PMP – Particle Measurement Program Informal Working Group
Task Force 2– Brake Dust Sampling and Measurement

Meeting #45 – Monday 30 MAY 2022 12:00 – 16:00 CEST

Minutes of Workshop – Draft Version

1. Participants: As in the file ***"45th TF2 Meeting Attendance"*** uploaded on TEAMS.

2. Introduction: Theo Grigoratos (TG) welcomed the TF2 members to the workshop. The aim is to discuss the remaining open points from the different clauses of the TF2 protocol. A short introduction on the status of the different documents was provided. The remaining final documents – including the material from the workshop – will be submitted to the TF2 by FRI 03.06. TF2 members shall provide their comments until FRI 10.06 COB. Comments received after that point will be taken into account at the PMP level at the next feedback stage.

Clause 1 – Open points

1. There is no clear definition of the "overall" brake emissions test that includes all three steps i.e. cooling air adjustment, bedding procedure, and emissions measurement. As a result, there are some parts of the text referring only to the last part (i.e. emissions measurement) without having specified the difference or provided a suitable definition.

JRC's Suggestion: Provide a suitable definition and clearly define already at the beginning of the document that a brake emissions test includes cooling air adjustment, bedding procedure, and emissions measurement. Clearly define that brake emissions measurement refers to only the last part of the overall test to avoid misunderstandings.

A proposal to define the overall procedure as "emissions test" and break it down to three sections corresponding to the three steps (cooling air adjustment, bedding procedure, emissions measurement) was submitted. The group agreed on this proposal and it was further suggested to prepare a flowchart to be introduced early in the document.

2. Excerpt from sub-clause 1.2.3 (a) ***"Commence Trip #1 of the WLTP-Brake Cycle at a brake disc temperature of 20±5°C, without conducting any warm-up stops or snubs"***. Submitted comment: ***"We would recommend 23+/-2°C as this temperature is defined for WLTP exhaust and would correspond to vehicle tests on a chassis dyno. It would also fit the temperatures defined in GTR15 and related legislation"***.

JRC's Response: The suggestion is to set the targets for the initial temperature aligned with the climatic settings of the cooling air temperature (20°C and 50% RH). We have been using these settings since the beginning of the development phase and we have based all analysis on the cooling method on these values. In general, we agree in aligning the regulations as much as possible. However, we see no added value in making such a change at this point particularly when we don't have a dataset that could support the change. Vehicle testing on a chassis dyno is a completely different approach, not foreseen to be applied for brake testing for any reason in the future. Therefore, temperature alignment for that reason is not a strong argument to make the change => JRC's Suggestion: Keep the temperature and humidity conditioning as is.

A discussion on this topic followed. The reasoning behind the submitted comment relates to regen braking testing and the possibility of running validation tests for certain parameters on the chassis dyno. It was proposed that data on whether this change might introduce differences in temperature regimes could be collected during a possible ILS exercise. It was noted that previous studies showed that a shift of 5°C in the cooling settings resulted in similar shift of brake temperature regimes. Several brake dyno manufacturers confirmed that there will be no technical problem in adjusting the cooling air temperature.

BMW and FORD supports shifting to 23+/-2°C – JRC prefers to keep the current setting due to lack of data. If the regen method requires running validation tests on the chassis dyno this could be revisited. Agreement to introduce a footnote briefly explaining the decision.

3. "WLTP-Brake Cycle quality checks" – Suggestion: ***"As distance is directly connected to the final emission factor, it seems to be appropriate to check for the actual "driving distance" in the test."***.

JRC's Suggestion: JRC does not have a strong opinion in favour or against adding such a quality criterion. A quick look at the ILS data showed that all labs that submitted correct Time-based files were well within 1% (0.1-0.2%) of the nominal distance (192.2 km). Would we like to add this and if yes what would be the recommended tolerance for successful execution of the cycle?

