EB2020-EBS-019

Influence of Test Cycle and Energy Input on Brake Emissions

Andreas Paulus* [1], Matthias Kloda [1]

[1]*TMD Friction Services GmbH*
Schlebuscher Str. 99, 51381 Leverkusen, Germany

https://doi.org/10.46720/EB2020-EBS-019

ABSTRACT: To contribute to the understanding of the test cycle influence on brake emissions, the present study investigates the differences between the novel WLTP-based brake emission test cycle and several commonly used real-world test cycles in terms of characteristic parameters like kinetic energy and disc temperature. Building on this comparison, the effects of those differences on brake emissions are shown based on a direct comparison of three cycles on a brake emission dynamometer. The dynamometer setup includes a climate-controlled environment as well as a brake emission enclosure with a filtered incoming airflow. Using particle sampling and downstream PM measurement it is shown that the used test cycle has a significant impact on brake emissions. This fact makes clear the necessity of using realistic and representative test procedures when aiming at the evaluation of PM_{10} brake emissions in a reproducible and conclusive manner. The novel WLTP-based brake emission test cycle provides such a procedure and is widely accepted as standard procedure to measure brake emissions.

KEY WORDS: Brake emissions, WLTP, Test cycle, Particle mass concentration, Disc temperature, Kinetic energy

1. Introduction and Background

In 2019, the novel WLTP-based brake emission test cycle was established as worldwide standard testing procedure for non-exhaust particle emissions, especially for brake emissions caused by passenger cars ([1]). It is meant to replace multiple other test cycles used in the past to investigate brake emissions. Even though many of those test cycles are based on real driving conditions, they mostly concentrate on specific regions or driving situations, which are not representative for worldwide or European driving behavior. Due to this fact, emission factors and absolute values for particulate matter (PM_{10}) emissions obtained via other test cycles are not comparable to results obtained using the novel WLTP-based brake emission test cycle.

This is mainly due to the fact that different test cycles represent different load conditions and driving behavior, which subsequently leads to different kinetic energy to be dealt with by the brakes and also to other temperature regimes in the brake system. Those effects have certain impacts on the PM_{10} emissions of the brake system, which have been shown by several authors ([2], [3])

It exists the actual risk, that the lack of awareness of these dependencies may lead to contradictory conclusions and thus impede effective brake emission reduction.

The present study aims at reinforcing the awareness of the test cycle influence on PM_{10} brake emissions based on an analysis of several commonly used real-world driving cycles. In the course of the analysis, the different test cycles are subject to a statistical analysis of prescribed load conditions (e.g. braking speed, brake energy) as well as measured responses of the brake system (e.g. disc temperature, PM_{10}). In a next step, the influence of braking energy and disc temperature are presented in detail.

2. Methodology

2.1. Test cycles

In this chapter, three of the most commonly used test cycles in the brake industry are analyzed, namely the Mojacar test cycle, the Los Angeles City Traffic (LACT) test cycle and the novel WLTP-based brake emission (WLTP) test cycle. Additionally, two Cologne-based real driving cycles, which were created by TMD Friction, are analyzed.

Both Mojacar and LACT cycles represent vehicle tests on test sites that are very relevant for the key markets of Europe and North America. Test results from these test sites are usually an obligatory requirement by the car manufacturers in the product development process. The representations of those cycles on a brake dynamometer are primarily used to evaluate comfort and wear behavior of a brake system ([4]).

In 2016 the Joint Research Center of the European Commission (JRC) published a comparison study of different industrial test cycles and the WLTP database aiming at defining “normal”, meaning commonly accepted, driving conditions to allow for a comparable and reproducible brake emission measurement. The WLTP database consists of vehicle activity data from five different regions in the world with a total mileage of over 700.000km. The major part of the data is real world data recorded during the actual use of the vehicle by drivers. The results of the report were presented within the framework of the UNECE Particle Measurement Programme (PMP) informal working group ([5]).

