PARTICLE MEASUREMENT PROGRAMME

PMP-IWG

TASK FORCE 2 – BRAKE EMISSIONS

CLAUSES 3-5 OF THE TF2 PROTOCOL

Cooling air conditioning and background Temperature Measurement

CLAUSES 3-5 – OVERVIEW

ILS data, the GRPE-81-12, and the TF2 protocol have been used to amend Clauses 3-5. The proposal amends Clauses 3-4 and substitutes the initial text with Clause 3:

- ✓ 3.1 – Provides general information related to the cooling air flow/speed measurement – Elements from the GTR 15 have been also used – Provisions for the flow accuracy and the measurement point have been introduced – Compliance criteria are proposed;

- ✓ 3.2. – Discusses the proposal for effective cooling air conditioning – TF2 Protocol + GRPE-81-12 + ILS data were introduced + Topic from the issues log were used – Suggestions have been introduced;

- ✓ 3.3. – Discusses the cooling air background concentrations – ILS data and the TF2 Protocol were used – Details on the calculation and reporting of the background are provided – A limit value is proposed based on the ILS data and emission levels;

- ✓ Cl.4. – Provides guidance on the brake disc measurement – TF2 Protocol + GRPE-81-12 were used – Further suggestions on the instrumentation might be required.

CLAUSE 3.1 – FLOW/SPEED MEASUREMENT

Provides general information related to the cooling air flow/speed measurement and the specifications of the measurement devices – Elements from the GTR 15 have been adopted:

- ✓ The method of measuring the cooling air flow/speed shall be such that measurement is accurate to ±2% under all operating conditions – this shall be validated by calibration certificates;
- ✓ A temperature sensor shall be installed immediately before the air flow/speed measuring device. The temperature sensor shall have an accuracy of ±1°C and a response time of 0.1 s;
- ✓ Measurement of the pressure difference from atmospheric pressure shall be taken upstream from the measuring device. The pressure measurements shall have a precision and an accuracy of ±0.4 kPa during the test.

AN ACCURATE FLOW MEASUREMENT IS FUNDAMENTAL TO ENSURE PM ISOKINETIC SAMPLING

THERE IS A NEED TO REPORT THE FLOW AT NORMALIZED CONDITIONS TO ENABLE COMPARISONS AMONG THE LABS

CLAUSE 3.1 – FLOW/SPEED LOCATION

The TF2 did not provide specifications for position of the flow/speed measurement location relative to the enclosure and the sampling plane(s) – Only recommendation was to place the device 8D dSP x 2D uFD (or) 2D uFD x 8D dFD:

Lab	Flow/Speed Measurement	Measurement Location (Up/Down)	Measurement Location Compliance
Lab-B	Speed	Upstream	STOP
Lab-C	Flow	Upstream	STOP
Lab-D	Flow	Both	STOP
Lab-F	Flow	Both	OK
Lab-G	Speed	Both	STOP
Lab-H	Speed	Upstream	OK
Lab-J	Speed	Both	OK
Lab-K	Flow	Both	OK
Lab-L	Speed	Downstream	STOP
Lab-M	Flow	Downstream	OK
Lab-N	Speed	Downstream	OK
Lab-P	Speed	Downstream	STOP
Lab-Q	Speed	Upstream	OK
Lab-R	Flow	Downstream	OK
Lab-S	Flow	Upstream	OK
Lab-T	Flow	Downstream	OK

- ✓ 8 Labs measured cooling air speed, while 8 Labs measured the cooling air flow;
- ✓ 5 Labs measured the cooling air speed/flow only upstream of the enclosure. 6 Labs measured only downstream. 5 Labs measured both – Only 2 Labs reported similar (<1%) flows up- & down-;
- ✓ 6 Labs did not follow the recommendation regarding the measurement location of the measurement device.

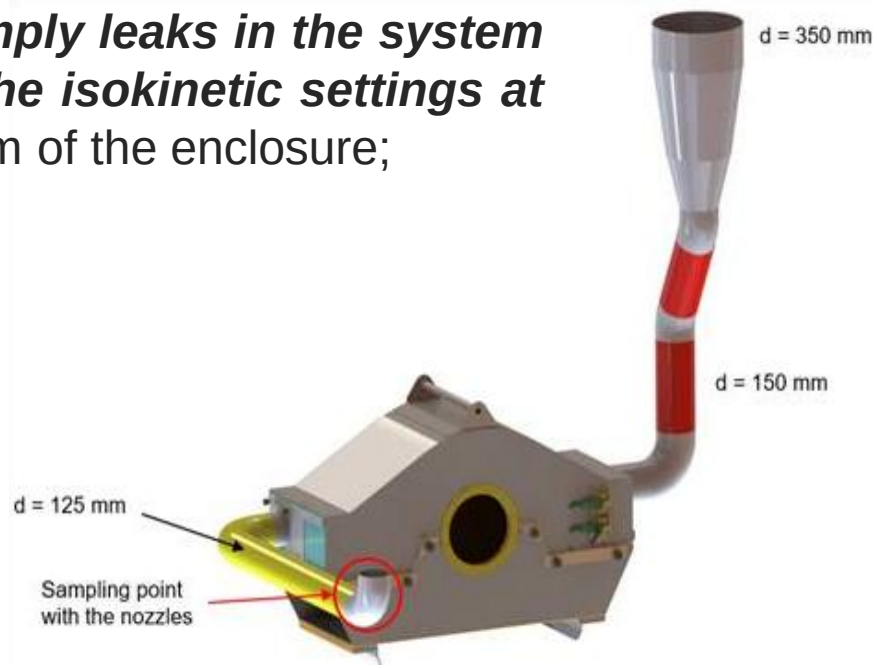
CLAUSE 3.1 – FLOW/SPEED LOCATION

Certain problems have been identified when measuring the cooling air flow/speed ustream of the enclosure:

- ✓ Three of the Labs that measured both upstream and downstream of the enclosure reported values that deviated – Lab-G reported 5% higher and Labs D and K 10% lower flow downstream compared to upstream – Probably this would have been the case if also other labs measured both;

- ✓ This situation is problematic as i. ***In certain cases might imply leaks in the system*** and ii. ***It does not allow for an accurate calculation of the isokinetic settings at the PM sampling plane*** which is always located downstream of the enclosure;

- ✓ Change of duct dimensions does not allow for knowing the exact flow at the PM sampling plane – Airflow is expected to be similar but not same because flow losses due to pressure differential may reduce the airflow in the narrower duct – ***Not possible to verify isokinetic sampling***.



