EB2020-EBS-029

Measurement of Dynamic Signature of Brake Emissions on a Pin-On-Disc Tribotester with Low-Cost Particulate Sensors

Ostermeyer, Georg-Peter[1]; Kwade, Arno[2] ; Sandgaard, Malte[1,*]; Schilde, Carsten[2]; Otto, Johannes[1]; Brandt, Sven[2]; Finke, Benedikt[2]; Gramstat, Sebastian[4]; Stebner, Frank[3]; Drescher, Thomas[3]

[1] Institut für Dynamik und Schwingungen, Technische Universität Braunschweig; Schleinitzstaße. 20, 38106 Braunschweig, Germany (E-Mail:gp.ostermeyer@tu-braunschweig.de)

[2] Institut für Partikeltechnik, Technische Universität Braunschweig; Volkmaroder Straße 5, 38104 Braunschweig, Germany (E-Mail:a.kwade@tu-braunschweig.de)

[3] Volkswagen AG, 38440 Wolfsburg
[4] Audi AG, 85055 Ingolstadt

https://doi.org/10.46720/EB2020-EBS-029

ABSTRACT: Since the Euro-5 standard for motor vehicles with internal combustion engines, the emissions of engines have been below the emissions of the vehicle brakes. As a result, non-exhaust emissions are increasingly coming in political and economic focus. Due to the particle size, the high concentration and the high-temperature processes in the boundary layer, brake emissions are considered to be particularly dangerous for the health of the population. So far, there are no consistent guidelines in the area of measurement methodology and limit values for brake emissions.

Since the emissions of conventional brake systems are influenced by a multitude of different factors, tribological investigation are carried out on a fully automated pin on disc tribotester. In the course of this work, new and low cost particulate sensors (<200 $) are used to determine a dynamic signature of the brake emissions for the first time. For this purpose, a special measuring frame is used to allow a spatial distribution of the sensors, so that swarm measurements around the friction contact can be carried out. The high number of particulate sensors enables a temporal and spatial resolution of the emissions. For this purpose, various brake pairings are examined using a specially developed procedure and then compared with each other using a statistical method.

KEY WORDS Emissions, Tribotester, Low-cost particulate sensors, Wear, Swarm measurement

1. Introduction

From the beginning of the millennium the regulations of the thresholds for the particle concentration were established Europe-wide [1]. The emission output is a very complex process and cannot be due to one source alone. Natural sources such as volcanoes and forest fires or anthropogenic influences such as traffic or industry have a significant impact in the total fine dust pollution. However, the steady reduction of the emission output from exhaust-oriented sources has brought other emission sources, primarily non-exhaust emissions, into the public and media attention. Tyre abrasion is considered less dangerous then brake dust due to the higher particle size and the main components, such as carbon. Particularly due to the high temperature processes in the boundary layer and the high chemical content of harmful elements, brake dust is regarded as a possible cause of an increased risk of cancer or lung damage [2]. Previous studies have already investigated size distributions and concentrations on conventional brake by using high resolution measuring devices. These investigations were primarily performed in clinical air and only at one measuring point on the inertia dynamometers, so that it is difficult to make realistic statements [6,7]. Due to the design of the inertia dynamometer it is not possible to identify the fundamental causes or processes for noticeable brake pairing or braking procedures. The option in those encapsulated system for measuring the topographies and wear behaviour can only be realized by time-consuming dismounting and remounting of the brake pair. In addition to the measurements on the inertia dynamometer, individual measurements have already been performed on real driving tests [8]. Brake emission measurements in road test are determined by a multitude of high complex and instationary parameters. Especially the local weather conditions, like ambient air and humidity, of a measuring point have huge impact on the emission output and agglomeration behaviour of produced particles. The measurements on real road test could mostly only be realized by using large test setups and are not suitable for fundamental investigations. For these investigations of a brake pair, tribometers have already been used to measure emissions at one local position. Thus no dynamic around the brake system can be depicted [9]. In general, a possible connection between friction coefficient, temperature, maximum concentration and the size distribution of the emission was investigated. Especially a high temperature rise was accompanied by a strong increase in the particle concentration and usually revealed a bimodal behaviour distribution. In this work, the emissions and their dynamics during a braking application are to be investigated by using a fully automated tribometer (see chapter Materials and Equipment). All measurements are performed without any enclosure and not in clinical, so that a realistic evaluation can be performed. Different brake pairing are to be investigated regarding to their brake emission behaviour.

