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EFFECT OF REPEATED VEHICLE BRAKING ON THE WARMING OF SELECTED PARTS OF THE VEHICLE

Summary. The friction brakes convert a significant part of a vehicle's kinetic energy into thermal energy. Some of its parts is distributed to the places around the brakes, and another part is accumulated in several vehicle components. This article is focused on the measurement of temperature increase of selected vehicle components during re-deceleration. These components include brake discs, brake pads, calliper, wheel rim and tire side in the area of its bead and tread. The measurements were performed during the repeated braking of a fully-loaded vehicle according to ECE Regulation No 13 - type I.
Keywords: repeated braking, temperature, brake, heat, road safety

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1. INTRODUCTION

The purpose of friction brakes during vehicle motion is to convert part of the vehicle's kinetic energy to another energy [1], and thus, enable the vehicle to stop or slow down [2]. In the vehicle's friction brakes, specifically, where the brake pads contact the friction disc, kinetic energy is primarily converted into thermal energy [3, 4]. Heat is further distributed to the other parts of the vehicle as well as to ambient air [5].

Heat accumulated in the friction disc and brake pads can increase the coefficient of friction to some extent [6]. However, after exceeding a certain heat value, which is usually 350°C for constant temperature and 800°C for peak temperature, permanent adverse changes in a material can occur [7]. As a result of too high temperatures, a vitreous layer can occur, so the coefficient of friction between the disc and pad is decreased. The disc can also change its shape, it can be corrugated [8]. Furthermore, concerning the brake pad, it can lead to separation or destruction of friction lining resulting in the loss of brake control [9].

Heat from the brake pads also runs to the brake calliper. There is a piston mounted which is extruded by brake fluid [10]. Therefore, brake fluid is similarly being heated. An important parameter of brake fluid is its boiling point. Since it is a hydroscopic fluid, it absorbs moisture through the rubber gaskets and hose's sides. The moisture accumulated in the brake fluid reduces its boiling point [11]. If the brake fluid is heated at boiling point, the water contained is being transformed into steam. Instead of fluid, steam is compressible, thus, heating the brake fluid above its boiling point can weaken the brake control. Wet boiling point, that is, the brake fluid's boiling point in a vehicle, usually varies about 170°C [12].

The cycle of heating further includes the rims of wheels as well as tire beads. The tire bead is the only place where the rim has a connection with the tire [13]. In the case of excessively high temperatures, there could be a lack of connection between the rim and tire bead, and it would adversely affect the vehicle features [14]. Heating of tire disc and rim causes heating of air in the tire, and it can have an effect on the increase of pressure in the tire [15].

This article focuses on the impact of vehicle intense deceleration on the temperature of brake disc and pads, brake calliper, rim of a wheel as well as on tire beads and sides. The measurements were performed during a vehicle driving according to the amended methodology of ECE Regulation No 13 - type I testing. This regulation sets the conditions of brake efficiency testing during re-deceleration [16]. The results, therefore, reflect the testing status under legislative conditions.

Significant consideration was given to the warming of brakes during repeated braking in scientific publications [28, 29, 30]. However, this research is predominantly focused only on the brake disc itself, or even on the brake pad [8, 31, 32]. Therefore, the purpose of this article is to measure the temperature of the other vehicle parts that are being warmed during repeated braking. Since some of the components are not part of the braking system, yet they are affected by it and determine the efficiency of braking.

Such research can likewise be done via mathematical modelling as seen in the publications [6,8,32,33]. The results published in this article were gathered trough real measurements, although it can be said that the results from mathematical modelling are not too diverse from those gathered via real measuring [32].

It can be expected that particular components of the brake disc will have different temperatures depending on their distance from the centre [31]. To achieve sufficient accuracy, the brake disc's temperature will be measured in the centre of its friction surface [34, 36]. Such accuracy supports the fact that the measurement in this article is focused on the vehicle operation, and not on the material from which the components are made [35].

It is assumed that the components at which the temperature is measured, will reach a limit temperature but they will not be destructed or permanently damaged.