CLAUSE 3.1 – FLOW/SPEED LOCATION

PROPOSAL

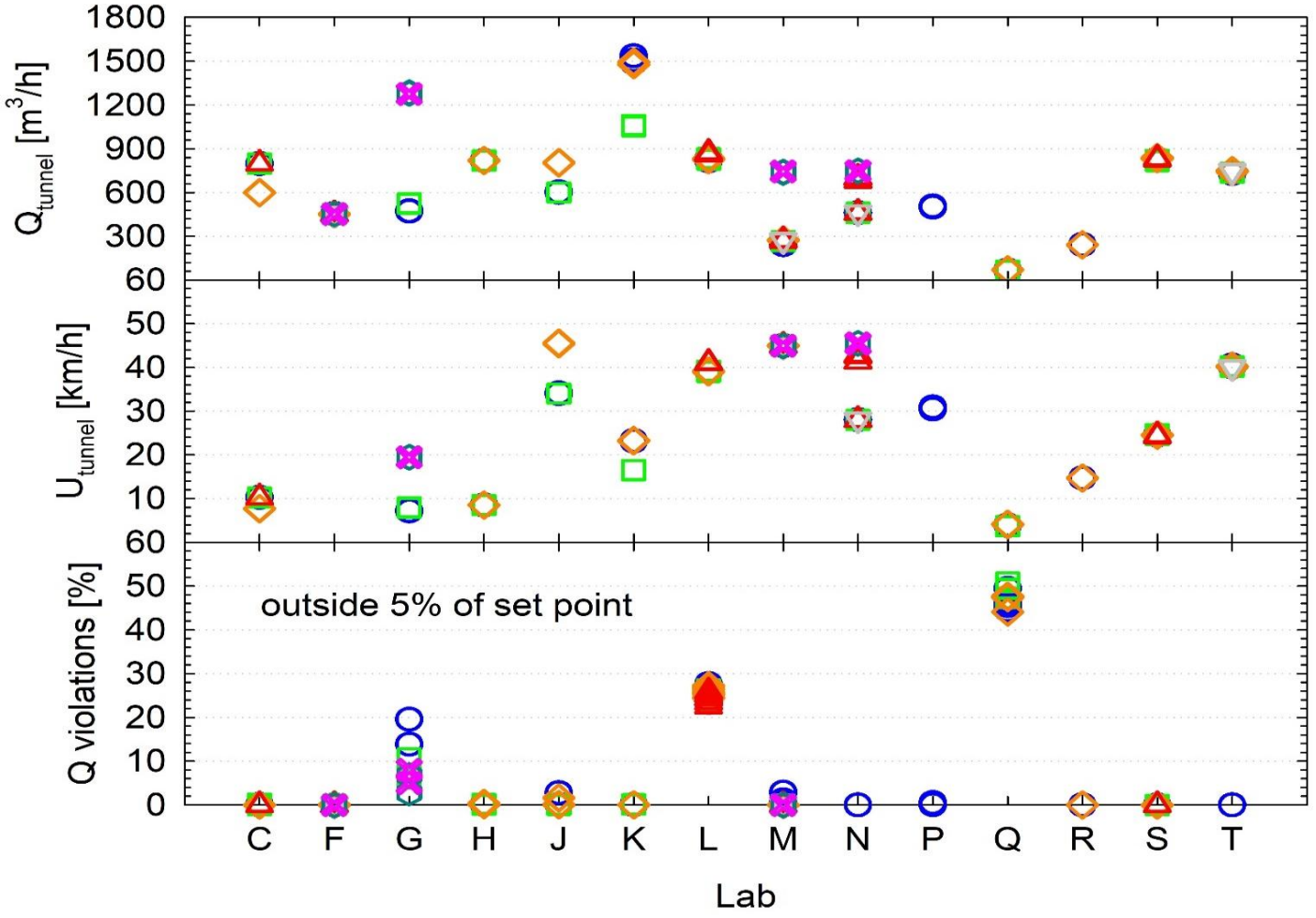
The cooling air flow/speed shall be measured downstream of the PM sampling plane. The flow/speed measurement element shall be located at the centre of the duct, at least 5 hydraulic diameters (5D dFD) downstream and 2 hydraulic diameters (2D uFD) upstream of any flow disturbance.

- ✓ Taking into account the need for specifying the location of the PM sampling plane at least 5 hydraulic diameters downstream of the enclosure and not too far away from it, the cooling air flow/speed shall be measured downstream of the sampling plane;

- ✓ According to the EPA Method 1A, the device shall be placed at least 8D dSP and at least 2D uFD. However, based on the agreed specification of 5D dFD for the PM sampling plane the proposal is to follow a similar recommendation for the flow/speed measurement device;

- ✓ There are at least two possibilities for realizing this architecture – Either through the use of very long horizontal ducts (provided that possible particle losses are well characterized) or through a smoothly curved 90° bend right after the PM sampling plane;

