PARTICLE MEASUREMENT PROGRAMME

PMP-IWG

TASK FORCE 2 – BRAKE EMISSIONS

CLAUSE 9 OF THE TF2 PROTOCOL

PM Measurement

CLAUSE 9 – OVERVIEW

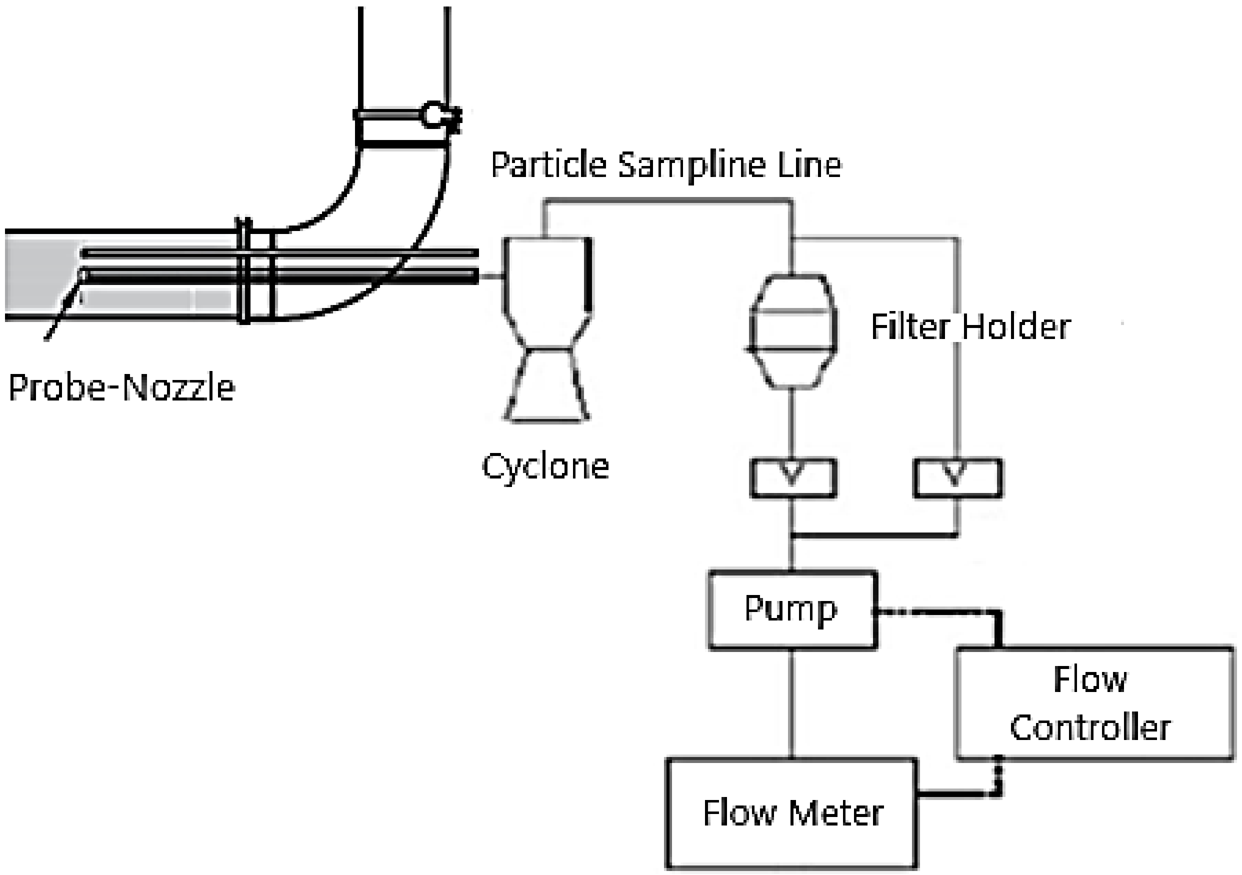
ILS data and the TF2 protocol have been used to amend Clause 9. Stricter and new specifications compared to the initial proposal have been introduced – Sub-clauses may further change:

- ✓ 9.1 – Describes the general elements related to the particle transport in the ducts focusing in the area between the enclosure exit and the sampling plane;
- ✓ 9.2. – Describes the general elements related to the particle extraction – Defines the sampling plane – Restrictions regarding the duct dimensions – Specifications about the nozzles;
- ✓ 9.3. – Discusses the PM separation device – Specifications about the cyclone and the sampling tubes are discussed – Provisions regarding the sampling volumetric flow;
- ✓ 9.4 – Describes the general specifications for the sampling media allowed for PM measurements – Alignment with the GTR15;
- ✓ 9.5 – Describes the general specifications for the weighing procedure – A major alignment with the GTR15 specifications.

CLAUSE 9 – PM PROPOSED SETUP

A PM sampling unit shall consist of the following elements:

- ✓ A sampling probe that transfers particles from the tunnel to the separation device;
- ✓ An appropriate nozzle located in the sampling probe tip;
- ✓ A cyclone applied as a PM separation device;
- ✓ A particle sampling line that transfers the particles to the filter holder;
- ✓ A filter holder that collects the particles;
- ✓ One or more pumps;
- ✓ Flow rate regulators;
- ✓ Measuring units.



CLAUSE 9 – SOURCES OF ERROR FOR PM

Potential sources of error and losses during particle transport from the enclosure to the sampling plane as well as during their extraction at nozzle include:

- ✓ Anisokinetic sampling
- ✓ Anisoaxial sampling
- ✓ Inertial impaction
- ✓ Gravitational deposition

Transport & extraction

Mamakos et al. 2021 – 28th TF2 Meeting

ADDITIONALLY:

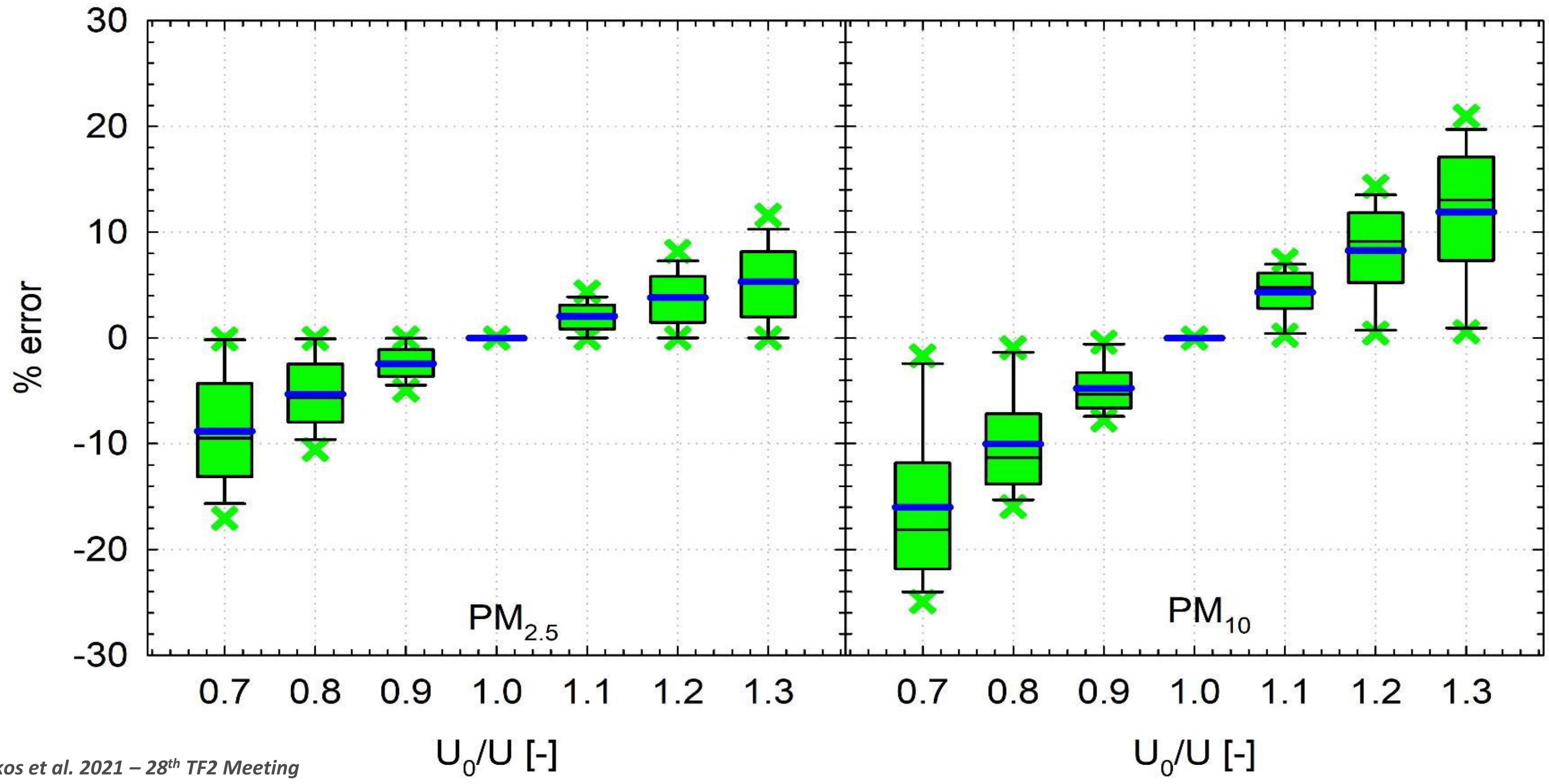
Classification

Weighing

Material from Mamakos et al. 2021 – 28th TF2 Meeting

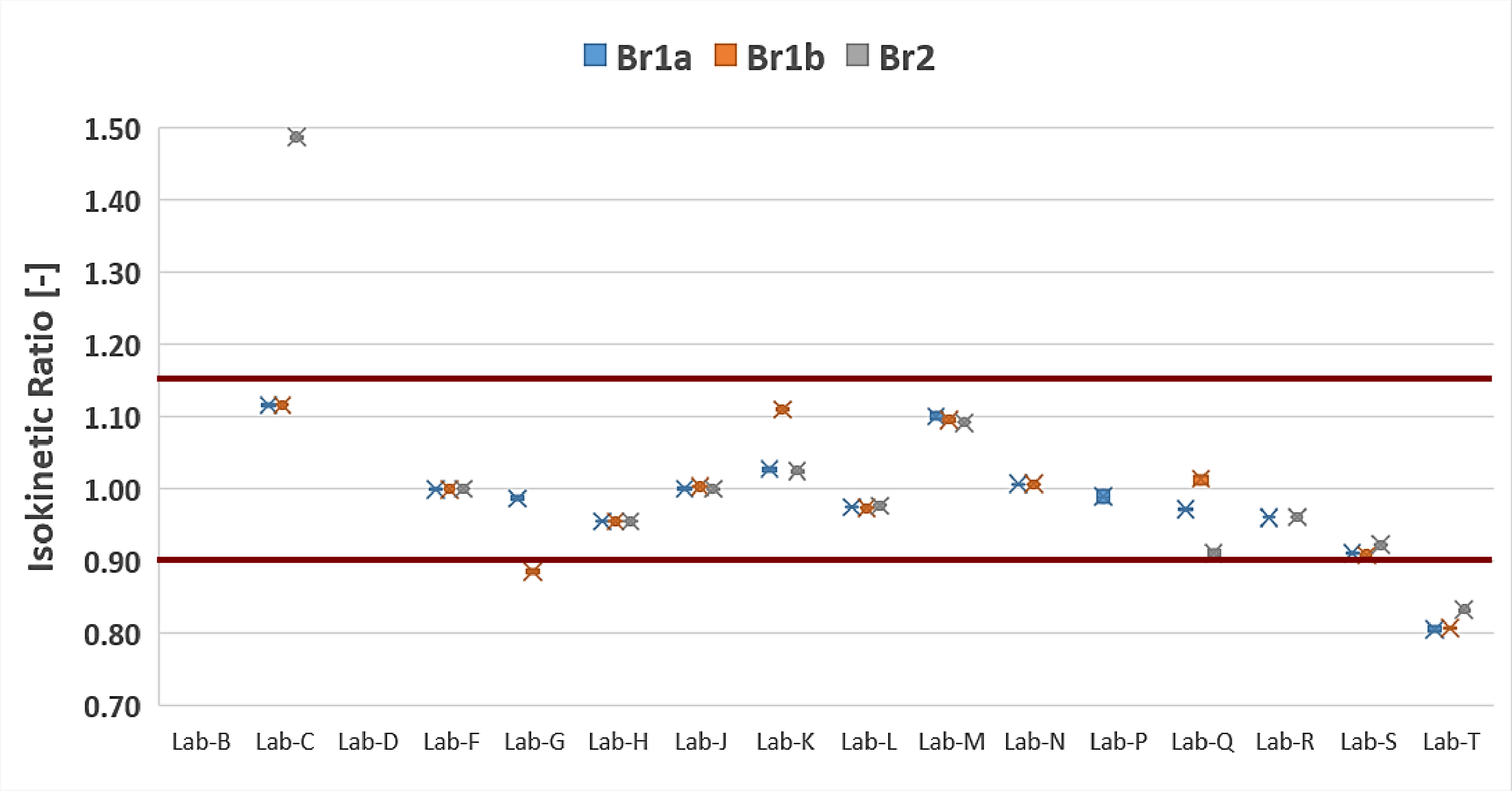
CLAUSE 9 – ISOKINETIC SAMPLING

Anisokinetic sampling can have a strong effect on both PM – Proposal to define a isokinetic ratio between 0.90-1.15 for the ILS (ISO9096).



Graph taken from Mamakos et al. 2021 – 28th TF2 Meeting

CLAUSE 9 – ILS ISOKINETIC RATIOS



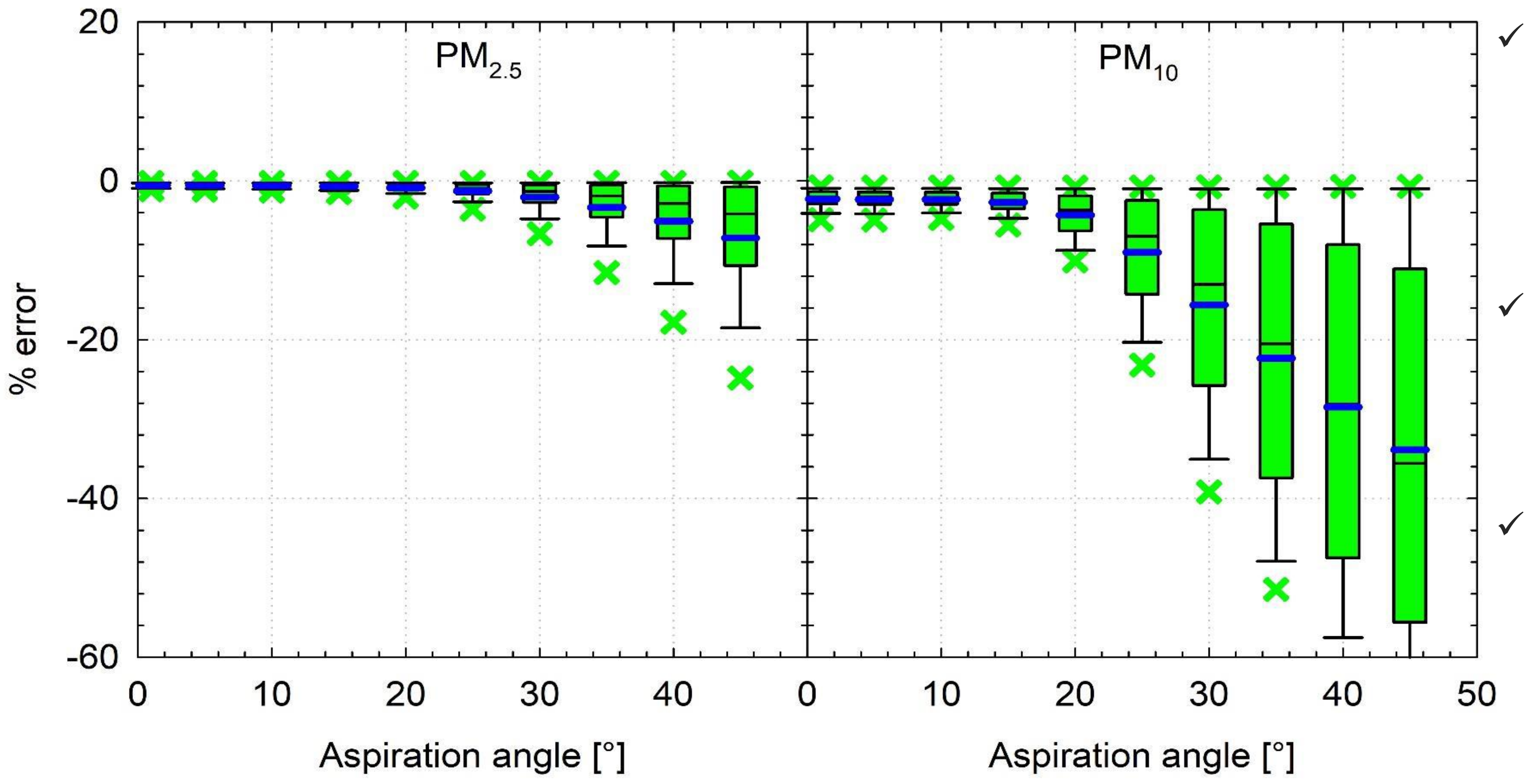
- ✓ *Calculation carried out using averaged cooling air flow of the tests – not always measured correctly;*
- ✓ *Calculation assumes a stable PM_{10} sample flow - might not have been always the case.*