A discussion on the added value of such a criterion took place. It was suggested to link this criterion to the velocity requirements. Additional calculations show that when the entire cycle runs with +2 kph there will be a difference in the overall cycle distance of approximately 9 km compared to the nominal distance – if the 10% of the cycle runs with +2 kph there will be a difference of less than 1 km. As a result, if the 3% maximum violations is met there will be a negligible difference in the overall distance. It was clarified that cooling sections are not part of the time-based file; therefore, any possible distance driven during these parts is not accounted for. As a conclusion, there is no added value in introducing this quality criterion.

Clause 2 – Open points

4. Subclause 2.3 – Cooling adjustment quality checks – There is an overlap of the first two quality check criteria (Linear Speed violations and kinetic energy dissipation) between Clause 1 and 2.

JRC's Suggestion: Mandate the quality checks already in Clause 1 also for the cooling adjustment method and not include them again here. Both criteria fit better the purpose of Clause 1 as they examine the correct execution of the cycle.

There is a third quality criterion that refers to the average cooling airflow. This mandates that the average cooling airflow during bedding and emissions measurement is within ±5% of the value defined during the cooling adjustment procedure. However, a similar provision has been foreseen in Clause 3.

JRC's Suggestion: Delete the quality criteria from this clause. They better fit in clauses 1 and 3 as described above.

The group agreed on removing the redundant criteria. It was also suggested that it would be beneficial to collect all quality criteria in one Table.

5. Topic "Cooling adjustment method" – Submitted question: ***Do the proposed temperatures apply to Ceramic disks / lightweight discs? From our testing experience, the NWL/DM categories are fine for all the GCI discs (coated discs included) but we think that a correction should be applied for carbo-ceramic discs. We propose to add a parameter to correct the NWL/DM which is the ratio between the density of the Cast iron and the one of the carbo-ceramic (equal to 3.3).***

JRC's Response: *The target temperatures apply to all types of discs. These temperatures were derived with 85%-90% of the data being from grey cast iron discs and 10-15% from other types of discs*. We understand there might be differences with other types of discs, including carbon-ceramic discs due to few data points considered in the development phase. In the current situation, we don't have the data to apply any kind of correction in the method and be safe that it will work. We believe that after i.e. 1 year of testing and collecting data we could introduce an amendment to cover different types of discs in case we see the need => JRC's Suggestion: Keep the proposal as is – do not create a sub-category without sufficient data – properly define lightweight discs in the period to come – test these discs with the new GTR – come up with a proposal for corrections (if necessary) on time and in any case very long ahead of any regulation on brake emissions.

During the follow-up discussion a concern was raised on what happens if the homologation fails with the currently proposed method. Based on JRC's proposal, this first years would not require any official regulatory testing; therefore, there will be no real consequences if these discs do not meet 100% of the requirements. The important thing will be to collect data and introduce the appropriate corrections in a future amendment well in advance of any homologation test. A proposal to test these discs by first adjusting their cooling settings with an equivalent cast iron disc was introduced. This proposal could be one of the solutions if the current method proves not sufficient for lightweight discs and if its feasibility is demonstrated with experimental data. Additionally, there will be a need to define this type of discs properly before introducing anything relevant in the GTR.

Clause 3 – Open points

6. Use of cooling air flow/speed throughout the text – We received several comments that since the parameter of interest is volumetric flow it would make sense to keep only cooling air flow in the text? Do we want to mandate only flow measurement? If this would be acceptable to the group, it would significantly simplify the text.

JRC's Suggestion: JRC does not have a strong opinion in favour or against removing speed measurement. *If there is an agreement at the TF2 for removing it, we could delete the option.*

There was an agreement that in this context the term "speed" shall be deleted from the text. The group agrees in keeping the flow measurement and specifications described in the text. If testing facilities want to measure speed they would anyway need to fulfil the specifications. An additional point relates to the possibility of the instrument manufacturer providing certain instructions on how to calculate flow from speed – these could be different from what is prescribed in the text now. The testing facilities shall ensure that the selection of the instruments does not contradict the GTR text.

