Particle Measurement Program Informal Working Group

BRAKE EMISSIONS TASK FORCE 2 (TF2)

MINIMUM SPECIFICATIONS FOR MEASURING AND CHARACTERIZING BRAKE EMISIONS

The PMP IWG TF2 on brake emissions comprises the following entities/participants (listed in alphabetical order): AUDI (S. Gramstat), AVL (T. Mamakos, M. Arndt), BMW (K. Kolbeck, J. Von-Wild, T. Schroeder), BREMBO (M. Federici, G. Perricone), CARB (Q. Yao, S. Yoon), CONTI (A. Reich, S. Fischer), DEKATI (M. Moisio), DRIV (M. Morbach, C. Koelsch), FORD (R. Vogt, J. Grochowicz, M. Mathissen), GM (M. Robere), HORIBA (G. Kanae Filler, D. Lugovyy), ITT (A. Sin, S. Ansaloni), JARI (H. Hagino), JRC (T. Grigoratos, B. Giechaskiel), LINK-EU (A. Hortet, C. Schmidt), LINK-US (C. Agudelo, R. Vedula), STELLANTIS (O. Bausch), TMD (P. Nyhof), TSI-EU (S. Percot), TSI-US (B. Anderson, F. Romay), TU ILMENAU (D. Hesse)

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Content

1 Test Cycle (WLTP-Brake Cycle)

The testing cycle shall be the time based WLTP-Brake Cycle profile*[1]*. The execution of the cycle shall follow the specifications prescribed in Clause 6.5 of the GRPE-81-12 in terms of speed violations. A maximum 10% of speed violations are allowed during the execution of the WLTP-Brake Cycle. A speed violation occurs whenever the actual speed of the dynamometer exceeds the upper or lower speed trace tolerance[2] compared to the nominal speed. All types of events (dwell, acceleration, cruising, and deceleration) shall be considered for the computation of speed violations. ***The 10% maximum allowed violation limit applies to the execution of WLTP-Brake Cycle during bedding and emissions testing as well as for the adjustment of the cooling air speed with the application of Trip #10 of the WLTP-Brake Cycle*** (see below "Clause 2. Cooling air speed adjustment").

The WLTP-Brake Cycle involves the performance of ten trips in succession. ***Trip #1 of the cycle shall commence at ambient temperature (20±5°C) without conducting any warm-up stops or snubs. For all subsequent trips, the lab shall wait until the brake reaches exactly 40°C*** (for temperature measurement see below "Clause 5. Measurement of brake temperature")***.*** This allows for a reduction of the soak period and the overall testing time. If multiple consecutive emission tests are conducted, Trip #1 of the second – and all additional cycles – shall commence at 40°C. If the final temperature of a section is below 40°C the subsequent trip shall commence immediately without any intervention to warm the brake. Specific provisions apply for soak times during the bedding-in procedure (see below "Clause 6. Bedding-in procedure").

In the event the test is interrupted during the bedding procedure, the lab shall continue bedding without conducting any warm-up stops or snubs to reach 40°C. In the event the test is interrupted in-between trips, the lab shall continue the test without conducting any warm-up stops or snubs to reach 40°C, provided that the interruption does not exceed a reasonable amount of time[3]. ***In the event, the test is interrupted during Trips #1 through #10 the lab shall discontinue the emissions test, substitute the used filters with new, and restart the emissions tests from the beginning***.

The adjustment of the cooling air speed for the different brakes and dynos shall be carried out using Trip #10 of the WLTP-Brake Cycle (see below "Clause 2. Cooling air speed adjustment"). ***Trip #10 of the WLTP-Brake Cycle shall commence at 40°C*** per Clause 7.5.1d of the GRPE-81-12***.*** In order to warm the brake to 40°C, a sequence of stops 1 to 7 of Trip #10 with subsequent cooling phase down to 40°C is recommended.

More information regarding the WLTP-Brake Cycle and the execution of the protocol are included in the Informal Document GRPE-81-12 "Part 1: Inertia Dynamometer Protocol to Measure and Characterise Brake Emissions Using the WLTP-Brake Cycle".

2 Cooling air speed adjustment[4]

To determine the appropriate airstream speed for a given brake, labs shall first classify the tested brake into a Wheel Load to Disc Mass (WL/DM) Group according to its WL/DM ratio. The "Nominal Wheel Load" is calculated taking into account the mass in running order of the vehicle on which the

[1] A copy of the spreadsheet with the 1 Hz speed traces is available at https://data.mendeley.com/datasets/dkp376g3m8/1

[2] The upper-speed tolerance is defined as 2 km/h higher than the highest point of the prescribed trace within ±1 s of the given time point. The lower-speed tolerance is defined as 2 km/h slower than the lowest point of the prescribed trace within ±1 s of the given time point.

[3] To be defined after the ILS and when more data will become available

[4] Deviation from Clause 7 of GRPE-81-12

tested brake (front or rear) is mounted (kg)[5] and the mass corresponding to additional 0.5 passengers (kg)[6]. The "Nominal Wheel Load" differs from the "Actual Wheel Load" applied during emissions testing. The "Actual Wheel Load" is reduced by 13% compared to the "Nominal Wheel Load" to account for parasitic losses. The WL/DM ratio is directly calculated by dividing the "Nominal Wheel Load" (kg) by the actual mass of the tested disc (kg). ***Four different Groups have been identified based on the WL/DM ratio:***

- ***1st Group: WL/DM ≤45;***
- ***2nd Group: WL/DM >45 & ≤65;***
- ***3rd Group: WL/DM >65 & ≤85;***
- ***4th Group: WL/DM >85.***

Each WL/DM Group comes with its own target values for each target temperature parameter discussed below. The target values and tolerances are given in Table 1.