	Br1a	Br1b	Br2
AVG	0.99	0.99	1.01
MIN	0.80	0.81	0.83
5th Perc.	0.81	0.85	0.83
50th Perc.	0.99	1.00	0.98
95th Perc.	1.11	1.11	1.49
MAX	1.12	1.12	1.49

Isokinetic sampling shall be ensured through the accurate control of the cooling air flow and the PM sampling flow *– the actual flows shall be checked and verified post-test. Appropriate nozzles shall be used for achieving an isokinetic ratio close to 1.0.*

CLAUSE 9 – ANISOAXIAL SAMPLING

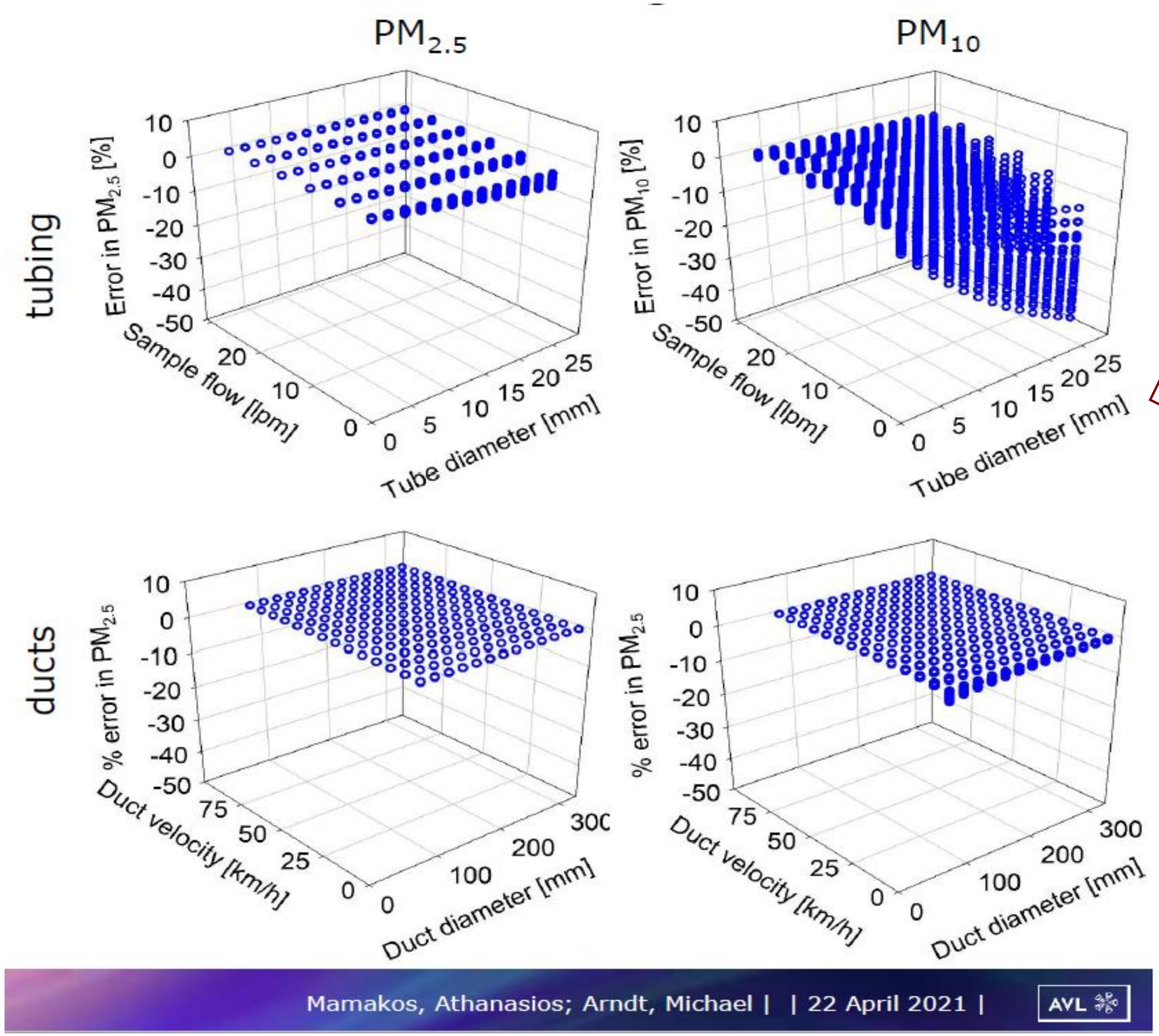
Assuming an isokinetic sampling, the effect of anisoaxial sampling is expected to be negligible for aspiration angles smaller than 15°.



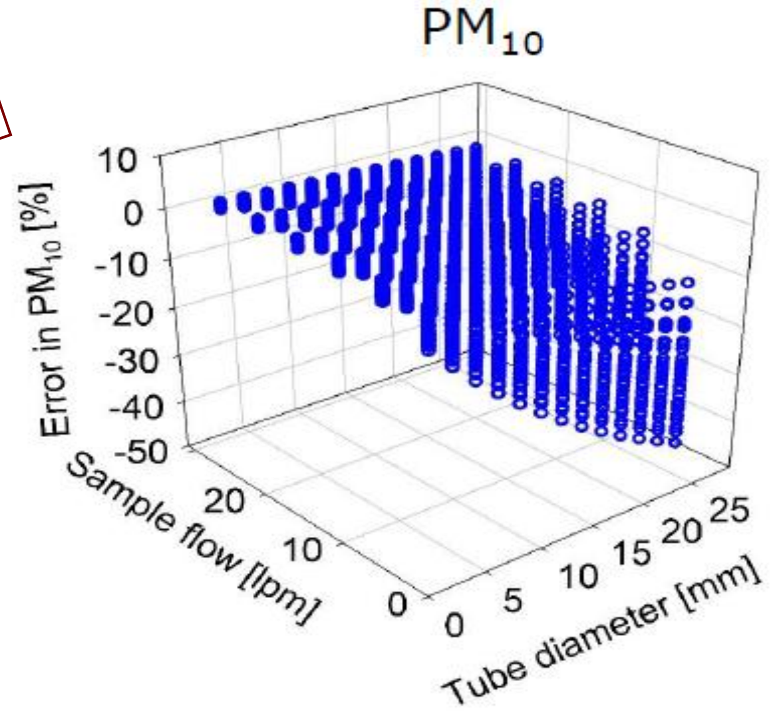
Graph taken from Mamakos et al. 2021 – 28th TF2 Meeting

- ✓ *All labs declared to have followed the specification for restricting the aspiration angle to a maximum 15°;*
- ✓ *It is not possible to extract any conclusion related to this parameter from the ILS;*
- ✓ *The proposal remains to keep the restriction of the angle as is.*