The JRC study concludes that Mojacar test cycle incorporates many brake events of higher deceleration and lower duration as found in the WLTP database. Thus the Mojacar test cycle cannot be used to reproduce real world urban driving conditions. The LACT test cycle is more suitable to represent real world driving conditions but also shows significant differences to WLTP database in terms of deceleration.

Based on this analysis, the novel WLTP-based brake emission test cycle was created to contribute to the aim of establishing a commonly accepted test cycle for measuring brake emissions ([1]). This novel cycle corresponds very well to the WLTP database in terms of initial velocity, deceleration and brake duration. Nevertheless it is pointed out that it is crucial to correctly reproduce the on-road temperature levels found in actual vehicle tests on the dynamometer to be able to reproducibly measure the brake emissions. This is due to the known fact, that particle number emissions are strongly connected to the disc temperature ([2], [6]).

The Cologne-based cycles are test cycles recorded during vehicle NVH endurance tests. The Cologne City cycle represents urban driving and the Cologne cycle represents a combination of urban and suburban driving. Both cycles are used for internal assessment of NVH and wear behavior of friction materials.

Table 1: Test cycle overview

Test Cycle	Ø Initial speed	Ø Deceleration
Mojacar	55,6 kph	25,1 %g
LACT	53,0 kph	11,3 %g
WLTP Brake	41,6 kph	9,9 %g
Cologne City	42,9 kph	18,7 %g
Cologne	55,2 kph	20,6 %g

Table 1 gives an overview of the investigated test cycles and some basic characteristics of the cycles. The Mojacar test cycle contains a relatively high average initial speed as well as the highest average deceleration, while the WLTP Brake cycle represents the opposite range of initial speed and deceleration. The LACT cycle represents slightly higher average deceleration than WLTP Brake cycle while the average initial speed is significantly higher. The Cologne City cycle resembles the WLTP Brake cycle in terms of initial speed but contains twice the average deceleration. The Cologne cycle resembles the Mojacar test cycle in average initial speed and a relatively high average deceleration.

As it is known that the disc temperature is an important factor for the generation of brake emissions, initial speed and deceleration of a brake application are not sufficient parameters to compare test cycles in terms of their brake emission characteristics. Two parameters that more directly influence disc temperature are also analyzed in the scope of this work. Those parameters are the kinetic energy to be converted in a brake event and the braking power of a brake event. Together with the brake system, the vehicle data and the environmental conditions, which are supposed to be constant during a dynamometer emission test, those parameters mainly determine the temperature regime of the disc and thus directly influence the brake emission behavior of the brake system.

2.2. Influencing parameters

When assuming that we compare the test cycles based on the same brake system and the same vehicle, the specific kinetic energy of a brake event can be defined as

$$E_{kin,spec} = 0{,}5 \cdot (v_{init}^2 - v_{final}^2) \qquad (1)$$

The specific kinetic energy is used to compare the load collective of different cycles independent of the actual vehicle or brake system used. In chapter 4, covering the results of actual dynamometer tests, the kinetic energy of a brake event is calculated according to equation (2):

$$E_{kin} = I \cdot \pi^2 \cdot (n_{init}^2 - n_{final}^2)/1800 \qquad (2)$$

As all test cycles that are covered in this study are based on prescribed deceleration for each brake application, the braking time is constant for each brake application and independent of the friction coefficient. Thus, the specific braking power is also an input variable of the test cycle and can be calculated as follows:

$$P_{brake,spec} = E_{kin,spec}/t_{brake} \qquad (3)$$

Equivalently to the specific kinetic energy, the specific braking power is used for the cycle comparison.

The braking power used in chapter 4 is defined in equation (4):

$$P_{brake} = E_{kin}/t_{brake} \qquad (4)$$

To get an overview of the load collective represented by the different cycles listed in Table 1, the average specific braking power per stop $\bar{P}_{brake,spec}$ is plotted over the average specific braking energy per stop $\bar{E}_{kin,spec}$. This comparison is shown in Figure 1.

