PARTICLE MEASUREMENT PROGRAMME

PMP-IWG

TASK FORCE 2 – BRAKE EMISSIONS

CLAUSE 10 OF THE TF2 PROTOCOL

PN Concentration Measurement

OUTLOOK

- ✓ Overview of Clause 10
- ✓ ILS Summary results and discussion
- ✓ Detailed proposal for Clause 10

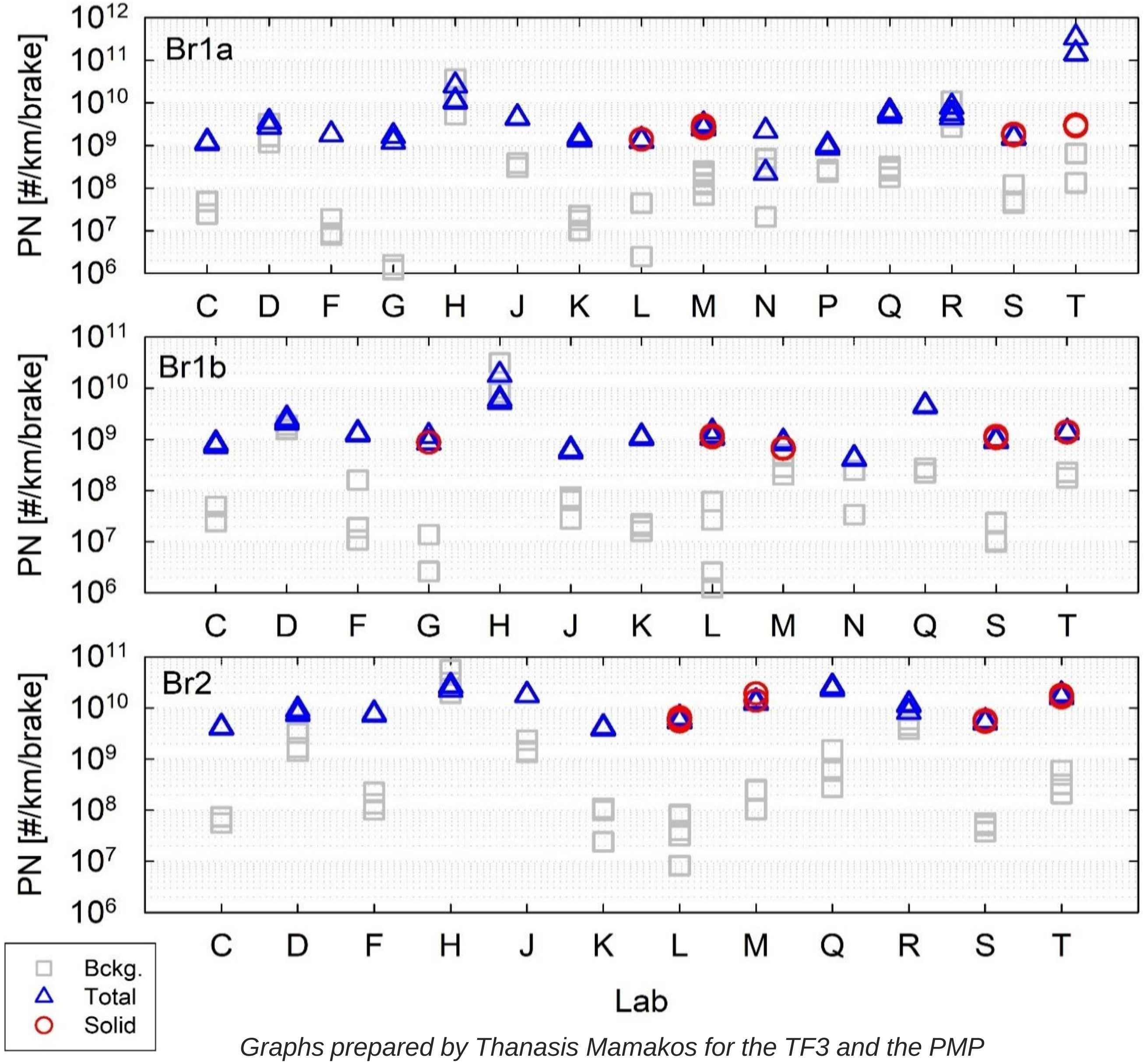
Clause 10 – OVERVIEW

ILS data and the TF2 protocol have been used to amend Clause 10. Stricter and new specifications compared to the initial proposal have been introduced – Many of the elements have been aligned to the GTR15 – Sub-clauses may further change:

- ✓ 10 (Introduction) – Discusses the target parameters (Total-PN and Solid-PN) – Provides a general description of the setup;
- ✓ 10.1 – Describes the general elements related to the particle extraction – Defines the sampling plane – Specifications about the probes – Specifications about the nozzles;
- ✓ 10.2. – Discusses the particle handling – Specifications about the pre-classifier and the particle conditioning (dilution system and volatile particle removal system) – Provisions regarding the particle transfer line to the measurement equipment;
- ✓ 10.3 – Describes the general specifications for the particle measurements – Specifications for the Particle Number Counter and the volumetric flow – Definition of the PN EF calculatio

ILS SUMMARY RESULTS AND DISCUSSION

ILS RESULTS - PN BACKGROUND



Graphs prepared by Thanasis Mamakos for the TF3 and the PMP

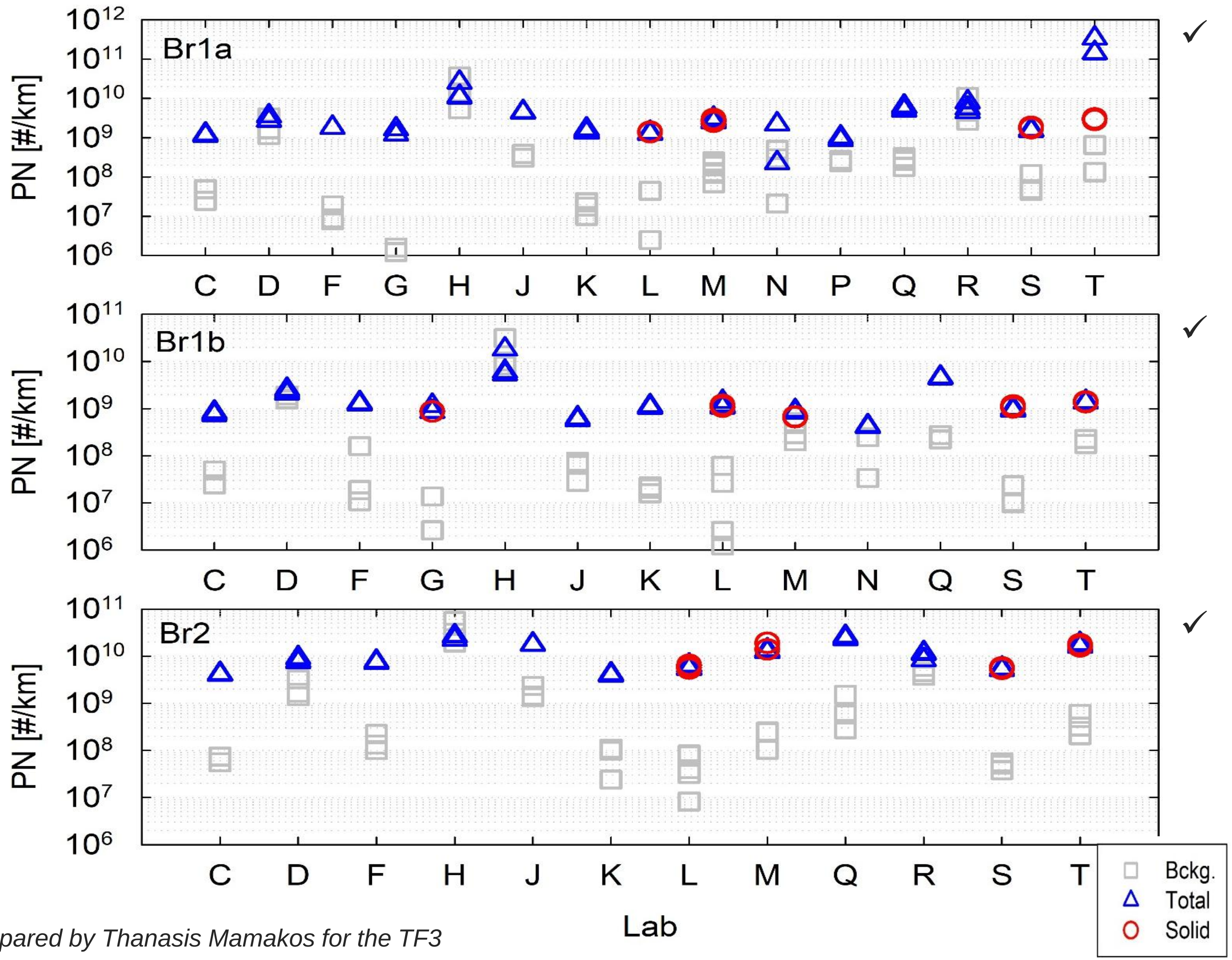
- ✓ In general, background PN concentrations in the tunnel were at least one order of magnitude below the cycle-average tunnel concentrations;