2. METHODOLOGY

2.1. Measurement procedure

The general binding ECE Regulation No 13H describes uniform provisions concerning the approval of passenger cars in terms of deceleration. Besides other tests, the regulation also provides type I testing. While testing, the service brakes are tested by being decelerated 15 times and released with the vehicle loaded under conditions listed in Tab. 1.

Tab. 1

Test conditions according to ECE 13, type I

V_1 (km.h^{-1})	V_2 (km.h^{-1})	Δt (s)	n
80% Vmax ≤ 120	0,5 V_1	45	15

where:
V_1 is initial speed at the beginning of deceleration,
V_2 is speed at the end of deceleration,
V_{max} is maximum vehicle speed,
n is number of deceleration,
Δt is duration of braking cycle, that is, time taken between the beginning of one deceleration and the following beginning of another deceleration [16].

If parameters of a vehicle are not able to keep the prescribed duration, the regulation permits to make this time longer. There must always be at least 10 s available for the initial speed of braking stabilisation.

To enable the temperatures to be distributed in the required measurement points at the measurement accuracy acceptable, it was necessary to keep the wheels stable during temperature measurements [17]. The methodology according to ECE No 13, I has been adjusted to this situation and, similarly to the situation at which mechanical energy that is transformed into heat during deceleration would have reached the same value as for unadjusted methodology. Therefore, the zero speed and the following relation were needed (1):

$$\Delta EK_{EHK} = \Delta EK_{MSR} \tag{1}$$

where:
ΔEK_{EHK} is the difference of kinetic energies at the beginning and at the end of one braking cycle according to ECE No 13 H,
ΔEK_{MSR} is the difference of kinetic energies at the beginning and at the end of one surrogate braking cycle.

Equation 1 can be detailed as follows (2):

$$\frac{m}{2}(V_1^2 - V_2^2) = \frac{m}{2}(V_A^2 - V_B^2) \qquad (2)$$

where:
m is vehicle mass,
V_1 is initial speed at the beginning of braking according to ECE No 13 H,
V_2 is speed at the end of braking according to ECE No 13 H,
V_A is initial speed wanted at the beginning of surrogate braking cycle,
V_B is speed at the end of the surrogate braking cycle. $V_B = 0$ [18].

After having the values substituted (3):

$$\frac{m}{2}(V_A^2 - 0^2) = \frac{m}{2}\left(\frac{120^2}{3{,}5^2} - \frac{60^2}{3{,}6^2}\right) \qquad (3)$$

After having the initial speed wanted V_A (4):

$$V_A^2 = 1111{,}11 - 277{,}778$$
$$V_A = 26.867\ \mathrm{m}.s^{-1} = 103.9\ km.h^{-1} \qquad (4)$$

To maintain the amount of energy transformed, the initial braking speed of 103.9 km.h^{-1} was calculated.

Time is very important for the distribution of heat. To maintain the time of mechanical energy transformation to thermal energy, it is necessary to maintain the same time of deceleration (5):

$$b = \frac{\Delta v}{t} \qquad (5)$$

where:
b is deceleration required according to ECE No 13 H, 3m.s^{-2},
Δv is speed difference at the beginning and at the end of deceleration [m.s^{-1}],
t is time needed for achieving the change required while deceleration b [19].

Deceleration time can be calculated via Equation 6, by substituting the values according to ECE Regulation No 13, Equation 5:

$$3 = \frac{\frac{120}{3{,}6} - \frac{60}{3{,}6}}{t} \qquad (6)$$

After having the time of deceleration t (7):

$$t = \frac{\frac{120}{3{,}6} - \frac{60}{3{,}6}}{3}$$
$$t = 5.56\ s \qquad (7)$$

The deceleration was repeated 15 times at the initial driving speed of 103.9 km.h^{-1} up to the final stopping. Duration of one deceleration was 5.56 s.

Fig. 1 depicts the actual course of driving speed depending on time.