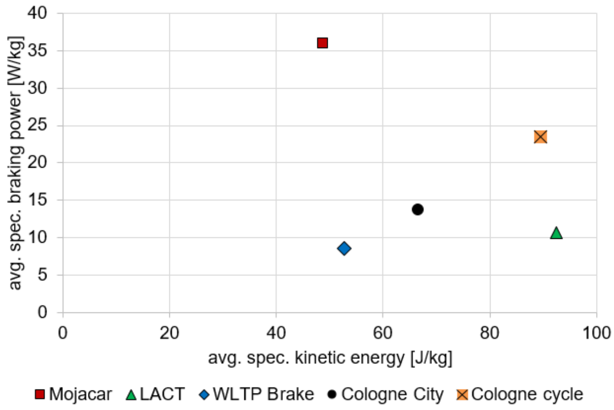

Figure 1 Comparison of specific kinetic energy and specific braking power per stop

It can be seen that WLTP Brake cycle and LACT cycle have similar average specific braking power of about 10W/kg, while LACT cycle has nearly twice the average specific kinetic energy. This is due to the fact that in LACT cycle the speed difference of the brake events is higher in average, while the average brake duration is longer in LACT cycle than in WLTP Brake cycle.

On the other hand Mojacar cycle has similar average specific kinetic energy while the average specific braking power is more than three times higher than in WLTP brake. The reason for this behavior is that Mojacar cycles incorporates many short and relatively high deceleration brake events.

In some ways, Cologne cycle represents a combination of characteristics of Mojacar and LACT cycles with relatively high braking energy and braking power. Cologne City cycle incorporates lower initial braking speeds and thus lower braking energy and also lower deceleration and braking power than Cologne cycle.

The question to be answered by this study is, which influence on PM_{10} brake emissions do the parameters braking energy, braking power and disc temperature have.

3. Experimental

3.1. Test procedure

In the framework of this study, three tests, each representing a different test cycle, are conducted on a brake dynamometer. The cycles that are investigated are Cologne cycle, Cologne City cycle and WLTP Brake cycle. The WLTP Brake cycle consists of 303 brake events in a journey of 192km distance. The Cologne City cycle consists of 188 brake events in a journey of 75km distance. The Cologne cycle consists of 520 brake events in a journey of 307km distance.

A Daimler rear axle brake system with fixed caliper design is chosen and the friction couple consists of a Cu-free low metallic brake pad and a massive grey cast iron brake disc. Temperature measurement is implemented into the disc.

All pads and discs have performed a bedding procedure before the emission test started, which means that the emission behavior has stabilized prior to the actual emission test.

3.2. Test setup

The brake dynamometer used for this study is equipped with a brake emission setup consisting of filtered and climate controlled incoming air, a brake emission enclosure and PM_{10} measurement in the air flow leaving the enclosure. The test setup is basically the one described in [2] and is depicted in Figure 2.

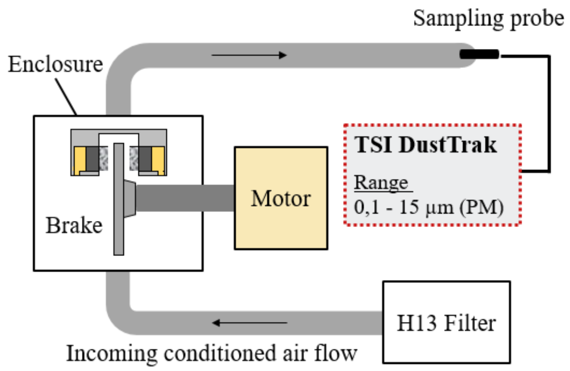

Figure 2 Test setup based on [2]

Filtered and conditioned air is entering the enclosure and generated particles are transported through the duct to the sampling probe. The constant air flow rate is 75m^3/h and the duct diameter is 125mm, which corresponds to an airspeed of 6,1kph. The temperature of the cooling air is set to 20°C and the relative humidity to 50%r.h.