CLAUSE 9 – GRAVITATIONAL LOSSES

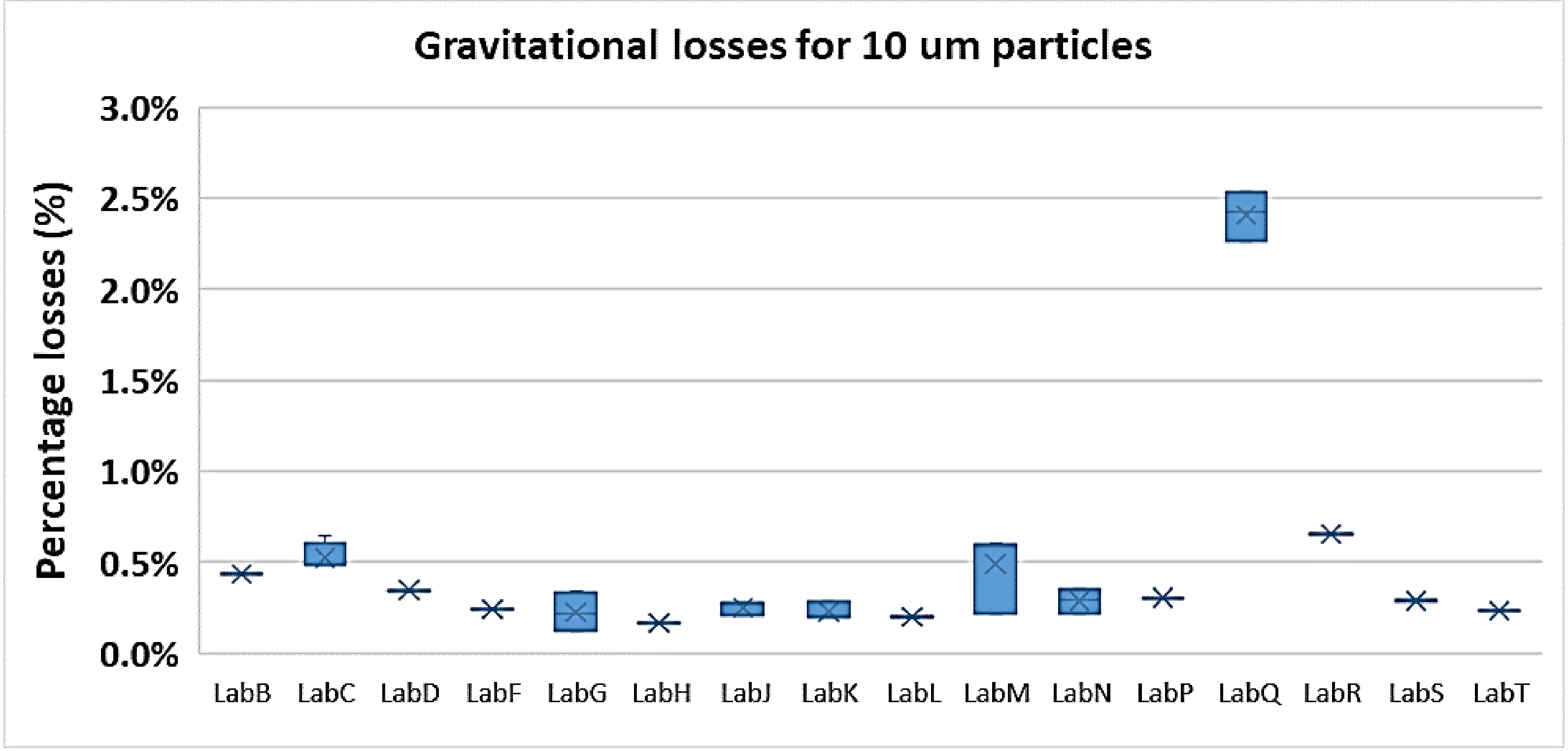


- ✓ *Gravitational losses on tunnel ducts are not typically critical;*
- ✓ *Gravitational losses in horizontal tubing can be significant at large diameters and small flows – this applies specifically to PM_{10}.*



CLAUSE 9 – GRAVITATIONAL LOSSES IN DUCTS

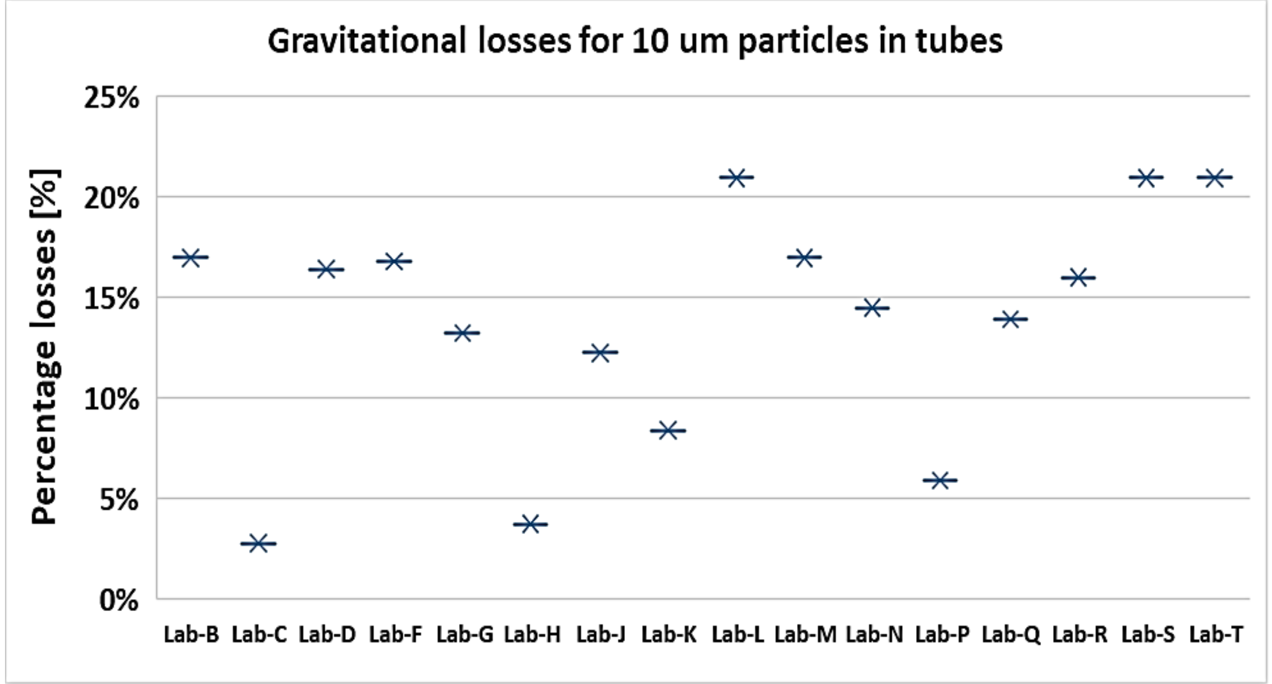
- ✓ An attempt to calculate the gravitational losses for the 10 μm particles in the different setups during the ILS has been made – Calculations for all applied flows were performed;
- ✓ The following assumptions are considered: **d_a=10 μm**, $V_{settling}$=0.00304 m/s, p_{air}=1.2 kg/m3, μ=1.83E-05, **L_{ref}=1 m** – Very similar results for typical 1.5 m distances from the enclosure to the sampling plane.



- ✓ *The gravitational losses in the tunnel are expected to be very low at the typical ILS operating conditions;*
- ✓ *This applies also to longer ducts than the 1m assumed for the calculations;*
- ✓ *The lower Reynolds number observed was close to 40000 excluding Lab-Q that had generally lower values.*

CLAUSE 9 – GRAVITATIONAL LOSSES IN TUBES

✓ Gravitational losses for the 10 μm particles in the tubes at the different setups of the ILS are calculated – similar assumptions as for calculating losses in the ducts – Diameters assumed apply for the sampling tube (not probe).