CLAUSE 3.1 – FLOW/SPEED SPECIFICATIONS

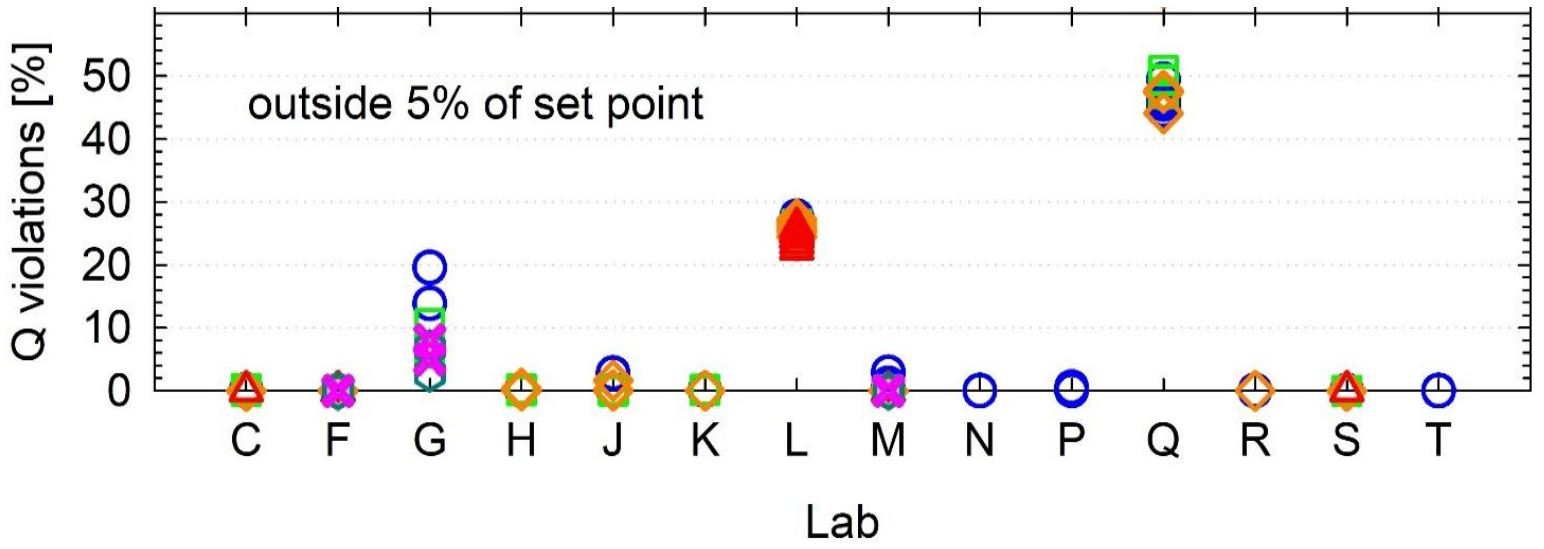


- ✓ A wide range of tunnel flows have been applied over the different labs during the ILS;
- ✓ These flows correspond to air speeds of <5 kph to almost 45 kph;
- ✓ Most of the tests were carried out with flows between 500-1000 m^3/h
- ✓ Most Labs applied the same or very similar flows for testing different brakes;

Analysis conducted by Thanasis Mamakos for the TF3 and the PMP

European Commission

CLAUSE 3.1 – FLOW/SPEED SPECIFICATIONS



	Air Flow Violations (%)
AVERAGE	7.8%
MIN VALUE	0.0%
5th Percentile	0.0%
25th Percentile	0.0%
50th Percentile	0.0%
75th Percentile	10.8%
95th Percentile	45.1%
MAX VALUE	50.9%

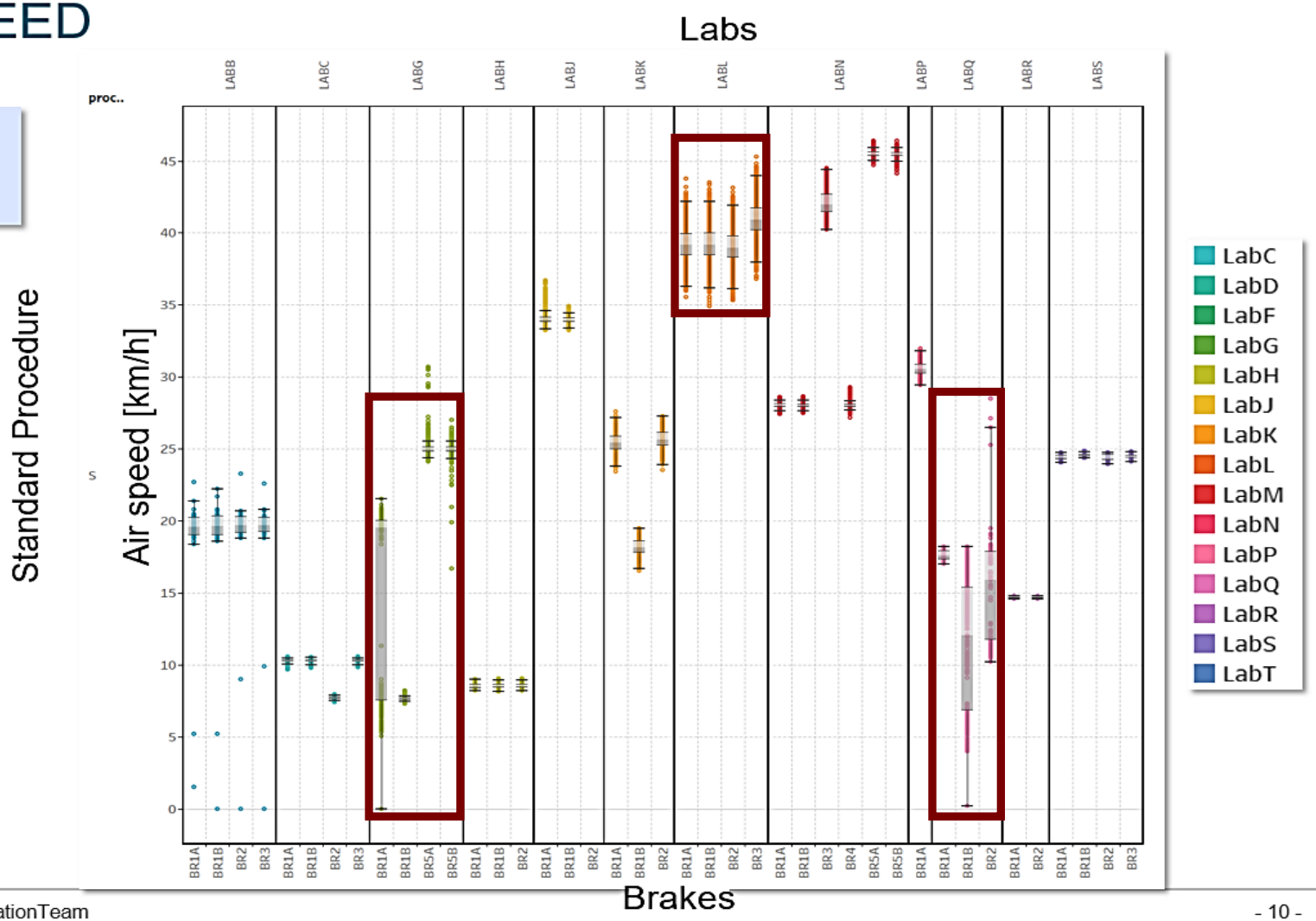
- ✓ The per cent "violations" were calculated using the 1Hz data from the Time-Based files – Each sec that the flow was outside the ±5% of the nominal was considered as a "violation" – 10% "violations" means that the Lab was outside the ±5% of the nominal flow for 10% of the cycle duration;