Total PN [#/km]	Br1a	Br1b	Br2	Br3	Br5a	Br5b
BG Unfiltered	2.0E+09	1.7E+09	3.9E+09	2.9E+08	4.4E+08	4.8E+08
AVG Unfiltered	1.9E+10	2.0E+09	1.2E+10	4.4E+09	5.8E+09	1.1E+10
BG Filtered	1.4E+08	9.2E+07	3.5E+08	2.9E+08	4.4E+08	4.8E+08
AVG Filtered	2.2E+10	9.4E+08	9.3E+09	4.4E+09	5.8E+09	1.1E+10

- ✓ 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

Total PN [#/km]	Br1a	Br1b	Br2	Br3	Br5a	Br5b
Background Lab-D	2.0E+09	1.7E+09	2.1E+09	N/A	N/A	N/A
Background Lab-H	1.9E+10	1.7E+10	3.5E+10	N/A	N/A	N/A
Background Lab-R	6.1E+09	N/A	4.8E+09	N/A	N/A	N/A

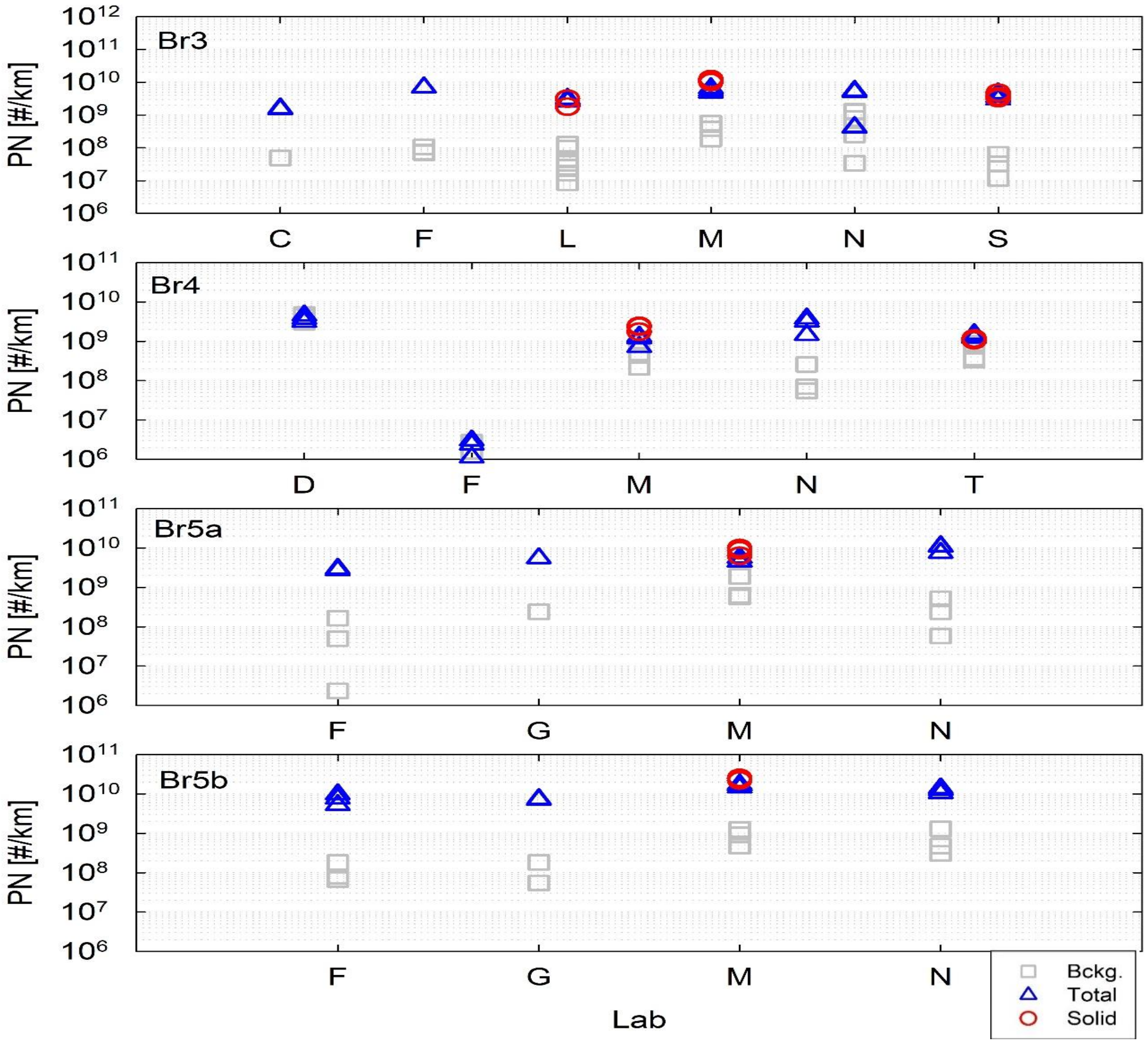
ILS RESULTS - PARTICLE NUMBER EMISSIONS



- ✓ Br1a: Labs measured Total PN and Solid PN EFs at similar levels with the exception of Lab-T that found volatiles - Labs D, H, Q and R shall not be considered (high background);
- ✓ Br1b: All labs measured very similar PN EFs with average Total- and Solid-PN being very low and close to 1.0E+09 - Labs D, H and Q shall not be taken into account;
- ✓ Br2: Labs reported similar Total PN levels with Lab-J and Lab-T reporting almost twice as high the average PN - Labs D, H, Q and R shall not be considered

