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Brake Emission Testing Process – Assuring Repeatability and Reproducibility of Emission Measurement Results

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Abstract

Non-exhaust emissions are clearly one of the focal points for the upcoming Euro 7 legislation. The new United Nations Global Technical Regulation (UN GTR) defining the framework for brake emission measurements is about to be officially published. The first amendment to this text is already on the way through the United Nations Economic Commission for Europe (UNECE) hierarchy for decision making. In real life, the final emission factor as the ultimate result of a test is influenced by inaccuracies of numerous parts of the measurement system as well as additional contributing factors like the performance of the particulate filter handling process, which might not be primarily related to equipment specifications. The regulation's definitions set the basic requirements for testing, whilst establishing a robust and efficient testing process requires a thorough assessment of the influencing factors on the measurement quality, which in turn can be described using e.g., repeatability and reproducibility. This study shows these influences of the system's inherent sources of imperfection on result quality, based on theoretical relations, simulations, measurement results and experience gathered during productive brake emission testing. Essential process performance indicators are derived to allow suitably low uncertainty of results for homologation and development purposes. Based on this, it might make sense for testing organizations to tighten their internal technical specifications for specific topics beyond current regulation's requirements to allow efficient testbed operation and deliver superior data quality. Considering lower absolute emission levels in the future, understanding these influencing factors will get even more important.

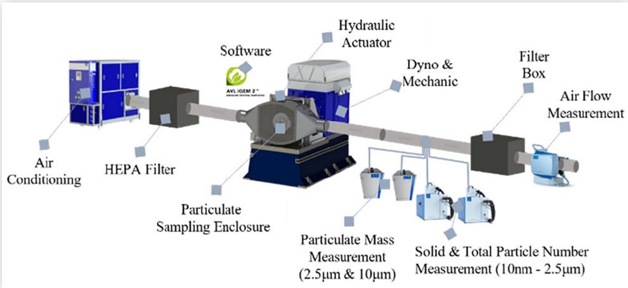
Introduction

Traffic-related particulate matter (PM) is recognized as one of the major sources of ambient PM emissions in urban environments [1, 2] Various adverse environmental and health hazards, such as inflammation and lung diseases, have long been associated with airborne PM [3, 4]. With continuously tightened automotive exhaust emission regulations, exhaust particulate matter steadily decreased over the last years [5]. One consequence of this is that non-exhaust emissions (NEE) originating from brakes, tires and roads, became dominant contributors to road transport PM, accounting for up to 86% of all transport related PM_{10} emissions [4, 6, 7]. Based on these facts, the Particle Measurement Programme (PMP), which is an informal working group under the supervision of the United Nations Working Party on Pollution and Energy (GRPE), was mandated to develop a harmonized methodology for sampling and measuring brake wear particles. Therefore, this group developed a new UN GTR which was finally adopted as UN GTR No. 24 recently [10].

The UN GTR No. 24 defines the technical details of how to determine an emission factor (EF) of a brake system. Therefore, in the first step a new driving cycle, the Worldwide harmonized Light-duty Vehicles Test Procedure for brakes (WLTP-Brake) was developed and implemented. In the next step a setup was defined for sampling and measuring brake wear particles. Two mass-based metrics $PM_{2.5}$ (all particulate matter up to 2.5µm in diameter) and PM_{10} (all particulate matter up to 10µm in diameter) as well as solid particle number (SPN) and total particle number (TPN) have to be measured. It was decided that the brake dynamometer approach with an encapsulation of the entire brake system in a full-flow sampling tunnel is currently seen as the optimal approach for a standardized measurement procedure.

The UN GTR No. 24 specifies essentially the conditions and prerequisites for brake emission measurement with the required technical limitations. The amendment which is already on the way will add provisions for the determination of emission factors for vehicles with regenerative braking

FIGURE 1 Schematic sketch of a brake wear emission measurement system



functions. Figure 1 shows a schematic sketch of the brake wear emission measurement system.

Based on this UN GTR No. 24 the European Union introduced the proposal for the new Euro 7 legislation including brake wear emissions as mandatory for vehicle homologation [8]. This text includes proposed limits for PM_{10} being 7mg/km for a complete vehicle (= 4 brakes) and one for SPN but without specifying a limit number yet. Consistently with the PM limit it is assumed that the number limit for brake emissions will also be in the same order of magnitude than the exhaust emission limit. Therefore, the future number limit of 6,0E+11 particles/km defined for vehicle's exhaust is used throughout this paper as reference value where required.

Measurement results in general will always be subject to errors. They can basically be systematic or random in nature. Various existing indicators describe different aspects of data quality. Especially repeatability and reproducibility have high relevance for testbed and test facility operators. For homologation purposes, reproducibility of measurement results between testbeds in different labs is the key performance indicator of a measurement method, whilst the repeatability of results is mainly seen as an indicator for the performance of each single laboratory's procedures. Therefore, these two parameters will be in focus for the subsequent statements.

Obviously, targeting excellent data quality requires the thorough analysis of the numerous influencing factors on these quality indicators. Such investigations are useful for estimating or defining future engineering target values for brake particulate emissions, and eventually for adapting technical specifications beyond regulation's actual requirements where necessary, to allow efficient testbed operation or increased reliability of the measurement results.

The allowed variability in geometry of the enclosure and ductwork can primarily be attributed to the reproducibility between testbeds. The impact of the design on particle transport and particle losses from enclosure and the ductwork and its dependency on the air flow has already been discussed and demonstrated [9]. Equally important are sampling and measurement systems (cyclones, sampling tubes and particle measurement devices) in this respect, where again the particle losses play an important role.

Due to the lack of a highly accurate and traceable standard for brake emissions, the stability of a particular unit under test (UUT) will always need consideration when assessing and interpreting data quality. Some specific aspects like the repeatability observed for fully bedded discs and the influence on results of one brake system after reassembling on the testbed will be discussed.