7. Cooling air humidity – Excerpt from sub-clause 3.2.2 ***"Cooling air relative humidity shall be constant throughout the entire brake testing procedure, including cooling air adjustment, bedding***

procedure, and emissions test as follows". Submitted comment: ***"it is almost impossible to design your control system to exactly stay within the borders of relative humidity during every second, especially, if the temperature is changing after the actual humidification has been done. That is why the controlling or air-conditioning system is done based on absolute humidity. We recommend applying the same for brake emissions"***.

JRC's response: Relative humidity has been used as the metric for humidity from the beginning of the development phase. JRC is not in favour of a last minute change: 1. Due to lack of measured values and study of the behavior with the absolute humidity, 2. Due to a relatively small proportion of tests that did not fulfil the specification (9 out of 155 standard tests with 7 out of 9 violations coming from one single lab that did not control temperature and humidity) => JRC's suggestion: Keep the requirement for relative humidity as is – we already significantly relaxed the provision for the instantaneous relative humidity due to the non-apparent relationship with emissions – if we collect enough data in the next months and come up with robust values to define acceptable and reasonable thresholds an amendment can be introduced to change this parameter.

During the follow-up discussion it was suggested that shifting from RH to AH does not introduce uncertainty in the proposed method since we are not changing the settings of the parameter but only the way to read its values. Additionally, AH would provide comparable results from testing facilities at different sea-level. Existing datasets would require pressure corrections to translate RH to AH – question mark if pressure data are available. The draft GTR will not change at this point; however, interested parties were invited to provide full datasets with both values to further examine the feasibility.

8. Background level – Excerpt from sub-clause 3.3.3 "The average background concentration in the tunnel shall not exceed the maximum limit of 10 #/cm^3 for both $PN_{Back\text{-}Total}$ and $PN_{Back\text{-}Solid}$" **– *Submitted comment: In the brake dust measurement case, we understand that the configuration of the measurement system is different from exhaust emission measurement system. Some systems consist of 2 stage diluter (Total DF: 100). Therefore, if the limitation is needed, by considering this situation, we would like to propose <50 #/cm3. We think this is an appropriate limit by comparing it to the exhaust emission system even if the tunnel background is included.***

JRC's response: Besides this comment there is consensus in TF2 with the proposed background limit. We have demonstrated that higher PN backgrounds (i.e. 50 #/cm^3) lead to PN levels of E+09 for relatively high tunnel airflows. This is the level where most brake PN emission concentrations have been measured. Additionally, regen brakes are expected to be at even lower levels. Thus, we believe that a fixed dilution ratio of 1:100 will not allow for correct measurements and therefore labs shall be able to provide lower dilution ratios between 1:10 and 1:100. Background tests shall be performed with the lower calibrated ratio which shall be 1:10 or similar => JRC's suggestion: Leave the background limit as is. As a compromise maybe set a background limit at 20 #/cm^3 – this would translate to PN background levels of 4E+08 #/km for a system operating at 850 m^3/h, which still is considered acceptable for the emission levels observed at the ILS (but questionable for regen braking systems).

The group agreed in not defining a direct upper limit for the dilution ratio. However, an indirect dilution ratio limit of 1:200 is imposed when considering the LOD of the PNC (0.1 #/cm^3) and the

maximum agreed background limit (20 #/cm^3). The background measurement for a brake emissions test shall take place with the applied dilution during the test. It was agreed that the testing facilities shall also have the capacity to apply a relatively low dilution ratio (1:10) as it will be crucial for regen brakes measurements.

Clause 7 – Open points

9. Topic – Verification of speed uniformity in the enclosure. Excerpt from the text "Apply Computational Fluid Dynamics (CFD) to calculate the airspeed values at nine positions of plane C as defined in Figure 7.2. ... Airspeed at each position shall not vary by more than ±20% of the arithmetic mean of all nine measurements for a given flow" – Question 1: "Is 20% satisfactory for demonstrating the airspeed uniformity or do we need to make this spec stricter". Question 2: Shall we also allow for experimental validation with the use of a flow meter for these points or shall we limit it to the CFD validation?

