EB2022-TSD-012

OVERVIEW OF TESTS AND DRIVING CYCLES CONDUCTED ON AN INERTIAL BRAKE DYNAMOMETER IN THE TESTING OF PARTICLES FORMED DURING BRAKE WEAR

Saša Vasiljević[1] *, Jasna Glišović [2], Jovanka Lukić[2], Nadica Stojanović[2], Ivan Grujić[2]

[1]Academy of Professional Studies Šumadija, Department in Kragujevac
Kosovska 8, 34000 Kragujevac, Serbia (E-mail: vailjevic.sasa036@gmail.com)
[2]University of Kragujevac, Faculty of Engineering
Sestre Janjić 6, 34000, Kragujevac, Serbia

DOI (FISITA USE ONLY)

ABSTRACT: The analysis of the braking system from the aspect of ecology is becoming an important topic today, bearing in mind that there is environmental pollution by particles that occur during the wear of the brake pairs. The use of an inertial brake dynamometer is one of the methods used in measuring the concentration of formed particles. Overview and analysis of tests applied by various authors in the research of particle formation during braking in laboratory conditions on inertial brake dynamometers is presented in this paper. Today, the driving cycles prescribed for this area have not yet been defined in Europe, so the analysis of numerous tests used in this area in the dynamometer tests has been conducted. UNECE (United Nations Economic Commission for Europe) will develop global methodology for measuring particle emissions from vehicles' braking systems. New steps are being taken to achieve this thanks to the World Forum for Harmonization of Vehicle Regulations' Working Party on Pollution and Energy (GRPE), which has initiated activities to develop a rigorous test procedure to measure brake particle emissions under standardized conditions. The problem of the non-existence of a standard defined test for measuring brake particles has inspired the authors to research that could lead to significant conclusions that are the best test could be used in this area. The analysis performed in this paper is mainly based on an overview of varied braking parameters, minimum and maximum parameter's values, number of braking events, etc. This study is important for future researchers in this field in terms of selecting cycles or the relevant braking parameters that have the greatest impact on the formation of particles (their mass and concentration) when braking a vehicle.

KEY WORDS: wear, braking, particles, tests, driving, cycles.

1. INTRODUCTION

Non-exhaust particulate emissions can be considered one of the newly identified problems faced by the modern automotive industry. The problem of reducing vehicle engine emissions has been successfully implemented, which has been achieved through the application of Euro standards, with an addition to modern exhaust gas purification systems. Furthermore, the emission from the propulsion unit was reduced by the application of hybrid vehicle propulsion, as well as the application of electric vehicles. However, non-exhaust particulate emissions have been identified, the source of which, among other systems on the vehicle, is the braking system. It is predicted that the brakes and tires will be one of the main sources of particles on the vehicle. When it comes to brakes, the most common research is related to PM_{10} and $PM_{2.5}$ emission tests. Particles formed by the wear of friction pairs can contain various materials that can be harmful to humans and the environment [1,2].

Brake wear testing is most often performed using an inertial brake dynamometer, pin on disc tribometer, using computer simulations or road tests. Although it is a laboratory method, the application of an inertial dynamometer can provide the same or the closest results to those obtained by road tests. The reason for this is that real friction pairs are used like those used on real vehicles.

Different driving cycles or tests are used to measure the brake's emission. Today, there is still no legally defined test that would be used to investigate brakes in terms of formation of particles from brake wear. The researchers use various existing driving tests that are not prescribed to test the formation of particles, but some have been adapted by the authors. Some tests used in the research were designed and proposed by the authors.

The aim of this paper is to review the cycles and tests that have been applied in research on the formation of particles during braking i.e. wear of friction pairs. Based on the analysis of applied driving cycles and tests, future researchers could choose a driving cycle, that would suit them or based on existing driving cycles they could develop their own driving cycle or test.

2. BRAKE DYNAMOMETERS, DRIVING CYCLES AND TESTS

Inertial brake dynamometers are devices used to test brakes in laboratory conditions. By their construction, dynamometers are closest to real vehicles, bearing in mind that real friction pairs (brake pads and rotor-disc) are used, such as those on vehicles. Bearing in mind that the tests are performed in laboratory conditions, this type of test in relation to real tests allows measurement in completely controlled conditions. Furthermore, the use of an inertial braking dynamometer also makes it easier to monitor and measure the impact of various parameters, but also make it possible to adjust different braking parameters. Inertial brake dynamometers can also be adapted for different tests, so they can be adapted for particle measurement. Brake dynamometer developed at the Faculty of Engineering, University of Kragujevac, shown in Figure 1, is adapted for measuring the concentration of particles formed during braking. The detailed construction of BrakeDyno 2020 is described in reference Stojanović, 2022 [3].