Graphs prepared by Thanasis Mamakos for the TF3

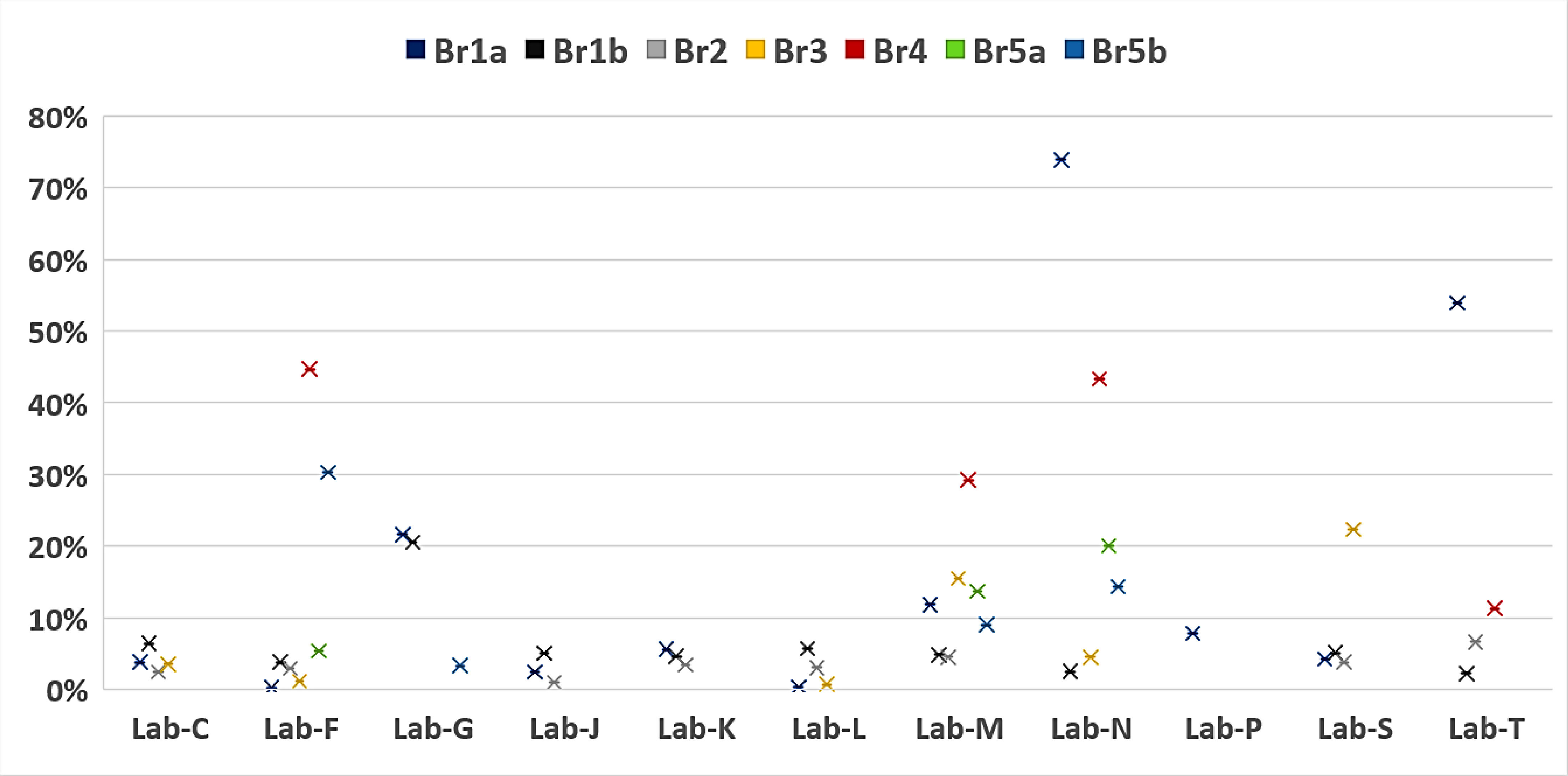
ILS RESULTS - PARTICLE NUMBER EMISSIONS



Graphs prepared by Thanasis Mamakos for the TF3

- ✓ Br3: All labs measured similar Total and Solid PN EFs with average PN being close to each other at the levels of 4.0E+09 and within the anticipated calibration uncertainty for PN;
- ✓ Br4: Labs measured very similar Total and Solid PN EFs with average Total PN being low and close to 1.8E+09 - PN emissions from Lab F are unrealistically low and below their reported background in other brakes;
- ✓ Br5a: Four labs measured very similar Total PN EFs with average Total PN being lower than for Br5b and close to 5.8E+09;
- ✓ Br5b: Four labs measured very similar Total PN EFs with average Total PN being close to 1.1E+10.

ILS RESULTS - PN EMISSIONS REPEATABILITY

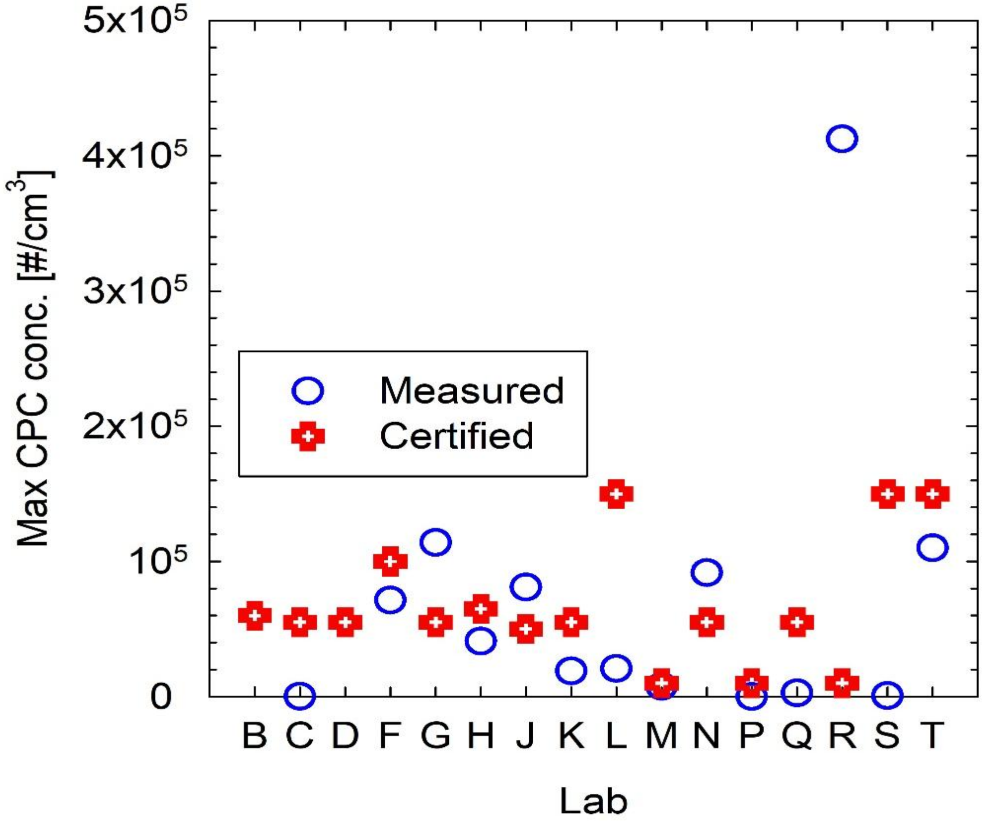


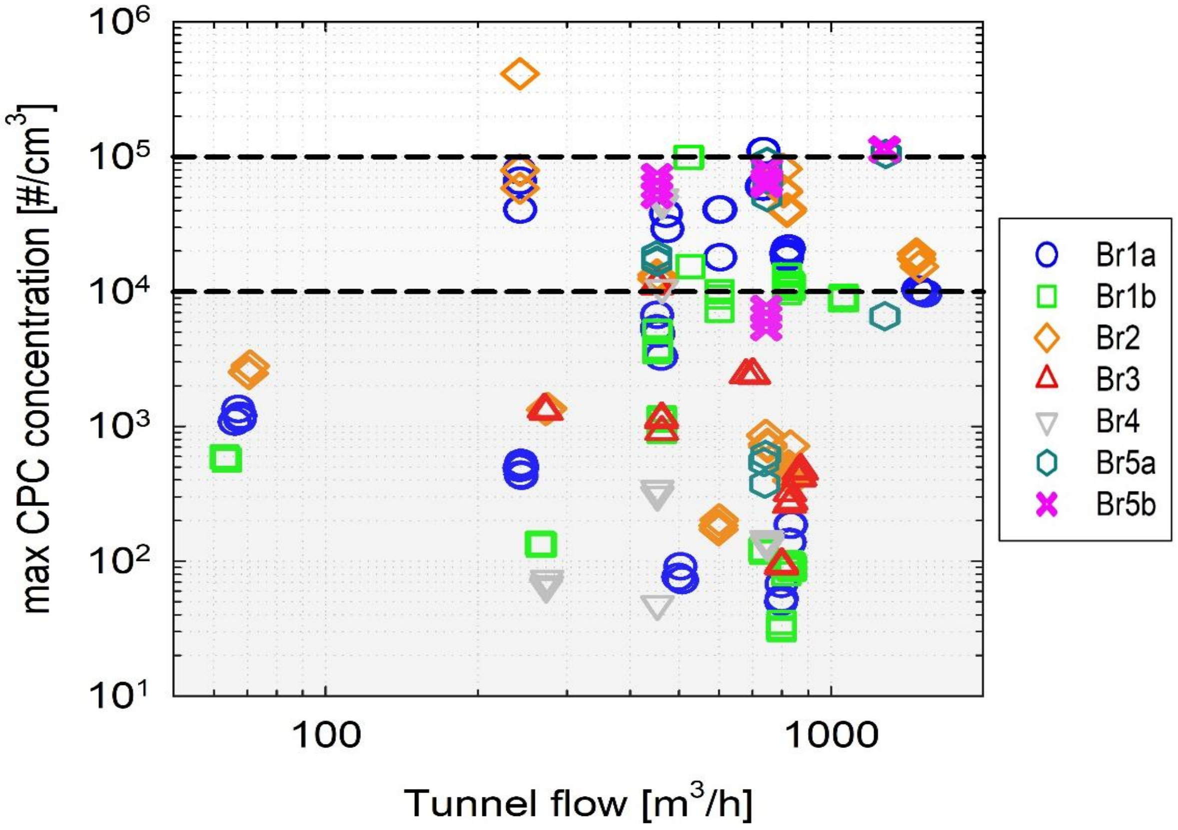
ILS RESULTS - PN EMISSIONS REPRODUCIBILITY