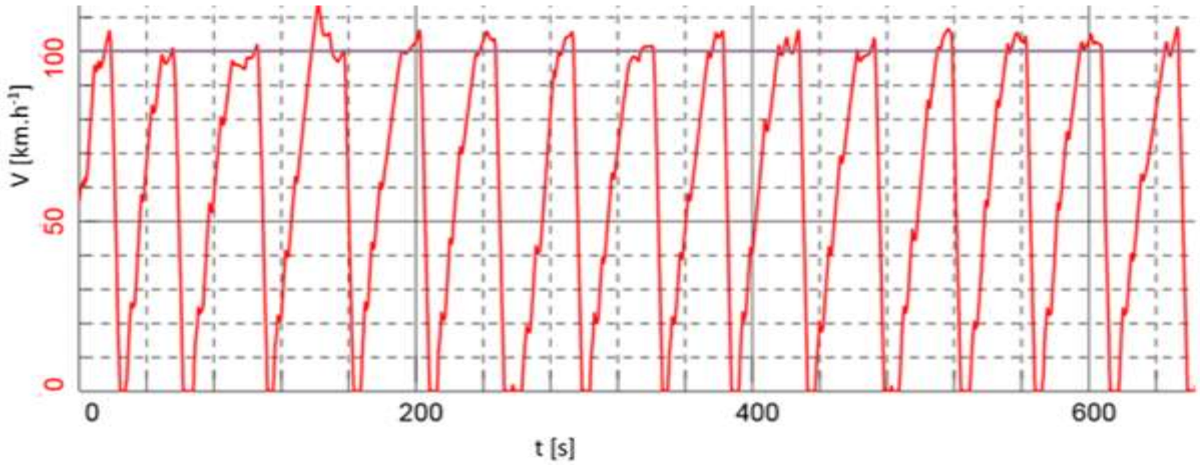

Fig. 1. Course of driving speed depending on time

2.2 Introduction of parameters into the dynamometer

The measurements were performed at the cylinder test station MAHA MSR 1050. Measuring under laboratory conditions was provided with higher accuracy when compared to road traffic measuring [20]. Fig. 2 shows the vehicle during its measuring at the cylinder test station MAHA MSR 1050.

Fig. 2. Vehicle used for measuring and MAHA MSR 1050

The cylinders of the cylinder test station can both be decelerated and accelerated. To have the cylinder values at the level of a situation in which a vehicle is real-road driving, it is necessary to introduce these values into the cylinder test station's control computer. The values are achieved by the coasting deceleration measurement of vehicle resistance under the conditions of Standard EN 30 0556. Such measurement relies on a vehicle with prescribed laden mass which is accelerated up to the speed about 110 $km.h^{-1}$; disconnection between the engine and wheels and on the recording of vehicle coasting. Fig. 3 depicts the vehicle deceleration during measurement.

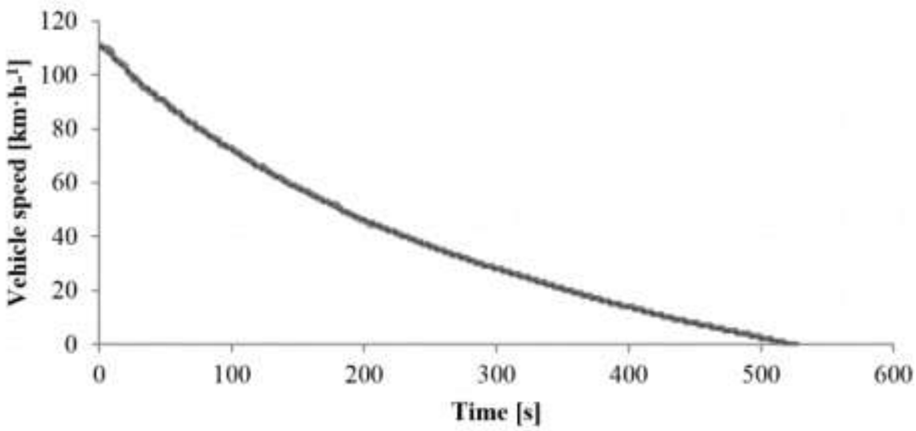

Fig. 3. Vehicle deceleration during coasting deceleration measurement

The recorded vehicle speed that depends on the time of disconnection between the engine and wheels is further introduced into the cylinder test station's computer. Based on these values and measurement results, the computer sets the values of deceleration or acceleration directly at the cylinders during particular driving modes. Thus, the cylinder test station can fully provide a road driving simulation.