Table 1 – Default temperature metrics and limits for brakes during Trip #10 of the WLTP-Brake Cycle

WL/DM Groups	Average [A_1] [°C]	IBT [A_2] ± Tolerance [°C]	FBT [A_3] ±Tolerance [°C]
≤45[7]	>50	55±15	85±25
>45 & ≤65	>55	65±15	105±25
>65 & ≤85	>60	75±15	120±25
>85	>65	85±15	140±25

After having classified the brake to its WL/DM Group, labs shall run Trip #10 of the WLTP-Brake cycle with new brake parts to obtain the parameters to populate the cells on Table 2 and compare to the limits described on Table 1 for the dedicated WL/DM Group. The following target parameters shall be used as reference against which the cooling adjustment results shall be compared to:

- ***Average brake temperature over the entire Trip #10 of the WLTP-Brake Cycle*** (A_1 – Value depends on the WL/DM Group);
- ***Average Initial Brake Temperature (IBT)*** of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle (A_2 – Value depends on the WL/DM Group);
- ***Average Final Brake Temperature (FBT)*** of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle (A_3 – Value depends on the WL/DM Group).

The same target parameters shall be calculated from the 1Hz dynamometer data after executing the first attempt to adjust cooling air speed over Trip #10 of the WLTP-Brake cycle for the tested brake system. More specifically the labs shall calculate:

- Average brake temperature over the entire Trip #10 of the WLTP-Brake Cycle (B_1 – Value shall be calculated from the brake dyno measurement);

[5] "Mass in running order" means the mass of the vehicle, with its fuel tank(s) filled to at least 90% of its capacity, including the mass of the driver, fuel and liquids, fitted with the standard equipment in accordance with the manufacturer's specifications and, when they are fitted, the mass of the bodywork, the cabin, the coupling and the spare wheel(s) as well as the tools as per GTR 15 Clause 3.2.5.

[6] Passenger mass corresponds to 75 kg

[7] Temperature values (Average, IBT, and FBT) of this group might be revisited when more data become available

- Average IBT of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle (B_2 – Value shall be calculated from $Y_{1…6}$) from the individual values ($Y_{1…6}$ – Individual values shall be recorded during the brake dyno measurement);
- Average FBT of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle (B_3 – This value shall be calculated from $Z_{1…6}$) from the individual values ($Z_{1…6}$ – Individual values shall be recorded during the brake dyno measurement).

After the calculation of the temperature values during Trip #10, the differences between target and dynamometer results for the following parameters shall be calculated:

- **Difference (C_1)** in average brake temperatures B_1 and A_1 as defined above (B_1-A_1);
- **Absolute difference (C_2)** in average IBT of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle B_2 and A_2 as defined above ($|A_2-B_2|$).
- **Absolute difference (C_3)** in average FBT of events #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle B_3 and A_3 as defined above ($|A_3-B_3|$).

Finally, labs shall compare the results from the previous step with the acceptance limits as given in Table 2 (also included in Table 1). ***All three criteria shall be fulfilled for a successful adjustment of the cooling air speed.***

Table 2 – Calculation of brake temperature metrics [°C] and limits during Trip #10

Event	Metric	Target Temperature	Dynamometer Temperature	Difference	Acceptance Criteria
–	*Average Temperature*	A_1	B_1	$C_1=B_1-A_1$	$C_1 \geq 0$
#46			Y_1	n/a	n/a
#101			Y_2		
#102			Y_3		
#103			Y_4		
#104			Y_5		
#106			Y_6		
–	*Average 5% IBT*	A_2	B_2=AVG(Y_1:Y_6)	$C_2=\|A_2-B_2\|$	$C_2 \leq 15$
#46			Z_1	n/a	n/a
#101			Z_2		
#102			Z_3		
#103			Z_4		
#104			Z_5		
#106			Z_6		
–	*Average 5% FBT*	A_3	B_3=AVG(Z_1:Z_6)	$C_3=\|A_3-B_3\|$	$C_3 \leq 25$

The cooling air adjustment method shall apply to all front conventional brake systems (Vented Gray Cast Iron). It is recommended to apply this method also to other types of available discs (i.e. Solid Gray Cast Iron, Coated Discs, Carbon Ceramic Discs, etc.). Target values for other types of discs and drum brakes might be revised when more data become available. ***It is recommended to perform the cooling adjustment of rear brake systems by applying the cooling air flowrate obtained for the corresponding front brake application (i.e. same vehicle data) through the method described above.*** Target values for rear brakes might be revised when more data become available.

3 Background concentration

Each laboratory shall follow the recommendations described below to perform the background concentration check:

The cooling air entering the brake enclosure during a brake particle emission test shall pass through a medium capable of reducing particles of the most penetrating particle size in the filter material by at least 99.95%, or through a filter of at least class H13 as specified in EN 1822. It is recommended that the cooling air entering the brake enclosure passes through a charcoal (or activated carbon) filter with the aim of removing volatile organic species[8]. In case that a charcoal (or activated carbon) filter is applied it shall be installed upstream of the H13 (or equivalent) filter. In case applied, the lab shall ensure that the installation of the filters will have no impact on the flow and the flow distribution.