Figure 1 BrakeDyno2020 at the Faculty of Engineering, University of Kragujevac

In order to perform the measurement, it is necessary first to define what is the goal and subject of the research and the method used. In order to be able to compare the obtained results of different researches, the prescribed driving cycles or tests are applied. Driving cycles, at least when it comes to testing brakes, and those that are legally prescribed, are generally characterized by the fact that some of the braking parameters are prescribed. Based on the prescribed driving cycles, several tests can be performed under the same conditions and under the same values of the braking parameters. In this way, uniform testing is achieved where the obtained values can be compared with other laboratories or different braking elements can be tested, and the obtained results can be evaluated. In addition to braking cycles, there are various driving cycles, among which various European standardized braking cycles, Japanese driving cycles, American driving cycles are well known. It is important to note that when it comes to driving cycles related to the emission of particles caused by brake wear, they are not prescribed at the time of writing this paper. That why many researchers use driving cycles that mainly aim to study other phenomena. But it is evidently striving to prescribe driving cycles and methodology in this area by the UNECE (United Nations Economic Commission for Europe). Working Group on Pollution and Energy of the World Vehicle Harmonization Forum (GRPE) has launched activities to develop a rigorous test procedure for measurement emissions of brake particles under standardized conditions [4].

In addition to prescribed tests or cycles, there are also tests that are formed by researchers. Thus, in some cases, based on their own knowledge or other research, some authors decide to form their own test for testing brakes. Thus, in this case as well, for the testing of the formed particles in some researches, tests were formed by these authors as a proposal for the future prescribed tests of the formation of brake wear particles or for their own research. This paper will enable researchers to form tests based on a review of applied tests and driving cycles, and thus to see the applied braking parameters.

3. REVIEW AND ANALYSIS OF APPLIED DRIVING CYCLES AND TESTS

In driving cycle analysis, Woo et al. [5] compared particulate emissions using five different driving cycles that are well-known in the field of motor vehicles. By presenting the obtained results, it is noticeable that different results can be obtained, so this review paper is important for selecting the appropriate driving cycle in the research.

In previous paper on EuroBrake, Almirall and Cabre [6] have analyzed some brake cycles used for testing in the automotive industry and worldwide, e.g. in Europe, the United States and China. The paper presents two representative driving tests from Europe and China, while one is presented from US. The tests shown in Figure 2, which are used in China are Yellow Mountain and Shanghai, in Europe, they are Mojacar and Barcelona, while the test from the United States is the Los Angeles test. The minimum speed on the tests is 20 km/h, while the maximum speed is 120 km/h, and depending on the driving cycle, these values differ. Speeds and decelerations per the braking cycle are shown in Figures 2 and 3. Average speeds per test are: Yellow Mountain 42 km/h, Shanghai 42 km/h, Mojacar 61 km/h, Barcelona 39 km/h, Los Angeles 39 km/h. It can also be noticed that the value of deceleration ranges from 0.5 m/s^2 to 4 m/s^2.

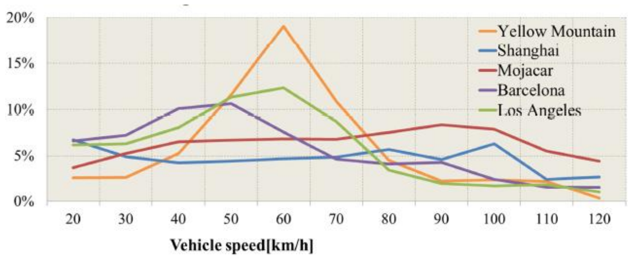

Figure 2 Percentage share of individual speeds in different driving cycles [6]

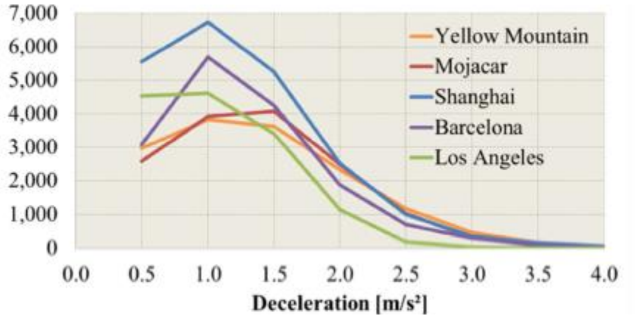

Figure 3 Number of brakes (stops) with different decelerations per driving cycle [6]