2.3. Vehicle used for measurements

The measurements were performed with the Kia Ceed. Its technical parameters are given in Tab. 2.

Tab. 2

Technical parameters Kia Ceed [21]

Engine	1.6 CVVT
Year of construction	2007
Engine power	92 kW/6200 min^{-1}
Engine torque	154 Nm/4200 min^{-1}
Transmission	5 gearbox, manual
Type of bodywork	Hatchback
Overall mass	1,730 kg
Front brakes	disc, air-cooled, ribbed
Outer diameter of brake disc	280 mm
Size of brake pads l x w x d	130 x 58.1 x 16.7 mm

2.4. Device used for temperature measurement

The temperatures of selected vehicle parts were measured via FLIR E60 Thermal Imaging Camera shown in Fig. 4.

Fig. 4. Device used for temperature measurement [22]

Table 3 shows the technical parameters of the device used.

Tab. 3

The technical parameters of FLIR E60 [23]

Ir resolution (array size)	76,800 (320 x 240)
Temperature range	-20 to 650°C
Accuracy	±2% rdg. or 2°C
Thermal sensitivity	<0.05°C (50mK)
Frame refresh	60 Hz
Field of view	25° x 19°; Optional lenses available

2.5. Measurement course

The vehicle brakes were heated up to the operational temperature by deceleration repetition [24, 25, 26]. Then, the pedometer sensor was fitted to the brake pedal and its screen was located in the driver's field of view to enable them to see the value of brake pedal force at every moment (Fig. 5).

Fig. 5. Pedometer sensor CORSYS

The brake pedal force at which the deceleration had achieved the parameters calculated was known. After having the operational temperature of brakes [27], the pictures by the thermographic camera were taken and the vehicle was accelerated up to the speed of 103.9 $km.h^{-1}$. Afterwards, using the fifth transmission gear, the driver depressed the brake pedal sharply in that force as had been measured during prescribed deceleration. When the engine had its speed under 900 min^{-1}, the driver depressed the clutch to avoid the engine's switching off. Then, the thermographic camera took the pictures when the wheels were stabilised and the driver again accelerated the vehicle up to the speed of 103.9 $km.h^{-1}$. The whole cycle was repeated 15 times and the time of one cycle was 45 s.

3. RESULTS

Fig. 6 shows the temperatures of measured points before the beginning of the measurement. The temperature is given in °C.

As seen from the comparison of both Figs. 6 and 7, before measuring and after heating, the highest temperature was on the wheel disc, in the area of its nave. After the fifteenth measurement, the highest temperature could be seen in the area of the brake disc.

The tables below show the temperatures of the components' surface after particular measurements. The results from 1^{st} up to 7^{th} measurement are given in Tab. 4, while Tab. 5 shows the measurements from 8^{th} and 15^{th}.

For better transparency, Fig. 8 shows the measurement results in the form of a graph.

As seen from the Fig. 8, the highest growth in temperature, from 41.6°C up to 566.7°C, relates to the surface of the brake disc. Such result is predominantly due to the brake disc's feature of absorbing thermal energy that is converted from kinetic energy and shifting such energy further. The brake pad has the same feature even though it had lower temperatures. This resulted from the measurement methodology since the temperature was measured opposite to the side when there is a connection with the friction area of the brake disc. The same course of temperature can also be seen in the surface of the brake calliper.