The PM filter weighing and handling process has a significant influence on the PM measurement result data quality and needs to be done with dedicated care. There are a lot of different influences to be considered when designing and assessing the way the PM filters are treated in productive testing.

Accuracy, Trueness, Precision, Reproducibility, and Repeatability

All different terms mentioned describe aspects of data quality and are sometimes not used in their narrow sense as defined in [11]. Figure 2 shows a simple graphical depiction of the terms commonly used.

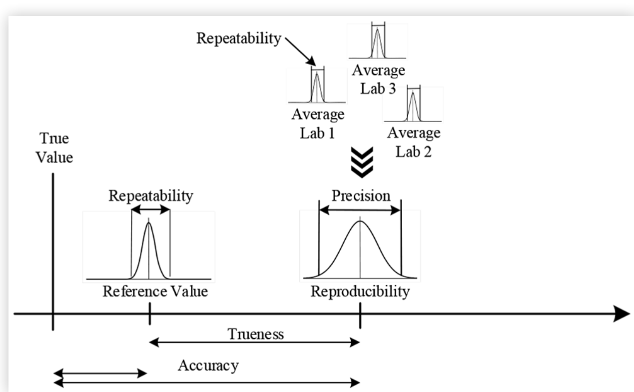
The true value of a quantity is in practice always unknown. The measurement accuracy describes the closeness of a measured quantity value and the unknowable true value and is therefore a rather scientific one. The reference quantity value is in fact used as basis for the other relevant quality descriptors. The challenge is typically to determine this reference value as close as possible to the true value by using e.g., a highly accurate measurement method where available.

The trueness is the closeness of the average of a theoretically infinite number of replicated measured values compared to the reference value. Precision represents the closeness of the agreement of replicate measurements under either repeatability or reproducibility conditions. Both, trueness and precision are typically condensed results of an interlaboratory testing exercise also known as round-robin test.

Repeatability can be referred to precision under repeatability conditions, which is practically often attributed to repeated measurements of the same UUT with its characteristic emission stability on the same testbed using the same test process. The precision of a measurement method can be interpreted as the average repeatability in different facilities.

Reproducibility conditions exist when the same part is tested in different testing facilities having their specific equipment and processes but following a published measurement method. In absence of a perfectly constant golden emission standard, reproducibility numbers will always include the

FIGURE 2 The difference between accuracy, precision, reproducibility, and repeatability



differences in emission behavior of UUTs taken from same production lot when tested on different testbeds with different measurement setup and different devices used.

Practically excellent repeatability of measurements is key for any R&D work to guide conclusions in the correct direction whilst minimized reproducibility is mandatory in view of e.g., homologation testing to set a level playing field for all market participants. These two quality indicators and the method of assessment are described in detail in ISO 5725 – Accuracy (trueness and precision) of measurement methods [12]. Both parameters repeatability and reproducibility are often given as confidence interval with a statistical probability of 95% as common standard and is therefore also used throughout this paper.

Generating high quality results require thorough assessment of the different possible influencing factors with their importance for the final test result. Gauss' error propagation law can be utilized to derive an importance indicator of a specific input value on the final test result and allows optimizations in view of the principle of cause and effect as well as costs involved.

The Gauss' error propagation law in general allows to calculate a resulting accuracy parameter for a given function $f(x_1, x_2, \cdots)$ based on the different inaccuracies of the input parameters, expressed as standard deviations, as follows:

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial x_1}\bigg|_{x_i}\right)^2 \sigma_{x_1}{}^2 + \left(\frac{\partial f}{\partial x_2}\bigg|_{x_i}\right)^2 \sigma_{x_2}{}^2 + \cdots} \qquad (1)$$

using

σ_f Standard deviation for the formula result

$\frac{\partial f}{\partial x_1}\bigg|_{x_i}$ Partial derivate evaluated using the values for x_1, x_2,

σ_{x_1}, Standard deviation of each single input parameters

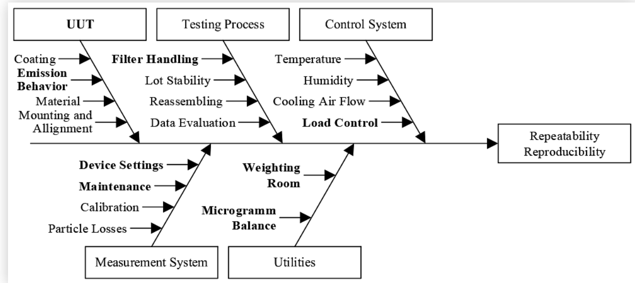
The summands below the square root in equation (1) can be further utilized to identify the importance of different input parameters with their specific influence on the final result's accuracy parameter.

Factors Influencing Data Quality Parameters

Influencing factors on repeatability and reproducibility of the emission factors have been assessed using the Ishikawa technique (= fishbone diagram). The unit under test, testing process, testbed control and measurement system as well as the utilities required were identified as main branches based on a testing facility operator's point of view (Figure 3).

As already mentioned, the UUT itself will always influence both parameters. Mainly the materials involved, special coatings if any, the mounting including the alignment as well as basic design parameters like e.g., the utilization factor influencing the emission behavior of a brake assembly are among the most important ones.

FIGURE 3 Main influencing factors on repeatability and reproducibility (topics in bold influence mainly repeatability)



The framework for the testing process is defined by the UN GTR No. 24. Additionally, necessary test facility specific guidelines like e.g., how to handle the particulate filters – even when fully within the specifications – can have a massive influence on data quality. Also, the production stability of the UUT might have an influence and should therefore be considered. Additionally, if a friction couple is remounted, any effect on the emission performance needs to be taken into account for the design of an experiment. It should be noted, however, that the latter is not allowed for official testing. Even though the regulation defines the basic calculations, there is some inherent uncertainty especially for the event-based evaluation using the transient signals in conjunction with a low acquisition frequency.