Total PN Filtered [#/km]	Br1a	Br1b	Br2	Br3	Br4	Br5a	Br5b
AVERAGE	2.2E+10	9.4E+08	9.3E+09	4.4E+09	1.3E+09	5.8E+09	1.1E+10
STDEV	6.9E+10	2.9E+08	5.5E+09	1.9E+09	1.2E+09	3.1E+09	4.1E+09
Variability	315%	31%	59%	43%	90%	53%	36%
MIN VALUE	2.3E+08	4.1E+08	3.9E+09	1.5E+09	1.1E+06	2.7E+09	5.3E+09
5th Percentile	9.1E+08	4.3E+08	4.1E+09	1.5E+09	1.8E+06	2.7E+09	6.2E+09
25th Percentile	1.3E+09	7.7E+08	4.9E+09	3.0E+09	5.4E+08	3.4E+09	7.5E+09
50th Percentile	1.5E+09	9.4E+08	6.5E+09	4.7E+09	1.3E+09	5.1E+09	1.0E+10
75th Percentile	2.4E+09	1.2E+09	1.4E+10	5.5E+09	1.5E+09	7.1E+09	1.4E+10
95th Percentile	1.4E+11	1.4E+09	1.8E+10	6.9E+09	3.5E+09	1.1E+10	1.7E+10
MAX VALUE	3.4E+11	1.4E+09	1.8E+10	7.0E+09	3.8E+09	1.1E+10	1.7E+10

*Conclusion: Despite the lack of strict specifications for the PN measurement and the lack of experience in measuring Total PN, **laboratories seem to have managed to measure these emissions in an acceptably reproducible manner when volatile particles are not present***

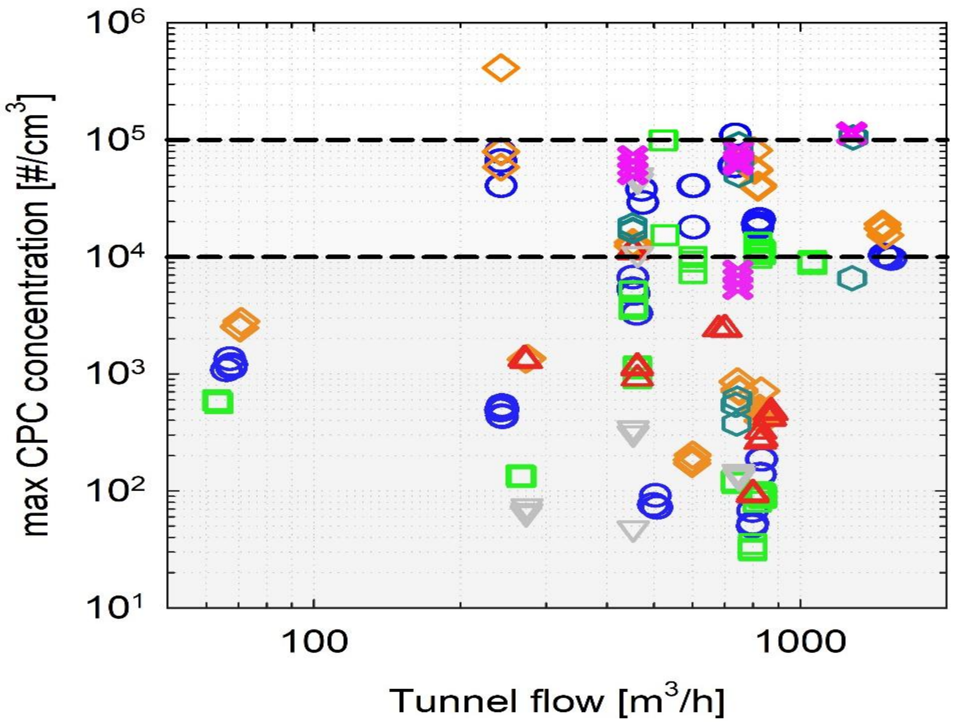
ILS RESULTS – MEASURED CONCENTRATIONS

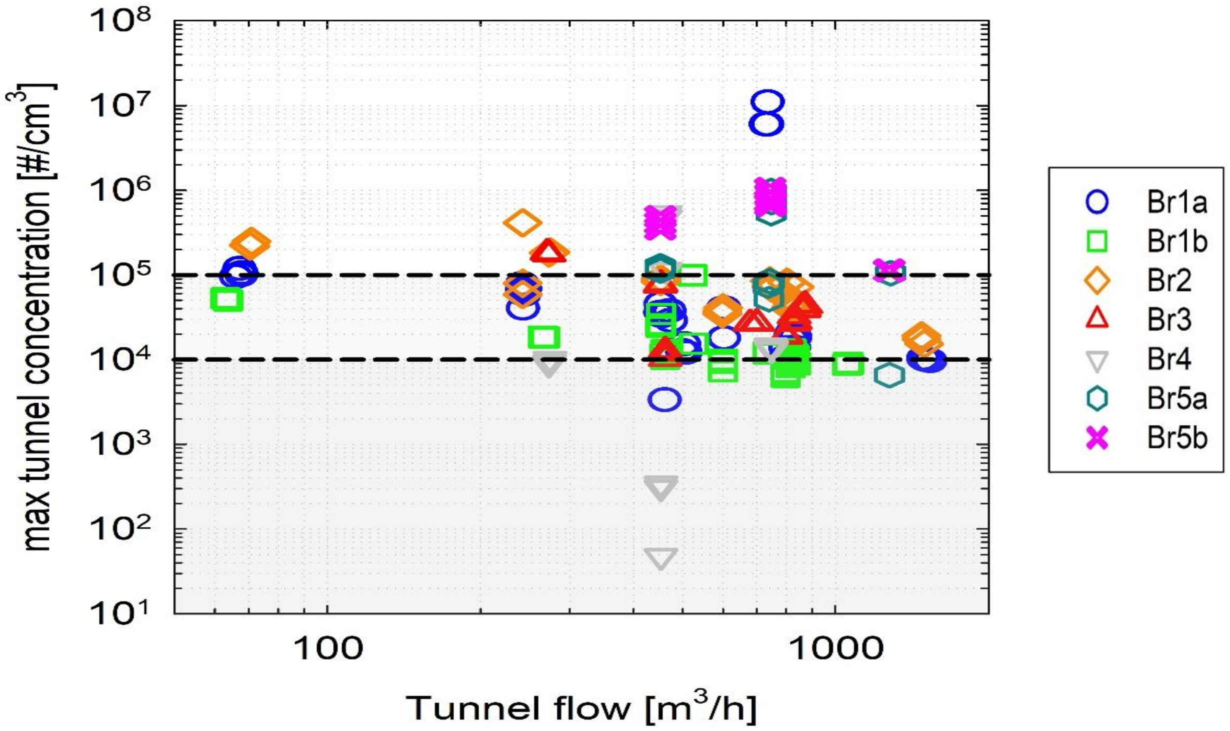




- ✓ Labs G, J, N, and R measured PN concentrations that were higher than the certified range of the employed CPCs – Only in case of Lab R the measured concentration was much higher;
- ✓ ***The maximum total PN concentrations measured by the CPCs (cumulative graph) ranged between 5×10¹ #/cm³ and 5×10⁵ #/cm³***