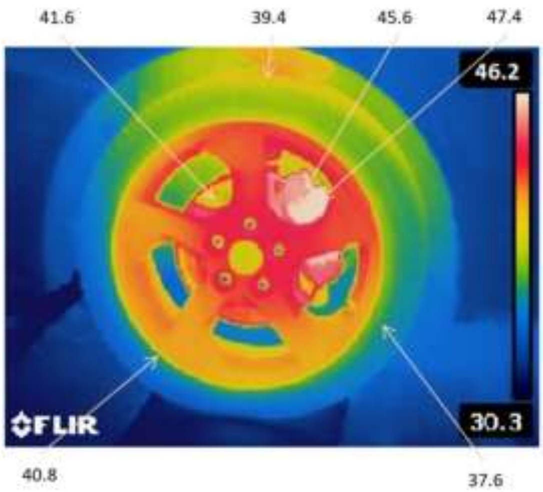

Fig. 6. Initial temperatures

Fig.7 shows the temperatures of particular components after the final (15th) measurement

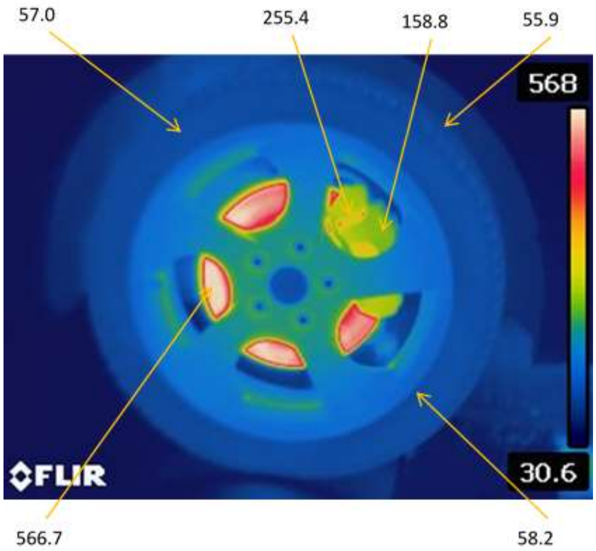

Fig. 7. Temperatures after the final measurement

Tab. 4

Measurement results no. 1-7

Measurement	0	1	2	3	4	5	6	7
Brake disc [°C]	41.6	100.9	149.4	230.2	288.5	301.4	348.1	415.2
Tire tread [°C]	39.4	44.2	45.2	46.9	48.7	50.2	51.4	52.4
Tire side [°C]	37.6	43.1	43.4	43.9	45.8	48.0	48.7	49.8
Rim [°C]	40.8	41.5	41.6	42.8	43.2	45.2	46.5	48.1
Brake pad [°C]	45.6	47.6	57.9	61.5	78.1	96.3	119.9	139.0
Calliper [°C]	47.4	48.8	54.5	59.1	63.1	70.8	86.0	92.1

Tab. 5

Measurement results no. 8-15

Measurement	8	9	10	11	12	13	14	15
Brake disc [°C]	417.3	464.4	512.2	552.5	555.0	557.1	565.1	566.7
Tire tread [°C]	53.2	53.9	54.2	54.6	54.7	55.0	55.3	55.9
Tire side [°C]	50.7	51.3	52.2	52.7	53.2	54.5	55.9	57.0
Rim [°C]	48.7	49.6	52.3	53.7	54.9	55.2	55.7	58.2
Brake pad [°C]	151.3	177.2	192.1	206.7	221.3	227.9	237.1	255.4
Calliper [°C]	99.0	121.9	127.9	132.5	148.8	154.3	158.8	171.1