The controllers for temperature, humidity and the cooling airflow do not play a significant role since these quantities can be typically controlled much more accurately than what the regulation requires. However, a smooth load controller might generate different emission effects when compared to an aggressive brake controller setting in special circumstances.

The influences of the measurement system need to be looked at from both repeatability and reproducibility perspective separately. A specific test setup causes mainly differences because of e.g., inherent losses or calibration tolerances of devices which is more attributed to reproducibility. Topics like maintenance status and device settings during the test are strongly related to repeatability also. The most important influencing topic in the area of the required utilities is the performance of the PM filter weighing facility.

Enclosure and Ductwork

The geometries of the enclosure and ductwork, in tandem with the cooling flow, may affect the final emission result in three ways. The first is the direct impact on the particle formation. The cooling of the brake and the subsequent dilution of the emitted aerosol play a crucial role in this (e.g., [13, 14, 15]). The flow field in the enclosure determines the cooling power (together with the cooling air- and brake temperatures), and the dilution characteristics. Furthermore, the flow field at the brake is determined by the flow rate of the air supply system, the tube diameter and geometry prior to the enclosure, as well as the enclosure geometry. The tolerances for the flow field in the cross section just before the brake are specified in the UN GTR No. 24.

The second way is the effect on particle losses. High flow velocity together with any abrupt changes that force the flow to change direction (e.g., bends in the ducting), result in impaction losses. Low flow velocity increases the residence time and therefore increases diffusion losses of small particles and gravitational losses of large particles. Turbulent flow results in turbophoretic losses. The aspiration efficiency of the inlet determines whether some particle sizes are over- or undersampled. Finally, the flow velocity in the duct determines the combinations of flows and nozzle sizes that can be used in the sampling system, so that isokinetic sampling is maintained. This in turn affects the losses in the sampling system. Electrostatic losses may occur in a situation where charged particles accumulate in one place creating an electric field. Charged particles will then deviate from the streamlines because of this field. In the UN GTR No. 24, this issue is countered by defining the conductive properties of the system's material.

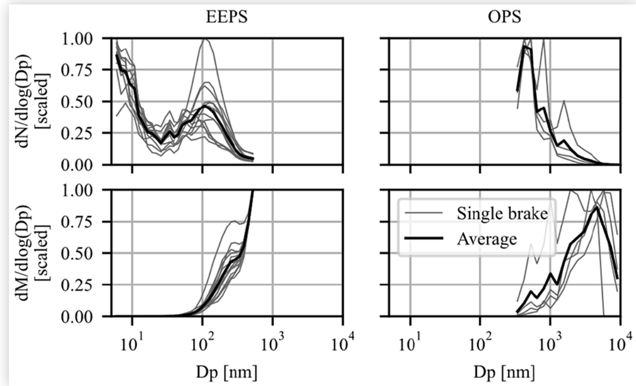
The third way the final emission result may be affected is the possible uneven particle concentration- or velocity profile in the tunnel. An insufficient mixing of particles in the tunnel before the sampling plane leads to non-representative sampling. An uneven velocity profile leads to different isokinetic ratios in different points on the sampling plane, and therefore different measured emissions. These would cause problems within a measurement setup (e.g., different samples drawn to PM_{10}, $PM_{2.5}$ and PN devices), or between measurement setups with different tunnel- and sampling configurations. This effect was investigated by Mamakos et al. [9] for their specific setup fulfilling the actual UN GTR No. 24 requirements and they concluded that the particles were properly mixed, and the flow profile was stabilized at the sampling plane.

The sensitivity of the final emission result on the geometries of the ducting and the sampling system (nozzles, probes, cyclones, sample transport lines), as well as on flow rates, has been previously examined by Grigoratos et al. [16]. In their study, they considered two cases: maximum and minimum particle penetration. These two scenarios were built by designing the ducting and the sampling system according to the tolerances in the UN GTR No. 24, maximizing the particle penetration in the first scenario and minimizing it in the second. They found that the losses in the tunnel are negligible within the tolerances specified in the UN GTR No. 24. Even with the minimum particle penetration setup, the losses of 11µm particles are well below 5%.

Mamakos et al. [9] state that the inertial loss mechanism is the dominant one in the duct and therefore they focus on the losses in a 90° bend. For the lower duct diameter limit in the UN GTR No. 24 (175mm), keeping the flow speed below ~30km/h (corresponding to a volume flow of ~700m^3/h) limits the PM_{10} losses to <10%. For the upper diameter limit (225mm), the same loss performance is reached by keeping the velocity below ~40km/h (corresponding to a volume flow of ~1600m^3/h). Their calculations were done with a size distribution having a geometric mean of 1.5µm and a geometric standard deviation of 2.5, which, according to their review, represents a worst-case scenario.

In Figure 4, particle size distributions obtained with 13 different brakes, measured with a TSI Engine Exhaust Particle Sizer (EEPS) and optical particle sizer (OPS, 4 brakes only), can be seen. Both number- and mass weighted distributions are shown (a density of 1000 kg/m^3 was assumed). The distributions are scaled with the respective maximum concentrations. Within its measured size range, EEPS shows a bimodal number size distribution, one mode repeatedly at 100nm and another extending below the lower size limit of the instrument (6nm). OPS shows a single mode with a mode diameter of 400-500nm. The particle mass distribution from the EEPS extends over the upper size limit (523nm), and OPS shows a mass mode diameter of 4-5µm.

FIGURE 4 Scaled particle number (top) and mass (bottom) size distributions measured with EEPS (left) and OPS (right). 13 brakes altogether. Density of 1000 kg/m^3 used in the conversion from number to mass.