The background concentration shall be defined on a PN basis. ***Background PN concentrations shall be measured in (# particles/cm^3) and expressed in (# particles/km) to reflect the changes of the cooling air flowrate when testing different brakes.*** Each laboratory shall report their background concentration over each emissions test as defined below (see second level background check). ***The background concentration shall not exceed the maximum allowed value of X[9] #/km calculated on the basis of Equation 1:***

$$[1] \quad PN_{Back}\,(\#/km) = 10^9 \times [PN_{Back}\,(\#/cm^3) \times Q_{Tunnel}\,(m^3/s)] / 12.14\,(m/s)^{10}$$

The background concentration shall be measured by means of the same instrumentation as applied for emission measurements. A decision for the need of the application of background subtraction/correction will be taken after the completion of the ILS.

The background concentration check shall be performed at two levels. The first level concerns the system background upon installation (or when there are indications of system malfunction) and shall run without the brake assembly or fixture being mounted. The background check shall commence 5 min after the incoming cooling air flow is stabilized and shall run at three different settings representing the whole range of the dyno capabilities (10%, 50%, and 90% of the maximum airflow). Each run at this level shall last at least 30 min (or as long as it takes for the background concentration to stabilize).

The second level concerns regular background checks before and after the execution of a brake emissions test. The regular background pre-test shall take place before the bedding-in procedure with the brake assembly mounted; however, with the disc/drum not rotating and the pads/shoes being fully retracted. The background check shall commence 5 min after the incoming cooling air is stabilized and shall run for 5 min (or as long as it takes for the background concentration to stabilize) at the airflow setting of the emissions test. The background check shall be repeated after the completion of the bedding-in procedure with the disc/drum not rotating and the pads/shoes not being disturbed. The regular background post-test shall run before purging and with the brake assembly mounted. The disc/drum shall not rotate, while the pads/shoes shall not be disturbed. The

[8] A decision regarding the use of these filters will be taken after the ILS.
[9] The value will be defined after the completion of the ILS.
[10] Corresponds to the average linear speed of the WLTP-Brake Cycle in [m/s]

background post-test shall run for at least 5 min (or as long as it takes for the background concentration to stabilize) at the airflow setting of the emissions test.

No pressure shall be applied to the brake assembly during background concentration checks. The incoming cooling air shall be conditioned to 20±2°C and 50±5% relative humidity. The background measurement shall take place by means of the same instrumentation as used for emission measurements.

4 Dyno Climatics

Volume flow shall be constant throughout the entire brake emissions test (bedding + emissions) as well as the cooling air adjustment procedure. ***Volume flow shall be reported in order to avoid wrong comparisons.*** Air speed or airflow is recommended to be measured either upstream of the enclosure or downstream of the sampling point. When measuring the volume flow upstream of the enclosure, it is recommended that the flow element is located at the centre of the duct and at least 8 hydraulic diameters downstream of any flow disturbance or sample probe and at least 2 hydraulic diameters upstream of any flow disturbance. When measuring the volume flow downstream of the sampling point, it is recommended that the flow element is located at the centre of the duct and at least 8 hydraulic diameters downstream of the sampling point and at least 2 hydraulic diameters upstream of any flow disturbance. When flow is measured downstream of the sampling point, the extracted flows for particle characterization need to be externally added in the reported tunnel flow[11]

Incoming cooling air temperature and relative humidity shall be set to 20°C and 50%, respectively. Labs need to make sure they stay as close to the target values as possible (20°C and 50% RH). ***Emission tests shall be considered successful when the average temperature of the incoming cooling air during the test falls within ±2°C with respect to the target value (i.e. 20±2°C) AND when the average relative humidity of the incoming cooling air during the test falls within ±5% of the target value (i.e. 50±5%). If the average temperature or the average relative humidity or both fall out of the predefined thresholds the test shall be considered invalid.*** The calculation of the incoming cooling air average temperature and relative humidity shall be conducted using the EED 1Hz data for these parameters (see below “Clause 11. Minimum parameters to be registered and test reports”). The temperature and relative humidity of the incoming cooling air are allowed to oscillate between 20±5°C (i.e. between 15-25°C) and 50±10% (i.e. between 40-60%), respectively, for no longer than the 10% duration of the cycle provided that the average targets as defined above are met.

The same temperature and relative humidity requirements for the incoming cooling air as described above shall apply during the bedding procedure as well as during the cooling air adjustment procedure.

5 Measurement of brake temperature

Embedded thermocouples shall be used for the measurement of the brake disc or drum temperature. The disc thermocouple shall be located in the outboard plate rubbing surface – radially positioned 10 mm outwards of the centre of the friction path – and recessed (0.5±0.1) mm deep into the face of the disc. On vented discs the thermocouple shall be centred between two fins

[11] In accordance with Figure 1A-1 of EPA Method 1A

of the disc plate. Figure 1 illustrates the proper installation of embedded thermocouples on brake discs. ***The drum thermocouple shall be located at the centre of the friction path (0.5±0.1) mm deep in the inside surface of the brake drum.*** The temperature readings of embedded thermocouples shall be used to control the test temperatures and initiate individual trips as described in Clause 1. Sliding thermocouples might be also used but always complementary to the embedded thermocouples.