- ✓ 14 Labs submitted good quality Time-Based files – ***10 Labs reported "violations" less than 1.0% with most of the cases being at 0.0% (56%) and lower than 1% (68%)*** – Lab-J reported "violations" <3% – Labs G, L, Q reported higher number of violations throughout the cycle (24%);

CLAUSE 3.1 – FLOW/SPEED SPECIFICATIONS

EEC FILES: AIR SPEED

- Deviations for Lab B
- High variations for Lab G & Q
- Bigger variations for Lab L



CLAUSE 3.1 – FLOW/SPEED SPECIFICATIONS

How does the flow fluctuation might influence the isokinetic sampling ratio? – A few theoretical examples based on the ILS tests are given below for different tunnel flows.

Lab	Tunnel Flow (m^3/h)	Deviation from the Set-point	PM Sample Flow (lpm)	Isokinetic Ratio
Lab-C	800.0	-	65.0	1.11
Lab-C	760.0	-5%	65.0	1.17
Lab-C	720.0	-10%	65.0	1.24
Lab-C	840.0	+5%	65.0	1.06
Lab-C	880.0	+10%	65.0	1.01
Lab-G	474.0	-	33.4	1.05
Lab-G	450.3	-5%	33.4	1.11
Lab-G	426.6	-10%	33.4	1.17
Lab-G	497.7	+5%	33.4	1.00
Lab-G	521.4	+10%	33.4	0.96
Lab-M	275.0	-	10.0	1.09
Lab-M	261.3	-5%	10.0	1.15
Lab-M	247.5	-10%	10.0	1.21
Lab-M	288.8	+5%	10.0	1.04
Lab-M	302.5	+10%	10.0	0.99

Actual ILS Tests | Theoretical Scenario

- ✓ Potential issues at all levels of different tunnel flows with average deviations >5%;
- ✓ Much higher deviations for long duration within the cycle will also be problematic;
- ✓ There is a need to restrict tunnel flow violations both at average and at instantaneous flow levels;
- ✓ Most Labs ILS performance showed that this combination is possible;

CLAUSE 3.1 – FLOW/SPEED SPECIFICATIONS

PROPOSAL

1a. For the cooling adjustment procedure, the average cooling air flow/speed shall be within ±5% of the set value defined at the beginning of the test.

1b. For the emissions test, the average cooling air flow/speed shall be within ±5% of the nominal value as defined during the cooling adjustment procedure for the given brake.

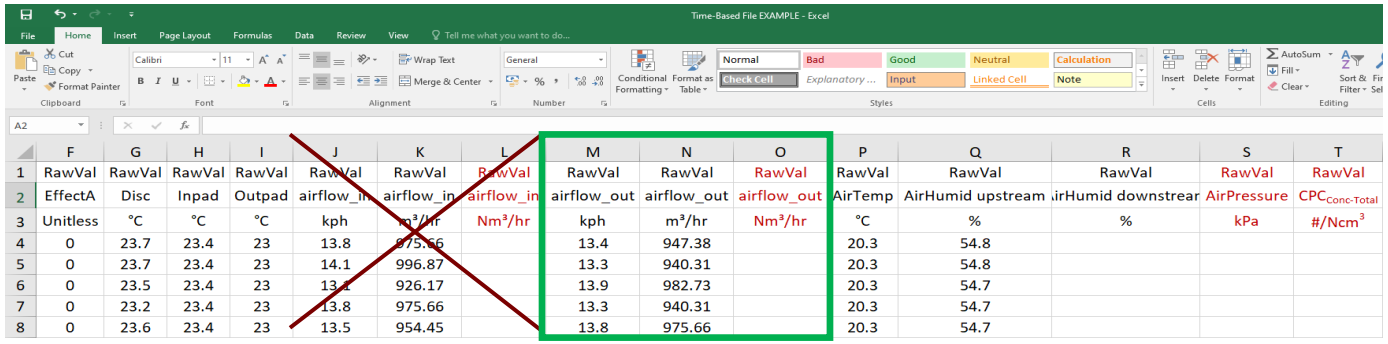
PROPOSAL

2a. The instantaneous tunnel air flow/speed, as recorded in the Time-Based file, is allowed to oscillate up to ±10% of the nominal value for no more than 5% of the duration of the cycle, provided that the average target of ±5% of the set value is met.

2b. The specification for the instantaneous tunnel air flow/speed applies for the cooling adjustment procedure and the emissions tests.