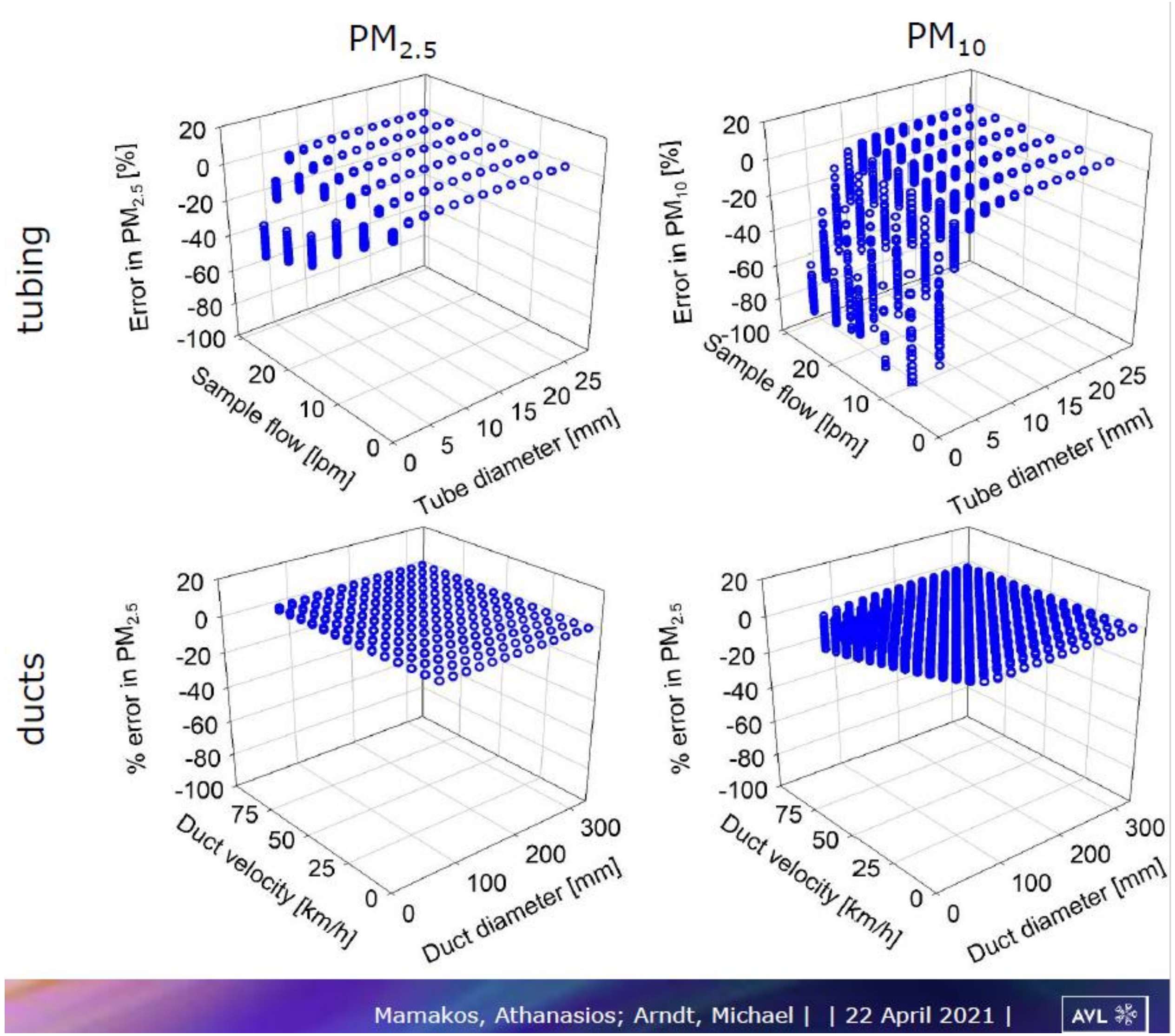


Lab	D [mm]	Q [lpm]	Re [-]	Turbulent Flow [-]	Losses
Lab-B	10	10	1395	FALSE	*17%*
Lab-C	10	65	9069	TRUE	*3%*
Lab-D	9.65	10	1445	FALSE	*16%*
Lab-F	16.5	16.7	1412	FALSE	*17%*
Lab-G	12.7	16.5	1812	FALSE	*13%*
Lab-H	6.25	30	6697	TRUE	*4%*
Lab-J	21.3	30	1965	FALSE	*12%*
Lab-K	12	25	2906	FALSE	*8%*
Lab-L	10	8.0	1116	FALSE	*21%*
Lab-M	10	10	1395	FALSE	*17%*
Lab-N	12.7	15	1647	FALSE	*14%*
Lab-P	10	30	4185	TRUE	*6%*
Lab-Q	7.87	9.7	1719	FALSE	*14%*
Lab-R	15.4	16.4	1485	FALSE	*16%*
Lab-S	10	8.0	1116	FALSE	*21%*
Lab-T	10	8.0	1116	FALSE	*21%*

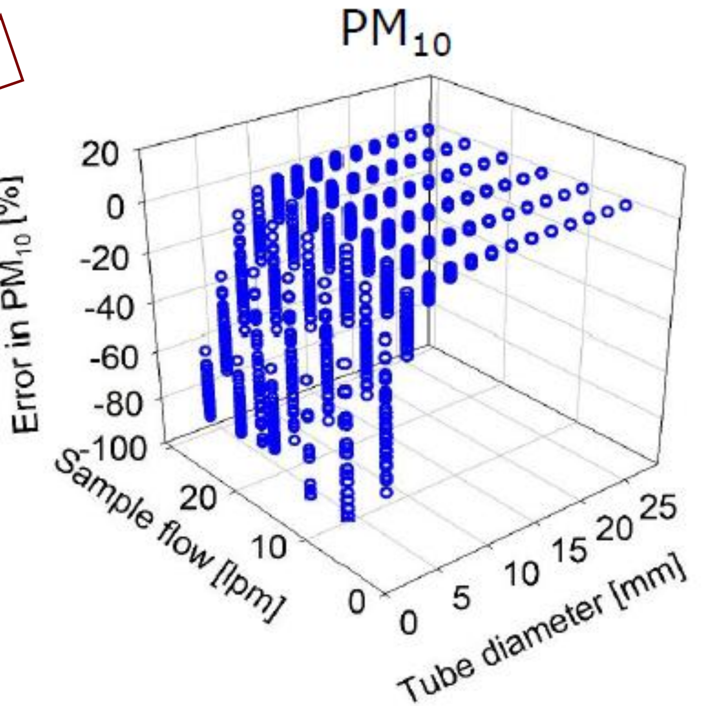
✓ *Gravitational losses can become more critical in tubes compared to the ducts – In the ILS conditions 10 μm losses of up to 20% are expected – **The overall influence to the PM_{10} fraction is expected to be lower**;*

✓ ***Take away is that a combination of long lines with large diameters with low flows will result in high losses** – optimization taking into account also inertial losses is needed.*

CLAUSE 9 – INERTIAL IMPACTION ON BENDS

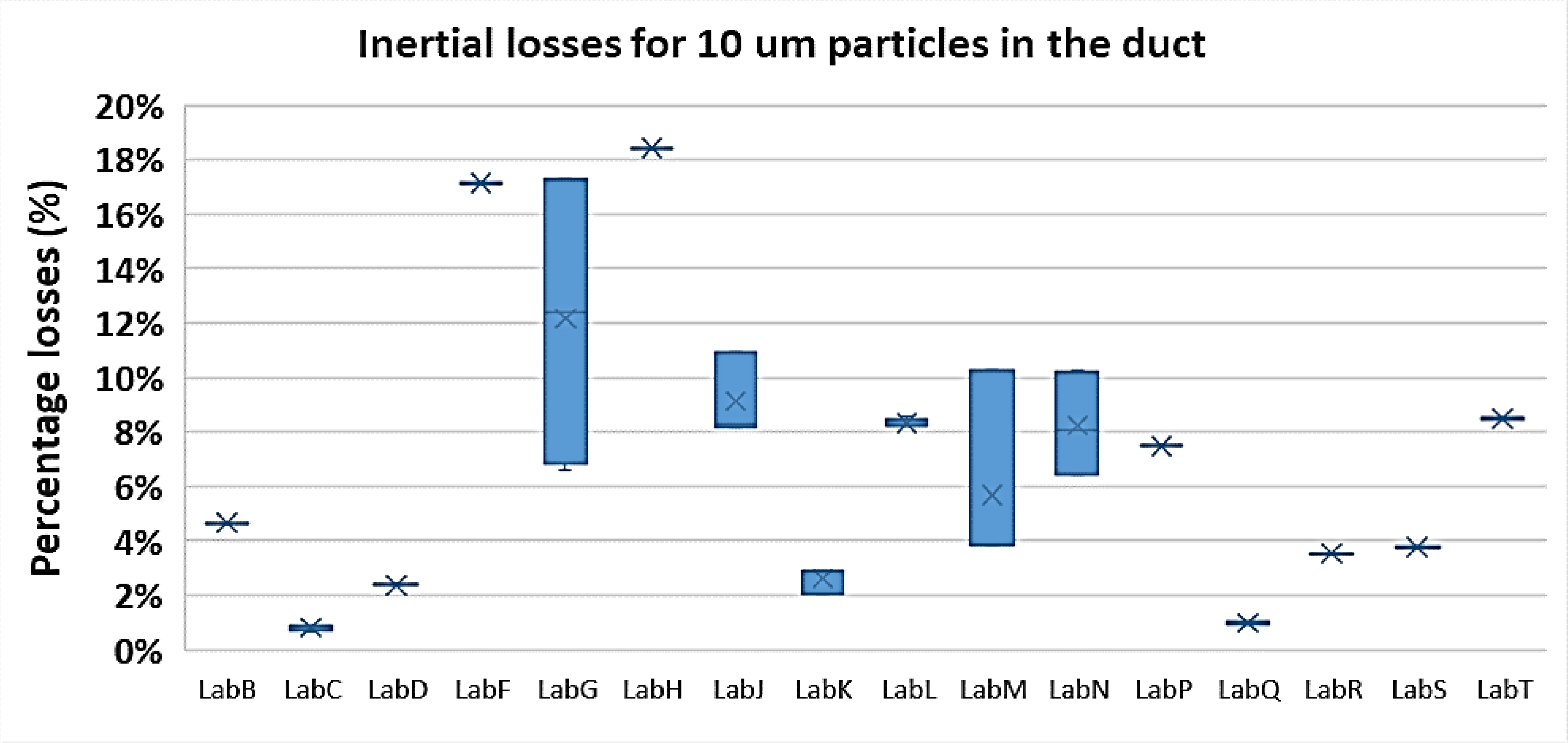


- ✓ *Inertial impaction on bends can become excessive;*
- ✓ *In ducts, inertial losses increase in high tunnel speeds;*
- ✓ *In tubes, inertial losses increase in high sampling flows and low tube diameters.*