2. Materials and Equipment

2.1. Low-Cost Particulate Matter Sensors

In order to be able to measure the dynamic of a brake system, a distribution of a large number of sensors around the brake contact is necessary. For the characterisation of the brake emission dynamic, low-cost (< 200 $) particle sensor are developed, which have been distributed around the brake system bsy using a measuring frame. The physical measuring principle of the low-cost fine dust sensors is the laser scattering method. A laser beam is deflected by a particle and concentric rings are formed on the photodetector, which are proportional to the diameter of the particles. The low-cost sensor of the type Plantower PMS 7003 is controlled by a Raspberry Pi Zero. For this purpose a data management system for storing the recorded data was developed. The details will be described elsewhere. Figure 1 shows an example of the used sensor.

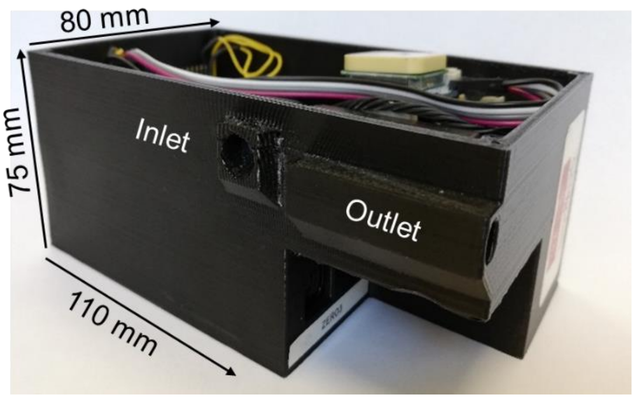


Figure 1 Visualization of the fine dust sensor for measuring the emission dynamics on the tribometer

A total of eight identical sensors will be install on the measuring frame. The unique identification number is set individually for each sensor via a configuration file. The distribution around the brake system on the tribometer and the corresponding identification numbers of the installed low-cost sensors are discussed in the following sections. The fine dust sensors measure the mass concentration in relation to a spherical particle with the density of 1 g/m³. The measurement is taken at a sampling rate of 1 Hz. The low-cost sensors are highly comparable to officially accepted reference measuring instruments [14,15]. Especially the Plantower PMS 7003 used here showed a high linearity to the reference instrument used with $R^2 > 0.85$. Only in the amplitudes the low-cost sensors showed different results, but not in the actual profile.

2.2. Reference Particulate Matter Sensors

In order to be able to evaluate the measured data of the low-cost sensors among each other, the characterization of the dynamics of the brake emissions and the measurement of the particle concentration is also performed with a reference measuring instrument. The state-certified Palas Promo 1000 can display a size distribution of the emissions in addition to the measurement of the number and mass concentration. Comparable to the low-cost sensor the measurement of the concentration and size distribution is also done with a sampling rate of 1 Hz. The installed particle sensor measures the scattered light intensity on the individual particle and uses a white light lamp as the light source. A T-shaped measuring volume minimizes edge zone errors. Edge zone errors are measurement inaccuracies of particle sizes at the edge of the measuring volume [12]. The measuring instrument allows unfiltered evaluation of raw data of concentrations and size distributions. The principle measurement setup of the sensor is shown in Figure 2.

