EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF DECELERATION ON BRAKE ELEMENTS TEMPERATURE IN ORDER TO IMPROVE TRAFFIC SAFETY

by

Bojana M. BOŠKOVIĆ[a*], Nadica R. STOJANOVIĆ[b], Ivan Lj. GRUJIĆ[b], and Saša Z. BABIĆ[a]

[a] Academy of Professional Studies Šumadija, College Trstenik, Trstenik, Serbia
[b] Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia

Original scientific paper
https://doi.org/10.2298/TSCI230925286B

Correct determination of deceleration is very important from the aspect of the investigation of traffic accidents, because deceleration of the vehicle involved in the traffic accident is of key importance for the preparation of a quality finding and opinion of traffic expert. In this paper it was conducted the investigation how the change of the pressure affects the change of the temperature of the brake couple and how this change is later reflected in the deceleration of the vehicle and the braking distance. In order to find how the temperature influences the deceleration, it was conducted experimental investigation. The experimental investigation was conducted on the experimental test rig, which simulates the braking process for the quarter of the vehicle mass, and the experimental investigation was conducted for four different braking pressures: 2 MPa, 3 MPa, 4 MPa, and 5 MPa. The temperature of the brake couple was measured during the entire braking process. Also the difference between mean fully developed deceleration and average vehicle deceleration is shown. It was found that for the case when the braking pressure was 5 MPa, the maximum deceleration value was greater than the value of gravity of Earth which may impair the stability of the vehicle. When the braking pressure was 2 MPa, 3 MPa, and 4 MPa, the temperature increased, respectively, but in the last measurement, when the braking pressure was 5 MPa, it began to decrease. Braking distance decreased with the increment of the braking pressure. Also, with the braking pressure increment, the deceleration increased in all cases.

Key words*: temperature of the brake couple, experimental investigation, mean fully developed deceleration, braking pressure*

Introduction

Motion with constant acceleration was studied in the 14th century and the Merton rule (at Merton College, Oxford), as we know it today, was deduced *An object with constant acceleration travels the same distance as it would have if it had constant velocity equal to the average of its initial and final velocities*.

In the 17th century, Galileo Galilei (1564-1642) and others discovered that, in a void, all falling objects have the same constant acceleration and Newton (1642-1727) and Leibniz (1646-1716) built on these ideas in developing the concept of the derivative. All of the aforementioned are ways how the deceleration can be calculated, which is very important from the aspect of traffic safety.

* Corresponding author, e-mail: bboskovic@asss.edu.rs

Correct determination of deceleration has great importance when traffic accidents are analysed. Traffic experts in real conditions determine several types of deceleration in various ways: the minimum deceleration value, the mean deceleration value, the maximum deceleration value, or deceleration based on the maximum instantaneous force that can be achieved on the technical inspection-line. Correct determination of the deceleration of the vehicle involved in the traffic accident is of key importance for the preparation of a quality finding and opinion of traffic expert. Various influential parameters on the deceleration value can be found in the existing literature. Deceleration is one of the braking parameters that is completely present in many calculations, but there is a small number of authors who investigated how the temperature of the brake couple elements (brake disc and brake pads) influence the vehicle deceleration. It is significant to investigate this subject because the deceleration is in direct connection with the braking distance achieved by the vehicle in accident situations.