CLAUSE 9 – INERTIAL LOSSES IN DUCTS

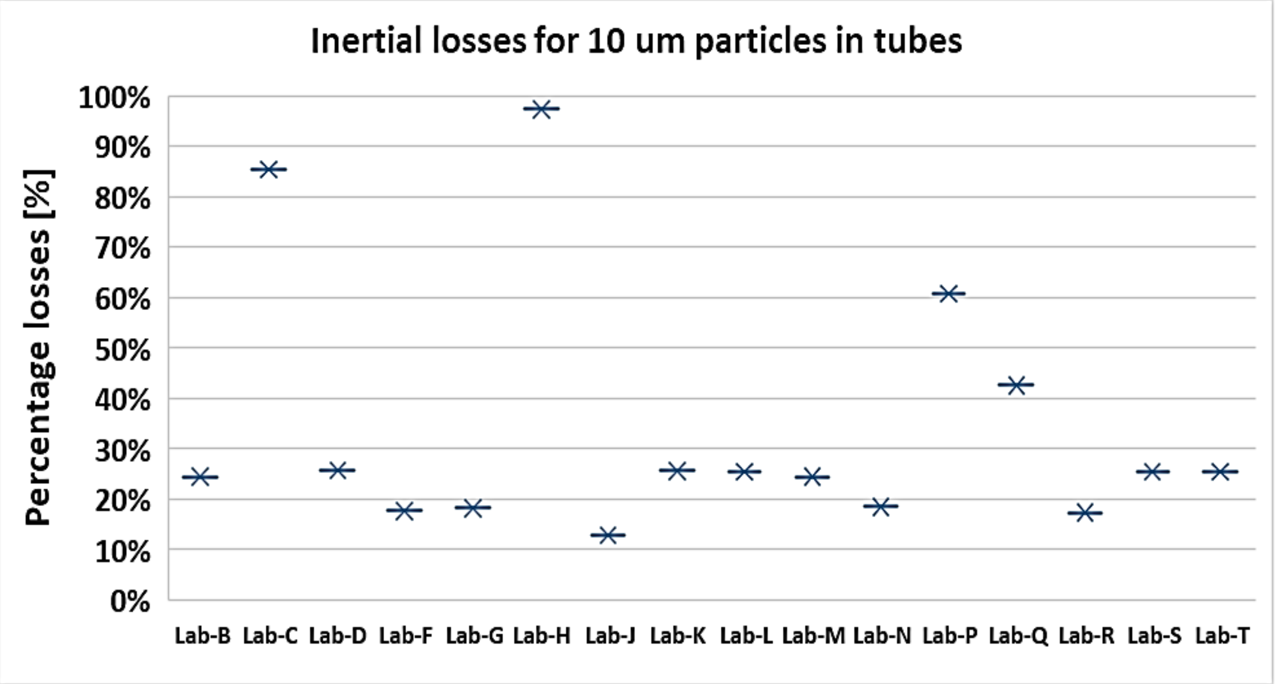
- ✓ An attempt to calculate the inertial losses for the 10 μm particles in the different setups during the ILS has been made – Calculations for all applied flows were performed;
- ✓ The following assumptions are considered: d_a=10 μm, $V_{settling}$=0.00304 m/s, p_{air}=1.2 kg/m3, μ=1.83E-05, t_{rel}=0.00031 s – In all cases, one 90° bend has been considered.



- ✓ *Inertial losses in the tunnel are expected to be low at the typical ILS operating conditions;*
- ✓ *They can become more critical at high air tunnel speeds like in case of Lab-F (54 kph), Lab-H (67 kph) and Lab-G with Br5 (74kph);*
- ✓ ***The overall influence to the PM_{10} fraction is expected to be lower.***

CLAUSE 9 – INERTIAL LOSSES IN TUBES

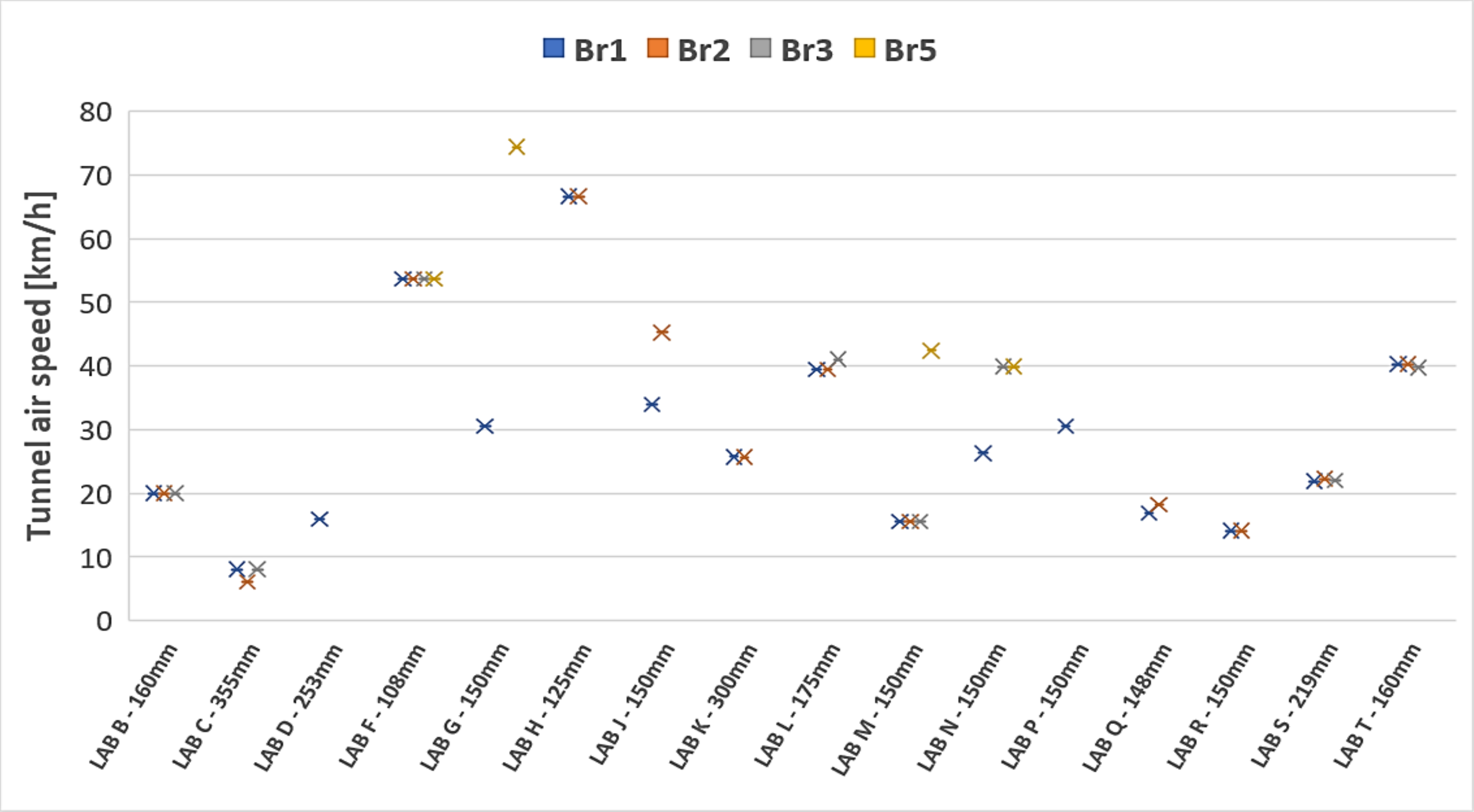
- ✓ Inertial losses for the 10 μm particles in the tubes at the different setups of the ILS are calculated – similar assumptions as for calculating losses in the ducts.