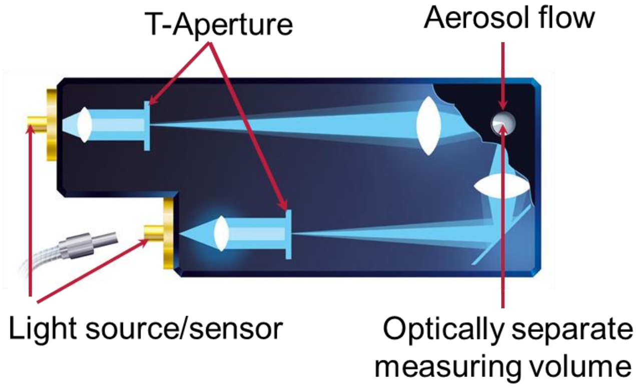


Figure 2 Principal construction of the reference measuring instrument Palas Promo 1000 of the manufacture Palas according to [12]

A detailed functional description of the reference measuring instrument is not explicitly discussed here. Reference is made to the source [12]. In the following, the Palas Promo 1000 is also used for the performed calibration to create a comparability between the low-cost sensors.

2.3 Calibration

In order to achieve comparability between the reference measuring instrument and the low-cost sensors, a calibration measuring stand is developed. Here the dynamics of the measuring instruments should be compared as well as the actual amplitudes during the test. For this purpose, a particle flow as constant as possible was generated in a flow tube, regarding to the mass loading and the constancy of the flow velocity. The exemplary test setup is shown in Figure 3.

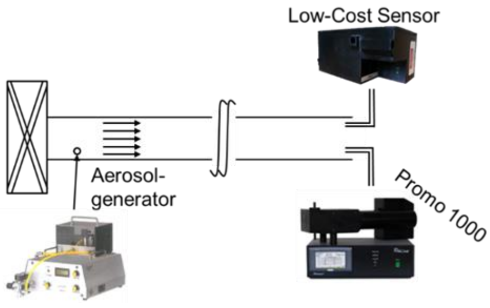
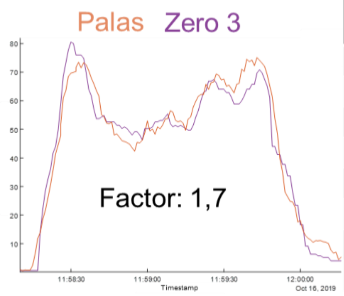


Figure 3 Schematic layout of the measurement setup for the calibration of low-cost sensors [13,16]

The emission source is a dust generator type 3410 from TSI which disperses the particles into an air stream cleaned by means of a micro filter. A quartz flour of the type SF800 serves as reference material. The sampling is performed isokinetically at the end of the flow tube.

In this way a comparability between the low-cost sensors and the reference measuring instrument was achieved. This is shown exemplarily with the sensor Zero 3. The particle concentration of the Palas (Promo 1000, orange) and the Plantower PMS7003 (Zero 3, purple) is shown in Figure 4. It can be seen that the temporal trend of the particle concentration is very similar between the reference instrument from Palas (Promo 1000) and the Zero 3. The signal of the Zero 3 sensor is divided by a transmission value of 1.7. The reason for this is that all low-cost sensors show a higher amplitude value than the Promo 1000. The other factors used for the later measurements on the tribometer are listed in the table on the right of Figure 4.



Sensors	Factor
Zero2	1,7
Zero3	1,7
Zero4	1,75
Zero5	1,95
Zero6	1,8
Zero7	1,7
Zero10	1,8
Zero11	1,78

Figure 4 Visualization of the measurement results of the calibration test and the factors (dimensionless)

The factors of the different sensors are very similar to each other and also show the quality of the low-cost sensors. With the factors integrated for the evaluation and the associated comparability of the sensors, the measurements on the tribometer are discussed in the following section.