If we lock some of the variables that affect the particle losses in the system, it is easy to examine the impact of each system component separately. A typical cooling air volume flow in the author's experience is around 1500m^3/h. Based on the size distribution data, a lognormal particle number size distribution with a count median diameter of 1µm is representative mass-wise (mass median diameter of 4.2µm), when a geometric standard deviation of 2 is used. This value is also used in [16] and is based on lognormal fittings in [15] and [17]. Keeping these parameters constant and varying the others (tunnel dimensions, probe dimensions etc.), we can estimate the relative importance of each system component. I.e., how big of a difference between the emission results (PM_{10}, $PM_{2.5}$, PN) could one expect, if an identical particle distribution was measured with two UN GTR No. 24 compliant systems, that are identical except for one component (e.g., a tunnel bend vs. no tunnel bend). The particle losses considered (when appropriate) are gravitational losses, diffusion losses, impaction losses and turbophoretic losses. With losses in the sampling nozzle, the isokinetic ratio and the probe angle have synergistic effects. In the calculations, they are taken into consideration. In addition to the nozzle aspiration efficiency, also impaction and gravitation are accounted for. The expressions used are from the textbook from Kulkarni et al. [18].

In Table 1, a comparison of the effects of having a bend in the tunnel and the tunnel length are presented. The values for the influence of the tunnel length are the maximum particle losses inside a tunnel with a length of 6 tunnel diameters. The losses with these calculations remain insignificant for both, which is in line with previous studies [9, 16].

TABLE 1 The effect of different parameter tolerances on the final emission result (PM_{10}, $PM_{2.5}$, PN). D_t = tunnel diameter. *Zero length vs. $6D_t$

Component/ parameter	Tolerance	Max. influence on $PM_{10}/PM_{2.5}$/PN [%]	Importance (high/ medium/low)
Bend	Bend/no bend	3.7/0.7/0.6	low
*Tunnel length	> $6D_t$	1.3/0.4/0.5	low

Sampling and Measurement Systems

According to Mamakos et al. [9] and Grigoratos et al. [16], the sampling system is the more critical part in terms of particle losses. The components that affect the particle losses are the nozzle (isokinetic ratio, aspiration angle), the probe (possible bend, probe length, probe diameter), cyclone (transmission efficiency curve), and the sampling line (possible bend, tube diameter, tube length). Sampling flow also plays a crucial role and is limited by the combination of flow speed in the tunnel, minimum nozzle diameter (4mm), and by the requirement for laminar flow (Re < 2300).

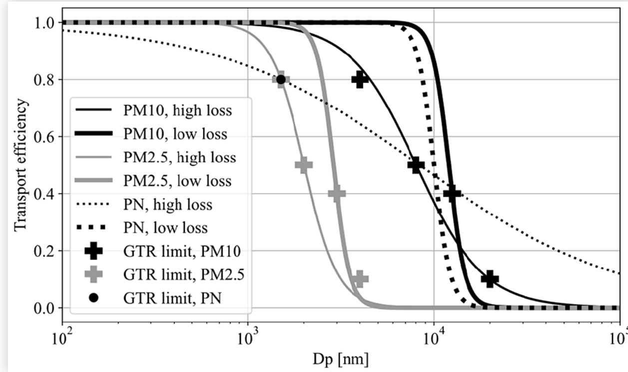
The effect of the cyclone particle transmission efficiency (TE) curve was estimated by constructing different TE curves with the following equation (used by e.g., [20]):

$$TE = 1 - \frac{1}{1 + \left(\frac{Dp_{50}}{Dp}\right)^{s}}, \quad (2)$$

where Dp_{50} is the particle diameter at 50% cutoff, Dp is the particle size, and s is a factor, that essentially determines the steepness of the curve (higher s – steeper curve). In these calculations, different transmission efficiency curves were constructed within the UN GTR No. 24 limits, scoping for the minimum and maximum losses of particles. The highest value for the shape factor s that was included in the calculation was 10, which always lead to lowest possible losses. At s = 10, the curve is already very close to vertical line, an unrealistically ideal curve shape. Therefore, the differences determined here can be considered as worst-case scenarios for the size distribution used in the calculations. The cutoff curves are presented in Figure 5, together with the defined limits in UN GTR No. 24. It should be noted that the PN cyclonic separator has a much wider tolerance and therefore, the presented TE curves for it are extreme cases that may not be applicable to real-world cyclones.

Technically, there are no limits for flow in the PM transfer line (the line from the cyclonic separator to the filter holder). In these calculations, it was assumed that the flow remains the same throughout the sampling system, i.e., the flow limits posed by the probe-nozzle-tunnel flow combination were applied. In the PN transfer line, there are restrictions: laminar flow, residence time of less than 1s and the line length – volume flow ratio of less than 60000s/m^2. The transfer line diameter must be at least 4mm.

FIGURE 5 Cyclone cutoff curves used in the calculations and the limits specified in the UN GTR No. 24.



Like Table 1, Table 2 shows the effects of individual sampling and measurement system components, considering all the cases within the regulation's limits, where two compliant systems, identical except for the component in question, are utilized.

As expected, PM_{10} is the most critical of the three measured quantities (PM_{10}, $PM_{2.5}$, PN). The components/ parameters that may cause a 'high' deviation (>15 %) in PM_{10} are the probe angle, isokinetic ratio, cyclone cutoff curve, and the bend in the transfer line. The line lengths for the probe and transfer line may cause a 'medium' deviation (5-15%). It should be noted, however, that line lengths of 0 and 1m were compared, while in reality, 0m lines are an impossibility. These results should be interpreted accordingly. For $PM_{2.5}$, only the

TABLE 2 The effect of different sampling and measurement system parameter tolerances on the final emission result (PM_{10}, $PM_{2.5}$, PN). I.e., how large of a deviation one can expect due to a single component. High refers to larger than 15 %, med 5 to 15 % and low below 5 %.