CLAUSE 3.1 – FLOW/SPEED REPORTING

- ✓ Cooling air flow/speed shall be measured and reported in the Time-Based file of the test at a 1Hz frequency;



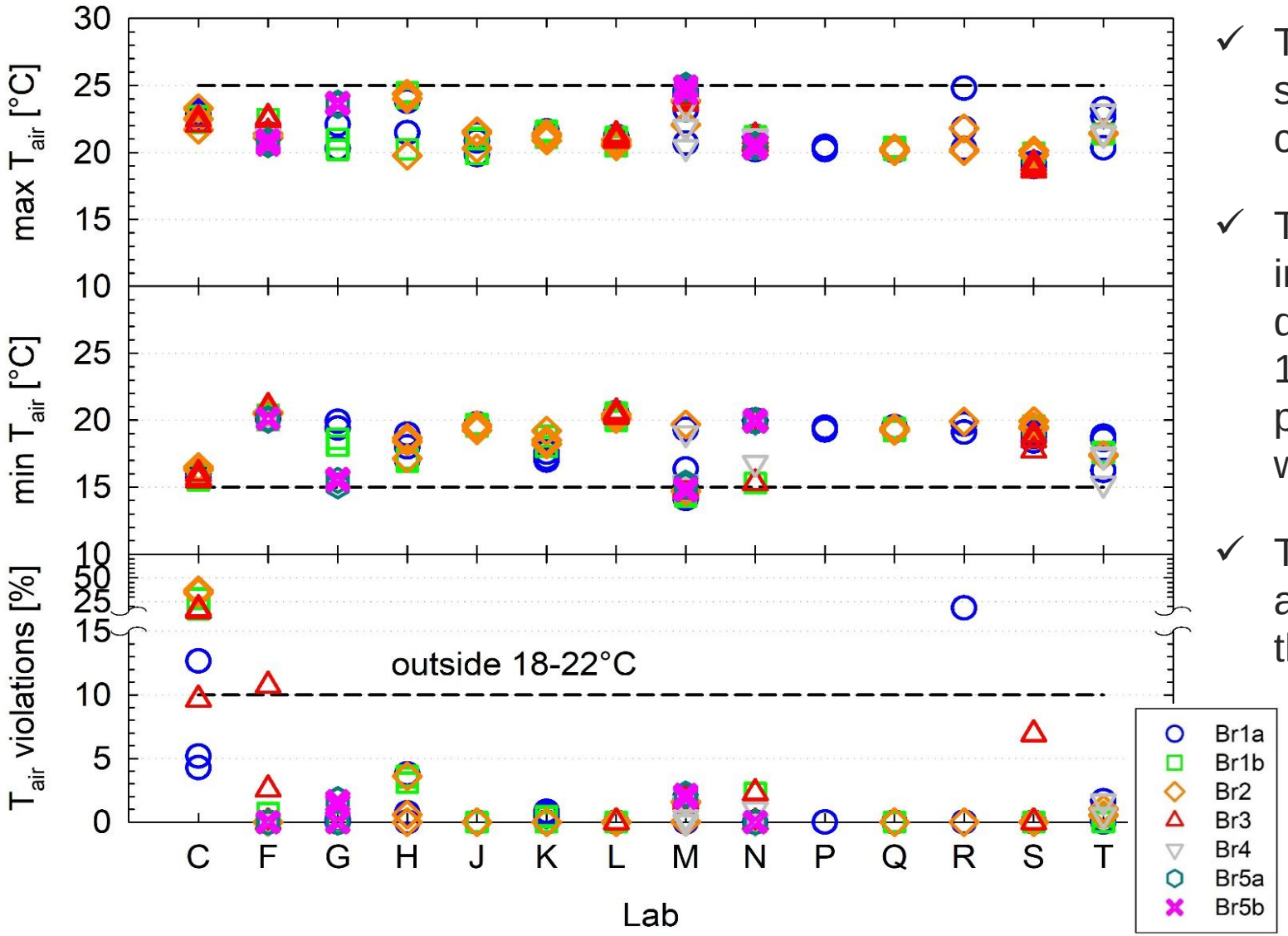
	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal	RawVal
2	EffectA	Disc	Inpad	Outpad	airflow_in	airflow_in	airflow_in	airflow_out	airflow_out	airflow_out	AirTemp	AirHumid upstream	irHumid downstrear	AirPressure	$CPC_{Conc\text{-}Total}$
3	Unitless	°C	°C	°C	kph	m^3/hr	Nm^3/hr	kph	m^3/hr	Nm^3/hr	°C	%	%	kPa	$\#/Ncm^3$
4	0	23.7	23.4	23	13.8	975.66		13.4	947.38		20.3	54.8			
5	0	23.7	23.4	23	14.1	996.87		13.3	940.31		20.3	54.8			
6	0	23.5	23.4	23	13.1	926.17		13.9	982.73		20.3	54.7			
7	0	23.2	23.4	23	13.8	975.66		13.3	940.31		20.3	54.7			
8	0	23.6	23.4	23	13.5	954.45		13.8	975.66		20.3	54.7			

- ✓ Both airflow and airspeed shall be reported in the Time-Based file – One parameter will be measured whereas the other shall be calculated following the Equation given below;

$$Q_{Tunnel\text{-}Speed}\ [km/h] = (3.6 * 4 * Q_{Tunnel\text{-}Flow}\ [m^3/h]) / (3600 * PI() * (d_{Duct})^2\ [m^2])$$

- ✓ ***The airflow shall be also normalized and reported to a common reference condition (273.15 K and 101.325 kPa)*** – Volumetric flow can change with the actual temperature and pressure. Thus, when volumes are divided the user needs to make sure they refer to the same conditions – This is necessary for correctly reporting of PM and PN EFs in a comparable manner.