It is recommended to also measure brake pad or shoe temperature in parallel to the disc temperature. It is recommended to embed one thermocouple at a depth of 1.0 mm near the centre of the friction surface on each pad. For disc brake pads with grooves it is recommended to install the thermocouple at least 4.0 mm from the groove edge on the leading side of the pad. For inboard pads on single-piston callipers it is recommended to install the thermocouple on the leading edge 3.0 to 4.0 mm from the piston outside diameter near the centre of the friction surface. For brake shoes it is recommended to embed one thermocouple at a depth of 1.0 mm near the centre of the friction surface of the most heavily loaded shoe. Special attention shall be paid to the tear, wear, and routing (to allow free calliper movement) of the thermocouple wire for inner pads.

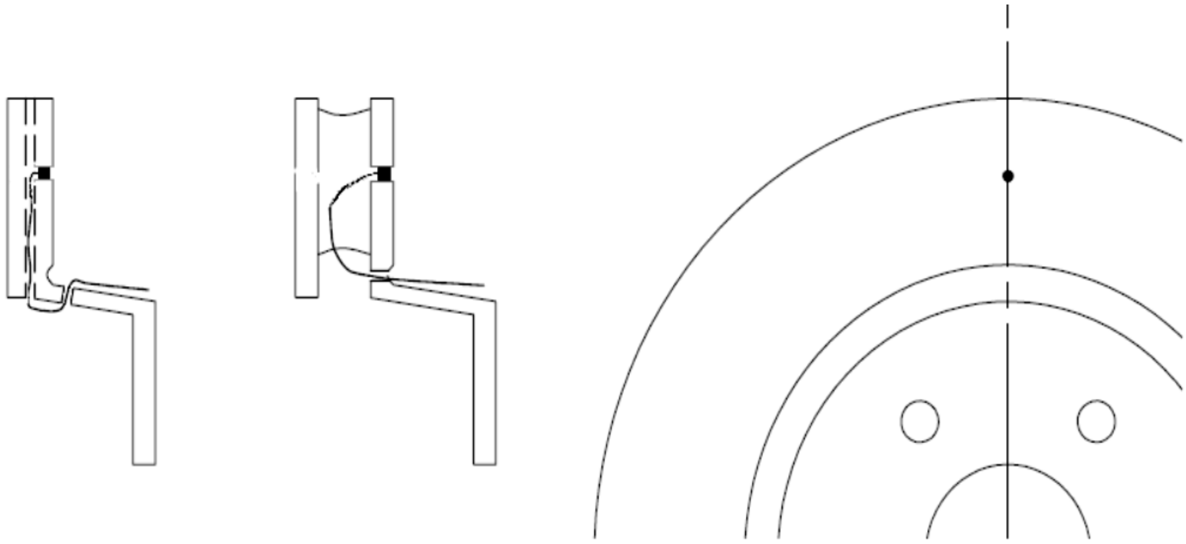

Figure 1: Schematic installation of embedded thermocouples

6 Bedding-in procedure

The bedding procedure is very important to stabilize the emission behavior of the brake couple prior to performing emission tests. On one hand, it shall be long enough to ensure the stabilization of the behaviour of the friction couple. On the other hand, there needs to be a compromise in terms of the stabilization of the couple in order to ensure a reasonable testing time.

Laboratories shall apply 5 WLTP-Brake cycles for the appropriate bedding of disc/pad couples and drum brakes[12,13]. The 5 WLTP-Brake Cycles shall run consecutively without any interruption. In the event the test is interrupted (or the dynamometer faults) during the bedding procedure, the lab shall continue the bedding without conducting any warm-up stops or snubs. ***Soak times shall not apply between the individual trips during the bedding procedure. However, each one of the 5 repetitions***

[12] The number of cycles required for the proper bedding of drum brakes might be revised after the ILS.

[13] Labs are invited to run an additional testing campaign with the aim of comparing the bedding of a brake couple with the application of 5 WLTP-Brake cycles against the application of 10 Trips #10 of the WLTP-Brake cycle. ***The latest shall not substitute the default bedding procedure but shall be done in parallel with brand new brake couples.*** The bedding of the brake couples will be evaluated based on their PN emissions and the friction coefficient.

(i.e. WLTP-based novel cycle) shall commence at 40°C (1st repetition shall commence at ambient temperature). No additional purging between the cycles is required. All other parameters shall be the same as of emissions testing.

The bedding procedure shall be carried out on the same dynamometer as the actual emissions measurement without disassembling the parts between the two procedures. This is to avoid modifying the contact points and subsequently the emissions behaviour.

It is recommended to record PN emissions during the bedding procedure but not use the values for emission calculation purposes as concentrations might be artificially increased. PN emissions reported along with the brake effectiveness can be used to evaluate the stabilization of emissions. The procedure shall apply for all existing conventional brake materials and couples.

7 Brake enclosure design

Design requirements for the enclosure are defined with the aim of achieving maximum transport efficiency, maximum particle distribution/uniformity, and minimum residence time. The definition of the geometric boundary conditions – as well as of the design of the enclosure – allows for adjustments and innovative further developments; however, provides some general guidance to ensure systems' comparability.