Component/ parameter	Tolerance	Max. influence on $PM_{10}/PM_{2.5}$/ PN [%]	Importance $PM_{10}/PM_{2.5}$/ PN
Probe angle (PM)	0-15° Downward/ upward sampling	15.9/1.4/1.3	high/low/low
Isokinetic ratio	0.9-1.15 (PM) 0.6-1.4 (PN)	16.1/4.6/6.5	high/low/med
Probe bend	Bend (90°)/no bend	2.8/0.03/0.1	low/low/low
Probe length	0-1 m	9.1/1.5/1.1	med/low/low
Cyclone cutoff curve	See Figure 5	19.6/37.7/16.6	high/high/ high
Transfer line bend	Bend (180°)/no bend	28.8/5.9/2.3	high/med/low
Transport line length	0-1 m (PM) T_{res} < 1s (PN) L_{line}/Q_{sample} < 60000s/m^2 (PN)	10.1/1.6/2.3	med/low/ low

cyclone cutoff curve may cause a high deviation, and $PM_{2.5}$ is actually more sensitive to the cutoff curve than PM_{10} (37.7% vs. 19.6%, respectively). This is due to the fact, that the cutoff size of ~2.5µm is relatively close to the mode diameter (4.2 µm) of the particle mass distribution. I.e., at this size range the total $PM_{2.5}$ mass is sensitive to any changes in the transmission efficiency curve.

The uncertainties related to the measurement instruments may also cause discrepancies to measurement results between repetitions. These uncertainties, however, are likely to be small compared to the aforementioned effects. E.g., the PN measurement device was used in a recent measurement campaign on heavy duty engines repeatedly measuring PN emissions during Worldwide Harmonized Transient Cycles (WHTC) and showed a covariance of the emission factor of approx. 0,4% which can be seen uncritical in this context.

PM Filter Weighing

After a thorough analysis of the sampling system, the practical particulate filter handling is a key process step for generating high quality PM results. An assessment of the calculation of the final PM emission factors allows to identify the most important influencing factors on repeatability and reproducibility of the PM results, beside those mentioned earlier.

Regardless of the different cyclone specifications used for sampling, both emission factors for $PM_{2.5}$ and PM_{10} are calculated using the general equation (3):

$$PM\ EF = \frac{m_{Filter} \cdot \frac{m_{Total}}{m_{Sample}}}{d} \tag{3}$$

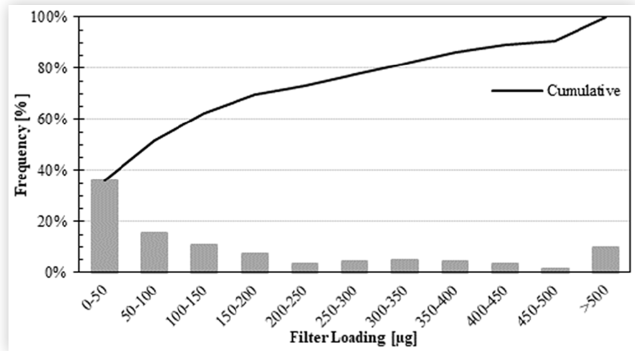
using

PM EF Emission Factor in mg/km
m_{Filter} Filter loading in mg
(weight difference between empty and loaded filter)
m_{Total} Total mass of cooling air flowing through the enclosure during PM sampling in kg
m_{Sample} Mass sampled through filter during PM sampling in kg
d Distance driven during PM sampling (= total distance) in km

Long term experience in measuring PM emissions of engine and vehicle's exhaust show that the absolute filter loading is an important parameter that defines the challenge for the weighing procedure in a laboratory. The measured filter loading of nearly 500 PM filters used for brake emission testing has been assessed (Figure 6).

50% of all filter loadings observed during productive brake emission testing were below a median of 94µg and approx. 1/3 of all filter loadings have been found even below 50µg. Most of the heavily loaded filters (>500µg) on the other end of the scale are primarily filters used to sample multiple WLTP-Brake cycles e.g., to observe bedding behavior. When comparing these numbers with the repeatability definitions for determining filter weights in UN GTR No. 24 one needs

FIGURE 6 Frequency of filter weights observed during real world brake testing in µg (bars) and their cumulative share (solid line).



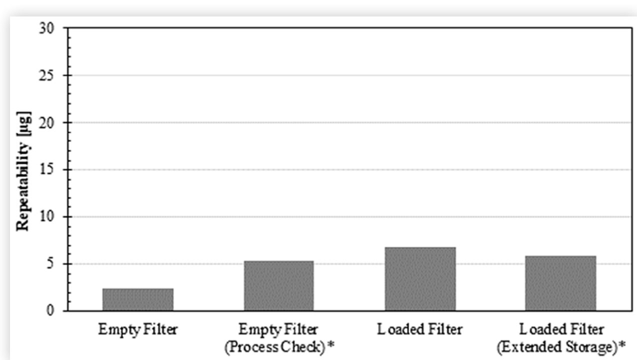
to conclude that it is absolutely required to control the handling process much more effectively than the regulation requires in order to assure high repeatability of emission results. Therefore, all measurements shown here have been done with a balance specified according to 40 CFR Part 1065 [19] which is far beyond UN GTR No. 24 requirements. The balance used is specified to have a repeatability better than ±0,25µg typically checked with certified metal weights.

Determining the filter loading requires the weight of the unloaded empty filter and the weight of the loaded filter after sampling. According to UN GTR No. 24, each of them is an average of two weights determined immediately one after the other in one weighing session and therefore under classic repeatability conditions. Teflon-coated glass fabric filters (TX40) are used as they are widely used in emission testing and ambient monitoring.

Figure 7 shows the actual performance of the weighing process by evaluating the difference between the first and second weight for both the empty filter as well as the loaded filter for again nearly 500 PM filters.