CLAUSE 3.2 – COOLING AIR CONDITIONING TEMPERATURE



- ✓ The TF2 protocol foresees that Labs shall run the tests with the cooling air conditioned at 20±2°C;
- ✓ The TF2 protocol foresees the instantaneous temperature might deviate up to 20±5°C for no longer than 10% of the WLTP-Brake cycle duration provided that the average temperature will be within the 20±2°C target;
- ✓ The same temperature requirements apply during bedding as well as during the cooling air adjustment procedure;

Analysis conducted by Thanasis Mamakos for the TF3 and the PMP

European Commission

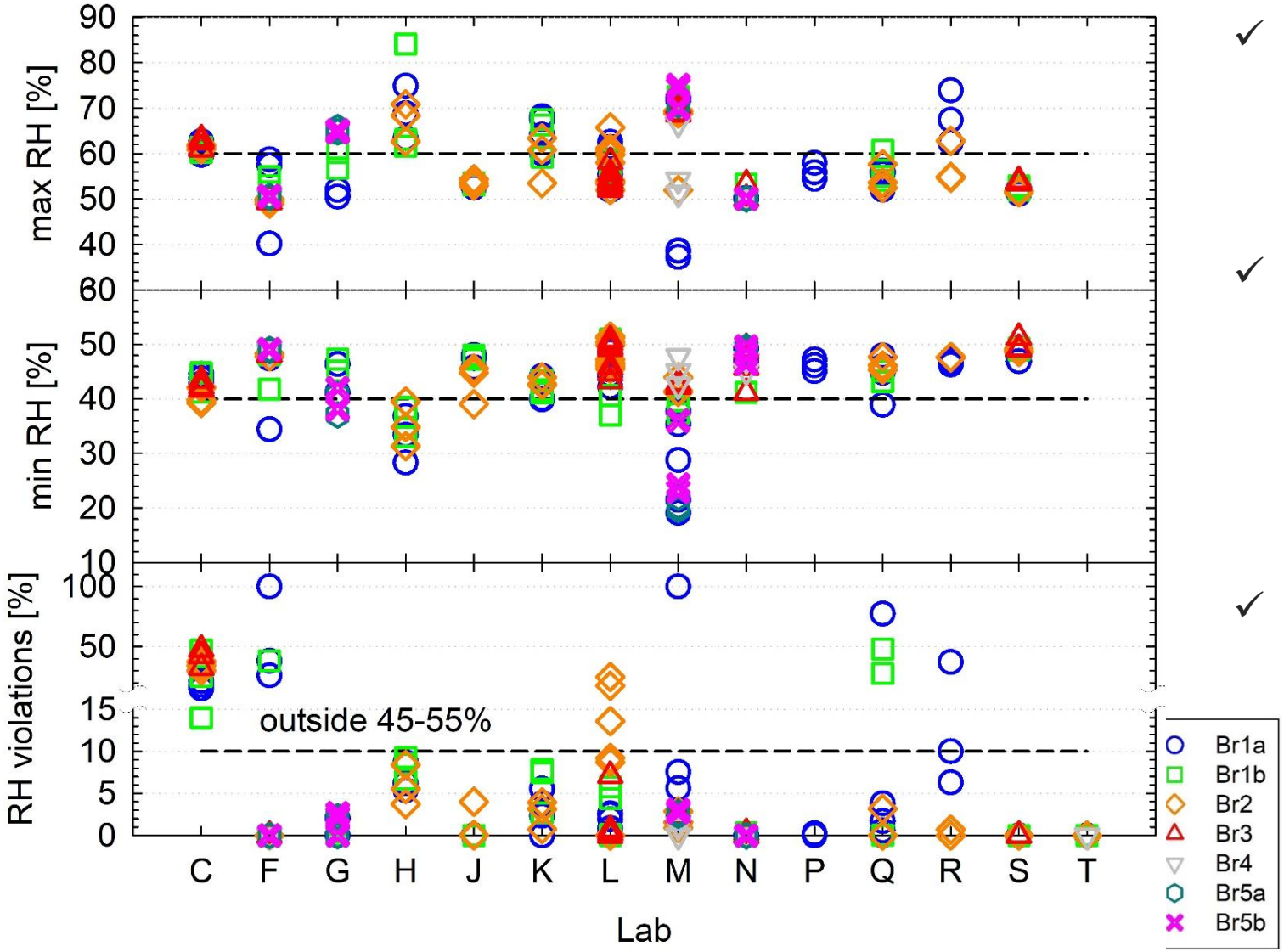
CLAUSE 3.2 – COOLING AIR CONDITIONING TEMPERATURE

Avg. Temp. [°C]	Br1a	Br1b	Br2	Br3	Br5a	Br5b
AVERAGE	20.1	20.2	20.2	20.1	20.1	20.1
STDEV	0.8	0.8	1.0	0.8	0.1	0.1
Variability	3.7%	3.8%	4.9%	4.2%	0.6%	0.6%
MIN VALUE	18.9	19.2	18.8	18.3	20.0	20.0
5th Percentile	19.3	19.3	18.9	18.6	20.0	20.0
50th Percentile	20.0	20.0	20.0	20.1	20.1	20.1
95th Percentile	21.8	21.9	22.6	21.2	20.3	20.3
MAX VALUE	22.7	22.8	23.7	21.4	20.3	20.3
TARGET	20±2	20±2	20±2	20±2	20±2	20±2

Avg. Temp.: 155 single data points (Std) – 7 "non-compliances" to the target value of 20±2°C (4.5%) – Lab-D (7 non-compliances) – Lab does not control the cooling air temperature and humidity

Inst. Temp.: 155 single data points (Std) – 20 "non-compliances" to the target value of 20±5°C for no longer than 10% of the WLTP-Brake cycle (12.9%) – Lab-D (8 non-compliances) does not control the cooling air temperature – Lab-C (10 non-compliances) reported an issue with the climatic controls – Labs F & R (1 non-compliance) with Br3 and Br1a – ***102 data points <1% violations (65.8%)***

CLAUSE 3.2 – COOLING AIR CONDITIONING RELATIVE HUMIDITY



Analysis conducted by Thanasis Mamakos for the TF3 and the PMP

- ✓ The TF2 protocol foresees that Labs shall run the tests with the cooling air conditioned at 50±5% for relative humidity;
- ✓ The TF2 protocol foresees the instantaneous relative humidity might deviate up to 50±10% for no longer than 10% of the WLTP-Brake cycle duration provided that the average value will be within the 50±5°C target;
- ✓ The same relative humidity requirements apply during bedding as well as during the cooling air adjustment procedure;