2.4. Test facility

The emission investigations are performed on the fully automated pin-on-disc tribometer (Automated Universal Tribotester, AUT) of the Institute of Dynamics and Vibrations at the TU Braunschweig [10]. The AUT has the opportunity of quasi in-situ measurements of the surface condition and the wear behaviour [17]. This makes it possible to give information about the change of the topography in relation to a single application without the need for any reconstruction measures, which can be directly related to the emission measurements. Furthermore, the AUT offers a high variation of parameters and setting options for extensive procedures. The following studies to describe the emission behaviour are performed with a test procedure specially developed for stationary measurements, see Figure 5 (derived from [11]). The test procedure includes the complete measuring range of the AUT in terms of velocity, duration and pressure. In addition, the data in brackets refer to the parameters relating to the vehicle.

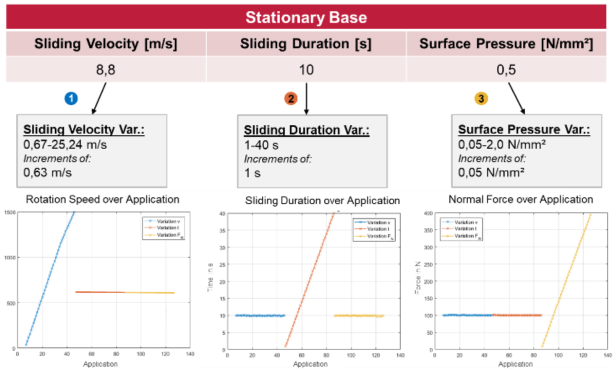


Figure 5 Stationary measuring procedure for the investigation of the dynamics of brake emissions according [11]

In the first section, the speed is increased from 20 rpm (4 km/h) to 1500 rpm (175 km/h) or the speed in contact from 0.67 m/s to 25.24 m/s equidistantly in 40 steps. Normal force or pressure and friction duration remain constant on the base of 10 s friction duration and 100 N (20 bar) force. In the second measuring range, the friction duration is also increased equidistantly from 1 s to 40 s with constant speed of 600 rpm (7 km/h) and normal force of 100 N (20bar). At the end, however, the force is equidistantly increased to 400 N (78 bar) or the pressure to 2 N/mm². After each application, topographies and wear information of the brake pad are recorded by an oscillating laser triangulator. Furthermore, camera images are taken after every 5th application [10]. For the measurement of the brake emission, as already mentioned, a measuring frame is constructed which allows the consistent distribution of the low-cost sensors around the brake disc. The developed measuring frame is shown in Figure 6.

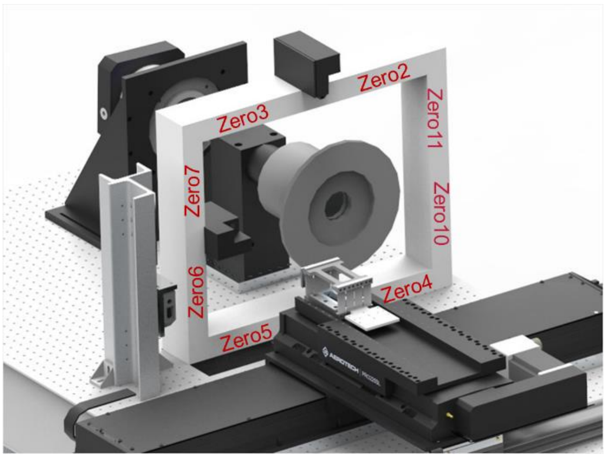


Figure 6 Designed measuring frame for emission measurements at the AUT

The width of this can be adjusted so that different sizes of discs can be taken into account. The labels on the frame represent one sensor each. Zero is the identification number stored in the configuration file, by which the sensors are uniquely assigned.

2.5. Comparison of the first results from Reference Sensor (Welas 1000) with Low-Cost Sensors on the AUT

To describe the emission dynamics at the AUT, a total of three different friction pairings are investigated. Low-Met brake pads are used. The brake discs are made of grey cast iron, but differ in size and in the geometry of the cooling fins. Especially the shape of the cooling channels is significant for the analysis of the dynamics, as they strongly influence the flow pattern. The sensors are positioned as shown in Figure 6. The inlet of the particles is placed at the height of the friction layer and the suction point of the reference instrument is placed in the corner of the measuring frame between the sensors Zero 7 and Zero 3. First a qualitative comparison is made between the reference instrument and the Zero 7 sensor, as the two inlets are close together. This is to evaluate to what extent the dynamics can also be described on the test bench with the low cost sensors. For this purpose the test procedure known from Figure 5 is used. The comparison between the reference and the low-cost sensor is shown in Figure 7.