The brake enclosure shall incorporate good aerosol sampling practice that includes the use of smooth internal surfaces (i.e. curved edges) and the avoidance of sharp bends and abrupt changes in cross-section with the aim of reducing flow recirculation zones. Gradual changes in the cross-section are permitted; however, it is recommended to apply smooth transition angles to overcome these cross-section changes and avoid application of ≥90° bends.

The brake enclosure shall come in dimensions which allow for measurements of all common sizes of LDV brake assemblies up to 3.5t. However, it is strongly recommended to avoid oversized enclosures due to higher residence times and increased particle losses.

To avoid particle losses by electrostatic deposition it is recommended to use electropolished surfaces (i.e. stainless steel) or other electrically conductive material for the design of the inner walls of the enclosure.

The enclosure shall be designed in such a way that a maximum particle residence time of X[14] sec is ensured. Every lab shall report the maximum residence time for their setup based on their specific design for a given cooling air flow rate. The calculation of the residence time shall be performed in house by means of a commonly acceptable methodology.

The calliper shall be positioned in a way to minimize a potential interference with the incoming cooling air. ***Depending on the orientation of the duct works (horizontal or vertical), it is recommended to install the calliper at the upper part of the disc in a position between 1 and 2 o´clock or 10 and 11 o´clock considering the direction of evacuation*****.** It is recommended to replicate calliper position as in vehicle whenever (and only if) it is within the above defined range. Other options for the calliper orientation might be considered (i.e. 3 o´clock), if experimental data proving similar evacuation efficiency to the recommended ones are provided. Options might be further

[14] Value to be defined after the experimental ILS

restricted in the future for standardization purposes when more data relative to the different options become available.

The brake disc shall rotate in the direction of the evacuation independently of the orientation of the duct works (horizontal or vertical) as shown in Figure 2. More specifically, if the incoming cooling air flows with a direction from right to the left the disc shall rotate Counter Clock Wise (CCW), whereas when incoming cooling air flows with a direction from left to the right the disc shall rotate Clock Wise (CW).

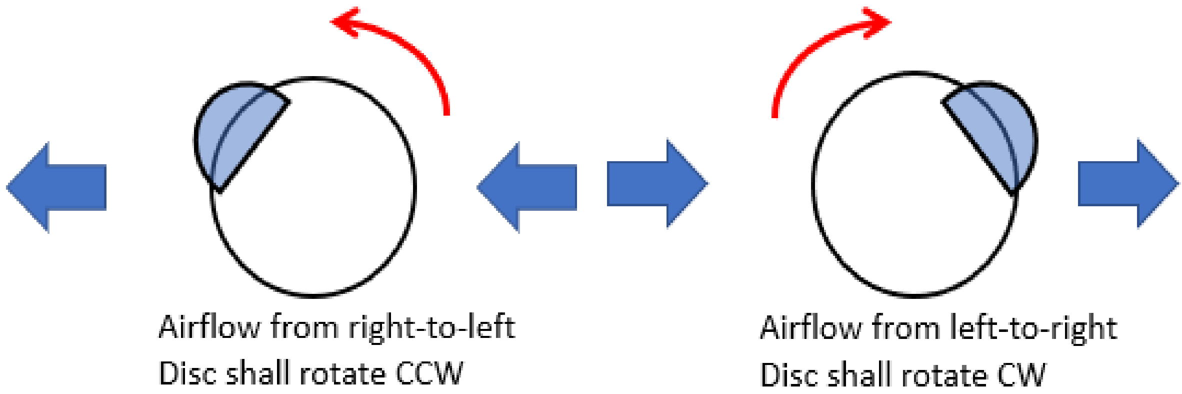

Figure 2: Schematic representation of disc rotation

8 Estimation of the losses in the duct and the sampling trains

Each lab shall report the estimation of the particle losses in the duct and the sampling train (from the tip of the sampling nozzle to the entry port of the given instrument or sampling device) based on calculations performed in house. Available options include but not limited to:

- Estimation of the losses by means of LINK PALS Macro (Optional)[15]
- CFD studies (Optional)
- Particle size distribution (Optional)

9 Measurement of PM Mass concentration

Brake PM_{10} and $PM_{2.5}$ mass emissions shall be measured gravimetrically. The following minimum specifications shall apply:

Transport and Extraction – ***It is recommended to limit bends to a minimum – and when necessary – design them with a radius greater than 1.5 times the duct/tube diameter (ISO 9096)***.

The sampling plane shall be located at least 5 hydraulic diameters downstream of the last flow disturbance element according to ISO 9096. Similarly, the sampling plane shall be located at least 2 hydraulic diameters upstream of a flow disturbance element according to ISO 9096.

Appropriate nozzles (i.e. isokinetic nozzles) to ensure isokinetic sampling for both PM_{10} and $PM_{2.5}$ shall be used. It is recommended that the inner diameter of the nozzles is >4 mm (ISO 9096). It is recommended to use thin-wall nozzles to minimize distortion of flow (i.e. nozzles with outer to inner

[15] It is recommended to use the LINK PALS Macro. LINK PALS Macro estimates the transport losses using empirical models in the aerosol literature for each individual geometrical element (transition, bend, straight duct, etc.) of the test system. It does not account for element-to-element flow interactions and wall impingements but provides an overall particle transport efficiency of the test system.

diameter ratio <1.1). ***The isokinetic ratio*** (the ratio of air velocity in the nozzle to the air velocity in the duct) ***shall be kept between 0.9 and 1.15. Aspiration angle shall be restricted to ±15°. Isokinetic nozzles shall be cleaned following the specifications of the manufacturer regarding the cleaning frequency and means.*** Cleaning usually includes soaking of the nozzle plates in a solvent (i.e. IPA) so that contaminant particles are fully removed.