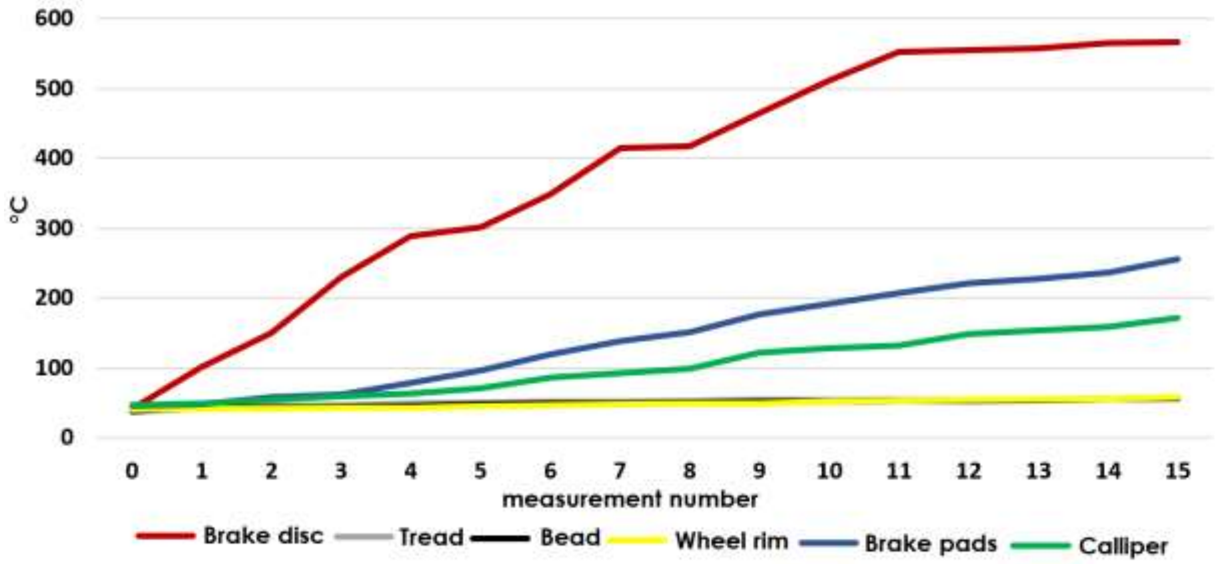

Fig. 8. Measurement results

4. Discussion and Conclusion

While the vehicle is decelerating, its kinetic energy is predominantly converted into thermal energy that leads to significant heating of particular components of the wheel and brake system. Therefore, the parts of the vehicle heated during deceleration must be constructed from high-temperature resistant materials to ensure the vehicle's ability to decelerate.

Using certified brake components reduces the probability of failure in the braking system during natural deceleration.

However, it is necessary to replace brake fluid on a regular basis, since the fluid's boiling point is reduced over time. During the measurements mentioned in this article, the temperature of the calliper was 171°C. It can be presumed that the brake fluid may have a similar temperature. The value measured, thus, highlights the need for regular review of the brake fluid's boiling point, or as the case may be its replacement every 3 years.

Concerning the brake disc temperature, the temperatures measured in the publication [7] were similar to the temperatures measured in this article. In the publication [7], a numerical solution of the heat-friction problem for a brake pad–brake disc system during repeated intermittent braking was obtained using the finite element method. During simulations, the disc's temperature was about 600°C, which is similar to our measurements. However, in our case, there were 15 decelerations made, while in the case [7], there were only 10 with substantially shorter duration of particular braking. Likewise in our measurements, an increase in temperature after exceeding 500°C was significantly less precipitous. Thus, there is an assumption that after reaching a certain temperature in the brake disc and brake pad, the temperature ceases to rise considerably. However, it can also lead to the damage of these brake components by the longer influence of high temperatures. This could correspondingly affect the increase in the temperature of the brake fluid [37].

The brake disc's temperatures of nearly 500°C were also reached during the measurements given in [3]. Through mathematical modelling, there were performed 10 consecutive decelerations during a period of about 150 s.

The brake disc's temperatures of over 500°C were also reached in the publication [36], where during simulations, the decelerations were not repeated but continuous.

Higher temperatures in the brake disc and brake pads, as seen in this research, were also measured in the publication [35], specifically 650°C. In this case, components of trucks' braking system were tested and they are of higher strains.

In the other publications explored [19, 28, 38], there were lower values in temperature measured during measurements. The reason lies in the fact that in most cases, the braking is not repeated as much as 15 times, or the decelerations are not performed at such high driving speeds. Additionally, concerning the high values measured in this article, another reason can demonstrate those as the vehicle decelerated was fully loaded and the braking intensity was fairly high. Since the braking was made until the vehicle stopped, cooling by air flowed was significantly restricted at low speeds.

The temperatures measured had comparably high values, however, not so high as to cause damages in vehicle components. These values highlight the necessity to cover all those features of particular components that are required by the relevant legislation.

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