Lab	D [mm]	Q [lpm]	Re [-]	Turbulent Flow [-]	Losses
Lab-B	10	10	1395	FALSE	***24%***
Lab-C	10	65	9069	TRUE	***85%***
Lab-D	9.65	10	1446	FALSE	***26%***
Lab-F	16.5	16.7	1412	FALSE	***18%***
Lab-G	12.7	16.5	1813	FALSE	***18%***
Lab-H	6.25	30	6697	TRUE	***97%***
Lab-J	21.3	30	1965	FALSE	***13%***
Lab-K	12	25	2907	FALSE	***26%***
Lab-L	10	8	1116	FALSE	***25%***
Lab-M	10	10	1395	FALSE	***24%***
Lab-N	12.7	15	1648	FALSE	***19%***
Lab-P	10	30	4186	TRUE	***61%***
Lab-Q	7.87	9.7	1720	FALSE	***43%***
Lab-R	15.4	16.4	1486	FALSE	***17%***
Lab-S	10	8	1116	FALSE	***25%***
Lab-T	10	8	1116	FALSE	***25%***

- ✓ *Inertial losses can become very much critical in tubes even with one bend only – Labs H and P experienced very high losses that compromised the **overall PM_{10} fraction** – cannot confirm for Lab-C;*
- ✓ ***Again, attention shall be paid to avoid combinations of low diameters with very high flows** – optimization taking into account also gravitational losses is needed.*

CLAUSE 9 – DUCTS AND TUNNEL SPEED



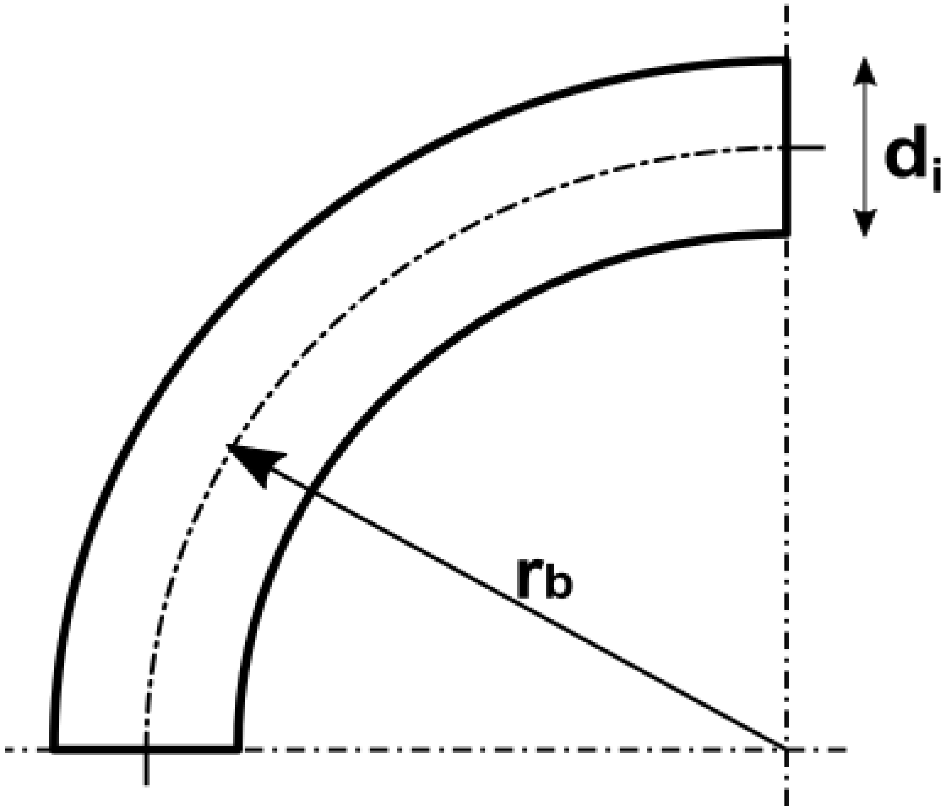
	Lab-B	Lab-C	Lab-D	Lab-F	Lab-G	Lab-H	Lab-J	Lab-K	Lab-L	Lab-M	Lab-N	Lab-P	Lab-Q	Lab-R	Lab-S	Lab-T
Bending radius	6d	2d	4d	10d	2d	1.5d	1.5d	2d	>1.5d	2d	2d	1.7d	3d	2d	2d	1.5d
Duct diameter	160	355	253	108	150	125	150	300	175	150	150	150	148	150	219	160

Valid Measurements | Questionable Measurements

- ✓ *Tunnel air speeds for all labs with (almost) all brakes are presented;*
- ✓ *Typical tunnel speeds observed at the ILS vary between 15-45 kph and cover all tested brakes;*
- ✓ *Labs F and H run systematically at high air speeds due to very small duct diameters;*
- ✓ *High speeds may result in high inertial losses depending on the setup – not confirmed for Lab-F;*
- ✓ *Lab-C run systematically at very low speeds due to very high duct diameters;*
- ✓ *Need to harmonize duct sizes based on the sampling needs.*

CLAUSE 9.1 – PARTICLE TRANSFER AND DUCTS

- ✓ The cooling air shall flow through round ducts with no or minimal variations in the cross-section between the enclosure exit and the sampling plane;
- ✓ The surfaces of the ducts that come into contact with the aerosol shall be made of stainless steel with an electropolished finish;
- ✓ The transition points, if any, shall not have imperfections or features that may collect brake particles that could become airborne again later during the test;
- ✓ When bends are applied in the setup, the bending radius of the ducts r_b shall be at least two times the duct diameter ($2 \cdot d_i$);



- ✓ ***The inner diameter of the ducts d_i shall be constant for a given setup and may vary between 175 mm and 250 mm in different setups***

CLAUSE 9.2 – SAMPLING PLANE

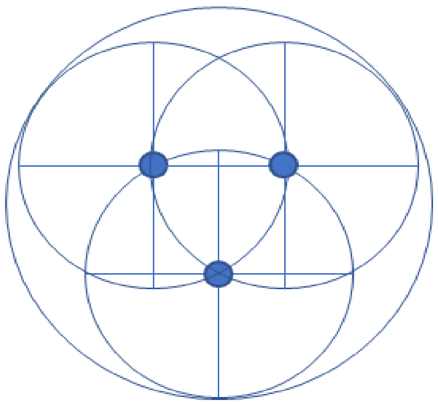
- ✓ The sampling plane shall be located at least 6·di downstream and 2·di upstream of any flow disturbance (Fulfils ISO9096);

	Lab-B	Lab-C	Lab-D	Lab-F	Lab-G	Lab-H	Lab-J	Lab-K	Lab-L	Lab-M	Lab-N	Lab-P	Lab-Q	Lab-R	Lab-S	Lab-T
Downstream	8D	5D	4D	5.5D	5D	6D	5D	0D	4D	5D	8D	5D	6D	8D	7D	6.5D
Upstream	6D	5D	?	2D	?	2D	2D	0D	1.7D	2D	2D	2D	2D	2D	2.3D	2D

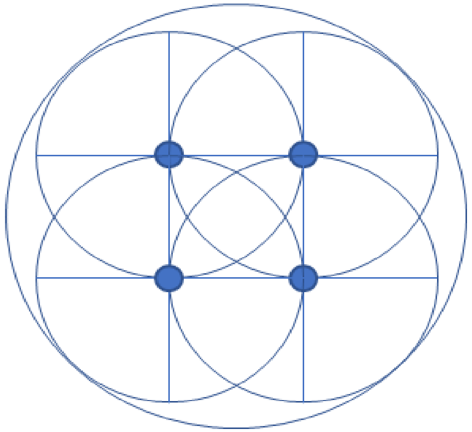
- ✓ A maximum of one bend of 90° may be applied before the sampling plane provided that the specifications for the design of the bend and the minimum distancing are met;
- ✓ A minimum of three (and a maximum of four) extraction points with corresponding probes are required to perform brake particle emissions measurements;
- ✓ Two extraction points shall be dedicated to PM measurements, one for $PM_{2.5}$ and one for PM_{10} - The use of flow splitters for PM measurements is not permitted;
- ✓ All extraction points shall be in the same cross-section area following the specification of the GTR15.

CLAUSE 9.2 – SAMPLING PROBES

- 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);
- In addition, the probe-to-duct wall distance shall also remain 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;



3-Probes Setup



4-Probes Setup

- Probes shall have an internal diameter of at least 10 mm and a maximum of 15 mm (?) and their length shall not exceed 1m;
- A maximum of one bend ≤90° may be applied to the probe - the bending radius r_p shall be at least three times the probe diameter (3·di);