ILS RESULTS – DILUTION REQUIREMENTS

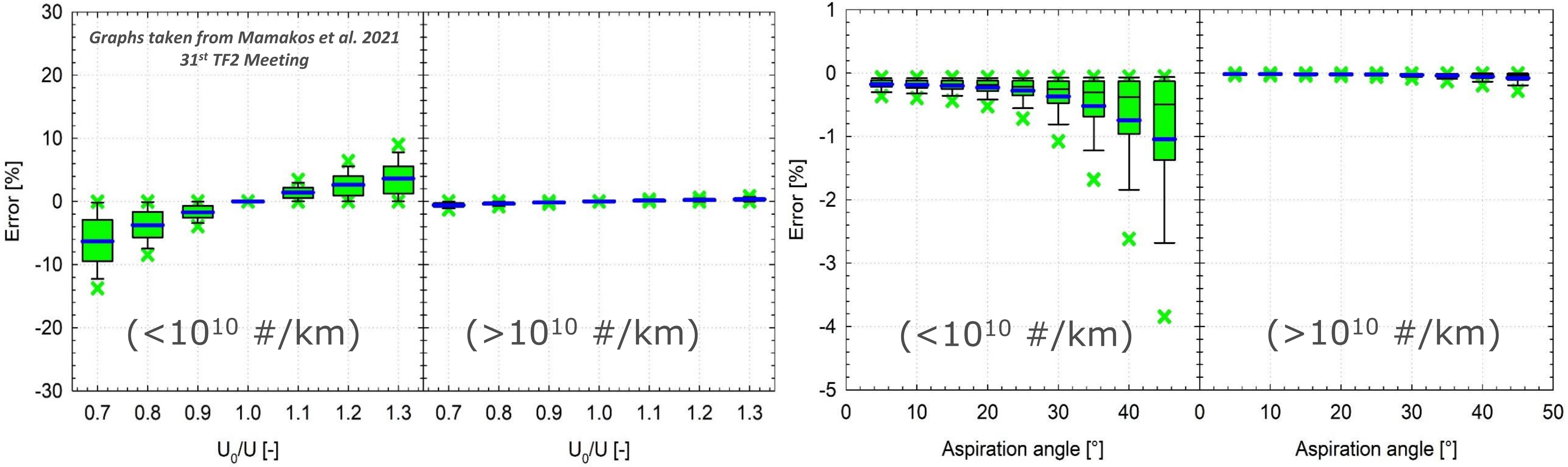




- ✓ ***Labs B, D, G, H, J, K, Q and R did not apply a dilution in some or all of their PN tests*** – Among these labs only G, J, and K reported "correct values"; however, Labs G and J measured higher than the certified values;
- ✓ The maximum total PN concentrations measured at the tunnel (cumulative graph) ranged between 3.5×10^{3} #/cm^3 and 1.1×10^{7} #/cm^3 (CPCs ranged between 5×10^{1} #/cm^3 and 5×10^{5} #/cm^3);
- ✓ ***A dilution stage between 1:10 and 1:100 is necessary to ensure that the certified range of the employed CPCs is respected***.

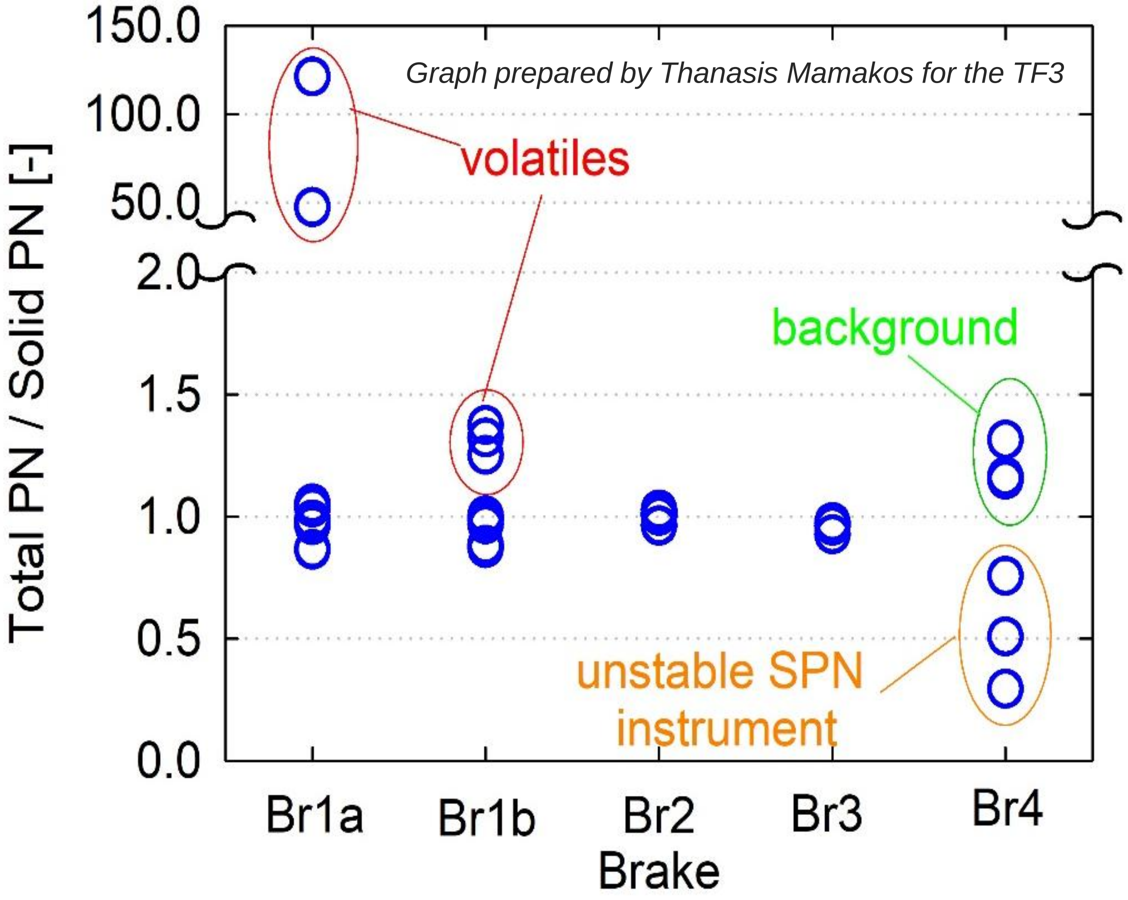
ILS RESULTS – ISOKINETIC AND ISOAXIAL

Based on the submitted data it was not possible to calculate isokinetic ratios for PN sampling in the ILS – also not possible to verify isoaxial sampling (*All labs declared to have followed the specification for restricting the aspiration angle to a maximum 15°*).



The effect of anisokinetic sampling becomes relevant for brake emissions with no nucleation mode – this is the case in most tested brakes. Similarly, the effect of anisoaxial sampling is relevant for lower PN concentrations

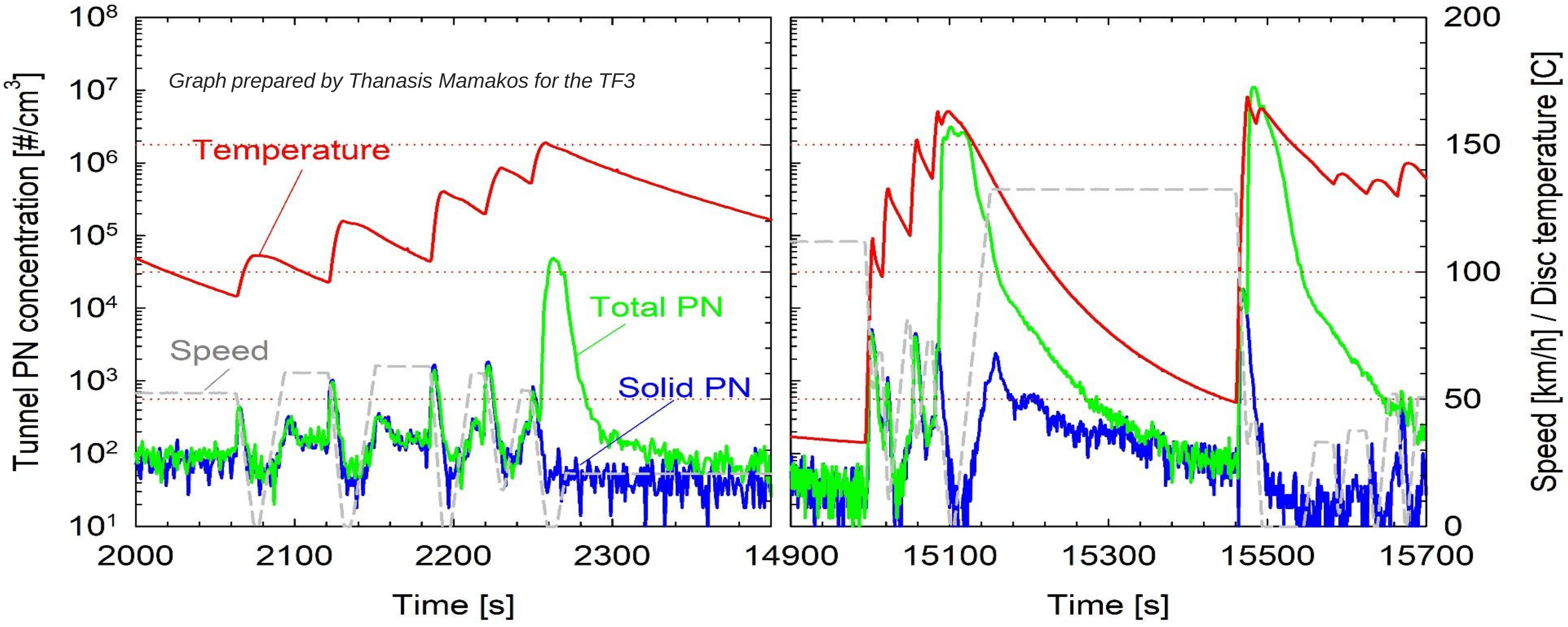
ILS RESULTS - VOLATILE PARTICLES



- ✓ The Total- to Solid- PN ratio has been calculated for the laboratories that performed simultaneous measurement with the aim of studying potential volatile particle formation;
- ✓ A limited number of labs performed solid PN measurements. In majority of labs the difference between total and solid ranged between -13% to +5%, which is within the anticipated calibration uncertainty for PN;
- ✓ Br4 emissions were generally low and the background levels for all labs that tested it were at almost 20-30% of the overall emission levels; therefore, it is not considered as a “positive” for volatile particle formation;