Emission measurement is implemented using a TSI DustTrak DRX device which provides data for the particle mass concentration with a frequency of 1 Hz. The DustTrak device utilizes the working principle of light-scattering laser photometer to measure the particles emitted during a test. The particles are divided in five size fractions in the measurement range of 0,1-15µm. In the scope of this study only the particles smaller than 10µm are considered as this is the size range covered by the EU directive 1999/30/EG. The mass of particles with a diameter smaller than 10µm is referred to as PM in this study. The DustTrak device is calibrated before each test using the zero filter. The background concentration is substracted from the emission data.

3.3. Evaluation

The PM results presented and discussed in this study are analyzed with regard to the number of brake applications in the case that they refer to the whole cycle. Otherwise it would not be useful to compare values between different cycles with different number of brake applications. In case of brake-event-specific analyses, the PM_{10} results are given as mass in mg emitted during the respective brake event.

Apart from that, all brake emission results are normalized to the largest value in the comparison.

4. Results

Due to the fact that different test cycles with different numbers of brake application and different covered distances are compared in the scope of this study, the absolute amount of PM is not a suitable measure. Instead the average PM per stop is analyzed. Figure 3 depicts the normalized average PM emissions per stop for the three cycles.

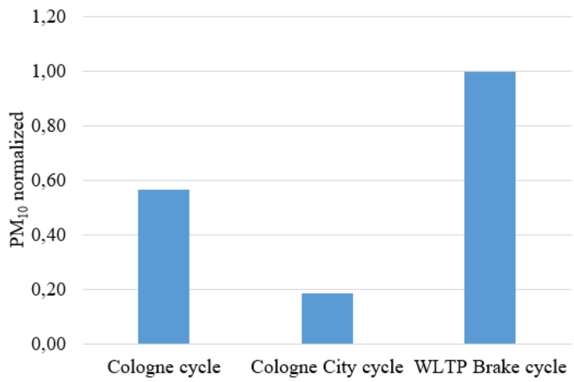

Figure 3 Normalized average PM emissions per stop

It can be seen, that the average PM emissions of the Cologne cycle are only ~56% of those measured in the WLTP Brake cycle and the PM emissions of the Cologne City cycle are only ~18% of those in the WLTP Brake cycle. This is a counter-intuitive first results when keeping in mind that the average kinetic energy as well as the average braking power per stop is significantly higher for Cologne cycle in comparison to WLTP Brake cycle.

This finding is confirmed by Figure 4, in which the average PM emissions per stop are plotted over the normalized average kinetic energy per stop in the respective cycle. The relatively low kinetic energy per stop in the WLTP Brake cycle does not lead to low PM emissions in comparison to the other two cycles.

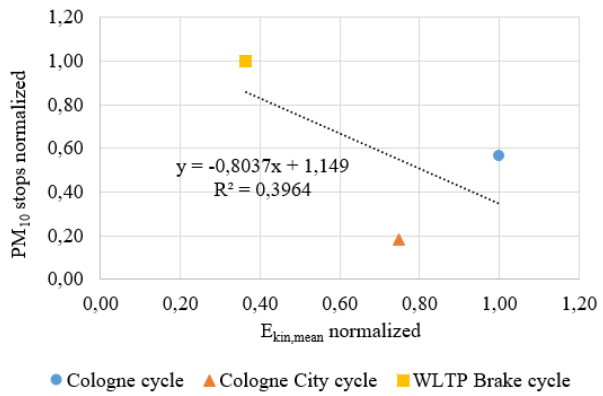

Figure 4 Normalized avg. PM emissions per stop over normalized avg. kinetic energy per stop in cycle

From past investigations it is known that the maximum disc temperature reached in a brake application has a strong influence on the emission behavior ([2]). This finding also applies to the tests conducted in the scope of this study. Figure 5 shows that the PM emissions linearly rise with maximum disc temperature.