CLAUSE 9.2 – SAMPLING NOZZLES

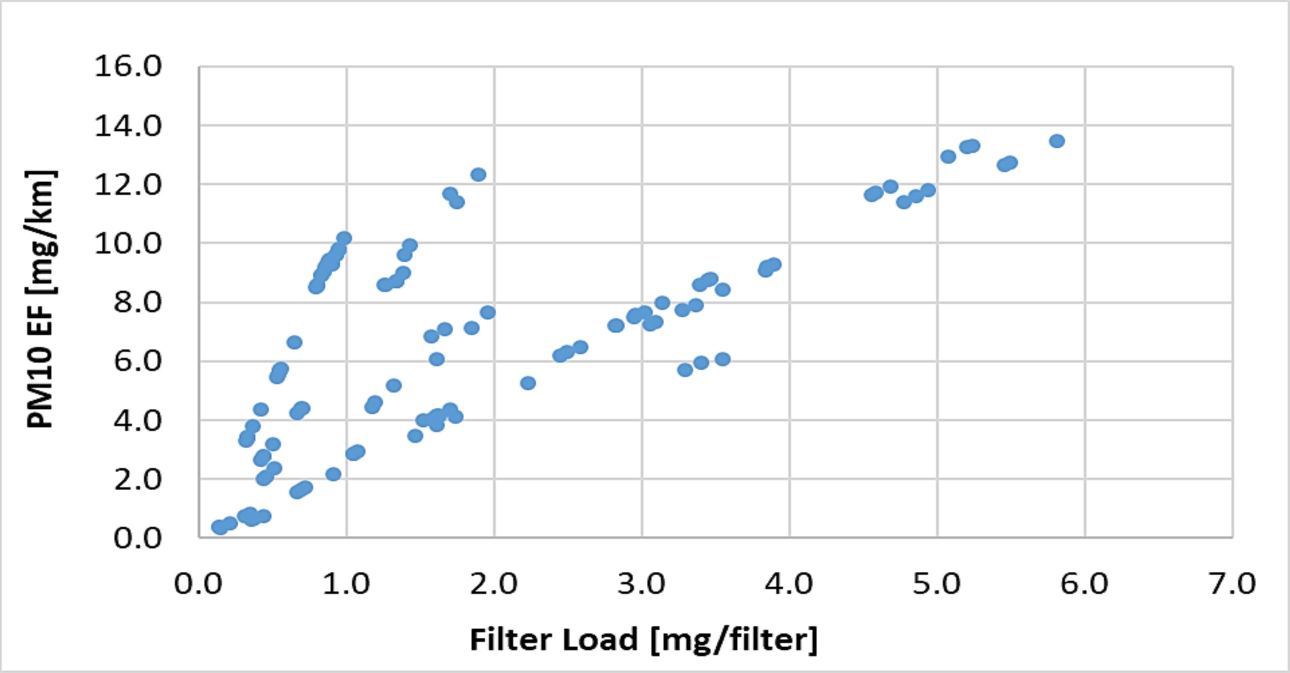
Appropriate nozzles to ensure isokinetic sampling for PM_{10} and $PM_{2.5}$ shall be used. The following requirements shall be met:

- ✓ The nozzles shall be compatible with all sample probes;
- ✓ The nozzle size shall be selected depending on the applied flow. The nozzle inner diameter shall not be lower than 4 mm (ISO9096);
- ✓ The appropriate nozzle size to achieve an isokinetic ratio (the ratio of air velocity in the nozzle to the air velocity in the duct) close to 1.0 shall be selected;
- ✓ Nozzles with at least 10 mm length with a constant internal diameter (ISO9096) shall be selected;
- ✓ Nozzles with thin-wall to minimize distortion of flow. These shall have an outer to inner diameter ratio lower than 1.1 (Mamakos et al. 2021 – TF2 Meeting #28);

CLAUSE 9.3 – SEPARATION DEVICE

	Separation Device
Lab-B	Cascade Impactor
Lab-C	Cyclone
Lab-D	Cyclone
Lab-F	Both
Lab-G	Cyclone
Lab-H	Cascade Impactor
Lab-J	Cascade Impactor
Lab-K	Single Impactor
Lab-L	Cyclone
Lab-M	Cascade Impactor
Lab-N	Cyclone
Lab-P	Cascade Impactor
Lab-Q	Cascade Impactor
Lab-R	Single Impactor
Lab-S	Cyclone
Lab-T	Cyclone

- ✓ Six out of eight labs that measured without obvious errors applied cyclones for the PM_{10} – Five of them applied cyclones also for $PM_{2.5}$;
- ✓ Six out of eight labs that used impactors had some errors in the PM measurement – These are not necessarily related to the impactor.



All Tests	Filter Load [mg]
Average	2.0
Minimum	0.1
5th Perc.	0.3
25th Perc.	0.5
50th Perc.	1.1
75th Perc.	3.0
95th Perc.	5.5
Maximum	15.0

As a rule of thumb, impactors shall not collect more than 1 mg per impaction stage – In 65% of the tests with impactors the PM_{10} filter load was higher (75th percentile is 3.9 mg/filter) – This may severely compromise both PM_{10} and $PM_{2.5}$ measurement.

CLAUSE 9.3 – SEPARATION DEVICE

- ✓ Single PM_{10} and $PM_{2.5}$ cyclonic separators followed by gravimetrical filter holders shall be used for the collection of the PM_{10} and $PM_{2.5}$ samples;
- ✓ Commercially available cyclonic separators with cut-off sizes of 10 µm and 2.5 µm shall be used for the collection of the PM_{10} and $PM_{2.5}$ samples, respectively;
- ✓ The cyclones shall fulfil the specifications for the separation efficiency described in the Table provided below at all operating flows;

PM_{10}	4.0 µm	8.0 µm	12.5 µm	20 µm
Separation Efficiency	<20%	<50%	>60%	>90%
$PM_{2.5}$	1.5 µm	2.0 µm	3.0 µm	4.0 µm
Separation Efficiency	<20%	<50%	>60%	>90%

- ✓ Since tubing losses can be excessive, the cyclonic separators shall be placed right at the end of the probe exiting the tunnel to minimize losses and possible tubing pollution.

CLAUSE 9.3 – FILTER HOLDERS

- ✓ The PM sample filter shall be located in the filter holder as close as possible to the cyclone's exit;
- ✓ The sampling line that transfers the particles to the filter holder shall be made of antistatic Teflon (or stainless steel shall be allowed too?);

Lab	D [mm]	Q [lpm]	Turbulent Flow [-]	Tube/bend Radius	Inertial Losses	Gravitational Losses
Lab-C	10	65	TRUE	4d	85%	3%
Lab-D	9.65	10	FALSE	>3.5d	26%	16%
Lab-F	16.5	16.7	FALSE	>10d	18%	17%
Lab-G	12.7	16.5	FALSE	>3d	18%	13%
Lab-L	10	8	FALSE	25d	25%	21%
Lab-N	12.7	15	FALSE	>3d	19%	14%
Lab-S	10	8	FALSE	3.5d	25%	21%
Lab-T	10	8	FALSE	3.125d	25%	21%

- ✓ Tubes shall have an internal diameter of at least 10 mm and a maximum of 20 mm (?) and their length shall not exceed 1m (?);
- ✓ The bending radius r_p shall be at least ten times (?) the tube diameter (10·di);
- ✓ The filter holder assembly shall be of a design that provides an even flow distribution across the filter stain area;
- ✓ The specifications described in EN-12341 (2014) shall be followed for the gravimetrical filter holders.

CLAUSE 9.3 – SAMPLING FLOW

The following provisions for the sampling volumetric flow apply:

- ✓ 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 ±5% of the set value for the given brake not to compromise the associated collection efficiency curve. Use a device with a flow control feature to ensure a stable flow through the filter medium;
- ✓ The set value for the isokinetic ratio shall be as close as possible to 1.0. The actual value during testing is allowed to deviate between 0.90-1.15.

CLAUSE 9.4 – SAMPLING MEDIA

The following provisions for the sampling media shall apply:

- ✓ The particulate sample shall be collected on a 47 mm single filter per test mounted within a holder in the sampled dilute gas flow;
- ✓ Fluorocarbon coated glass fibre filters or fluorocarbon membrane filters shall be used for the brake PM10 and PM2.5 mass measurement;
- ✓ All filter types shall have a 0.3 µm DOP (di-octylphthalate) or PAO (poly-alpha-olefin) CS 68649-12-7 or CS 68037-01-4 collection efficiency of at least 99% at a gas filter face velocity of 5.33 cm/s measured according to the standards specified in the GTR15.

  (a) U.S.A. Department of Defense Test Method Standard, MIL-STD-282 method 102.8: DOP-Smoke Penetration of Aerosol-Filter Element;

  (b) U.S.A. Department of Defense Test Method Standard, MIL-STD-282 method 502.1.1: DOP-Smoke Penetration of Gas-Mask Canisters;

  (c) Institute of Environmental Sciences and Technology, IEST-RP-CC021: Testing HEPA and UPLA Filter Media.

CLAUSE 9.5 – WEIGHING PROCEDURE

The following provisions for the weighing procedure applied at the ILS:

- ✓ Pre-sampling conditioning of 24h and post-sampling conditioning for a minimum of 1h at 22±3°C and 50±10% RH;
- ✓ Weighing room environmental conditions shall be continuously regulated to ensure controlled conditions at 22±1°C and 50±5% RH;
- ✓ Weighing balance of a minimum resolution of 1 µg and PM data shall be validated using reference filters.

It is proposed to fully align with the GTR15:

- ✓ Pre- and post- sampling conditioning of at least 1h at 22±2°C and 45±8% RH. Additionally, filters shall be conditioned the maximum 6h after the test end;
- ✓ Weighing room environmental conditions shall be continuously regulated to ensure controlled conditions at 22±2°C and 45±8% RH;
- ✓ Weighing balance of a minimum resolution of 1 µg (additional specifications apply) and PM data shall be validated using reference filters.

Thank you

European Commission