The two driving cycles used in the automotive industry are the Worldwide Harmonized Light Vehicle Test Procedure (better known as WTPL) and The New European Driving Cycle (better known as NEDC) [7]. Figures 4a and 4b graphically show these two cycles, i.e. the appearance of these procedures. In the case of NEDC, the maximum variable speed is 120 km/h, and the average speed is 34 km/h. The maximum deceleration in the case of the NEDC cycle is 1.04 m/s^2, while the average deceleration is 0.5 m/s^2. In the case of the WLTP test, the maximum speed is 131 km/h, i.e. the specific values of the speeds that are varied are 56.5 km/h, 76.6 km/h, 97.4 km/h and 131.3 km/h. The maximum deceleration in the case of WTLP is 1.58 m/s^2, while the value of the average deceleration is 0.39 m/s^2.

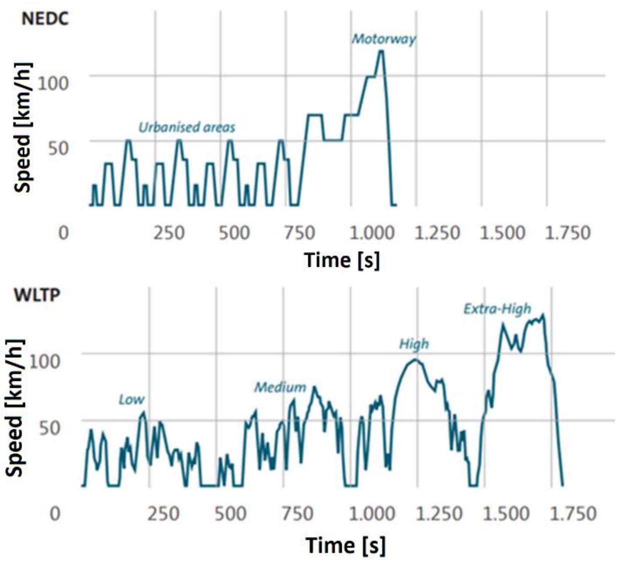

Figure 4 Graphical representation of driving speed versus test duration where: a) NEDC b) WTLP [7]

Hesse et al. have in research [8] applied WTPL, which has been modified and applied for testing brakes, better known as the WTPL brake cycle. This test is performed so that there are 310 brakes according to [9], while according to [10], there are 303 brakes. In the case of this test, vehicle speed and vehicle deceleration vary. Speed varied in the range of 40 km/h to 130 km/h. The deceleration varied in the range of 0.5 m/s^2 to 2 m/s^2. Also, in the research [11], the WLTP-Brake test driving cycle was applied, with the average deceleration being 0.9 m/s^2 or 2.2 m/s^2; the average speed is 42 km/h and the maximum speed is 132 km/h, and 303 brakes were performed. The cycle generally lasts 6 hours, and ten trips are performed. Figure 5 shows a graphical representation of this driving cycle

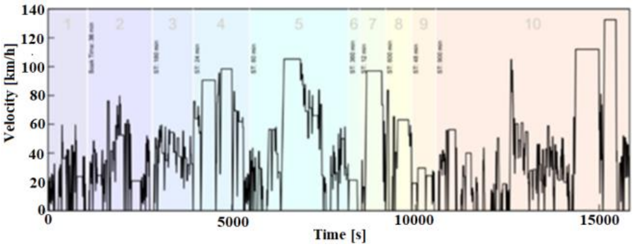

Figure 5 Graphic representation of Worldwide Harmonised Light Vehicle Test Procedure - Brake test driving cycle [12]

One of the tests that are often used in the brake wear and the particle emission research during braking is the test carried out under the SAE J2522 standard, namely the AK-master test. Based on the SAE J2522 standard, the velocity/pressure test, i.e. chapters 6.4.1 to 6.4.5 of the standard, are most often used for the analysis of particulate emissions. Table 1 shows the values of the parameters that vary, i.e. the specifically prescribed values of the initial speed, final speed and brake pressure. The braking pressure varies for each initial and final speed value.

Table 1 Brake parameters of SAE J2522, AK-Master test [13,14]

	Initial speed (km/h)	Final speed (km/h)	Brake pressure (bar)
4.1	40	5	10, 20, 30, 40, 50, 60, 70, 80
4.2	80	40	
4.3	120	80	
4.4	160	130	
4.5	200	70	

Furthermore, one of the tests that are conducted based on the standard is the test according to the SAE standard J2707 method B, known as Block Wear Evaluation. The cycle is divided into several tests or blocks in which the speeds of both initial and final speeds, initial conditions and deceleration are varied. Table 2 shows the values that varied in the braking cycle according to the blocks. The braking blocks are divided into run-in test (BT), urban road (UR), rural road (RR), highway (HR) and downhill (DH).