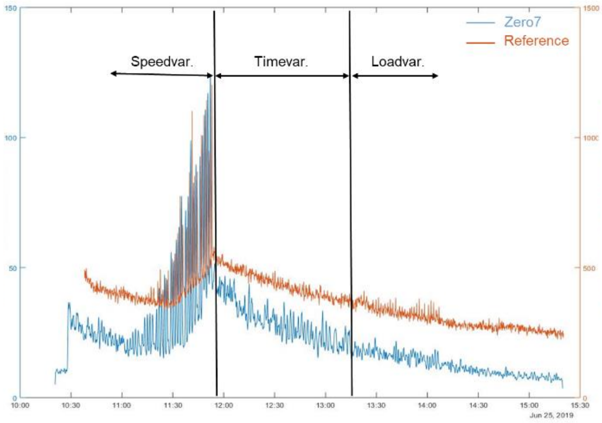


Figure 7 Comparison of the mass concentration of the reference instrument with the number concentration of the low-cost sensor (dimensionless)

It must be ensured that this is a comparison of the number concentration of Promo 1000 and the mass concentration of the Plantower PMS 7003. Figure 7 shows an increase of the particle concentration both in the reference instrument and in the low-cost sensor, especially in the area of velocity variation. Moreover, it can be seen that the background noise also increases with increasing speed and decreases to a minimum again with time and force variation. Furthermore, in the speed variation, individual applications can be significantly differentiated from the background noise by the emission peaks. In general, however, it can be seen that the two measuring instruments show the same dynamics during the stationary test procedure on the tribometer.

3. Measurement results of emissions at the pin-on-disc tribometer

First of all, it should be evaluated where the measurement frame from Figure 6 should be placed for the stationary measurements. For this purpose, a series of measurements is made which varies the position in the plane. In total, five measuring positions are examined. By calibrating the fine dust sensors, the results, especially the amplitude of the individual sensors, can be validly compared with each other. It was found that the most significant emission peaks were detected on the friction layer already described. The friction layer is used as reference position for further measurements.

In the following, the three different friction pairings will be characterized with respect to their emission dynamics. Furthermore, it will be evaluated to what extent they differ in their emission output. First, the smallest brake disc with a diameter of 310 mm will be measured. An exemplary temporal trend of the emission output is shown in Figure 8.

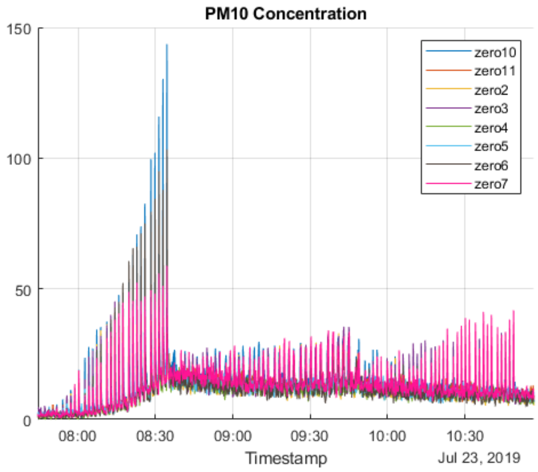


Figure 8 Result of the emission output of the smallest brake disc over time of all eight low-cost sensors (dimensionless)

The result shown is representative for all tests performed on this disc, because the results are highly reproducible. In the speed variation, Zero 10 detects the highest amplitude, which is about 150. Zero 7 is constantly dominant over all three variations and is increased in amplitude. To be able to display the dynamics, the median value of the maxima of the individual applications is used to create a basis for comparison. For this purpose, a script is first developed which automatically identifies the maximum values of the individual braking applications. Then the median value is determined from these 125 maximum values. For each sensor this calculation is performed and plotted at the respective position on the measuring frame. The dynamic diagram belonging to Figure 8 can be seen in Figure 9.