The deceleration is crucial from the aspect of the traffic safety. One of the ways to increase the safety is earlier reaction of the vehicle, *i.e.* earlier start of vehicle deceleration, if the braking is necessary, which can be achieved by the use of automated vehicle [1-3]. In this case, the communication between the automated vehicle and pedestrian is crucial to start braking process at the right time, and to achieve deceleration for safe braking [4]. The deceleration depends on the type of the vehicle as well. This is quite important not only from the aspect of the safety but also from the aspect of various applications like length of yellow light at intersection, determination of sight distances at intersection, ramp design, traffic simulation modelling, emission modelling, instantaneous fuel consumption rate modelling, *etc.* [5, 6]. Besides that, if the vehicle is equipped with trailer, it can influence on the braking performances [7]. Also, the deceleration is crucial from the aspect of braking distance. So, in the case of heavy vehicles, it is very important to have adequate deceleration, in order to stop a great kinetic energy of the vehicle. Therefore, the solution is to use the systems which use information about tire-road friction coefficient, and use this information control brake system [8]. Apart from the traffic safety and traffic infrastructure, the deceleration can be crucial from the aspect of the analysis of the traffic accident which already happened [9]. The braking process is quite complex so the efficiency of the braking system along with the deceleration are conditioned by many parameters such are vehicle speed, thermomechanical behaviour of the brake couple, thermal characteristics of the brake couple elements and braking parameters such as the braking pressure [10-15]. At the end, the most important thing is actually the safety of the traffic participants. So, the main role of the brake system is to prevent traffic accidents. Thus, it is important to have the brake system with good braking characteristics [16], and also to have an adequate driver reaction. However, nowadays, the driver reaction can be improved by the use of Advanced Emergency Braking Systems which can be very useful from the aspect of safety [17].

The main aim of this paper is to investigate the influence of the braking pressure on the temperature of brake elements, and how it affects the deceleration as one of main parameters from the aspect of the traffic safety.

Dependence of braking distance on deceleration

The simplest definition of average deceleration is a change of the speed, *i.e.* a decrease of the speed in some time interval:

$$d = \frac{v_{\text{initial}} - v_{\text{final}}}{\Delta t} \tag{1}$$

According to ECE 13 regulation, the performance prescribed for braking systems is based on stopping distance of mean fully developed deceleration (MFDD). The effectiveness of the braking system is determined by measuring the stopping distance in relation the initial speed of the vehicle and/or by measuring the mean full deceleration during the test. According to ECE 13 regulation, the MFDD can be calculated [18]:

$$MFDD = \frac{V_b^2 - V_e^2}{25.92\left(S_e - S_b\right)} \tag{2}$$

The braking distance is the distance travelled by the vehicle from the moment the driver starts to brake, until the moment the vehicle stops. In this process, the initial speed is the speed at the moment when the driver starts to activate the braking system, and it must not be less than 98% of the prescribed speed for the given test.

Braking distance is one of the basic standards for road design and maintenance practices. The braking distance is a part of the stopping distance. Often these two distances are equated, but there is actually a huge difference, and that is the driver. Stopping distance can be calculated:

$$S_s = S_k + S_r \tag{3}$$

In this paper only the braking distance will be calculated, because temperature of the brake is influencing the deceleration, and deceleration is the part of braking distance. Deceleration is an important part of the findings made by experts in the traffic, which is often of crucial importance for defining the oversight of the participants in the traffic accident.

Figure 1 shows the procedure of the conducted experiment. At the beginning, four measurements were made. During these measurements the pressure values in the brake installation were varied.

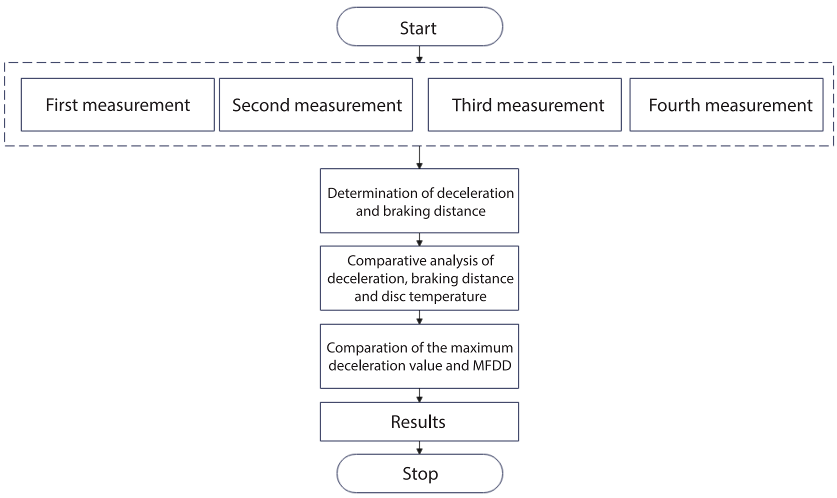

Figure 1. Experiment procedure

The pressure in the brake installation for the 1st, 2nd, 3rd and 4th measurements was 2 MPa, 3 MPa, 4 MPa, and 5 MPa, respectively. For each of these four measurements the mean value was taken. Before each measurement, the temperature of brake couple elements was returned at the initial conditions, which provided for the braking process to start always at almost the same temperature (45.5 °C ±0.5 °C). During each measurement, in parallel with the measurement of the speed, the temperature of the brake couple elements was measured. After the obtained results, the deceleration and braking distance were calculated according to the speed change during the time. The resulting deceleration, *i.e.* its maximum value, was compared with the MFDD.