Table 2 Brake parameters of Block Wear Evaluation test [15]

	Initial speed (km/h)	Final speed (km/h)	Disc temperature (°C)	Deceleration (g)	Number of stops
BT	50	4	100	0,25	50
UR 1	50	4	150	0,25	20
HR 1	150	80	150	0,4	10
RR 1	80	4	200	0,35	20
RR 2	100	4	125	0,4	20
HR 2	180	80	100	0,5	5
UR 2	50	4	150	0,25	20
RR 3	100	4	125	0,4	20
DH	80	4	350	0,35	5

Perricone et al., in the driving cycle used in [16], have carried out the variation of parameters: initial and final speed, initial disc temperature and deceleration. Table 3 shows the varied parameters, which are divided into several tests, i.e. according to the category of the road.

Table 3 Test brake parameters [16]

	Initial speed (km/h)	Final speed (km/h)	Disc temperature (°C)	Deceleration (g)	Number of stops
BT	50	4	100	0,25	100
UR 1	50	4	150	0,25	20
RR 1	80	4	200	0,35	20
RR 2	100	4	125	0,4	20
UR 2	50	4	150	0,25	20
RR 3	100	4	125	0,4	20

Similar to the AK-Master test in reference [17], the braking speeds were varied and the pressures in the braking system were varied for each speed. The test consists of different blocks in which there are different number of brake activations (200 to 1000) at the same initial temperature (150°C), different pressure values (10 bar to 50 bar) and different initial speeds (60 km/h to 180 km/h). Table 4 shows the braking parameters values as well as the number of stops depending on the number of brakes. When analyzing the noise generated by braking in the study [18], the pressure values are 0.25 MPa (2.5 bar), 0.50 MPa, 1 MPa and 1.5 MPa (15 bar). In the study [19], the pressure also varied, and the values were 5 bar, 10 bar and 15 bar at a constant disc speed of 135 rpm.

Table 4 Brake parameters in reference [17]

Number of test	Number of stops	Initial speed (km/h)	Final speed (km/h)	Brake pressure (bar)
1	1000	60	3	10, 20, 30, 40, 50
2	1000	80	53	
3	1000	100	80	
4	500	120	104	
5	500	140	126	
6	500	160	148	
7	200	180	170	

One of the tests used in the study [20] is 3h-LACT (Los Angeles City Traffic). This cycle was also applied in the LOWBRASYS project, according to reference [21], where an abbreviated version of this test was conducted. An abbreviated version of this test was also applied in the research [22]. Based on the previous reference a graphical representation of this test is shown in Figure 5, as well as an abbreviated version, i.e. the part that was used in the mentioned research. The maximum speed value in this test is 154.33 km/h, the minimum speed value is 16.90 km/h, while the average speed value is 53.79 km/h according to [22], while according to [15] the average speed value is 49 km/h. During the test, 217 brakes were performed [21], and the simulated distance was 147.8 km.

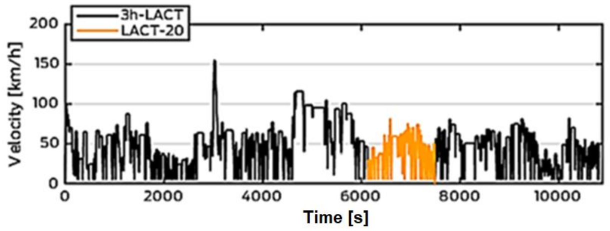

Figure 5 Graphical representation 3h-LACT i LACT-20 [22]

FTP-75 (Federal Test Procedure) is another driving cycle that can be used to test brake wear and particle formation. It is important to note that this is one of the tests from the United States. Based on [23, 24], data were obtained that the maximum speed in this case is 91.25 km/h, while the value of the average speed is 34.12 km/h, the length of the simulated trip is 17.77 km, and the cycle duration is 1877 s. Some of the maximum speed values that are reached are 36.86 km/h, 49.57 km/h, 51.82 km/h, 76.44 km/h and 91.25 km/h. Figure 6 is a graphical representation of this test.