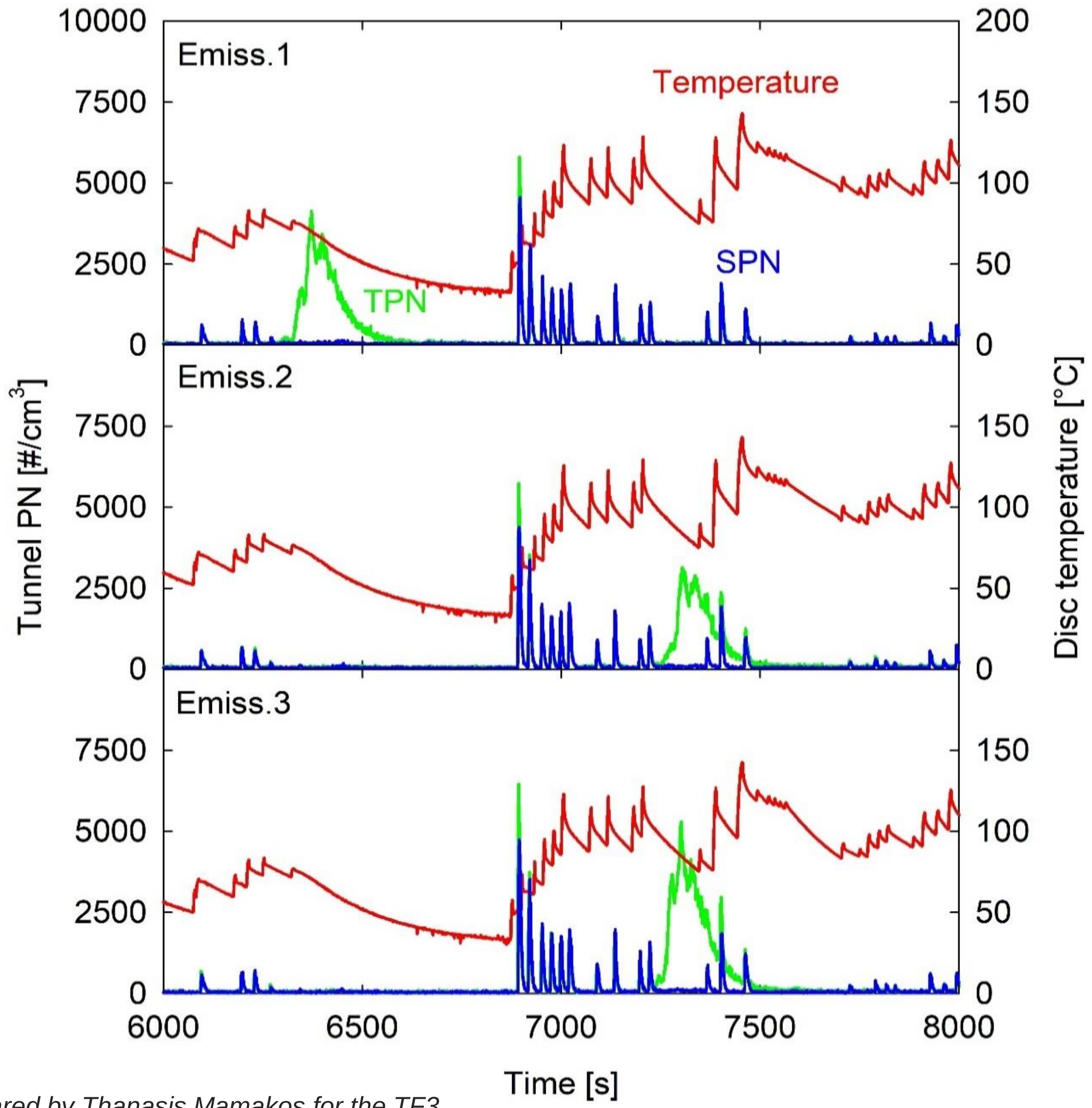
Probable volatile particle formulation with Br1a at Lab T and indications (questionable) for Br1b at Lab M are drawn from the Total/Solid PN ratio.

ILS RESULTS – VOLATILE PARTICLES LAB-T



*Lab T observed a release of volatile PN with Br1a. During the actual event Total PN concentrations are 3-5 orders of magnitude higher than solid PN – **The overall effect results in a cycle-average emissions 100-fold higher than for Solid-PN***

ILS RESULTS - VOLATILE PARTICLES LAB-M

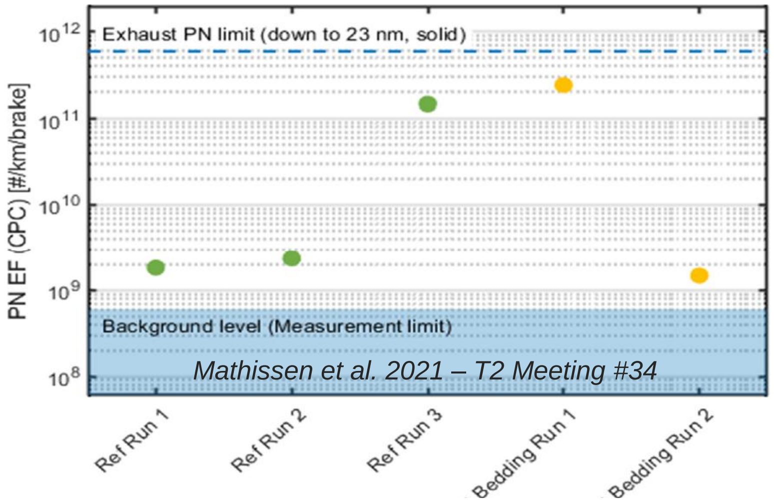


Graph prepared by Thanasis Mamakos for the TF3

- ✓ *Lab M recorded some repeatable release of volatile particles with Br1b approximately halfway through the cycle;*
- ✓ *The exact location differed between the three repetitions, while the release was observed at relatively low temperatures (<100°C);*
- ✓ *These events resulted in an approximately ~20% higher Total PN emissions compared to Solid PN emissions;*
- ✓ *Cycle average results do not show clear indication and the overall emission levels are very low to extract a solid conclusion (BG level at 30-40% of the emissions).*

ILS RESULTS - VOLATILE PARTICLES

Volatile particle formation has been reported also in the past in TF2 – FORD presented in Meeting #34 and concluded that UFP are formed due to burning of pad binder and assumed that these UFP are likely volatile.