Experimental research

In the conducted experiments the braking pressure was varied from 2-5 MPa, and the temperature of the brake couple elements was measured during the entire braking process. The experimental investigation was conducted in the inertial dynamometer, which simulates the quarter of the vehicle mass. The scheme of the used experimental installation is shown in fig. 2.

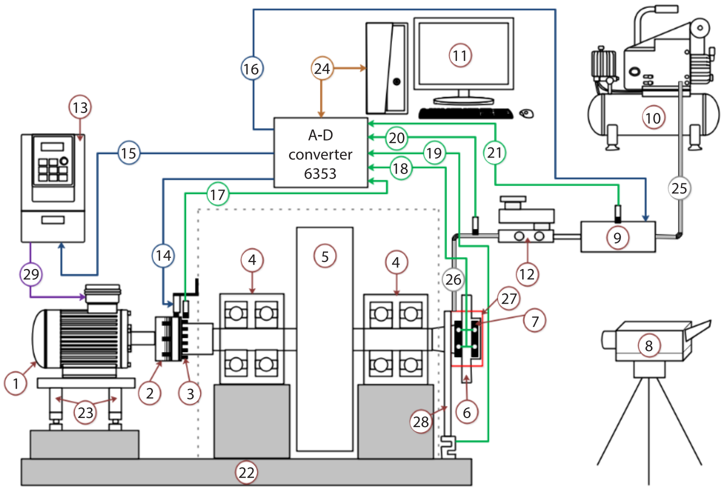

Figure 2. The scheme of the experimental test rig [19]

The test rig simulates the quarter of the vehicle mass, that is it simulates the kinetic energy which quarter of the vehicle mass has in the moment when braking process starts. Main parts of the test rig are driving part, which consists of electric motors – 1 and frequency regulator – 13, flywheel mass – 5, and braking system (brake disc and brake pads – 6, calliper – 27, and hydraulic installation – 12 and 26. The brakes are activated by pneumatic installation – 9. All data are collected by PC – 11, and the control of the test rig is provided by program installed on the PC. The temperature of the brake is measured by thermal imager – 8, while the temperature of brake pads is measured in four points by temperature sensors – 7, which are mounted in the brake pads at 2 mm from the contact surface. The braking pressure is regulated by the pressure in pneumatic installation, while the simulated kinetic energy is adjusted by the rotational velocity of the flywheel mass.

During the first measurement, the pressure in the brake installation was 2 MPa (20 bar), braking started when the speed of the simulated vehicle was 100 km/h, and the braking was conducted until the complete stop, that is, until the speed of the simulated vehicle was 0 km/h. The same procedure was conducted for other three values of the braking pressure.

All four measurements were made separately, they are not consecutive measurements in order to obtain the same previously mentioned initial conditions for each measurement. The complete stop was taken as the experimental parameter in order to simulate dangerous traffic situations, only for different braking pressures.

Based on the obtained data on the drop in speed over time, the actual value of the deceleration was obtained. The braking distance is calculated as the integral of the speed in a certain time interval:

$$S = \int_{t_1}^{t_2} V(t)\,\mathrm{d}t \tag{4}$$

The monitoring of the heat spread over the surface of the brake disc was performed with a thermal imager Testo 868, and the measurement range selected in the settings of the thermal imager, for the purposes of this measurement was from 0-650 °C. This is based on similar research which determined that the expected temperatures were in this range during the braking process.

The experiment was done on the BRAKE DYNO 2020 test rig.