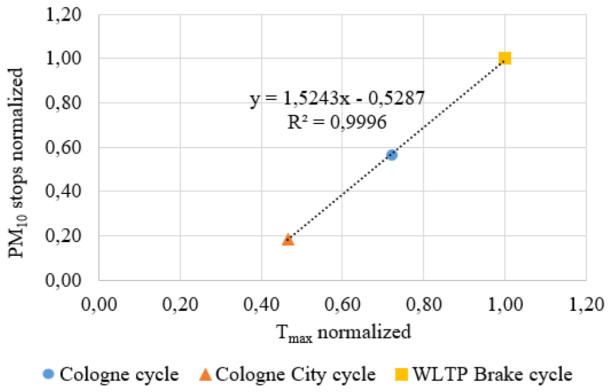

Figure 5 Normalized avg. PM emissions per stop over normalized maximum disc temperature in cycle

A detailed analysis of the brake events with the highest PM emissions in the WLTP brake cycle reveals that the combination of high kinetic energy and high disc temperature leads to the highest PM emissions. To account for that fact, in the following sections the parameter brake intensity (BI) of a brake application is defined as:

$$BI = E_{kin,max} \cdot T_{max} \qquad (5)$$

In Figure 6 all brake applications of the WLTP Brake cycle are categorized according to their brake intensity (BI) and sorted in 25 normalized BI classes. For each BI class the PM emissions of the respective brake applications are summed up and displayed as bars. The orange line represents the cumulated PM emissions over the brake intensity classes. The graph shows that ~15% of the PM emissions occur in the highest BI class. Actually there is only one brake event in this class.

The top 1% of brake applications according to brake intensity are responsible for ~23% of PM emissions in WLTP Brake cycle. This means that those three brake applications contribute very disproportionately to the PM emissions, specifically 23 times higher than one could expect based on their number.

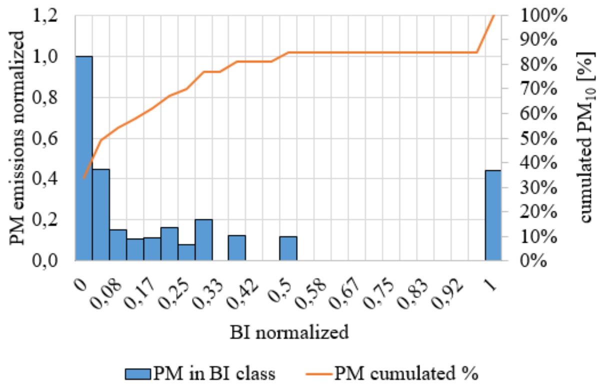

Figure 6 Cumulated normalized PM emissions in WLTP Brake cycle depending on brake intensity

Figure 7 shows the results of the Cologne cycle in an equivalent way. The PM and BI values are normalized to the same maximum value than for the WLTP Brake cycle. It can be seen that the maximum brake intensity of the Cologne cycle is only about half of the maximum brake intensity of the WLTP Brake cycle. The top 1% of brake applications according to brake intensity are responsible for ~4% of PM emissions in the Cologne cycle, which means that those 5 brake events influence the PM emissions much less than the top 1% BI brake events of the WLTP Brake cycle do.

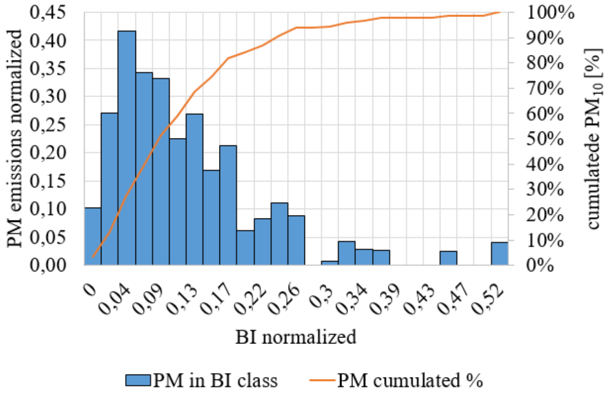

Figure 7 Cumulated normalized PM emissions in Cologne cycle depending on brake intensity

The Cologne City cycle has the same characteristics in terms of PN emissions depending on BI as the Cologne cycle has. That is why in the following only the comparison of WLTP Brake cycle and Cologne cycle is further discussed.