Comparing these two measurements of the empty filter weight done in sequence show a repeatability of 2.5µg (left bar). The same comparison done for the loaded filters results in a repeatability of 6.8µg (Figure 7 - 3rd bar). Both values are much lower than the allowed maximum difference between the first and the second weight of 30µg. The average difference in weight is found below 0.1µg and therefore a systematic

FIGURE 7 Assessment of filter weighing and handling process performance. (* smaller population – see text)



deviation between these repeated measurements is unlikely to occur in both cases. One possible reason for the higher repeatability value seen for loaded filters might be attributed to static effects. This could be further improved by focusing on more thorough neutralization when handling loaded filters.

Beside these repeatability numbers for the filter weights, the performance of the overall filter handling process is, based on our experience, even more important. The required manual filter handling often consists of the following steps: A prepared filter is taken out of the weighing environment in a closed petri dish. This filter is manually put into a filter holder by the testbed operator and the filter holder is then inserted into the PM sampler to be ready for sampling. After a test, the filter holder is removed from the PM Sampler and the PM filter is subsequently taken out of the filter holder, carried to the weighing facility, conditioned and weighted.

To investigate the influence of this manual handling process itself, a total of 10 properly prepared empty filters have been subject to this process, but without sampling any aerosol. I.e., they have been taken out of the weighing room, inserted into the PM sampler, and subsequently taken out of the PM sampler without sampling and reweighted. The differences of empty weights and the filter weights when reweighing afterwards have been assessed. Both values used represent the required average of two weights and have been conditioned properly, of course.

Ideally, the filter loading determined in this experiment should be neglectable. The observed filter loading was 0,9µg on average with a repeatability of 5,3µg for 10 filters (Figure 7 - 2nd bar). I.e., some filters get slightly lighter by losing filter material and some become heavier by catching some material from the uncontrolled testbed environment during manual handling. Real world data show that the handling process doubles the repeatability value to be expected.

This influence of the manual filter handling could be further reduced by several measures. E.g., preparing a filter holder or a filter stack in the clean room by dedicated personnel minimizes the exposure of a filter to the uncontrolled testbed environment. Prepared filter stacks used in automatic filter changers are designed to avoid this unprotected exposure completely. Weighing robotic helps to minimize those effects even further by no longer requiring result relevant manual handling.

In general, test facility operators try to optimize the utilization of their testbeds as much as possible since these are expensive assets. A complete brake emission test takes roughly 1.5 days including bedding and a state-of-the-art testbed with its devices is in principle able to complete this task in unmanned operation. The only remaining limitation to maximize testbed utilization found in UN GTR No. 24 is that the regulation currently defines a maximum period of 8 hours between end of sampling and PM filter weighing.

Therefore, the influence of a prolonged storage period on the filter loading has been determined for in total 30 randomly chosen loaded PM filters in the following way: The loaded weight for each filter has been determined according to the regulation's requirements as basis for this investigation. These filters were then stored at the testbed in a closed petri dish and therefore exposed to an uncontrolled environment for different periods. Thereafter they have been conditioned again and reweighted. The last bar in Figure 7 represents the repeatability between initial weighing (following the standard process) compared to the filter loading after a period of more than 48h. The determined repeatability amounts to 5.8µg and showing a filter loading increase of 2.1µg on average. Since these values have been found in the same order of magnitude than those attributed to the other influencing factors discussed, it can be concluded that an extended storage period in an uncontrolled environment does not add significant systematic error to the filter weighing process. This has practical relevance especially for highly automated testbed operation.

TABLE 3 Specifications of the devices required for determining PM EF. The sensitivity is classified high to low and allow ranking of importance.

Component	Repeatability	Sensitivity
Cooling airflow	0.25% of meas.	low
PM sample flow	0.05dm^3/min	medium
Distance	5m	low
Filter Loading	8.6µg	high

Summing up the numbers of independent influences, i.e., the empty filter weight including the handling process and the determination of the loaded filter weight results in a repeatability of the filter loading of 8.6µg when carefully handling the filters. Compared to this, fulfilling the minimum regulation's requirement only would theoretically end up in a repeatability of more than 40µg.

According to equation (3), the calculation of both final PM emission factors requires the mass of the cooling air flow and the aerosol mass sampled thru the filters as well as the driven distance in addition to the filter loading as discussed before. Combining the specifications of the currently used sensors with the above-mentioned weighting capabilities, using the Gauss' error propagation law according to equation (1) allows one to derive the repeatability of the PM emission factors and the sensitivity of each input parameter. Table 3 summarizes the specifications for the current setup with 8 dm^3/min PM sample flow.

Figure 8 shows the resulting repeatability to be expected depending on the emission factor of the brake and the cooling airflow used.

As soon as the emission factor falls below approx. 1.5mg/km the actual settings used for testing get more and more important. The by far most important quality determining contributor is the performance of the filter weighing process for such low emitting brakes. Above this threshold, the repeatability is primarily influenced by measurement devices' accuracy specifications and the sensitivity to user settings like the cooling air flow as the only easily adaptable quantity is comparably low.

Unit under Test

In contrast to method performance assessments found in other industries like the chemical industry there is no possibility for a test design without including the influence of the UUT itself. Therefore, it is obvious that any measurement

FIGURE 8 Calculated repeatability of PM emission factors with different cooling airflow settings as parameter

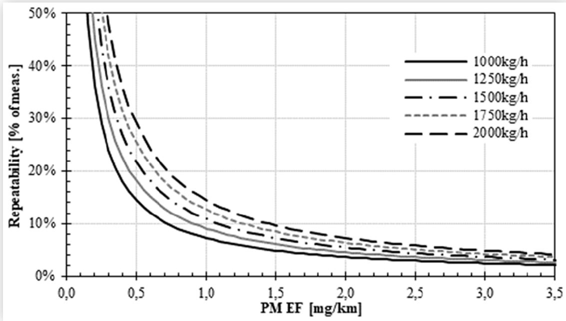
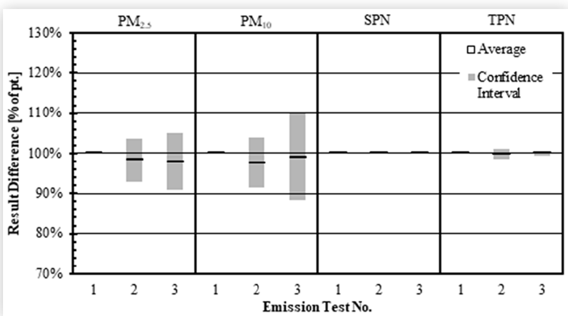


FIGURE 9 PM an PN repeatability after bedding has completed – 3 WLTPs in a row after bedding for 28 different friction couples covering a broad emission level spectrum (100% represents the result of the first emission test after bedding).