ADDITIONALLY: Mamakos et al. reported at the TF2 Meeting #32 "*However, in our latest joint campaign with BMW we observed a distinct nucleation mode when braking from top cruising speed that was detected both with GTR15 method and a CPC sampling directly from tunnel → thermally stable nucleation mode.* ***This lasted ~20 s but led to ~1 order of magnitude increase in PN over the cycle"***

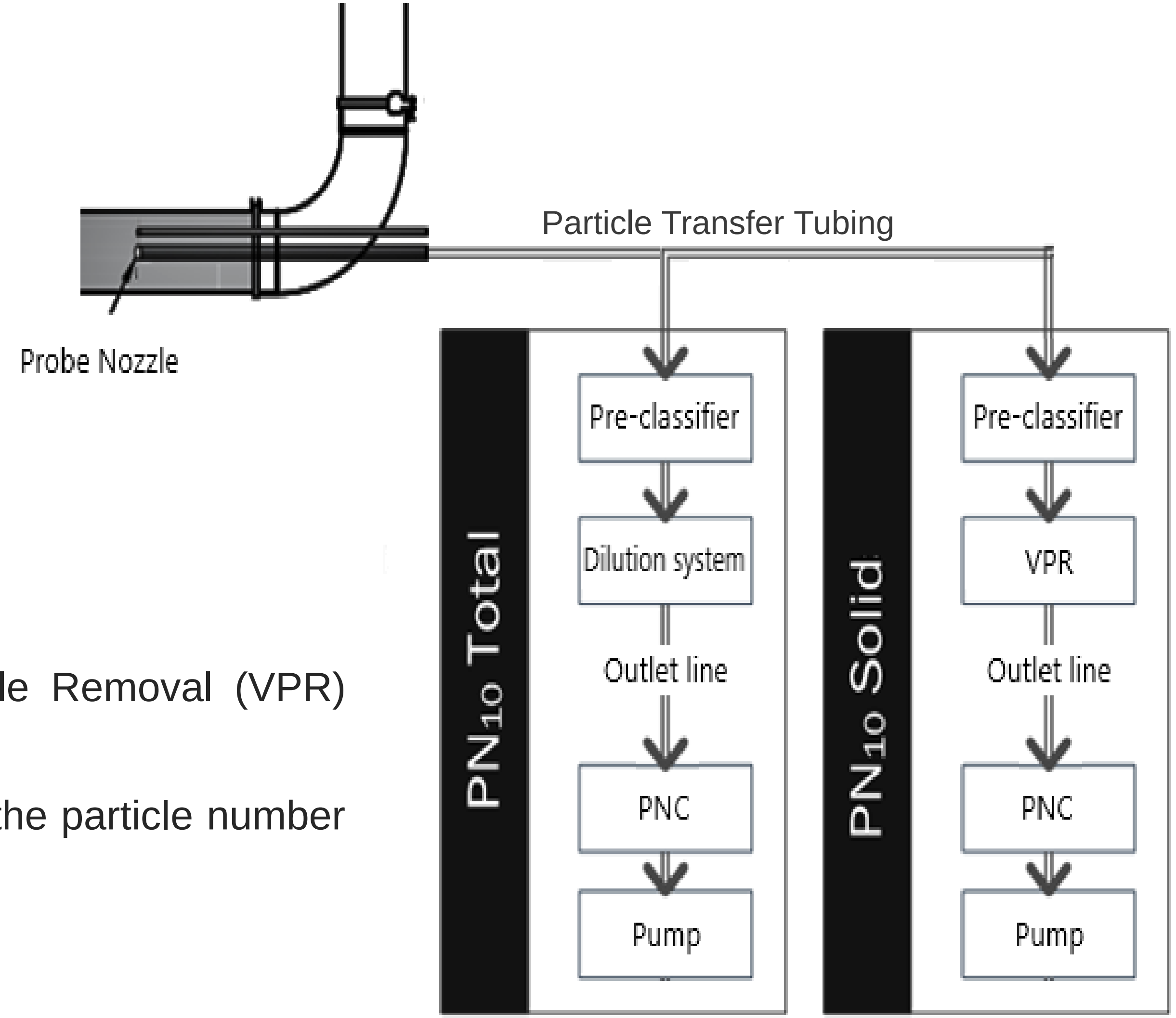
- ✓ ***Total PN measurement seems repeatable and reproducible; however, there are cases that presence of volatiles is reported;***
- ✓ ***Total PN measurement is very useful as it provides indications of possible high PN emission brakes that wouldn't be identified if only Solid PN was measured;***
- ✓ ***Solid PN measurement is necessary to serve as reference PN measurement for lab to lab comparisons.***

DETAILED PROPOSAL FOR CLAUSE 10

Clause 10 – PN PROPOSED SETUP

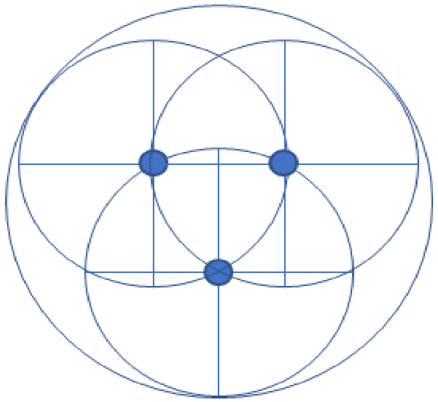
A Total-PN (TPN10) and Solid-PN (SPN10) sampling and measurement unit shall consist of:

- ✓ A sampling probe that extracts a sample from the dilution tunnel;
- ✓ An appropriate nozzle located in the sampling probe tip;
- ✓ A suitable transfer tube (Particle Transfer Tubing) that transfers particles to the pre-classifier;
- ✓ A cyclone applied as a pre-classifier before the dilution system;
- ✓ A dilution system (TPN10) and a Volatile Particle Removal (VPR) system (SPN10);
- ✓ A particle outlet line that transfers the particles to the particle number counting device;
- ✓ The particle number counting (PNC) device;
- ✓ One or more pumps.

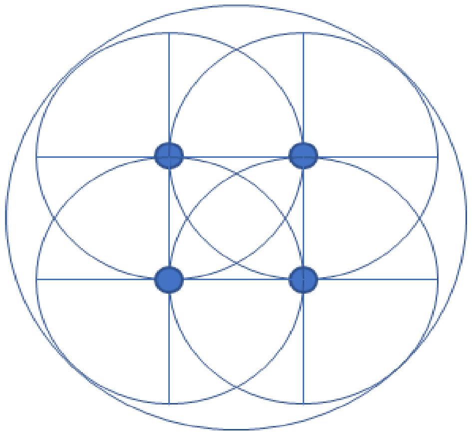


Clause 10.1 – PARTICLE EXTRACTION

- ✓ Probes shall be equally spaced around the central longitudinal axis of the dilution tunnel, with the spacing between them being at least 50 mm (ISO 9096);
- ✓ The 3-probes setup requires a minimum duct diameter of 175 mm. The 4-probes setup requires a minimum duct diameter of 190 mm;
- ✓ Two sampling probes are proposed for the PN concentration measurements, one for TPN10 and one for SPN10 – Alternatively, one probe can be used with the application of an appropriate flow splitting device



3-Probes Setup



4-Probes Setup

- ✓ Specifications for the probe diameter and length are defined. The particles residence time shall be less than 3 s;
- ✓ A bend ≤90° may be applied to the probe - the bending radius r_p shall be at least five times the probe diameter (5·di);

Clause 10.1 – SAMPLING NOZZLES

Appropriate nozzles to ensure sampling with an isokinetic ratio between 0.6-1.5 shall be used (To be discussed). The following requirements shall be met (to be complemented if isokinetic is required) – nozzle requirements are the same for TPN10 and SPN10:

- ✓ The nozzles shall be compatible with all sample probes;
- ✓ The nozzle inner diameter shall not be lower than 4 mm (ISO9096);
- ✓ The selection of the nozzle size shall depend on the applied flow to keep the isokinetic ratio within the defined specifications. The minimum inner diameter shall be lower than 4 mm;
- ✓ Nozzles with a thin-wall at the tip to minimize distortion of flow shall be used. These shall have an outer to inner diameter ratio lower than 1.1 at the nozzle tip
- ✓ The nozzles shall be placed with their axis parallel to that of the dilution tunnel making sure that the aspiration angle remains lower or equal to 15°.

Clause 10.2 – PARTICLE TREATMENT PRE-CLASSIFIER

- ✓ A single cyclonic separator shall be used as a pre-classifier to protect the instrumentation and avoid the possibility of contaminating the system;
- ✓ Commercially available cyclonic separators with a cut-off size between 2.5 µm and of 10 µm shall be used;
- ✓ The cyclone shall achieve a minimum penetration efficiency of 80% for a particle aerodynamic diameter of 1.5 µm
- ✓ Cleaning of the cyclones shall be done frequently following the specifications of the instrument manufacturer regarding the cleaning frequency and means;
- ✓ The specifications for the pre-classifier are the same for both TPN10 and SPN10 sampling and measurement.

Clause 10.2 – PARTICLE TREATMENT CONDITIONING – TPN10

The dilution system shall comprise at least a particle number diluter. A similar to the VPR system may be used; however, heating of the evaporation tube and the second diluter shall be deactivated. ***The following specifications are proposed for the dilution system for measuring TPN10***:

- ✓ It shall be capable of diluting the sample in one or more stages (at least 10:1) to achieve a PN concentration below the upper threshold of the single particle count mode of the PNC;
- ✓ It shall be capable of keeping the dilution factor constant throughout the entire emissions test - It shall monitor the dilution of each dilution stage in real time and report it at frequency of at least 1 Hz;
- ✓ It shall be capable of maintaining the diluted gas temperature at the inlet to the PNC below 38°C;
- ✓ It shall achieve the particle concentration reduction factor (PCRF) requirements specified in the GTR15 (similar to those followed at the ILS);
- ✓ It shall be capable of operating at sample pressures in the 850-1050 mbar range and relative pressure differences from ambient in the ±50 mbar range.