Results and discussion

For the analysis of the correlation between the temperature and the deceleration, it was taken the highest value of the temperature measured during each test. In all cases, this was the temperature measured on the entering part of the external brake pad. The reason why the temperature on the entering part of the external brake pad is the highest, is so-called umbrella effect [20], that is, the disc tends to bend to the external side, which loads more the external brake pad than the internal one. Also, the entering side of the brake pad is the side which first enters in contact with the rotating brake disc.

Figures 3-6 show results for the deceleration, braking distance and temperature when the pressure in the brake installation was 2 MPa, 3 MPa, 4 MPa, and 5 MPa, respectively, while the values for the maximum deceleration and MFDD are given in tab. 1.

The values of the average deceleration and the braking distance were calculated according to eqs. (1) and (4).

In the first measurement when braking from 100 km/h to 0 km/h (complete stop) while the braking pressure was 2 MPa, the disc needed 8.25 seconds to stop, had a braking distance of 132.2 m, while the maximum temperature was 45.9 °C. The maximum established deceleration in the first measurement was 4.2 m/s^2.

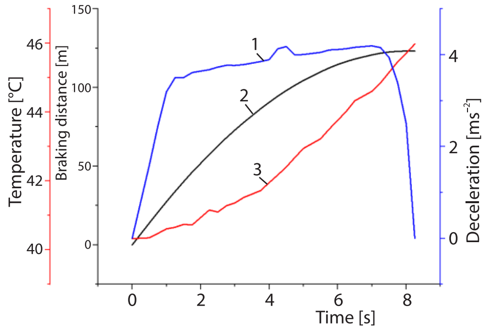

Figure 3. The deceleration – 1, braking distance – 2, and temperature – 3, for the braking pressure of 2 Mpa

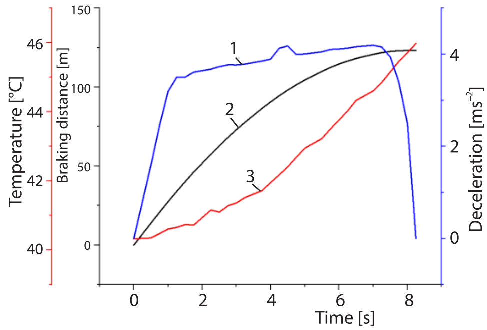

Figure 4. The deceleration – 1, braking distance – 2, and temperature – 3, for the braking pressure of 3 MPa

For the second measurement, under the same conditions (constant braking from 100 km/h to 0 km/h) with a braking pressure of 3 MPa, it was obtained that the time needed

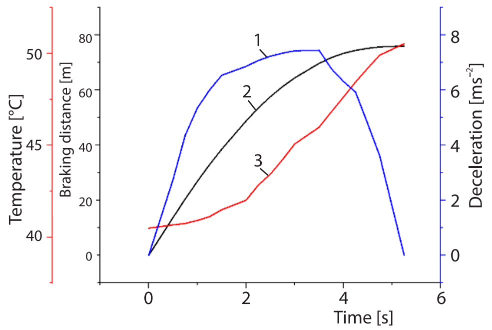

Figure 5. The deceleration – 1, braking distance – 2, and temperature – 3, for the braking pressure of 4 MPa

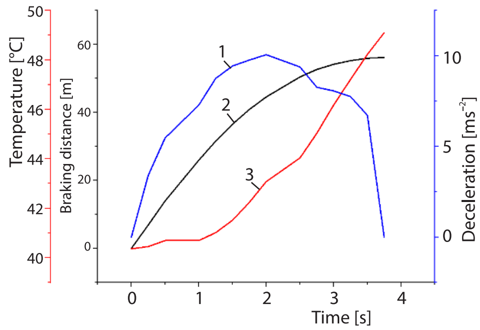

Figure 6. The deceleration – 1, braking distance – 2, and temperature – 3, for the braking pressure of 5 MPa

Table 1. Difference between maximum deceleration value, average deceleration value and MFDD for four measurements

	Max deceleration [ms^{-2}]	MFDD [ms^{-2}]	Difference [%]
1st measurement	4.2	3.2	23.8
2nd measurement	6.5	4.7	27.7
3rd measurement	7.4	5.1	31.1
4th measurement	10.1	6.8	32.7

to completely stop the disc is 6 seconds (which is 27.3% shorter compared to the first measurement when the pressure in the brake installation was 2 MPa). The braking distance in the second measurement was 82.5 m, and the maximum temperature was 49.2 °C. The maximum deceleration value during the second measurement was 6.5 ms^{-2}.