To confirm that there exist significant differences between the WLTP Brake cycle and the Cologne cycle, the cumulated frequency of specific kinetic energy per stop as well as cumulated frequency of maximum disc temperature per stop are shown in Figure 8 and Figure 9.

It can be seen, that the Cologne cycle represents higher mean kinetic energy per stop, but that the highest energy stops are part of WLTP Brake cycle. Additionally, the WLTP Brake cycle represents a higher temperature level as well as higher maximum temperatures in the tests conducted in the scope of this study. This combination of just a few stops with relatively high kinetic energy and at the same time relatively high temperatures in the WLTP Brake cycle is the main reason for the higher PM emissions in WLTP brake cycle. This holds true despite of higher average deceleration and average kinetic energy in the Cologne cycle.

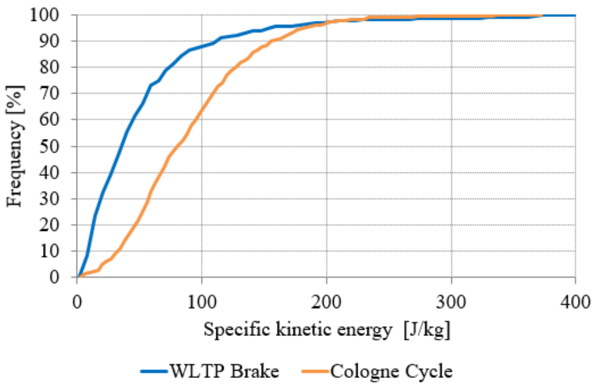

Figure 8 Cumulated frequency of specific kinetic energy per stop

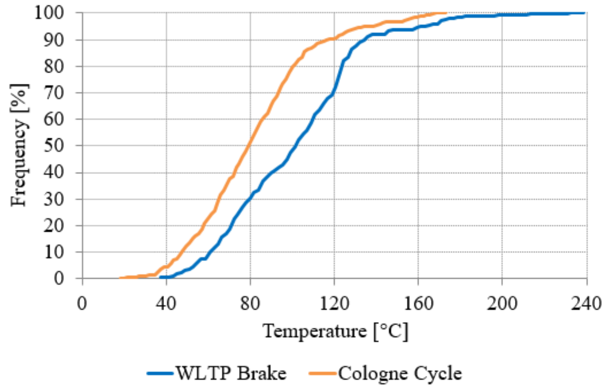

Figure 9 Cumulated frequency of maximum disc temperature per stop

In the next step of the analysis the correlation between the average PM emissions of each brake event and the brake intensity of the respective brake event is evaluated. Figure 10 and Figure 11 depict this correlation for the WLPT Brake cycle and the Cologne cycle in each case for the 10% of brake events with highest PM emission values. Again the PM emissions and the BI values are normalized to the overall maximum values.

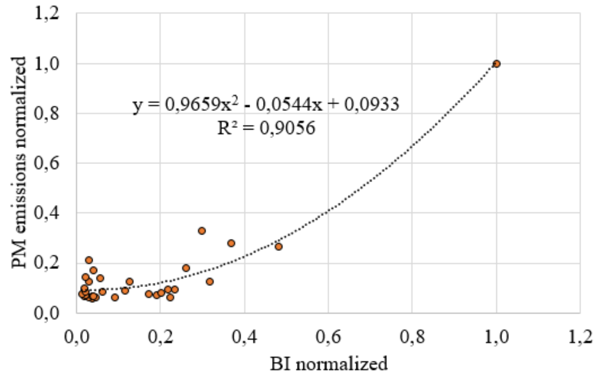

Figure 10 Normalized PM emissions over BI for 10% of brake events with highest PM in WLTP Brake cycle