Clause 10.2 – PARTICLE TREATMENT CONDITIONING – SPN10 (1/2)

The VPR shall comprise at least one particle number diluter (PND1) and an evaporation tube. A second diluter (PND2) may be optionally installed in series with the PND1 and the evaporation tube. ***The following specifications apply to the VPR for conditioning particles when measuring SPN10***:

- ✓ It shall be capable of diluting the sample in one or more stages (at least 10:1) to achieve a PN concentration below the upper threshold of the single particle count mode of the PNC;
- ✓ It shall be capable of maintaining the gas temperature at the inlet to the PNC below a maximum allowed inlet temperature specified by the PNC manufacturer;
- ✓ It shall include an initial heated dilution stage which outputs a sample at a wall temperature of ≥150°C and ≤350°C;
- ✓ It shall include a catalytically active evaporation tube which is controlled to a wall temperature greater than or equal to that of the PND1. The wall temperature of the ET shall be held at a fixed operating value at 350°C;
- ✓ It shall control heated stages to constant nominal operating temperatures to a tolerance of ±10°C. Additionally, the VPR system shall provide indication of whether heated stages are at their correct operating temperatures;

Clause 10.2 – PARTICLE TREATMENT CONDITIONING – SPN10 (2/2)

The VPR shall comprise at least one particle number diluter (PND1) and an evaporation tube. A second diluter (PND2) may be optionally installed in series with the PND1 and the evaporation tube. ***The following specifications apply to the VPR for conditioning particles when measuring SPN10***:

- ✓ It shall achieve the particle concentration reduction factor (PCRF) requirements specified in the GTR15 (similar to those followed at the ILS);
- ✓ It shall achieve more than 99.9% vaporization of tetracontane particles with count median diameter >50 nm and mass >1 mg/m^3, by means of heating and reduction of partial pressures of the tetracontane
- ✓ It shall achieve a solid particle penetration efficiency of at least 70% for particles of 100 nm electrical mobility diameter;
- ✓ It shall monitor the dilution of each dilution stage in real time and be capable of reporting it at frequency of at least 1 Hz;
- ✓ It shall operate at sample pressures in the 850-1050 mbar range and relative pressure differences from ambient in the ±50 mbar range.

Clause 10.2 – PARTICLE TREATMENT TRANSFER LINE

The outlet lines that transfer the particles from the dilution system and the VPR to the inlet of the Particle Number Counter shall follow the specifications described below. These apply to both TPN10 and SPN10 sampling:

- ✓ The outlet transfer lines shall be appropriately designed to minimize particle transport losses between the dilution system and the VPR and the inlet of the PNC;
- ✓ The outlet transfer lines shall have a constant inner diameter of at least 4 mm, whereas the flow shall be laminar flow under all operating conditions;
- ✓ The overall length of the outlet lines from the exit of the dilution system and the VPR to the inlet of the PNC shall not exceed 1 m;
- ✓ The particles residence time inside the outlet lines shall be less than 1 s (to be confirmed by the instrument manufacturers);
- ✓ A bend may be applied to the outlet lines provided that the bending radius r_p shall be at least twenty-five times the outlet line diameter ($25 \cdot d_p$).

Clause 10.3 – PARTICLE MEASUREMENT PARTICLE NUMBER COUNTER (1/2)

The Particle Number Counters (PNC) shall meet the following requirements for both TPN10 and SPN10 concentrations measurement:

- ✓ The PNC shall operate under full flow operating conditions;
- ✓ Have a counting accuracy of ±10% across the range from 1 # per cm^{-3} to the upper threshold of the single particle count mode of the PNC against a traceable standard;
- ✓ The Particle Number Counter shall have a readability of at least 0.1 # per cm^{-3} at concentrations below 100 # per cm^{-3};
- ✓ The PNC shall have a linear response to particle concentrations over the full measurement range in single particle count mode;
- ✓ Report PN concentrations both at operational and standard conditions at a reporting frequency equal to or greater than 0.5 Hz;
- ✓ The Particle Number Counter shall have a t_{90} response time over the measured concentration range of less than 5 s;

Clause 10.3 – PARTICLE MEASUREMENT PARTICLE NUMBER COUNTER (2/2)

The Particle Number Counters (PNC) shall meet the following requirements for both TPN10 and SPN10 concentrations measurement:

- ✓ The PNC shall incorporate an internal calibration factor from the linearity calibration against a traceable reference which shall be applied to determine the PNC counting efficiency. The counting efficiency shall be reported including the calibration factor;
- ✓ The PNC calibration material shall be Emery oil or soot-like particles (e.g. flame generated soot or graphite particles);
- ✓ The PNC shall have counting efficiencies at nominal particle sizes of 10 nm and 15 nm electrical mobility diameter of 65±15% and >90%, respectively. These counting efficiencies may be achieved by internal (e.g. control of instrument design) or external (e.g. size pre-classification) means;
- ✓ If the Particle Number Counter makes use of a working liquid, it shall be replaced at the frequency specified by the instrument manufacturer.

Clause 10.3 – PARTICLE MEASUREMENT SAMPLING FLOW

The following provisions for the sampling volumetric flow apply to both TPN10 and SPN10 sampling and measurement (to be defined and agreed in TF2 if this is necessary):

- ✓ The method of measuring sampling volumetric flow shall be such that measurement is accurate to ±2.5% of reading or ±1.5% full-scale, whichever is the least, under all operating conditions;
- ✓ The volumetric flow measurement device shall be calibrated to report flow at both operating and standard conditions (273.15 K and 101.325 kPa);
- ✓ The set value for the sampling volumetric flow shall be the same and constant during the testing of a specific brake system;
- ✓ The sampling volumetric flow shall be within ±10% of the average value for the given test. Use a device with a flow control feature to ensure a stable flow;
- ✓ The set value for the isokinetic ratio shall be between 0.60-1.50 (range to be defined and agreed in TF2).

Clause 10.3 – PARTICLE MEASUREMENT CALCULATION OF PN EFs

The testing facility shall report the PN emissions concentration in a number of particles per distance driven (TPN10 [#/km] and SPN10 [#/km]). The calculation of the PN emissions concentration in a number of particles per distance driven follows the equations below:

$$TPN10\ (\#/km) = 10^6 \times [TPN10\ (\#/Ncm^3) \times Q_{Tunnel\text{-}AVG}\ (Nm^3/h)]\ /\ V_{Avg}\ (km/h)$$

$$SPN10\ (\#/km) = 10^6 \times [SPN10\ (\#/Ncm^3) \times Q_{Tunnel\text{-}AVG}\ (Nm^3/h)]\ /\ V_{Avg}\ (km/h)$$

- ✓ The normalized PN concentrations (TPN10 and SPN10 [#/km]) are the average PN values over the emissions measurement and are calculated from the parameters in the Time-Based file;
- ✓ The average normalized cooling airflow throughout the emissions measurement ($Q_{Tunnel\text{-}AVG}$) shall be calculated from the given parameter in the Time-Based file;
- ✓ The average velocity of the WLTP-Brake cycle (VAvg) is assumed to equal the nominal average value over the WLTP-Brake cycle (V_{Avg}=43.7 km/h).

Clause 10.3 – PARTICLE MEASUREMENT PN SYSTEM CHECK PROCEDURES

The testing facility shall apply the following PN system check procedures to verify the whole system is fully operational:

- ✓ Prior to each test, the particle counter shall report a measured concentration of less than 0.5 particles cm^{-3} when a HEPA filter of at least class H13 of EN 1822:2008, or equivalent performance, is attached to the inlet of the entire particle sampling system;

- ✓ On a monthly basis, the flow into the particle counter PNC shall have a measured value within 5% of the particle counter PNC nominal flow rate when checked with a calibrated flow meter. Here the term ‘nominal flow rate’ refers to the flow rate stated in the last calibration for the PNC;

- ✓ On a daily basis, a zero check on the PNC, using a filter of appropriate performance at the PNC inlet, shall report a concentration of $\leq 0.2\ cm^{-3}$. Upon removal of the filter, the PNC shall show an increase in measured concentration and a return to $\leq 0.2\ cm^{-3}$ on replacement of the filter. The PNC shall not report any errors.

Thank you