European Commission

CLAUSE 3.2 – COOLING AIR CONDITIONING RELATIVE HUMIDITY

Rel. Hum. [%]	Br1a	Br1b	Br2	Br3	Br5a	Br5b
AVERAGE	48.9%	49.5%	49.2%	50.1%	49.9%	49.9%
STDEV	4.5%	1.6%	4.2%	1.1%	0.2%	0.2%
Variability	9.2%	3.2%	8.5%	2.1%	0.5%	0.3%
MIN VALUE	31.0%	44.5%	30.7%	48.6%	49.7%	49.7%
5th Percentile	38.4%	45.6%	40.4%	48.6%	49.7%	49.7%
50th Percentile	50.1%	50.1%	50.2%	50.0%	49.8%	49.9%
95th Percentile	52.7%	50.5%	52.3%	51.9%	50.2%	50.1%
MAX VALUE	54.6%	50.6%	52.6%	52.3%	50.3%	50.1%
TARGET	50±5	50±5	50±5	50±5	50±5	50±5

Avg. RH.: 155 single data points (Std) – 9 "non-compliances" to the target value of 50±5% (5.8%) – Lab-D (7 non-compliances) does not control the cooling air relative humidity – Labs F & Q (1 non-compliance) with Br1a – ***118 data points <1% violations (76.1%)***

Inst. RH.: 155 single data points (Std) – 30 "non-compliances" to the target value of 50±10% for no longer than 10% of the WLTP-Brake cycle (19.4%) – Lab-D (9 non-compliances) does not control relative humidity – Lab-C (12 non-compliances) reported an issue with the climatic controls – Labs F, Q, & R (9 non-compliances) had occasional problems – ***66 data points <1% violations (42.6%)***

CLAUSE 3.2 – COOLING AIR CONDITIONING TEMPERATURE & RELATIVE HUMIDITY

Excerpt from	Reporting lab & date	Description of the issue	Possible solution	Issue Closed
Clause 4	Lab-G 08/09/2021	***There is a test where the humidity was above 60% for a small period of time. The exact time was 115 seconds which constitutes to 0.727 % of the total time***. Would the 10% tolerance of oscillation between 40–60% cover scenarios like this or should we address a specific scenario for similar situations?	Based on the current wording the test shall be considered invalid. However, while the requirements for the average temperature and humidity are relatively easy to meet, this might not be the case for the instantaneous temperature and humidity values. And while it is important to make sure that temperature does not get out of the defined ranges as it strongly affects the measurement, this might not be 100% the case for humidity.	NO

PROPOSAL

1a. Keep the same requirements for cooling air temperature both at average and instantaneous values level (20±2°C and 20±5°C for no longer than 10% of the duration of the test).

1b. Keep the requirements for the average RH and amend them for the instantaneous RH (50±5% and allow instantaneous RH to oscilate without setting a limit value for no longer than 10% of the duration of the test and provided that the average target is respected).

CLAUSE 3.3 – COOLING AIR PARTICLE BACKGROUND

Need for the air to 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 (EN 1822) – ***Definition of a maximum allowed BG limit after the ILS was agreed*** – BG control at two levels:

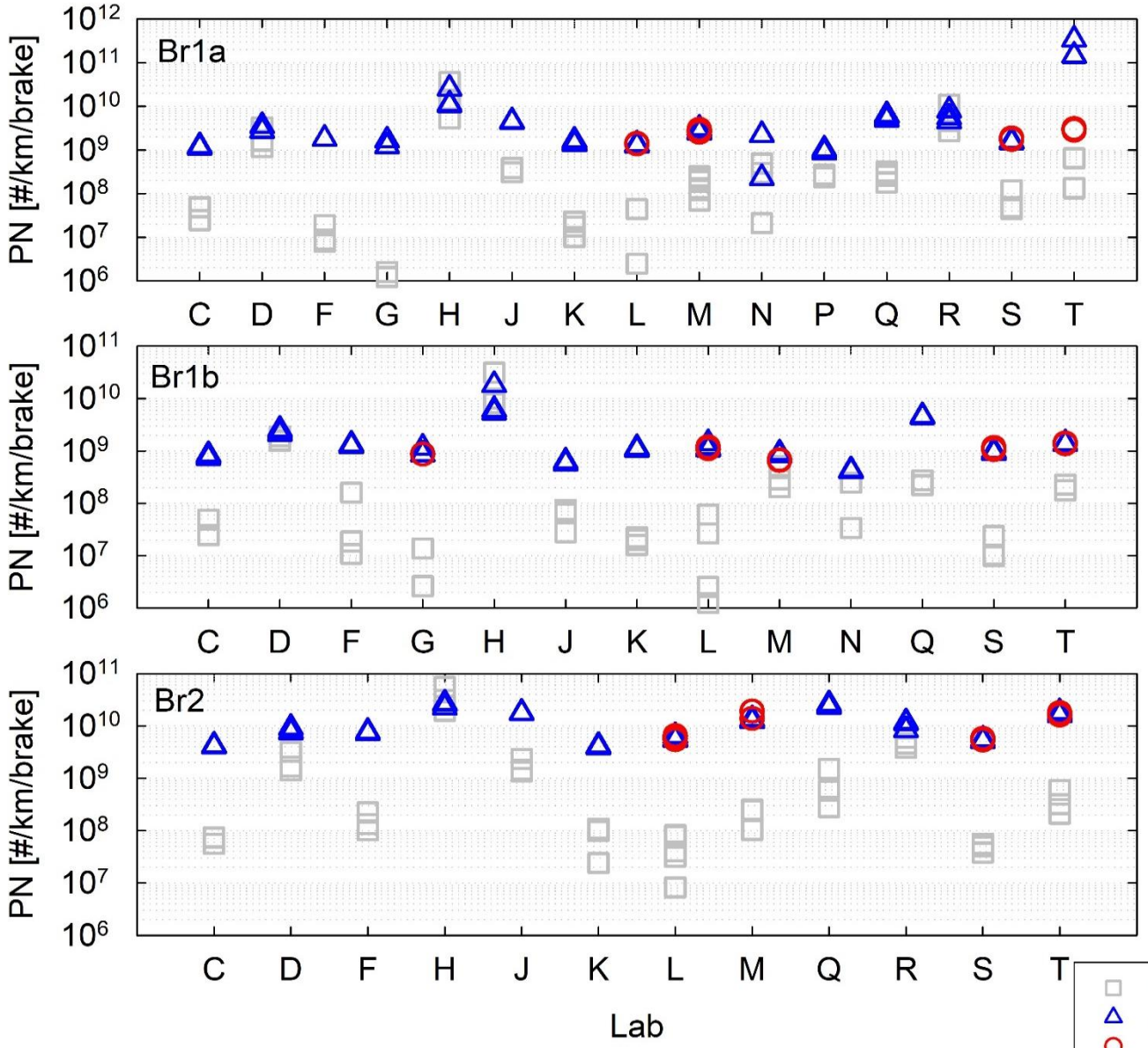
- ✓ ***System level:*** BG control upon the installation of the setup (or when there is a system malfunction.) The BG control shall run without the brake assembly being mounted at three different settings representing the dyno capabilities (10%, 50%, and 90% of the max airflow). Each run shall last 30 min or as long as it takes for the BG to stabilize;