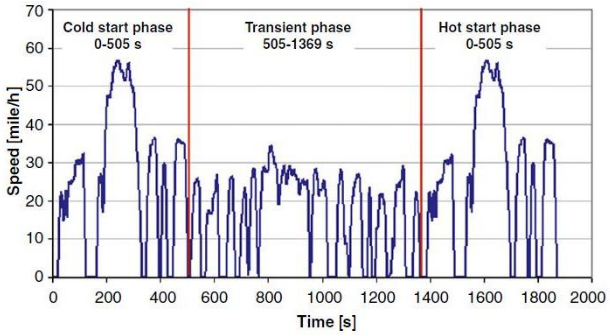

Figure 6 Graphical representation of FTP-75 [25]

Sanders et al. [26] used two different tests: UDP (Urban Dynamometer Program) and the second test is a braking simulation according to AMS (Auto Motor und Sport magazine). In the case of UDP, initial braking speeds, deceleration and initial brake temperature were varied. Initial braking speeds are in the range from 37 km/h to 89 km/h. The deceleration in this case varied from 0.6 m/s^2 to 1.6 m/s^2. The initial brake temperature depends on which vehicle the research refers to, but for passenger vehicles, it ranged from 54°C to 177°C. Twenty-four different combinations of parameters were performed in the test, and each variation had 41 stops. The AMS test consisted of a total of 10 repetitions of braking with a deceleration of 0.8g from an initial speed of 100 km/h, and the test was repeated 3 times, i.e. a total of 30 braking.

In some studies, Japanese driving cycles have been used for research particulate emissions, as in [27]. The tests JC05 and JE08 used to measure the exhaust gas emissions were used. The JC05 test is used to test the emissions of passenger vehicles, while the JC08 test is used for emissions of diesel trucks; both cycles are cycles for urban tests. The maximum speed in the case of the JC08 test is 81.6 km/h, while for the JE05 test, the maximum speed is 87.6 km/h. According to [28], the average speed of the JE05 test is 26.94 km/h, and the duration of one cycle is 1800 seconds. The test duration in the study for the JS08 test, was 1230 seconds. The total number of stops is 50 per one brake. Figures 7a and 7b show graphical representations of these tests.

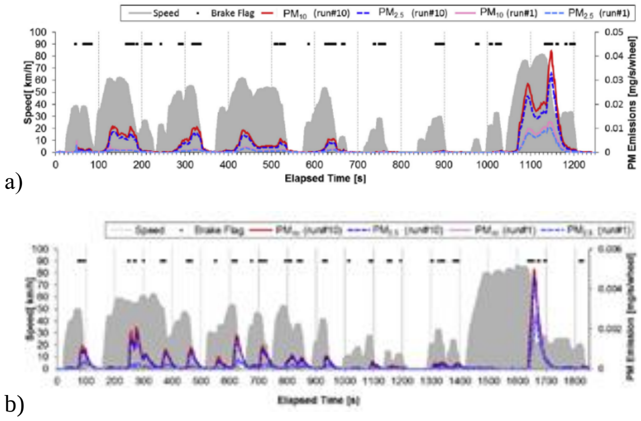

Figure 7 Japanese driving tests, a) JC08, б) JE05 [27]

Hagino et al. [29] varied the speed and deceleration of the vehicle on an inertial brake dynamometer in a test developed by the authors. The speed values applied in this case were 20 km/h, 40 km/h, and 60 km/h, while the deceleration values were 0.5 m/s^2, 1.0 m/s^2, 1.5 m/s^2, and 3.0 m/s^2. An example of the measurement of PM_{10} particles according to the varied parameters is shown in Figure 8. In this case, the release of particles during re-acceleration of the vehicle was also examined.

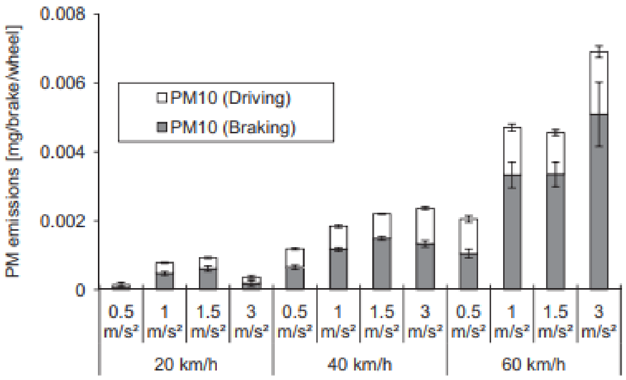

Figure 8 Influence of varied parameters during measurement of PM_{10} particle emission [29]

Similar to previous research, Iijima et al. [30] during the research also investigated the influence of particle formation by varying the vehicle speed and deceleration during braking for three different brake pads. Table 5 shows the combinations of parameters that varied during the research. The three simulated speeds are 40 km/h, 50 km/h and 60 km/h, and the deceleration values are 1.0 m/s^2, 2.0 m/s^2 and 3.0 m/s^2.