The use of flow splitters for PM measurements is not encouraged. If a flow splitter is used it is recommended to keep the change in the flow angle to within 20^o for each outlet.

PM Sampling Devices[16] – ***Single- or multi-stage PM_{10} and $PM_{2.5}$ cyclonic separators followed by gravimetrical filter holders shall be the primary choice for the collection of the PM_{10} and $PM_{2.5}$ samples. Alternatively, single- or multi-stage inertial impactors can be used for the collection of the PM samples***. Commercially available cyclonic separators and inertial impactors shall be used and the penetration as a function of aerodynamic diameter shall be provided. The separation efficiency specifications described in ISO 23210 and ISO 25597, respectively, shall be followed. The specifications described in ISO-16000-37 shall be followed for the gravimetrical filter holders.

If an additional pre-classifier is applied before the actual PM collection device it shall feature a cut-off point ≥11.5 µm. This is necessary to avoid compromising the efficiency of the actual PM sampling device. The pre-classifier outlet may be configured with a means of bypassing any PM sample filter so that the pre-classifier flow can be stabilized before starting a test. ***PM sample filter shall be located as short as possible without exceeding 1 m downstream of the pre-classifier's exit.***

Inertial classifiers shall not be changed when performing different emission tests where there is a need for adjusting tunnel flows to meet the cooling requirements. Sampling flows to the inertial classifiers shall be adjusted by means of the appropriate isokinetic nozzles. The sampling volumetric flow shall be maintained constant not to compromise the associated collection efficiency curve. It is recommended to apply a device with a flow control feature to ensure a stable flow through the filter medium and ensure that the flow rate remains within 5% of set point throughout the test.

It is recommended for the PM sampling devices to have the capability to by-pass the main flow during the application of soak times of the WLTP-Brake cycle.

The inner walls and nozzle plates – if applicable – (i.e. impaction nozzles) of the impactors or the inner walls of the cyclones shall be cleaned following the specifications of the instrument manufacturer regarding the cleaning frequency and means. Cleaning includes soaking of the nozzle plates in a solvent (i.e. IPA) so that contaminant particles are fully removed. The individual nozzles of the impactor nozzle plates or the cyclone inlet tubes shall be clean and free of particle deposits.

Sampling media – Filters used to sample brake PM emissions shall comply per EN12341 with at least the following minimum requirements: Plane filter efficiency better than 99.5% on a test aerosol with a aerodynamic diameter of 0.3 µm at the maximum sampling flow rate or better than 99.9% on a test aerosol of 0.6 µm aerodynamic particle diameter. This efficiency shall be certified by the filter supplier.

[16] Pre-classifier – A cyclonic separator placed upstream of the classifier; Classifier – An inertial impactor consisting of impaction substrates (or) a cyclonic separator placed upstream of the filter holder; Isokinetic nozzle – Probe to sample particle-laden airflow from the cooling duct into the sampling tube; Nozzle plate – Size classification component of an inertial impactor

Teflon-coated Glass Fiber filters (i.e. Pall EMFAB TX40) or PTFE 47 mm Membrane filters with polymer support (i.e. Pall Teflo) or an appropriate impaction substrate as specified below shall be used for the brake PM_{10} and $PM_{2.5}$ mass measurement.

Cyclonic Separators – ***Both types of filters (i.e. Teflon-coated Glass Fiber filters and PTFE 47 mm Membrane filters with polymer support) are allowed when a cyclonic separator is applied for PM sampling. Special care shall be taken during handling and weighing to neutralize collected electrostatic charge when PTFE 47 mm Membrane filters with polymer support are used.***

Inertial Impactors – ***When inertial impactors are applied for PM sampling it is highly recommended to use aluminium foils or polycarbonate film as impaction substrate. The impaction substrate shall be properly coated with a thin layer of adhesive collection substrate (stable vacuum grease or silicone oil) to eliminate the particle bounce and re-entrainment.*** Alternatively, PTFE 47 mm Membrane filters with polymer support (i.e. Pall Teflo) may be used. This type of filters is recommended when inertial impactors are applied for PM sampling and a subsequent chemical analysis of the collected PM is required. Special care shall be taken during handling and weighing to neutralize collected electrostatic charge. ***Membrane filters shall be used without the application of a grease coating[17].*** It is generally not recommended to use Teflon-coated Glass Fiber filters as impaction substrates[18] unless all specifications described in JASO C 470 are met[19].