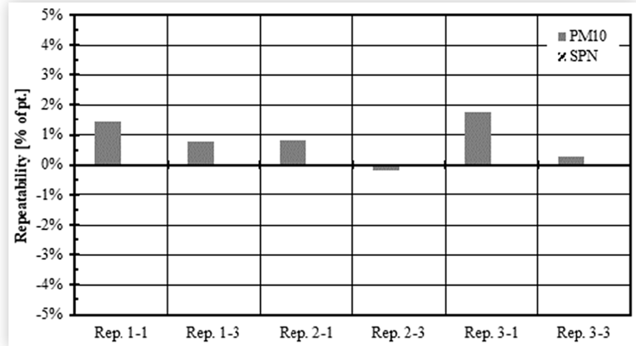
method's performance data will also include the UUT's behavior when following the defined testing process. Similarly, a very typical question in practical testing is if an observed difference is within the expected tolerance or not.

Any brake test procedure has essentially to start with a fresh friction couple which is run in by using the defined bedding procedure (5x WLTP-Brake). The emission result for the subsequent test is then the decisive one. Repetitive emission testing in a row allows to estimate the UUT emission stability. Figure 9 shows a statistical evaluation of the observed differences between official emission test and 2 more repeated tests for 28 different brakes covering a wide spectrum of emission levels and materials.

All brakes have been properly bedded before the first emission measurement and the two repetition tests have been done in a row without changes. The first emission result of each individual brake is defined as 100%. The absolute differences from test to test are scaled as percentage of the applicable limits (7mg/km for PM and 6,0E+11 for PN). This scaling reflects the practical relevance of an observed difference. The gray bars represent this repeatability of the measurements.

On average the $PM_{2.5}$ results show a slightly more decreasing tendency than PM_{10} results. The observed PM mass for the first repetition has been found within ±5,4% of the applicable limit for $PM_{2.5}$ and within ±6,3% for PM_{10}.

FIGURE 10 Emission results after remounting an already bedded low emission brake



Since the average and median of the PN values observed in this study is more than 2 orders of magnitude lower than the referenced exhaust limit, the deviations are nearly invisible in this scale. In absolute numbers the repeatability for SPN is in a range of 2,1E+8 particles/km and 5,3E+9 for TPN.

Most testing labs in the automotive industry operating more than one emission testbed of a kind recognized the need to assure the comparability of results among their testbeds. Therefore, they often have established an intra-laboratory comparison experiment as internal data quality assurance procedure like e.g., recurring emission test using a golden car on a chassis dynamometer. In case of brake emission testbeds any test design involving a reference UUT will implicitly include either the emission behavior variance within a production lot or deviations introduced by re-using golden brake parts. Figure 10 shows an example for the PM_{10} and SPN results of repeated measurements for a low emitting brake after remounting the brake on the same test cell. This brake has been properly bedded according to UN GTR No. 24 and the average of the first 3 emission test were used as reference number for this investigation.

The friction couple has been removed from the testbed and remounted in total 3 times (repetition 1 to 3). The first measurements (-1) for each repetition show higher PM emission results as expected but this effect introduced a maximum deviation of slightly below 2% of the applicable limit or 0,12 mg/km for PM_{10} in the WLTP brake cycle. If the third test result (-3) is used as reference for each repetition (which essentially means 2 WTLPs as additional bedding after reassembling) this difference is further reduced to below 1% of pt. in all cases. The same is true for $PM_{2.5}$. The influence on both particle number results is invisible because the absolute value as well as the maximum observed difference is again 2 orders of magnitude below compared to an assumed limit but here with a steady decrease in number emissions visible over time.

Based on these data it can be concluded that brakes can realistically be reused for emission testing and the concept of having a golden brake is one possible way to go. This could reduce testing effort and resources. Total runtime for a friction couple may be the limiting factor here since the distance driven per test is quite high.

Assure Data Quality

There are only very few parameters apart from the equipment specifications and setup considerations already mentioned the user can influence during productive testing.

The most important parameter in view of data quality is the cooling airflow setting. The value for the cooling airflow is determined in the cooling airflow adjustment test which evaluates the brake disk's temperature behavior during six predefined brake events of trip 10 of the WLTP-Brake. Since the allowed range for initial and final brake disc temperatures measured are quite large, there is a certain range of choices available. As a general guideline the optimal cooling airflow setting will be a compromise between the lowest possible flow to stay within the temperature limits and the increased risk of having volatile particle formation the hotter the disk gets during the test. This optimization reduces the dilution and aims to raise the concentration and filter loading for a specific brake.

The lower the emission factor of a brake is, the more important the particulate background is going to be. UN GTR No. 24 defines a maximum background PN concentration to be checked before and after a test. As long as this PN background value is within 20 particles/cm^3 for both devices the test is fine. This looks reasonable in view of the order of magnitude of the limit expected. A correction for an observed background concentration as it is in other emission regulations is currently not foreseen.