Table 5 Test brake parameters [30]

Brake pad number	Initial speed (km/h)	Deceleration (m/s^2)	Number of stops
1.	60	3.0	15
1.	60	2.0	15
1.	60	1.0	15
1.	50	3.0	20
1.	50	2.0	20
1.	50	1.0	20
1.	40	3.0	30
1.	40	2.0	30
1.	40	1.0	30
2.	60	2.0	15
2.	50	2.0	20
2.	40	2.0	30
3.	60	2.0	15
3.	50	2.0	20
3.	40	2.0	30

Based on the road test [32], a cycle was made in [31], in which various parameters such as specific braking power (SBE), initial and final speeds and deceleration were varied. Table 6 shows the applied parameters, however, it is important to say that the deceleration values in this study is from 0.16 m/s^2 to 0.31 m/s^2 and depending on the initial speeds which are 36 km/h, 52 km/h, 57 km/h, 70 km/h and 79 km/h.

Table 6 Brake test parameters [31,32]

SBP (J/kg)	Initial speed (km/h)	Final speed (km/h)	Disc temperature (ºC)	Decele-ration (g)	Num. of stops
25	36	26	70	0.16	2
	36	26	90	0.16	18
	36	26	110	0.16	83
	36	26	130	0.16	56
	36	26	150	0.16	24
	36	26	170	0.16	8
75	52	28	70	0.23	5
	52	28	90	0.23	16
	52	28	110	0.23	22
	52	28	130	0.23	25
	52	28	150	0.23	12
	52	28	170	0.23	8
125	57	5	70	0.25	2
	57	5	90	0.25	3
	57	5	110	0,25	6
	57	5	130	0,25	8
	57	5	150	0,25	1
175	70	17	110	0,31	1
	70	17	130	0,31	2
	70	17	170	0,31	1
225	79	20	110	0,24	1

An interesting test was performed by Niemann et al. [33] where it is specific that, in addition to other parameters, the braking torque is also varied. In the test, four speeds of 50 km/h, 74 km/h, 98 km/h and 123 km/h were applied. Braking torque in this study depended on speed. The braking torque had values of 1120 Nm (for a speed of 50 km/h), 753 Nm, 568 Nm and 455 Nm (for a speed of 123 km/h). 350 stops were made in the measurement.

In the research [34] a test was conducted in 5 cycles of 500 braking at speeds from 60 km/h to 0 km/h. Braking was performed with a constant deceleration of 2 m/s^2. Each cycle has a constant temperature at the beginning of braking, the first at 100°C, the second at 200°C, the third at 300°C, the fourth at 400°C and the fifth again at 100°C. The purpose of repeating the cycle at 100ºC is to check whether the wear is repeated, even after exposure to high temperatures.

Two tests were performed in the research [35], namely variations of contact pressure between the contact surface of friction pairs and velocities. During the speed variation test, the pressure between the friction pairs was always 2.44 N/mm^2 (24.4 bar), while the varied speed values were 19.8 km/h (136 stops), 62.6 km/h (44 stops) and 153.4 km/h (18 stops). In the case of pressure variations between friction pairs, the disc speed was always 62.6 km/h, while the variations in pressure values were 0.54 N/mm^2 (5.4 bar) and 2.44 N/mm^2 (24.4 bar), a total 44 stops were performed.

4. CONCLUSION

The importance of studying brake wear and particle formation is of great importance for reducing the emission of generated particles that tend to be one of the leading environment polluters whose sources are vehicles. One of the ways to test the brakes is to use an inertial brake dynamometer, which provides the results closest to those that would be obtained in real conditions.

Today, different driving cycles are used to test the formation of particles during braking. For now, there is no standardized methodology for conducting the test. Therefore, the authors use driving cycles that are intended for some other tests or develop their own driving cycles, i.e. tests.

Based on a review of various studies in which the measurement of particles formed during braking was mainly performed, it can be concluded that parameters such as initial brake disc temperatures, initial speeds and final speeds, deceleration or pressure in the braking system varied. When it comes to final speeds, in some studies, depending on the initial speed, final speeds are defined, which are often higher than 0 km/h, i.e. there is no complete stopping of the rotor. In some cases, however, the final speed is equal to the speed of complete stop of the rotor. Also, when it comes to the defined braking cycles, in some cases the whole cycle was not performed, but only a part of that cycle. There is also a difference in the number of repetitions of the same test or the same cycle.