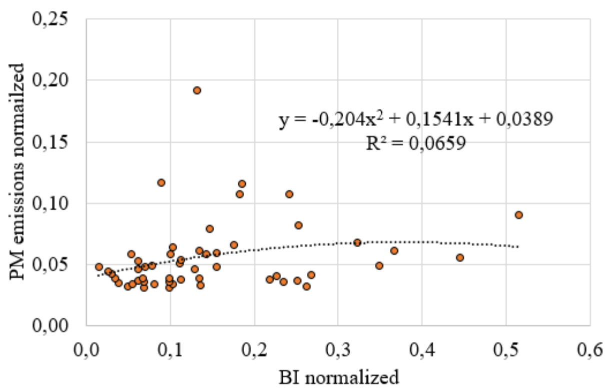

Figure 11 Normalized PM emissions over BI for 10% of brake events with highest PM in Cologne cycle

The graphs indicate that there is a quadratic correlation between PM emissions and BI for the WLTP Brake cycle. It has to be pointed out that there is one outstanding brake event in the WLTP cycle that is associated with the by far highest brake intensity and also PM emissions and which dominates the correlation. Nevertheless, a clear trend can be identified for an increase of PM with increasing brake intensity.

For the Cologne cycle no such correlation can be found. Up to a normalized brake intensity of 0.52 there is no significant increase of PM emissions. For normalized BI below ~0.3 the PM emissions per brake event are on a comparable level for both cycles. In Cologne cycle the BI is low enough to not reach the point where PM emissions increase dramatically, which is why also the overall PM emissions of the whole cycle are only ~60% of those measured in WLTP cycle.

The results clearly show that the brake intensity and thus the maximum kinetic energy and the maximum disc temperature in a brake application mainly determine the level of PM emissions during this brake application. Due to different brake intensities present in different cycles, the PM emission results cannot be compared between tests utilizing different cycles. This means that great care has to be exercised when analyzing PM brake emission results from different laboratories.

5. Outlook

Based also on the findings presented in this study, future brake emission measurement at TMD will be conducted on the basis of the novel WLTP-based brake emission cycle and according to the standards regarding e.g. cooling air setup and particle sampling defined by the UNECE PMP group.

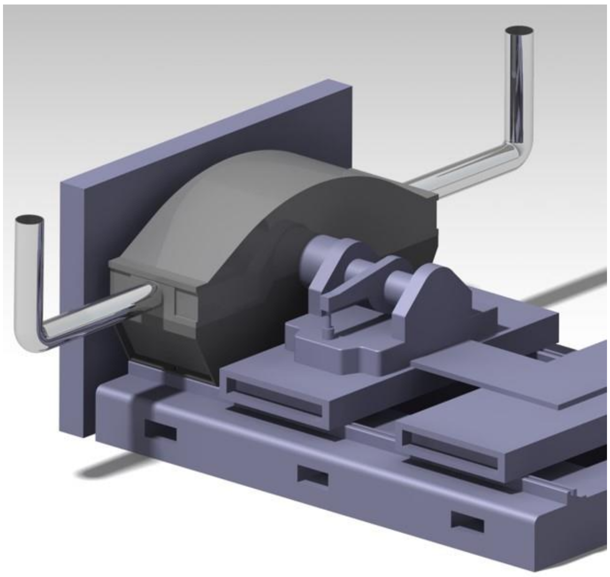

Figure 12 New brake emission dynamometer setup

As an integral part of compliance to those standards, a new brake emission enclosure has been developed and is integrated in the emission setup for all future brake emission measurements at TMD. The new setup is depicted in Figure 12.

Based on the findings presented in this study and other similar studies, the medium-term aim is to develop an effective method to optimize the brake emission behavior of a brake system while fulfilling all the customer requirements. Such an effective method is in great demand especially in the context of the automobile megatrends of electrification and autonomization. Those will lead to new requirements for the brake system with a special focus on brake emissions, corrosion, NVH and lifetime.