A discussion on the definition of the points and the distance between them took place. It was suggested not to use a disc as reference point but the actual geometry of the enclosure – it was agreed that the points shall be evenly distributed in plane C. The text will change accordingly to properly describe the definition of the points. The group agreed to leave the option for the experimental validation of the speed uniformity in the GTR. Finally, it was agreed to accurately define the 10%, 50%, and 90% of the maximum operational flow capacity.

10. Topic – Minimum dimensions for the enclosure. Submitted comment***: "Are the defined minimum dimensions for length and height necessary? Is the defined minimum 60% ratio necessary? Could we further relax these specifications?"***

JRC's response: We understand the need for an enclosure as standardized as possible based also on the request of several TF2 members. For that reason, we have further restricted maximum length and height based on the ILS available systems. We have proposed lower limits for all dimensions (length, height, depth) based on the ILS data. We have further limited the transition angle and defined a ratio for h_i/h_c (>60%). *We still believe that within these specifications the testing facilities shall have the opportunity to research for the optimal solution in terms of both temperature and particle transfer* => JRC's suggestion: Keep the requirements for the enclosure's dimensions as-is and not further neither relax nor restrict them.

A strong concern was raised regarding the proposed layout for the enclosure. There could be certain combinations that might not work. JRC agreed that this may happen; however, commented that the proposal has been based on actual designs that have been proven to be successful, not only during the ILS but also in other campaigns. JRC highlighted that this is still a draft document and expects that if there are combinations that do not work this will be brought to our attention and corrections will be applied. A comment that the optimal enclosure design shall be selected for all testing facilities followed – TG replied that we cannot be sure that a specific design is the optimal. We have seen in the past designs being validated by CFD studies that turned out to be non-functional. Additionally, we don't want to mandate a specific design with fixed dimensions because different labs have different needs. Furthermore, this might be interpreted as an intervention to the market and this is not acceptable. A question regarding the necessity of mandating two diameters horizontal tunnel before

the enclosure's inlet was raised – this is introduced for harmonization purposes and to ensure a similarity in the flow evaluation for the enclosure.

Clause 9 – Open points

11. Topic – Filter holder specifications. Excerpt from the text "Design the filter holder arrangement in such a way that the temperature of the filter holder and the filter are kept as close as possible to ambient temperature. Do not apply active heating or cooling and avoid water condensation" – ***Comment: This requirement does not make sense. If we are not allowed transfer energy to the system (no heating or cooling), how should condensation be avoided? If the temperature allowed to be within 15°C and 25°C (20+/-5°C) this cannot be handled. Recommendation: Actively condition the device to 23+/-2°C. Alternatively, require the whole lab to be within 23+/-2°C. …similar to humidity.***

JRC's suggestion: JRC does not have a strong opinion in favour or against the recommendation. Is there any other way to handle this?

The group agreed in defining a minimum temperature (15°C) for the entire sampling line outside the tunnel. This would also regulate the temperature at the filter holder allowing the testing facilities to control it in the way they consider most appropriate.

12. Topic – Minimum duct dimensions. Excerpt from the text "Ducts shall have a constant inner diameter d_i of at least 175 mm and a maximum of 225 mm." (THIS HAS BEEN RESTRICTED TO 225 mm BASED ON FEEDBACK RECEIVED) – ***Submitted comment: According to ISO 9096, B.1.1 General rule for circular ducts, the distance x of each sampling point i from the duct wall should be the center of the probe shown in Fig.B1, right? If so, the inner diameter would be 158 mm? Larger ducts result in higher airflow to cool the brakes, resulting in lower particle concentrations. We are concerned that regenerative braking emissions cannot be measured.***

JRC's comment: We used ISO 9096 in this case (but also in other cases in the text) to have a reference guideline for the system's design. We do not need to be 100% ISO 9096 (or any other ISO or regulation) compliant. This is an entire new GTR on a topic that no previous regulation exists. We shall have the flexibility to use elements from the different regulations or standards when we think they fit our purposes. We have seen that layouts with 150 mm ducts were successful when other parameters in the system were appropriately designed. Since this is a global technical regulation maybe we should consider allowing for ducts down to 150 mm => JRC's suggestion: *TF2 to decide on whether we shall relax this specification and allow for 150-225 mm or stay with the 175-225 mm*.