The third measurement was carried out like the previous two, while the braking pressure was 4 MPa. The time required for the disc to come to a complete stop under these conditions was 5.25 seconds. The braking distance in the third measurement was 76 m, while the maximum temperature was 50.5 °C. The maximum value of the deceleration during the third measurement was 7.4 m/s^2.

In the fourth measurement, braking was also initiated from 100 km/h to 0 km/h, where the braking pressure was 5 MPa. The time required to completely stop the disc was 3.75 seconds. The braking distance under these conditions was 56.2 m. The highest measured temperature was the temperature at the end of the measurement and it was 49.1°C, which is approximately close to the temperature obtained for the third measurement. The maximum deceleration value during the fourth measurement was 10.1 m/s^2. As the value of the maximum deceleration is 10.1 m/s^2 (greater than the acceleration of the gravity of Earth which is 9.81 m/s^2) it can be concluded that these braking conditions can lead to the loss of the vehicle stability.

For all four measurements, the maximum measured temperature was the temperature measured at the moment when the disc completely stops.

As different adopted deceleration values (maximum, minimum, mean, MFDD) can be found in the literature when it comes to experimental research, a comparison was made between the maximum adopted deceleration value (the one that is most often taken as a reference value during technical inspections of a vehicle) and the MFDD value calculated by eq. (2), which is defined by ECE 13 regulation [18], shown in fig. 6. It can be concluded that with the increase in pressure in the brake installation, the difference between the maximum values of deceleration and the MFDD also increases. Error between maximum deceleration value and MFDD increased by each subsequent measurement as shown in tab. 1.

If the changes of temperature are observed, it can be seen that the greatest temperature rise happens exactly after the achievement of the maximum deceleration. Also, after the achievement of the maximum deceleration, the change of the braking distances decreases. All this happens due to the stable friction coefficient, that is, at the moment of the maximum deceleration achievement, braking pressure stays constant, until the end of the braking process. More accurately, it takes some time for the braking pressure to achieve defined value, which corresponds to the behaviour of the driver, and brake system installation during the braking. The comparison of average deceleration and MFDD**,** for the braking pressures 2 MPa, 3 MPa, 4 MPa, and 5 MPa, is shown in figs. 7-10.

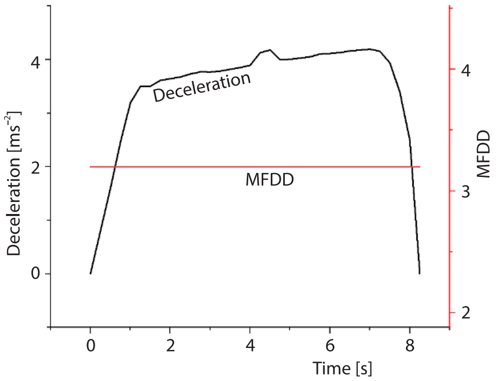

Figure 7. The comparison of average deceleration and MFDD, for the braking pressure of 2 MPa

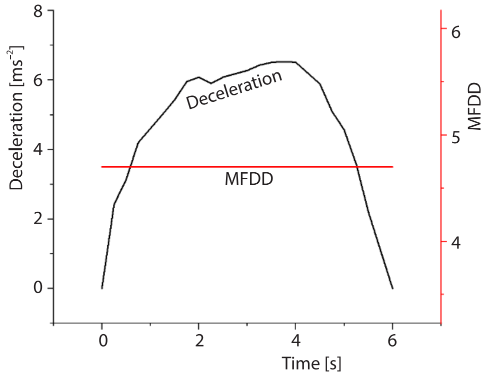

Figure 8. The comparison of average deceleration and MFDD, for the braking pressure of 3 MPa

