Brake-wear PM

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Methodology

- 1D expressions (either analytical or empirical) are available in the literature describing the transportation and collection efficiencies. If more than one expressions are available, the worst case condition is considered.
- While size-dependent efficiencies provide some valuable insights, it is difficult to assess the end effect.
- To address this shortcoming, some Monte-Carlo simulations were performed, to capture the anticipated size distributions of brake-wear and collection efficiencies of commercial components.
- In case there are no analytical expressions, or the available ones are based on empirical fits that require extrapolations outside the dataset on which they were based, some numerical simulations were performed with COMSOL Multiphysics.

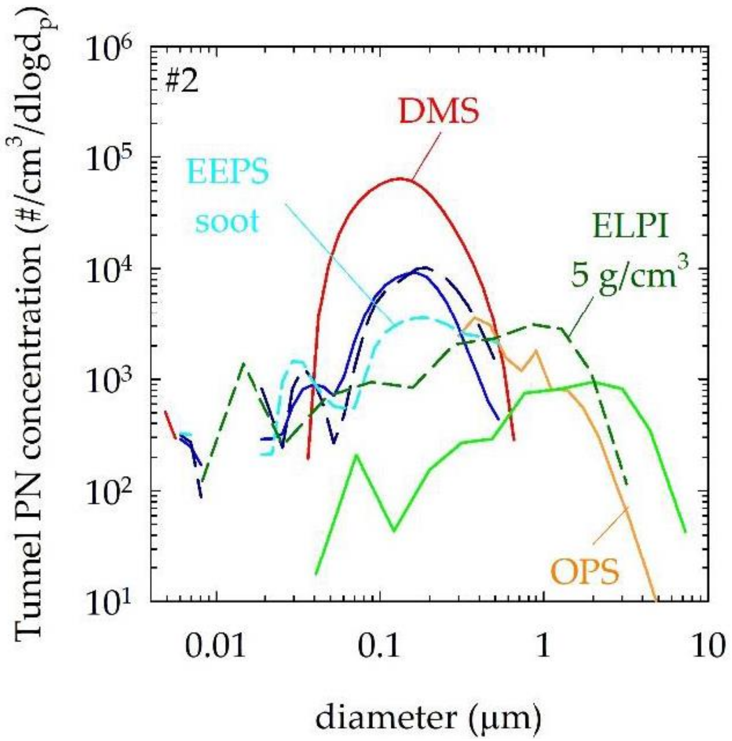
Particle size distributions - literature

- Measured number-weighed size distributions strongly depend on the operating principle (i.e. equivalent diameter) and underlying assumptions (i.e. morphology / density).

- Based on the definition of PM_{10} and $PM_{2.5}$, the aerodynamic size is the relevant quantity. When expressed this way, the mass can be directly calculated from aerodynamic diameter, d_a, through:

$$m_a(d_a) = N(d_a) \cdot \pi \cdot \frac{d_a^3}{6} \cdot \rho_0,\ \rho_0 = 1000\ ^{kg}/_{m^3}$$

- Published data on aerodynamic number-weighted distributions, suggest:
  - Peak in the 0.8 to 1.5 μm aerodynamic diameter
  - Broad distributions (σ_g=2-2.5)