The arrow on the brake disc symbolises the direction of rotation of the brake disc. The particle concentration of the PM10 size class is shown in colour. Zero 3 represents the highest median value with a particle concentration of 27. After that, the sensors Zero 7 and Zero 10 with particle concentrations of 26 and 25 are significantly higher in comparison to the others.

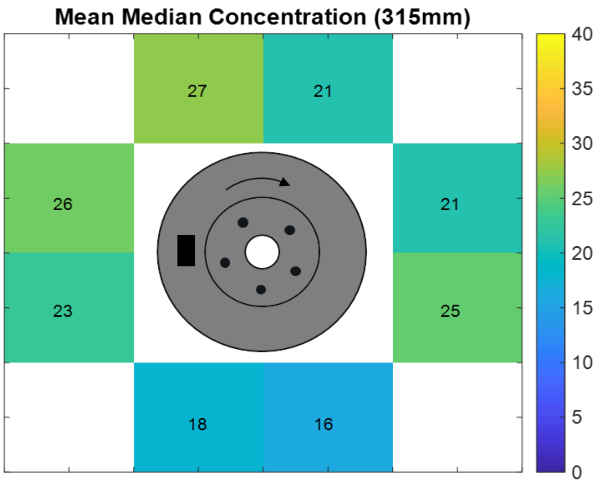


Figure 9 Representation of the emission dynamics based on the median of the maximum concentrations during the stationary test procedure (dimensionless)

In order to validate these results and investigate reproducibility, the stationary procedure is repeated five times. For this purpose, the mean deviation of each individual sensor in the measurements is shown, see Figure 10.

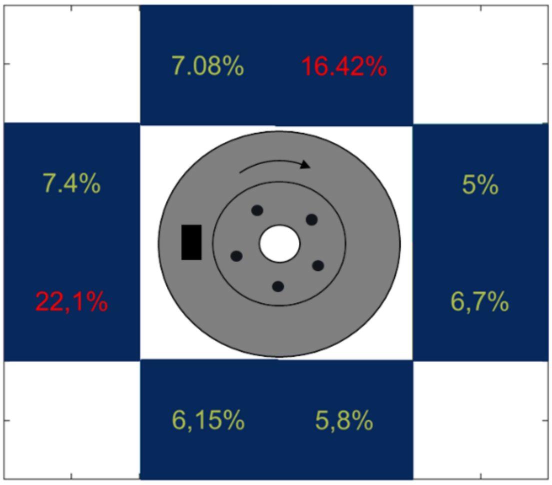


Figure 10 Depiction of the reproducibility of the results based on the average percentage deviation of individual sensors

A very high degree of reproducibility has been shown for six of the eight sensors used over the tests performed. The average deviation for most of the sensors is less than 10%, which is considered very good. The high deviation for sensor Zero 2 and Zero 6 results from two outliers during the tests. Nevertheless, the significant sensors presented are given with a small deviation for the description of the dynamics at this brake disc.

For a statement on the output dynamics of brake discs and their maxima, two further friction pairings are examined. With a diameter of 400 mm and 415 mm respectively, these are considerably larger than the first brake disc with 315 mm. Due to the sizes as well as the difference in geometry, a different fluid mechanics around the friction contact can be expected. This becomes clear in Figure 11, where the median concentration of the brake disc with a diameter of 400 mm can be seen. The median concentration is averaged over all the tests performed.