Weighing Procedure – ***Only the filter – or the impaction substrate – shall be weighed and not any other part of the testing equipment***. When cascade impactors are employed for particle separation and collection, the impaction substrates shall be coated beforehand with a thin layer of adhesive material (such as silicone grease). The coated substrates shall then be heated in an oven (at 100°C for aluminum foils) to evaporate any volatile components in the applied coating. In such case the impaction substrates shall then be weighed with the pre-conditioned grease coating. The following minimum requirements shall be ensured:

- Pre-sampling conditioning – ***The filters or substrates shall be conditioned for a minimum of 24h in standard temperature and humidity conditions before sampling. It is proposed to condition filters at 22±3°C and 50±10% RH per clause 1 of CFR 1065.190 if the stabilization area is separate from the weighing area***. Longer conditioning might apply when prescribed by the filter manufacturer. The environmental chamber air shall be filtered by a HEPA H13 filter as minimum.
- Post-sampling conditioning – Filter samples after testing shall be taken to the conditioning room within a reasonable time frame[20] and conditioned. ***This includes conditioning for a minimum of 1h at 22±3°C and 50±10% RH as prescribed above***. Longer conditioning might apply when prescribed by the filter manufacturer; however, in such case post-sampling conditioning shall be identical to pre-sampling conditioning.
- Weighing room – Weighing room environmental conditions shall be continuously regulated to ensure ***controlled conditions at 22±1°C and 50±5% RH***. Air-flow for the air exchange should not influence the balance stability. ***A charge neutralizer (radioactive or corona-based) shall be placed in the proximity of the balance so that filters can be discharged before being positioned on the***

[17] Particle bounce is expected to be low due to the surface of the filter being relatively soft. It can still happen particularly at low RH.
[18] Teflon-coated Glass Fiber filters may change the impactor efficiency curves as the jets can penetrate into the filter and remove some particles by filtration in addition to the impaction.
[19] Teflon-coated Glass Fiber filters may be used as impaction substrates if the impactor does not significantly change the distance between the tip of the particle acceleration nozzle and the top of the filter media for particle collection (JASO C 470).
[20] Shall be evaluated during the ILS and might be amended

balance to avoid electrostatic forces interference. It is recommended that the static-electricity neutralizer is electrically grounded in common with the balance.

- Weighing balance – The same microbalance for both pre- and post-tests weighing shall be used in a given emission test. The balance shall be isolated from vibrations, electrostatic forces, and air streams. ***In addition, it shall be placed in a controlled environment – the weighing room – following the specifications described in the previous clause. The balance resolution should be at least 1 µg.*** Certified calibration weights to verify the stability and the proper function of the microbalance shall be used on a regular basis. It is recommended to repeat balance performance checks if the difference between the measurement and certified value exceeds 10 µg.
- Storage and transfer conditions – ***Weighed filters to be stored shall be kept in appositely made filter boxes designed to host the specific filter size. Stainless steel tweezers shall be used for filter handling.*** Minimize filter movement within the petri dishes/bags and transport as much as possible. Agree with test requestor for any transport outside the test facility.
- Reference Filters – PM data shall be validated using reference filters. At least two reference filters that match each sampled filter media shall be selected. Reference filters shall be weighed at the beginning and the end of a weighing session. ***The average difference between the initial and final measurement for the Teflon-coated Glass Fiber and the PTFE reference filter shall remain within ±10 µg and Quartz fiber filter shall remain within ±40 µg***[21].

Sample weighing – It is recommended to weigh each filter sample twice. ***When the difference between the first and second measurement is higher than 30 µg (subject of revision after the Interlaboratory Study) the sampled filter shall be measured for a third time.*** If the difference between the second and third measurement is higher than 30 µg the measurement shall be considered invalid and the filter void.

10 PN concentrations measurement

The Particle Number (PN) measurement system shall consist of a pre-classifier, a sampling line, a diluter incorporating one or more dilution stages, and a Condensation Particle Counter (CPC). Alternative particle measurement technologies are allowed but shall be used always in parallel to the CPC for comparison purposes.

1. ***The sampling plane of the probe shall be located at least 5 hydraulic diameters downstream of the last flow disturbance element*** similarly to the PM Mass sampling plane. ***Additionally, the sampling plane shall be located at least 2 hydraulic diameters upstream of a flow disturbance element*** similarly to the PM Mass sampling plane.

2. In order to protect the PN system from contamination a pre-classifier with a cut-off point between 2.5 and 10 µm shall be used. It is recommended to use a pre-classifier with a cut-off point close to the lower range of the aforementioned interval (i.e. 2.5 µm).

3. The sampling line from the probe tip to the diluter (without considering the pre-classifier) shall have a maximum residence time of 1.5 s (to minimize coagulation) as well as a maximum Length (L) to Sample Flow (Q_{sam}) ratio of 60000 s/m^2 (to minimize diffusion losses). ***The transport tube connecting the diluter to the sampling probe is recommended not to include any flow splitting***[22]. When a flow splitter is applied for the simultaneous measurement of total and solid PN it is

[21] Shall be evaluated during the ILS and might be amended
[22] This is necessary to properly characterize losses for any complex flowpaths/splits inside a diluter

recommended to keep the change in the flow angle to within 20° for each outlet. Additionally, the extracted flows shall be balanced and the splitter bias shall be reported at the ***Particle Concentration Reduction Factors*** (PCRF) calibration sizes (15, 30, 50 and 100 nm).

4. ***The diluter shall provide sufficient dilution to ensure that the measured concentrations during testing do not exceed the certified linearity range of the CPC in single count mode. The dilution ratio shall be continuously monitored in real-time and the average PCRF/dilution recorded during each test shall be reported.*** The dilution ratio shall not be modified during emissions testing. The diluter shall be capable of operating at sample pressures in the 850 to 1050 mbar (sea level) and relative pressure differences from ambient in the ±50 mbar. ***In case the dilution is affected by the sample or relative pressure it shall measure the corresponding pressures and correct the PCRF accordingly.***

5. ***The PCRF[23] for the diluter at 15, 30, 50 and 100 nm at each operating condition shall be determined and reported***. It is recommended that these fulfill the requirements specified in GTR 15. More specifically, it is recommended to respect the following ratios: $PCRF_{15}/100 \leq 2$, $PCRF_{30}/100 \leq 1.3$, $PCRF_{50}/100 \leq 1.2$. ***The reported average PCRF at 30, 50 and 100 nm shall be used for the calculation of the number concentrations from the measured CPC concentrations***. A calibration certificate of the diluter issued no more than 1 year before the test shall be available[24].