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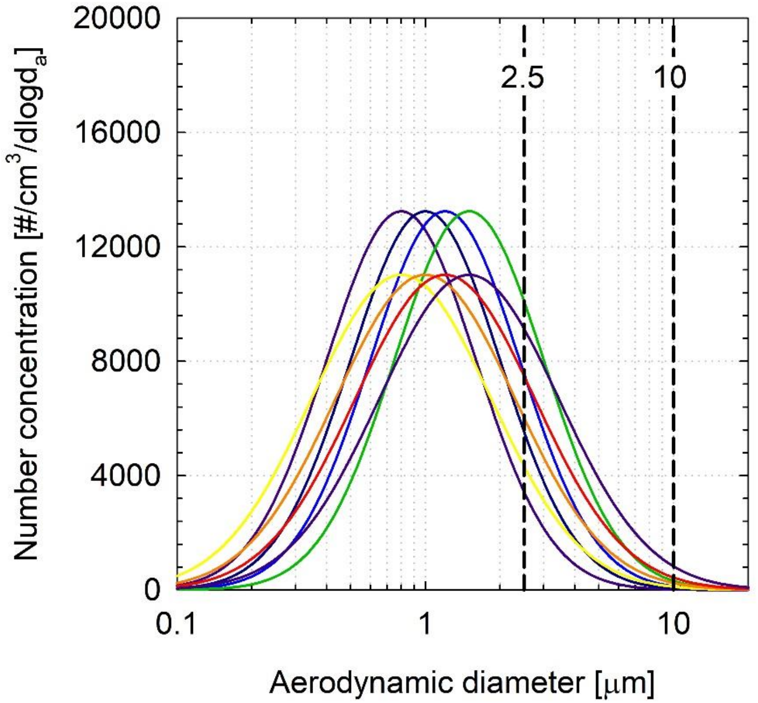
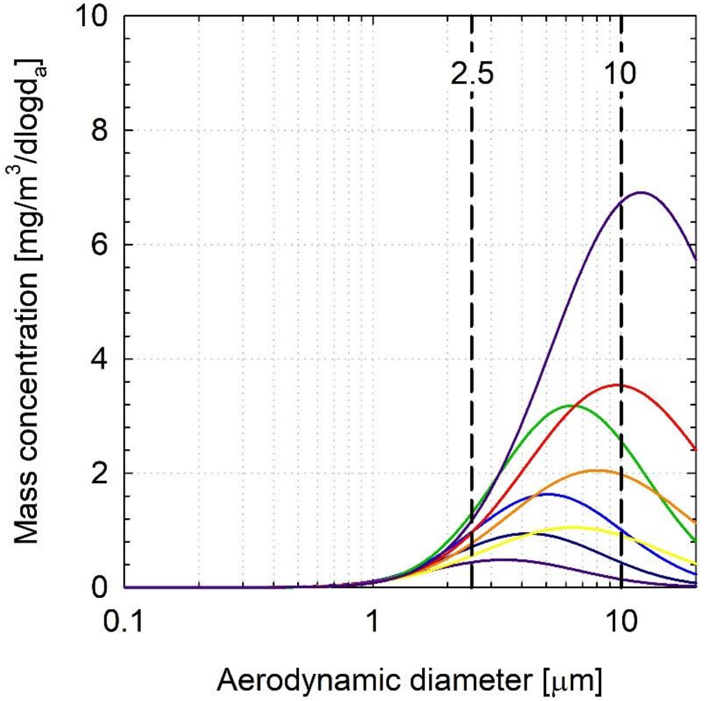
Particle size distributions - reference

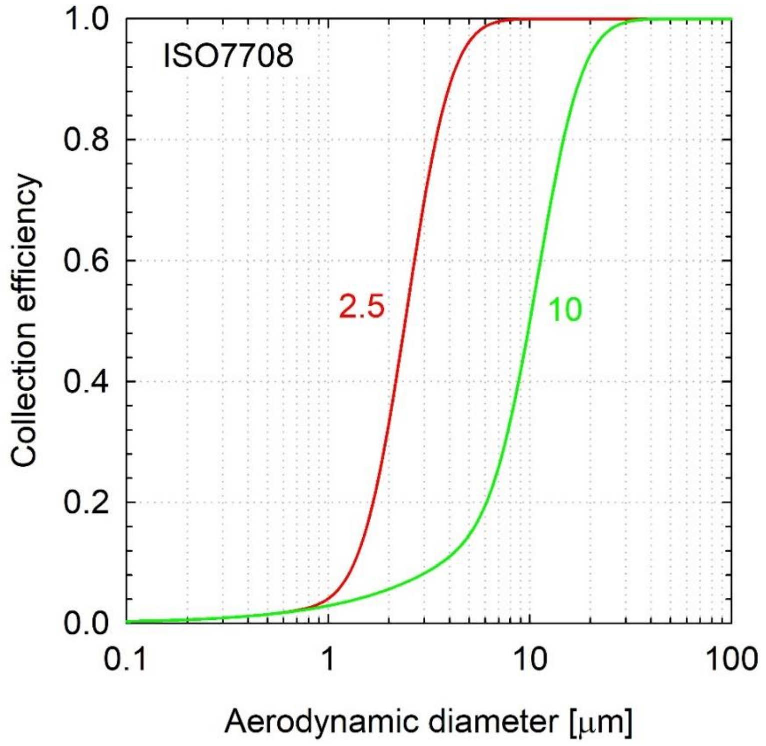
- In order to allow for quantitative assessment of potentially critical components, it is important to establish some representative reference distributions.
- Lognormal distributions with a mode in the 0.8 to 1.5 µm range and a geometric standard deviation in the 2 to 2.5 range allow for some Monte-Carlo simulations.
- While the assumption of unimodal distribution is not strictly valid, the scaling of mass with the d_a^3 implies that the coarse mode is dominating and thus focusing on supermicron mode is justifiable for PM.

