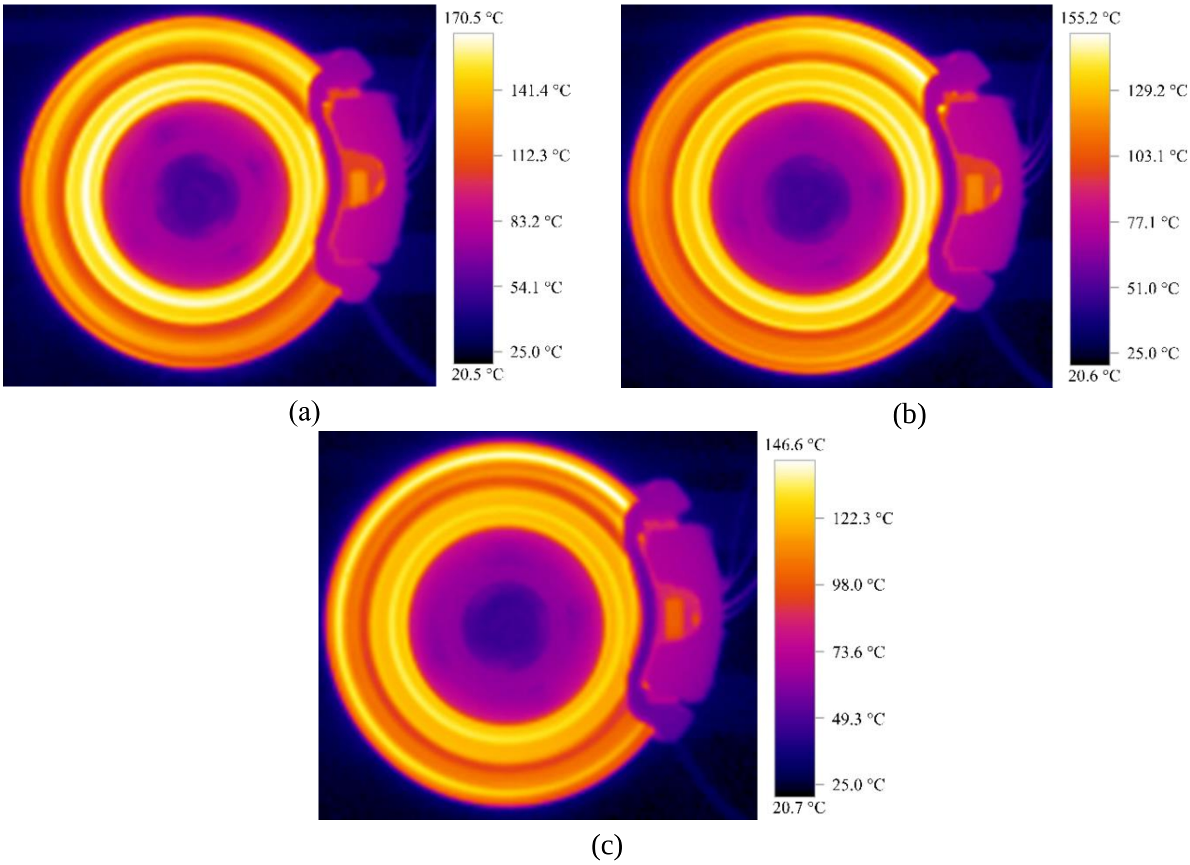


Figure 9. The thermographic representation of the contact surface of the brake disc for the tenth braking cycle (a) BC0, (b) BC1, and (c) BC2

6. Conclusion

Traffic safety is quite an actual subject of nowadays society, while the brake system is very important from the aspect of traffic safety. While on the braking efficiency influences several factors, such are construction, applied materials, environmental conditions, and similar. The conducted research leads to the next conclusions:

- Traffic conditions as well as vehicle technical conditions influence braking efficiency.
- The number of traffic accidents, the number of harmed or died, between whose are young and older, in traffic, significantly influences one country. The life loss is firstly the great loss for the families, as well as the economic loss for the country.
- The achieved temperature in the contact between the brake disc and brake pads, has a significant influence on the braking efficiency.
- No matter if the cooling of the disc brake exists or not, always will come to the increment of the disc brake temperature during the braking.
- The forced cooling can have a negative effect on the braking distance and can lead to the violation of traffic safety. So it should implement a control unit, which will on the basis of temperature and braking distance, determine either the cooling is necessary or not.

The obtained results from this research can find application in the automotive industry. These results are a good start to think about the development of a vehicle system which will simultaneously follow the brake system temperature and vehicle stopping distance. On the basis of these parameters, this system should decide if is necessary a forced cooling of the brake system or is not.

Further researches should include and the anti-lock braking system during the testing, because today, this system is mandatory equipment for all vehicles. The non-existence of the anti-lock braking system is the disadvantage in this research.

Nomenclature

a_h	- braking deceleration [ms^{-2}]
a_{hm}	- maximum braking deceleration value [ms^{-2}]
g	- gravity of Earth [ms^{-2}]
P_N	- brake pedal force [N]
P_{Nm}	- maximum brake pedal force value [N]
S_z	- stopping distance [m]
V_o	- speed in the moment of brake activation [ms^{-1}]
t_n	- braking deceleration rise time [s]
t_r	- total system response time [s]
t_{rh}	- brake systems response time [s]
Greek symbols	
μ	- tyre-road adhesion coefficient (peak or sliding) [-]

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