6. Conclusion

In the scope of this study, two test cycles based on real driving data were compared with regard to their influence on PM_{10} particle emissions. The presented study allows to draw the following main conclusions:

- The maximum kinetic energy and the maximum disc temperature during a brake application have the largest influence on the PM emissions during the respective brake application. The 1% of brake applications with the highest brake intensity (rf. Equation (5)) are responsible for ~23% of PM emissions in the WLTP Brake cycle.
- It exists a certain brake intensity threshold above which a quadratic increase of PM emissions is observed. In the tests conducted in the scope of this study this threshold is only reached in the WLTP Brake cycle, mainly due to three brake events with relatively high kinetic energy and relatively high disc temperature. Consequently, in this study higher PM emissions are measured for the WLTP Brake cycle in comparison to the Cologne cycle.
- The results confirm that it is not possible to compare PM emission results obtained utilizing different test cycles due to different kinetic energies and different maximum temperatures resulting from the cycles even if the same brake system and the same test rig is used.
- When comparing results obtained by using the same test cycle, great care has to be exercised considering the temperature level. The disc temperature is not only dependent on the brake system, the inertia, the load collective, etc. but also on the emission setup, the air flow rate and the cooling conditions when it comes to dynamometer testing. This means that the temperature behavior of a brake system on the vehicle has to be known or at least to be estimated with sufficient accuracy. The temperature behavior then has to be replicated on the dynamometer according to those measurements or estimations. Only then can quantitative PM emission results be reasonably obtained via dynamometer testing and be compared to other tests that comply with the same standards.

The requirement to adjust the cooling air flow rate in a way that the temperature behavior on the vehicle is similar to the one on the dynamometer was also formulated by the PMP group in October of 2019 ([7]).

The present study emphasizes the fact that brake emission measurements have to be conducted according to international standards regarding test cycle, cooling air setup, particle sampling and other relevant factors that are not yet finally defined. Those standards are currently developed by the UNECE PMP group and will ensure reproducible and repeatable brake emission measurement as the basis for future development and regulation.

Acknowledgements

The results presented in this study could not have been achieved without the support of many TMD colleagues from testing area, laboratory and engineering. I especially would like to thank Ilja Plenne, Dirk Welp and Arslan Ahmed.

References

[1] M. Mathissen *et al.*, “A novel real-world braking cycle for studying brake wear particle emissions”, *Wear*, vol. 414–415, pp. 219–226, Nov. 2018, doi: 10.1016/j.wear.2018.07.020.

[2] A. Paulus, “Investigation of Brake Emissions of Different Brake Pad Materials with Regard to Particle Mass (PM) and Particle Number (PN)”, in *XXXVIII. Internationales μ-Symposium 2019 Bremsen-Fachtagung*, 2019, pp. 81–94, doi: 10.1007/978-3-662-59825-2_11.

[3] F. H. Farwick zum Hagen *et al.*, “On-road vehicle measurements of brake wear particle emissions”, *Atmos. Environ.*, vol. 217, Nov. 2019, doi: 10.1016/j.atmosenv.2019.116943.

[4] P. Mody, W. Rumold, F. Attia, and S. Ansmann, “Mojacar and Los Angeles city traffic vehicle testing: A comparison & analysis of subjective ratings and objective measurements”, in *SAE Technical Papers*, 2002, doi: 10.4271/2002-01-2600.

[5] T. Grigoratos and G. Martini, “Development of a Test Cycle for the Investigation of Brake Wear Particles”, *UNECE PMP IWG 41st session*, 2016. [Online]. Available: https://wiki.unece.org/download/attachments/36896976/PMP-41-12 Comparison WLTP and Industrial Cycles.pdf?api=v2. [Accessed: 10-Jan-2020].

[6] T. Grigoratos and G. Martini, “Brake wear particle emissions: a review”, *Environ. Sci. Pollut. Res.*, vol. 22, no. 4, pp. 2491–2504, 2015, doi: 10.1007/s11356-014-3696-8.

[7] T. Grigoratos, C. Agudelo, and J. Grochowicz, “Cooling Air Flowrate Adjustment - Introduction to the Proposed Method”, *UNECE PMP IWG 51st session*, 2019. [Online]. Available: https://wiki.unece.org/download/attachments/92012742/2019-30-10_02-Cooling Air Adjustment.pdf?api=v2. [Accessed: 10-Jan-2020].