10
Labs Completed
63%

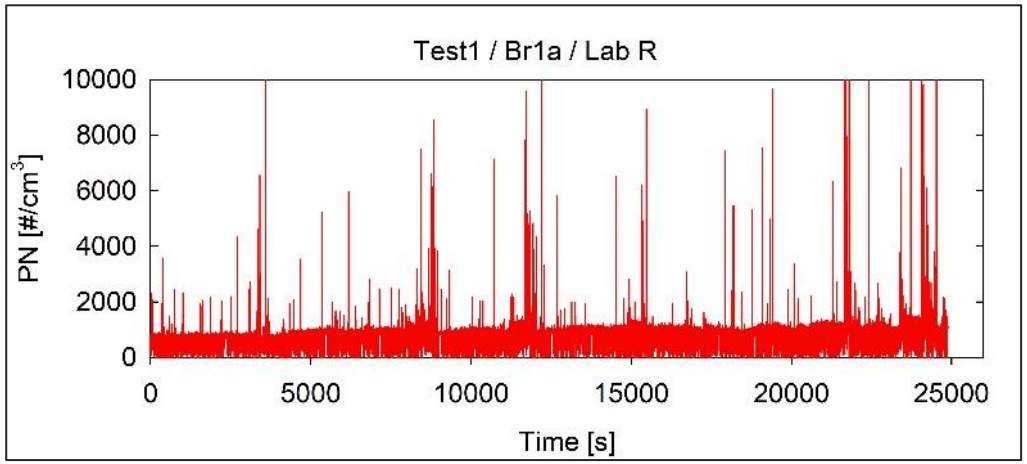
- ✓ ***Test level:*** Regular BG controls before and after the execution of a brake emissions test. The regular BG pre-test shall take place before bedding with the brake assembly mounted (no rotation – pads/shoes retracted). The regular BG post-test shall run before purging with the brake assembly mounted. No pressure shall be applied to the brake. Each run shall last 5 min or as long as it takes for the BG to stabilize.

173
Completed Checks
78%

CLAUSE 3.3 – COOLING AIR PARTICLE BACKGROUND



- ✓ In general, background PN concentrations in the tunnel were at least one order of magnitude below the cycle-average tunnel concentrations (Br1a: $2x10^9$ vs. $2x10^{10}$ – Unfiltered data);
- ✓ Labs (D, H & R) had background levels similar to measured emission levels (1000-2000 #/cm^3) → PN results from these specific labs shall be treated as unreliable.



Analysis conducted by Thanasis Mamakos for the TF3 and the PMP

CLAUSE 3.3 – COOLING AIR PARTICLE BACKGROUND

The BG PN concentrations shall be measured and reported in number of particles per cm^3 (PN_{Back} [#/cm^3]) - The BG shall be also reported also in number of particles per distance driven (PN_{Back} [#/km]) to reflect the changes of the cooling air settings when testing different brakes.

$$PN_{Back}\ (\#/km) = 10^6 \times [PN_{Back}\ (\#/cm^3) \times Q_{Tunnel}\ (m^3/h)] / V_{Avg}\ (km/h)$$

Lab	Tunnel Flow (m^3/h)	BG Concentration (#/cm^3)	BG Levels (#/km)
Lab-X	250	10	5.7E+07
Lab-X	250	50	2.9E+08
Lab-X	250	100	5.7E+08
Lab-Y	550	10	1.3E+08
Lab-Y	550	50	6.3E+08
Lab-Y	550	100	1.3E+09
Lab-Z	850	10	1.9E+08
Lab-Z	850	50	9.7E+08
Lab-Z	850	100	1.9E+09

Theoretical Scenarios	High PN BG levels

PROPOSAL

The background concentration shall not exceed the maximum limit of 10 #/cm^3. The limit applies to the BG concentration at both system and test levels. The BG concentration values will not be subtracted from the PN concentration values of the emission tests.

CLAUSE 4 – BRAKE TEMPERATURE MEASUREMENT

Excerpt from	Reporting lab & date	Description of the issue	Possible solution	Issue Closed
Clause 5	Lab-N 19/11/2021	While conducting the cooling air adjustment for the BMW X7 brake, Lab-N noticed that the pad TC when embedded in the centerline of the friction material was causing a tight fit causing excessive drag. Did any other lab notice such behavior? Lab-N came across such issues in the past where sometimes the customer asks to route the TC wire through a hole drilled on the caliper. However, that solution most probably does not apply here.	The installation of the TC is not easy as described in the protocol – a TC 1 mm below the surface would result in the brake pad material crumbled in this area. The installation of the TC wire on the back plate would result in additional brake torque which would affect particle measurement due to the narrow space between the brake pad and the brake caliper. It seems that for the GTR there might be a need to remove the recommendation regarding the pad temperature as it might create similar situations.	NO

PROPOSAL

Remove the specification for measurement of pad/shoe temperature from the GTR – This info has been useful for research purposes; however, when it comes to official emissions testing we shall make sure that no interferences or artificial temperature increase is caused.

Thank you

European Commission