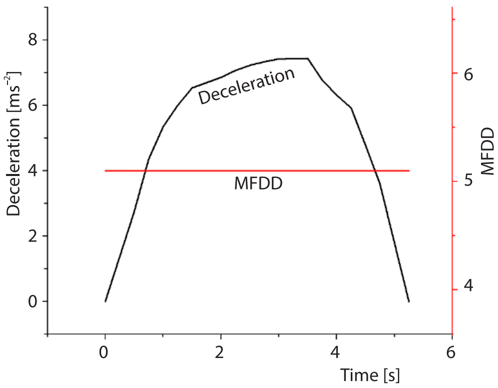

Figure 9. The comparison of average deceleration and MFDD, for the braking pressure of 4 MPa

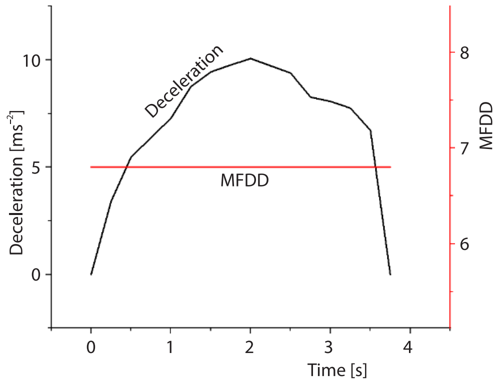

Figure 10. The comparison of average deceleration and MFDD, for the braking pressure of 5 MPa

The obtained results are quite logical from the aspect of braking pressure. That is, with the increment of the pressure the value of deceleration rises, which leads to the shorter braking distance. With the pressure increment the temperature also rises. The deceleration was higher although the temperature rose, which means that the friction coefficient did not decrease. This happened due to the fact that the temperature did not reach the level which affects the friction coefficient decrease. Otherwise, the temperature would cause the increase of the friction coefficient. The same conclusion was reached in [19, 21]. This means that the temperature of the brake couple elements did not reach the critical levels which can cause the fade of the braking performances. More accurately, the friction coefficient rises until the temperature reaches value around 150 °C [21], and after that friction coefficient starts to fall.

Conclusions

It can be concluded that it is necessary to think carefully which deceleration value to adopt, because the errors that occurred between the maximum deceleration value and the MFDD are not negligible. With the increase of the braking pressure, there was also an increase of the temperatures. The increment of the braking pressure as well as of the brake couple elements temperature caused the reduction of the braking distance. Therefore, deceleration increment was accompanied by the pressure increment. This indicates the good and stable friction coefficient, due to the non-critical temperatures, which was proven by other researchers.

In the fourth measurement (when the pressure in the brake installation was 5 MPa), the maximum deceleration value was 10.1 m/s^2, which may lead to a disturbance of the vehicle stability (value greater than gravity of Earth). It can be concluded that the braking pressure values less than 5 MPa are acceptable from the aspect of stability. However, with the reduction of pressure in the brake installation, the braking distance extends, which is extremely unfavourable from the aspect of safety.

In this experimental research, four individual measurements were involved, which simulated dangerous traffic situations that are unexpected. In further research, it is necessary to investigate how the temperature of the brakes changes when it comes to measurements with successive repetitions.

It is important to deal with this subject, because the correct determination of the deceleration of the vehicle involved in the traffic accident is of crucial importance for the preparation of a quality finding and opinion of traffic expert, which can help to avoid further traffic accidents.

Nomenclature

d – average deceleration, [ms^{-2}]
MFDD – mean fully developed deceleration, [ms^{-2}]
S_b – distance travelled between V_0 and V_b, [m]
S_r – drivers reaction distance, [m]
S_e – distance travelled between V_0 and V_e, [m]
S_k – braking distance [m]
S_s – stopping distance [m]
V_b – vehicle speed at 0.8 V_0, [kmh^{-1}]
V_e – vehicle speed at 0.1 V_0, [kmh^{-1}]
v_{final} – final speed, [ms^{-1}]
v_{initial} – initial speed, [ms^{-1}]