REFERENCES

[1] Amelia Piscitello, Carlo Bianco, Alessandro Casasso, Rajandrea Sethi. Non-exhaust traffic emissions: Sources, characterization, and mitigation measures. Science of The Total Environment, 2021, 766:144440.

[2] Victor R.J.H. Timmers, Peter A.J. Achten. Non-exhaust PM emissions from electric vehicles. Atmospheric Environment, 2016, 134:10–17.

[3] Stojanović N., Identification of thermal stresses of disc brakes for different operating parameters. Doctoral thesis, University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia, 2022.

[4] Unece. UNECE to develop global methodology to measure particle emissions from vehicles' braking systems. Available at: https://unece.org/environment/press/unece-develop-global-methodology-measure-particle-emissions-vehicles-braking (Accessed: 03.01.2022)

[5] Sang-Hee Woo, Yongrae Kim, Sunyoup Lee, Young Choi, Seokhwan Lee. Characteristics of brake wear particle (BWP) emissions under various test driving cycles. Wear, 2021, 480-481:203936.

[6] Bernart Ferrer Almirall, Roger Mateu Cabre. Study of the chinese brake durability patterns and comparison with the main worldwide programmes. Eurobrake 2018 conference, 2018, EB2018-VDT-020.

[7] Volkswagen. An overview of WLTP for passenger cars and light commercial vehicles. Available at: https://www.volkswagenag.com/presence/konzern/group-fleet/dokumente/WLTP_Basic_Knowledge.pdf (Accessed: 03.01.2022)

[8] David Hesse, Christopher Hamatschek, Klaus Augsburg, Thomas Weigelt, Alexander Prahst, Sebastian Gramstat. Testing of Alternative Disc Brakes and Friction Materials Regarding Brake Wear Particle Emissions and Temperature Behavior. Atmosphere 2021, 12:436.

[9] Agudelo C. Thermal regimes during proving ground measurements using WLTP-Brake cycle. Available at: https://wiki.unece.org/download/attachments/73924923/PMP-48-04%20-%20Thermal%20Regimes%20During%20PG%20Using%20WLTP%20Cycle%2006NOV2018%20Public.pdf?api=v2(Accessed: 05.01.2022)

[10] Theodoros Grigoratos, Carlos Agudelo, Jaroslaw Grochowicz, Sebastian Gramstat, Matt Robere, Guido Perricone, Agusti Sin, Andreas Paulus , Marco Zessinger, Alejandro Hortet, Simone Ansaloni, Ravi Vedula, Marcel Mathissen. Statistical Assessment and Temperature Study from the Interlaboratory Application of the WLTP–Brake Cycle. Atmosphere, 2020, 11(12):1309.

[11] Carlos Agudelo, Ravi Teja Vedula, Quinn O'Hare, Jaroslaw Grochowicz, Theodoros Grigoratos. (2021) Experimental validation of the pmp air cooling adjustment for brake emissions measurements. Eurobrake 2021 conference, 2021, EB2020-STP-018.

[12] Marcel Mathissen, Jaroslaw Grochowicz, Christian Schmidt, Rainer Vogt, Ferdinand H. Farwick zum Hagen, Tomasz Grabiec, Heinz Steven, Theodoros Grigoratos. A novel real-world braking cycle for studying brake wear particle emissions. Wear, 2018, 414–415:219-226.

[13] Sebastian Gramstat, Thilo Mertens, Robert Waninger, Klaus Augsburg, Christopher Hamatschek David Hesse. Functional Coatings of Gray-Cast Iron Brake Discs – Impact on the Tribology. Berichte aus dem µ-Club 2020, Reports from the µ-Club 2020, 2021, 162-170.

[14] SAE J2522, Dynamometer Global Brake Effectiveness, 2003

[15] Alemani Mattia, Perricone Guido, Olofsson Ulf, Söderberg Anders, Wahlström Jens, Ciotti Alessandro. A proposed dyno bench test cycle to study particle emissions from disc brakes. Eurobrake 2014 conference, 2014, EB2014-SE-001.

[16] Guido Perricone, Mattia Alemani, Ibrahim Metinöz, Vlastimil Matějka, Jens Wahlström, Ulf Olofsson. Towards the ranking of airborne particle emissions from car brakes – a system approach. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2016, 231(6): 781–797.