A strong disagreement was raised regarding further relaxing the duct dimensions. It was also mentioned that it would have implications also in the enclosure design. The groups seem to agree that the current flexibility (175-225 mm) is acceptable for the GTR.

13. Topic – Wear measurement. During the ILS we requested the labs to apply SAE J2986:2019-01 for wear measurement of the brakes. The application of the protocol was successful in the vast majority of the cases. Total wear of 1-40 g was reported for the different brakes (Br1b the lowest and Br2 the

highest). The measurement has proven useful (particularly weightings) for the analysis and for identifying issues in the overall test.

JRC's suggestion: *Mandate weighing of the brake system before and after the brake emissions test and reporting total wear rate only as indicative and informational value*. The text shall read as follows (subject to changes after the PMP meeting):

Brake Mass Weighing

The mass loss of the brake couple provides useful information regarding the correctness of the execution of the test campaign and helps identify possible issues during emissions measurement. Measure the initial and final mass of the brake couple by applying the following:

(a) Measure the brake disc or drum mass before and after the complete brake emissions tests. Measure the brake pads or shoes mass before and after the complete brake emissions tests. Do not disrupt the brake assembly during the test;

(b) Measure the mass of each part separately with the thermocouple installed and the thermocouple connector removed (in case of discs and drums);

(c) Vacuum clean the parts before conducting the measurements to remove any possible contamination;

(d) Use a weighing scale of a resolution of at least 0.1 g. Install the weighing scale in a room with controlled air and humidity to standard laboratory conditions (20±5°C and 50±10% RH);

(d) Ensure the brake parts are cool down to ambient temperature before weighing. The test facility can also measure the thickness of brake discs or brake drums after waiting until the component is at 30 °C or below;

(f) Clean the parts to remove any grease or contamination before performing the final measurements.

A concern regarding the complexity and the added value of the procedure was raised. Other TF2 partners argued that this is a standard measurement that provides useful information regarding the brake and the success of the testing procedure. A suggestion to add the wear measurement as a provisional item was submitted. Overall, the group agreed in mandating the mass measurement and keeping the wear measurement as a non-mandatory part.

Clause 10 – Open points

14. Topic – Probe outlet – Pre-classifier. Excerpt from 10.1.4: "A suitable transfer tube shall be used to transfer particles from the probe's outlet to the pre-classifier when the pre-classifier is not directly connected to the probe's outlet". **Submitted comment: The pre-classifier should be mounted directly to the probe outlet."**

JRC's suggestion: If TF2 agrees we could mandate mounting of the pre-classifier directly to the probe outlet and avoid one possible source of losses (i.e. the connecting tube).

A comment that PN measurement is less critical for losses compared to PM was submitted. It was agreed not to mandate the direct placement of the pre-classifier to the probe's outlet; however, not too long lines will be allowed. Additionally, no changes in the transfer diameters will be allowed.

Additional points

15. Topic – Influence of engine friction on dissipation of stopping energy in WLTP-Brake cycle. Jarek Grochowicz (JG) presented a slide suggesting that engine friction can reduce the required use of the friction brake from 4-16% depending on the vehicle application. Data for four different vehicles were shown with diesel and bigger vehicles being more "penalized".

On the technical side, TG commented that these figures strongly depend on the driving behavior since many drivers apply the clutch during braking. TG highlighted that this is the first time this topic is brought in our attention regarding full-friction brakes – in the past we have been suggested that the effect is negligible; therefore, it was decided not take it into account in the development phase. All available measurements and PM/PN emission factors have been derived not accounting for this parameter. As a result, JRC thinks it shall not be considered for full-friction brakes.