6. ***The CPC shall be full flow and in accordance with the specifications of GTR 15 for 10 nm measurements***. ***These include a counting efficiency of 65% (±15%) at 10 nm and >90% at 15 nm*** (including the calibration factor) ***and operation in single count mode only. The linearity shall be determined at 5 concentration levels across the measurement range. All concentrations (including the calibration factor) shall be within 5% of the reference instrument***. ***PN instrument warnings and errors should be reported. An error would invalidate the measurements.*** The CPC shall be calibrated in an ISO 27891 accredited laboratory using either emery oil or soot-like particles in accordance to the GTR 15. A copy of a calibration certificate of the full flow CPC issued no more than 1 year before the test shall be available[25].

7. ***The sample flowrate of the full flow CPC shall be measured before each test with external calibrated flowmeter following the specifications of the instrument manufacturer.*** The measured flows shall be reported at normal conditions and shall be within 5% of the most recent calibration certificate. Sample pressure and temperature inside the CPC shall also be reported during the measurement of the sample flow rate of the full flow CPC.

8. It is recommended to also measure Solid PN (SPN) in parallel to the total PN concentrations. ***The provisions described for the total PN shall apply also to SPN. Thermal treatment of the sample should be done following the specifications described in GTR 15.*** More specifically, the system shall be capable of diluting the sample in one or more stages to achieve a PN concentration below the upper threshold of the single particle count mode of the CPC and a gas temperature below the maximum allowed inlet temperature specified by the CPC manufacturer at the inlet to the CPC. It shall include an initial heated dilution stage that outputs a sample at a temperature of >= 150°C and ≤ 350°C±10 °C and dilutes by a factor of at least 10. It shall achieve a solid particle penetration efficiency of at least 70% for particles of 100 nm electrical mobility diameter. It shall achieve a PCRF

[23] Defined as the ratio of upstream to downstream PN concentration of the diluter
[24] A copy shall be provided to JRC by the end of the ILS (31.12.2021)
[25] A copy shall be provided to JRC by the end of the ILS (31.12.2021)

for particles of 15 nm, 30 nm, and 50 nm that is no more than 100%, 30%, and 20%, respectively, higher, and no more than 5% lower than that for particles of 100 nm for the VPR as a whole.

11 Minimum parameters to be registered and test reports

Labs shall collect continuously and automatically the following channels. These channels shall be registered at least 10 Hz[26] during all brake deceleration events and at 10 Hz during other brake events (dwell, acceleration, and cruising).

- Brake torque
- Brake pressure
- Brake equivalent linear speed

Labs shall collect continuously and automatically the following channels at 10 Hz during the entire WLTP-Brake Cycle.

- Brake disc or brake drum temperature
- Brake pads or brake shoe temperature
- Cooling air temperature
- Cooling air relative humidity
- Cooling airstream speed or cooling airflow

Deceleration rate and friction coefficient shall be calculated at 10Hz for the entire WLTP-Brake cycle and reported within the EED file (see below). PM Mass concentrations shall be calculated and reported in a g/km basis following the weighing procedure described previously. PN concentrations shall be calculated and reported in a #/km basis.

The two main outputs of the brake inertia dynamometer test shall be the EEC and EED files. These file formats are agnostic to the control technology and software and allow other stakeholders to have direct access to the test outputs. It is recommended to include also the following elements to the test report:

- The test facility, brake inertia dynamometer identification, test number, testing dates, and main instruments used for brake emission measurements;
- Description of the main parameters and settings for cooling air and sampling system;
- Description of the vehicle application, brake hardware and sizes or dimensions, friction material edge codes, wheel load, tire size or tyre dynamic rolling radius;
- Digital pictures of test parts.

EEC Files – Labs shall use the VDA 305/EKB 3008 standard to generate a CSV or MS Excel™ file for the entire test. This file shall include one row for each brake deceleration event. More information regarding the EEC file is included in Annex C of the Informal Document GRPE-81-12 "Part 1: Inertia Dynamometer Protocol to Measure and Characterise Brake Emissions Using the WLTP-Brake Cycle". In addition to section or event markers, the EEC file includes timestamps, and values corresponding to initial, final, average, minimum, and maximum level for different control and output variables.

EED Files – Labs shall use the VDA 305/EKB 3008 standard to generate a CSV or MS Excel™ file for the entire test. This file shall include data sampling at 1Hz. *More information regarding the EED file is included in the Informal Document GRPE-81-12 "Part 1: Inertia Dynamometer Protocol to Measure*

[26] It is strongly recommended to register these channels at 250Hz

*and Characterise Brake Emissions Using the WLTP-Brake Cycle". **The EED file shall include at least the following parameters: trip #, timestamp, brake speed, deceleration, brake torque, brake pressure, friction coefficient, brake temperatures, cooling air speed, cooling air temperature, cooling air humidity**.*