[17] Mlodzikowski Maciej, Banach Damian, Orlowski Tomasz. Wear of friction material in function of mechanical load and speed during real scale dynamometer tests. Eurobrake 2017 conference, 2017, EB2017-SVM-011

[18] Naotaka N., Toru M. (2018) Moan noise generating mechanism and development of reduction technology. Eurobrake 2018 conference, 2018, EB2018-BSY-002.

[19] Asmawi Sanuddin, Shahriar Kosarieh, Carl Gilkeson, Peters Brooks, David Barton, Suman Shrestha. Preliminary comparisons of particulate emissions generated from different disc brake rotors. EuroBrake 2020 conference, 2020, EB2021-STP-020.

[20] Athanasios Mamakos, Katharina Kolbeck, Michael Arndt, Thomas Schröder, Matthias Bernhard. Particle emissions and disc temperature profiles from a commercial brake system tested on a dynamometer under real-world cycles. Atmosphere, 2021, 12(3):377.

[21] Marcel Mathissen, Charles Evans. Mendeley data. Lowbrasys brake wear cycle - 3h LACT. Available at: https://data.mendeley.com/datasets/4cgs6myx9d/1 (Accessed: 15.01.2022)

[22] Marcel Mathissen, Theodoros Grigoratos, Tero Lahde, Rainer Vogt. Brake Wear Particle Emissions of a Passenger Car Measured on a Chassis Dynamometer. Atmosphere, 2019, 10(9):556.

[23] U. S. Environmental Protection Agency. Federal Test Procedure. Available at: https://www.epa.gov/emission-standards-reference-guide/epa-federal-test-procedure-ftp (Accessed: 16.01.2022)

[24] U. S. Environmental Protection Agency. Federal Test Procedure. Available at: https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules (Accessed: 16.01.2022)

[25] Zsuzsanna Bede, Tamás Péter. The extraction of unique velocity processes from a macro model, Periodica Polytechnica Transportation Engineering, 2010, 38(2):105.

[26] Paul G. Sanders, Tom M. Dalka., Ning Xu, Matti M. Maricq, Rena H. Basch. Brake dynamometer measurement of airborne brake wear debris. SAE Technical Paper Series. 2002, 111(6):1693-1699.

[27] Hiroyuki Hagino, Motoaki Oyama, Sousuke Sasaki. Laboratory testing of airborne brake wear particle emissions using a dynamometer system under urban city driving cycles. Atmospheric Environment, 2016, 131: 269–278.

[28] Diesel net. Japanese JE05 Cycle. Available at: https://dieselnet.com/standards/cycles/jp_je05.php (Accessed: 16.01.2022)

[29] Hiroyuki Hagino, Motoaki Oyama, Sousuke Sasaki. Airborne brake wear particle emission due to braking and accelerating. Wear, 2015, 334-335:44–48.

[30] Akihiro Iijima, Keiichi Sato, Kiyoko Yano, Masahiko Kato, Kunihisa Kozawa, Naoki Furuta. emission factor for antimony in brake abrasion dusts as one of the major atmospheric antimony sources. Environmental Science & Technology. 2008, 42(8), 2937–2942.

[31] Guido Perricone, Mattia Alemani, Jens Wahlstrom, Ulf Olofsson. A proposed driving cycle for brake emissions investigation for test stand. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2019, 234(1):122-135.

[32] Jens Wahlström, Mara Leonardi, Minghui Tu, Yezhe Lyu, Guido Perricone, Stefano Gialanella, Ulf Olofsson. A study of the effect of brake pad scorching on tribology and airborne particle emissions. Atmosphere, 2020, 11(5):488.

[33] Hartmut Niemann, Hermann Winner, Christof Asbach, Heinz Kaminski, Georg Frentz, Roman Milczarek. Influence of disc temperature on ultrafine, fine, and coarse particle emissions of passenger car disc brakes with organic and inorganic pad binder materials. Atmosphere, 2020, 11(10):1060.

[34] Thais Rodrigues Gomes, Marcos Roberto Farias Soares, Carlos Pérez Bergmann. The size effect of silicon carbide particles on the wear of brake pad materials. Eurobrake 2020 conference, 2020, EB2020-FBR-024.

[35] Langhof Nico, Alber-Laukant Bettina, Greuel Christian, Hilpert Martin, Kozub Alexander, Voigt Rebecca, Krenkel Walter. Fiber reinforced ceramic friction pads for automotive applications – the dependence of friction and wear on speed and braking pressure. EuroBrake 2012 conference, 2012, EB2012-FM-06.

ACKNOWLEDGEMENT

This paper was realized within the framework of the project “The research of vehicle safety as part of a cybernetic system: Driver-Vehicle-Environment”, ref. no. TR35041, funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.