References

[1] Ackermann, C., *et al.*, Deceleration Parameters and Their Applicability as Informal Communication Signal between Pedestrians and Automated Vehicles, Transportation Research – Part F: Traffic Psychology *and Behaviour*, *62* (2019), Apr., pp. 757-768
[2] de Clercq, K., *et al.*, External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions, *Human Factors*, *61* (2019), 8, pp. 1353-1370
[3] Dey, D., *et al*., Communicating the Intention of an Automated Vehicle to Pedestrians: The Contributions of eHMI and Vehicle Behavior, *Information Technology*, *63* (2021), 2, pp. 123-141
[4] Tian, K., *et al.*, *Braking Behavior of Automated Vehicles as Critical Implicit Communication for Pedestrians' Vehicle Behavior Estimation and Road Crossing*, Accident Analysis and Prevention, SheRPa, On-line first, https://doi.org/10.31234/osf.io/234k8, 2024

[5] Akhilesh, K. M., Study of Deceleration Behaviour of Different Vehicle Types, *International Journal for Traffic and Transport Engineering*, *2* (2012), 3, pp. 253-270
[6] Bokare, P. S., Maurya, A. K., Acceleration-Deceleration Behaviour of Various Vehicle Types, *Transportation Research Procedia*, *25* (2017), July, pp. 4737-4753
[7] Marienkaa, P., *et al.*, Comparison of Braking Characteristics of Solo Vehicle and Selected Types of Vehicle Combinations, LOGI 2019 – Horizons of Autonomous Mobility in Europe, *Transportation Research Procedia*, *44* (2020), 4, pp. 40-46
[8] Kalakos, D., Westerhof, B., Heavy Vehicle Braking using Friction Estimation for Controller Optimization, M. Sc. thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2017
[9] Kolla, E., Characteristics of the Specified Modern Electric Vehicle During Intensive Braking, *Advances in Science and Technology Research Journal*, *14* (2020), 3, pp. 125-134
[10] Labuda, R., *et al.*, Vehicle Braking Parameters Influencing Factors, *Journal of KONES Powertrain and Transport*, *4* (2009), 16, 256
[11] Belhocine, A., Bouchetara, M., Thermomechanical Behaviour of Dry Contacts in Disc Brake Rotor with a Grey Cast Iron Composition, *Thermal Science*, *17* (2013), 2, pp. 599-609
[12] Milenkovic, P., *et al*., The Influence of Brake Pads Thermal Conductivity on Passenger Car Brake System Efficiency, *Thermal Science*, *14* (2010), Suppl., pp. S221-S230
[13] Viderščak, D., *et al*., Influence of Brake Pad Properties to Braking Characteristics, *Promet – Traffic and Transportation*, *34* (2022), 1, pp. 91-102
[14] Vrabel, J., *et al*., The Quality of the Brake Components and its Impact on the Basic Parameters of Braking, *Machines, Technologies, Materials*, *2* (2014), 6, pp. 28-30
[15] Stojanović, N. R., *et al*., Pressure Influence on Heating of Ventilating Disc Brakes for Passenger Cars, *Thermal Science*, *24* (2020), 1A, pp. 203-214
[16] Samsona, J. R., *et al.*, Analysis of Stopping Sight Distance (SSD) Parameters: A Review Study, *Procedia Computer Science*, *201* (2022), May, pp. 126-133
[17] Papis, M., Matyjewski, M., Assessment of the Influence of the Advanced Emergency Braking Systems on Pedestrian Safety, *The Archives of Automotive Engineering – Archiwum Motoryzacji*, *3* (2017), 77, pp. 97-109
[18] ***, UN Regulation No 13-H – Uniform Provisions Concerning the Approval of Passenger Cars with Regard to Braking 2023/401, Official Journal of the European Union, 2023
[19] Stojanović, N., Identification of Disc Brake Thermal Strains for Different Braking Operating Parameters, Ph. D. thesis, University of Kragujevac, Kragujevac, Serbia, 202.
[20] Jassim, M., *et al*., An Investigation into the Behaviour of Disc Blake Wear, *Al-Khwarizmi Engineering Journal*, *3* (2007), 2, pp. 49-66
[21] Ahmed, I., *et al*., *Experimental Investigations of Disc Brake Friction*, SAE Technical Paper, 2000-01-2778, 2000

Paper submitted: September 25, 2023
Paper revised: November 13, 2023
Paper accepted: November 15, 2023