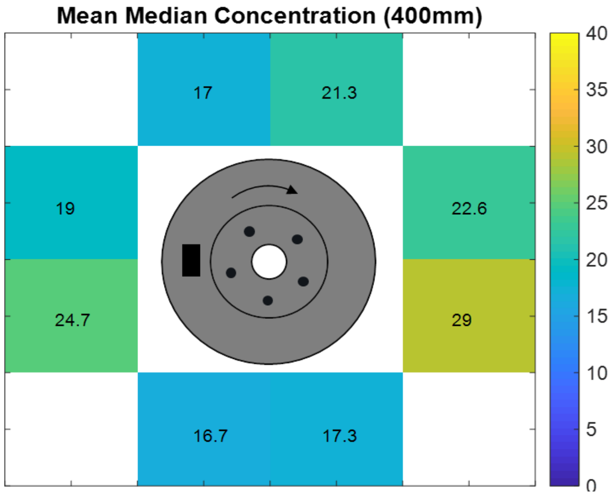


Figure 11 Median concentration of the maximum concentration of emissions per application (dimensionless)

It can be seen that the sensors Zero 10 and Zero 6 measure significantly higher brake emissions concentration than the other sensors. Zero 5 and Zero 4 have a low concentration under friction contact. The main differences between the results of this disc (Figure 11) and the results of the small disc (Figure 9) are also found in the sensors Zero 7 and Zero 3. With the first mentioned friction pairing, the amplitudes of 19 and 17 are much lower compared to 26 and 27 of this pairing. The same procedure and evaluation methods are used to perform the measurements with the largest brake disc with a diameter of 415 mm. The averaged results from this brake pairing are shown in Figure 12. The amplitude of the concentration is significantly higher in all fine dust sensors compared to the previous results. Furthermore, different sensors respond to this friction pairing. In particular, the sensors Zero 3, Zero 6, Zero 10 and Zero 11 with an amplitude of over 35 should be mentioned here.

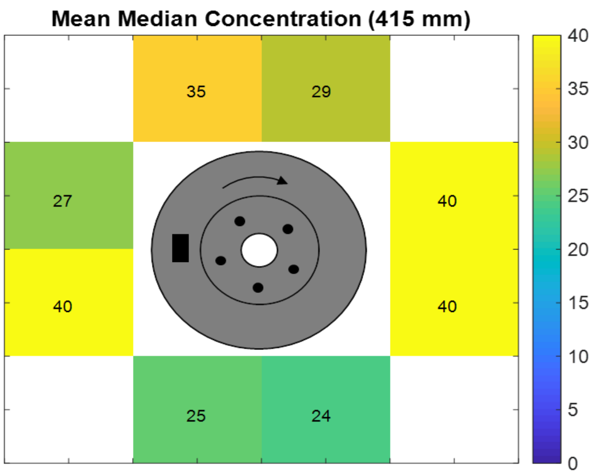


Figure 12 Median concentration of the maximum concentration of the largest brake disc per application (dimensionless)

On the other hand, the concentration values below the brake disc are also higher compared to the brake discs shown so far.

4. Conclusion and Outlook

Previous investigations have shown that the emission output at the tribometer can be described qualitatively very well using low-cost sensors. Even without calibration tests, it could be observed that the temporal trend of the particle concentration is complementary between the reference measuring instrument and the multitude of low-cost sensors. The subsequent calibration allowed the amplitude of the sensors to be adapted to the reference measuring instrument. As a result, the sensors are also valid among themselves and can be compared in amplitude. However, it must be noted here that the calibration of the sensors is carried out with a measured test dust, which may result in other differences. By using the large number of sensors, it was possible to determine the dynamics of brake emissions at different brake pairings. It was found that different friction pairings emit significantly different amounts of dust, which could be recorded by the distributed sensors. In order to obtain further information about the dynamics of the brake emissions on the tribometer, it is essential to carry out further in-depth measurements, also with additional brake discs and brake pads. For further analysis of the friction pairings, the emission values should also be related to the recorded friction data, such as surface condition, wear or the friction coefficient. This should provide information about the emission behaviour of individual brake pairings, in order to be able to design low-emission friction pairings in a future-oriented manner.

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