Equally important to maintain high quality PM results is a frequent PM background check especially when attempting to measure low emission brakes, even if this is not required by the current legislation. Unfortunately, an accurate background determination requires a sample duration similar to the emission test and therefore is time consuming but required to assure enough filter loading in case there is some background in the system. The applicable limit needs to be defined as an internal quality standard perhaps depending on the emission level observed.

Experimental Verification

Grigoratos et al. [21] present the results of an interlaboratory study on brake emissions organized by the Particle Measurement Programme Informal Working Group. 16 testing facilities tested 7 brakes and the measurement repeatability and reproducibility were analyzed in terms of PM_{10} and $PM_{2.5}$, using coefficient of variation as the metric. They state that for PM_{10} repeatability, the CoV for the reference brake (the most widely used in the study) was always below 10%, except for one testing facility. Similarly, for $PM_{2.5}$, the CoV was always below 10 %, except for two testing facilities. Altogether, including all the brakes they tested, 16 of the total 51 PM_{10} CoVs have been tagged as 'not good repeatability' (CoV >10 %). A similar metric for $PM_{2.5}$ was 18 of the 47.

In addition to just CoV, it is important to look at the deviations in terms of absolute masses, and to compare them to the PM_{10} limit value of 7 mg/km per vehicle. The mean emission factor obtained in the study for this brake was 5 mg/km per brake. Multiplying this value with the 10 % CoV would give a standard deviation of 0.5 mg/km, which is approximately 7 % of the limit.

For the reproducibility, Grigoratos et al. [21] present CoVs of 17-54% and 28-52% for PM_{10} and $PM_{2.5}$, respectively. In most cases, the CoV was approximately 30-35%. However, they state that most of the test facilities did not comply to the agreed technical specifications, and with a subset of test facilities that had the fewest deviations from the specifications, the PM_{10} reproducibility was better (23 % instead of 35 % for the reference brake). Additionally, after "filtering" the data (see [21] for details), they finally state that for most brakes, the reproducibility was close to 20% for PM_{10} and close to 30 % for $PM_{2.5}$. As a similar comparison to the PM_{10} limit value, for the reference brake the CoV after filtering was found to be 19 %. This equates to a standard deviation of 0.95 mg/km, which is approximately 14 % of the limit.

Summary/Conclusions

The upcoming Euro 7 legislation which will come into force most probably in 2025, will include limits for brake wear emissions. As basis for this limitation the PMP as organization within the UNECE has generated the technical regulation defining the details of the measurement procedure, which will officially be published as UN GTR No. 24 soon. The sampling and measurement systems are specified in detail but still allowing some freedom in designing the testbed systems.

In general, data quality is key for efficient testbed operation and product certification testing, but it is a product of numerous influencing factors from different sources. The most important ones have been summarized from a testbed operations point of view. The measurement result following the defined method must be reproducible between different laboratories primarily for homologation testing and must generate repeatable results to allow efficient development.

The different components of the sampling and measurement system contribute in different ways to the final data quality. Most parameters of the hardware design of the sampling systems and the measurement devices influence the reproducibility. Cyclone cutoff characteristics, isokinetic ratio during sampling, transfer line bending and length as well as probe alignment are among the most important ones to properly measure PM. The PN measurement has been found less critical from the setup point of view.

PM sampling requires the availability of a highly professional filter weighing facility and robust internal processes to assure good repeatability of PM results. The importance is even more elevated as soon as low emitting brakes are measured. Realistically, the actual performance of the weighing process must be better than that specified by the regulation. Testing facilities will have to setup strict internal guidelines and observe their process robustness as it is the case for state-of-the-art exhaust emission labs.

Apart from some considerations given to guide test engineers to support quality in measurement by choosing quality optimal user settings, a few remarks on the setup of an intra-laboratory experiment have been given. Such quality assurance procedures are mandatory for larger facilities – especially for ISO 17025 compliant testing labs.

There have been a lot of measures implemented during the generation of the UN GTR No. 24 in order to increase the reliability of the results based on good engineering judgment and small single comparison experiments. The final method as it is defined right now has not been proven by a comprehensive accuracy experiment. Such experiment is planned by the PMP group for the near future.

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Definitions/Abbreviations

CoV - Coefficient of variation. Standard deviation divided by the average

d - Distance driven

dNdlogDp - Particle number concentration in the size bin scaled by the width of the size bin

dMdlogDp - Particle mass concentration in the size bin scaled by the width of the size bin

Dp - Particle diameter

Dp_{50} - Particle diameter at 50 % cutoff

D_t - Tunnel diameter

EEPS - Engine Exhaust Particle Sizer

EF - Emission factor

Empty Filter Weight - Represents the average between two weighing results for an empty filter as required by UN GTR No. 24

GRPE - Working Party on Pollution and Energy

GTR - Global technical regulation

Loaded Filter Weight - Represents the average between two weighing results for a loaded filter as required by UN GTR No. 24

m_{filter} - Filter loading

m_{sample} - Mass sampled through filter during PM sampling

m_{total} - Total mass of cooling air flowing through the enclosure during PM sampling

OPS - Optical particle sizer

PM - Particulate matter

$PM_{2.5}$ - Particulate mass of all particles with a diameter up to 2.5µm

PM_{10} - Particulate mass of all particles with a diameter up to 10µm

PMP - Particle Measurement Programme

Repeatability - 95% Confidence Level

s - Cyclone cutoff curve steepness parameter

SPN - Solid particle number

TE - Transmission efficiency

TPN - Total particle number

UNECE - United Nations Economic Commission for Europe

UUT - Unit under test, in the context of this paper consisting of brake disc, brake pads and caliper

WHTC - Worldwide Harmonized Transient Cycles

WLTP-Brake - Load cycle used for brake emission testing as defined in UN-GTR 24

% of meas. - Refers to the actual (flow-weighted) mean value over any test interval [19]

% of pt. - Refers to an overall (flow-weighted) mean value expected at standard or the standard [19]

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