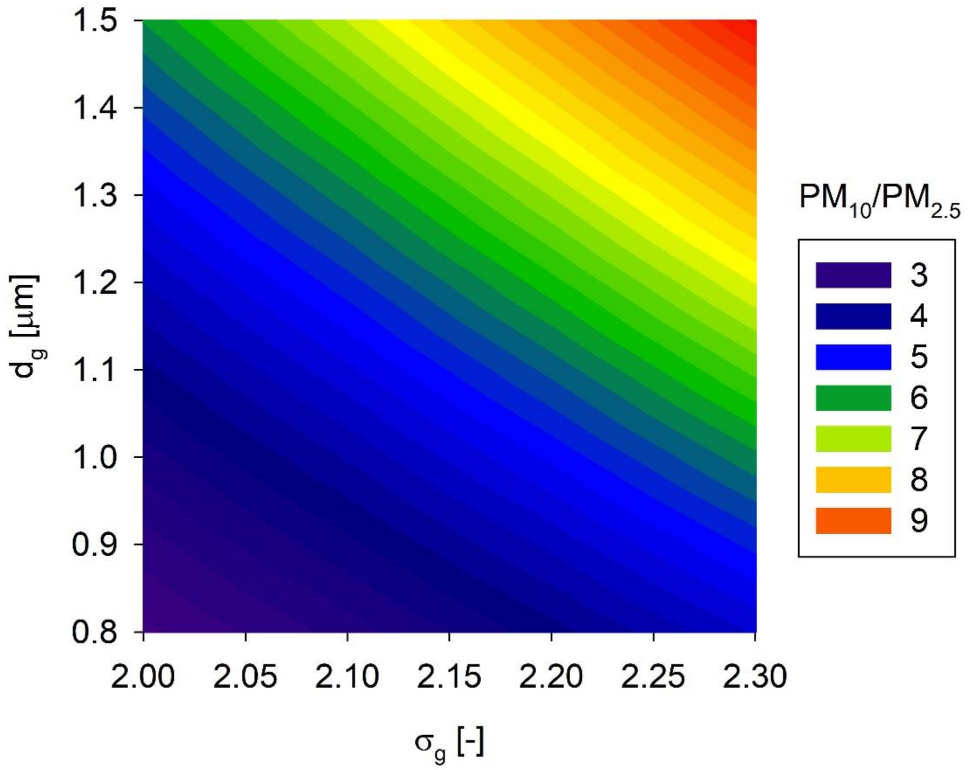




Definition of $PM_{2.5}$ and PM_{10}

- $PM_{2.5}$ and PM_{10} are not based on a sharp cut-off size, but rather on desirable collection efficiency curves representative of respirable (2.5 μm) and thoracic (10 μm) fractions (ISO 7708).
- Based on targeted collection efficiency curves, the assumed size distributions would result in $PM_{10}/PM_{2.5}$ ratios in the range of 3 to 9.





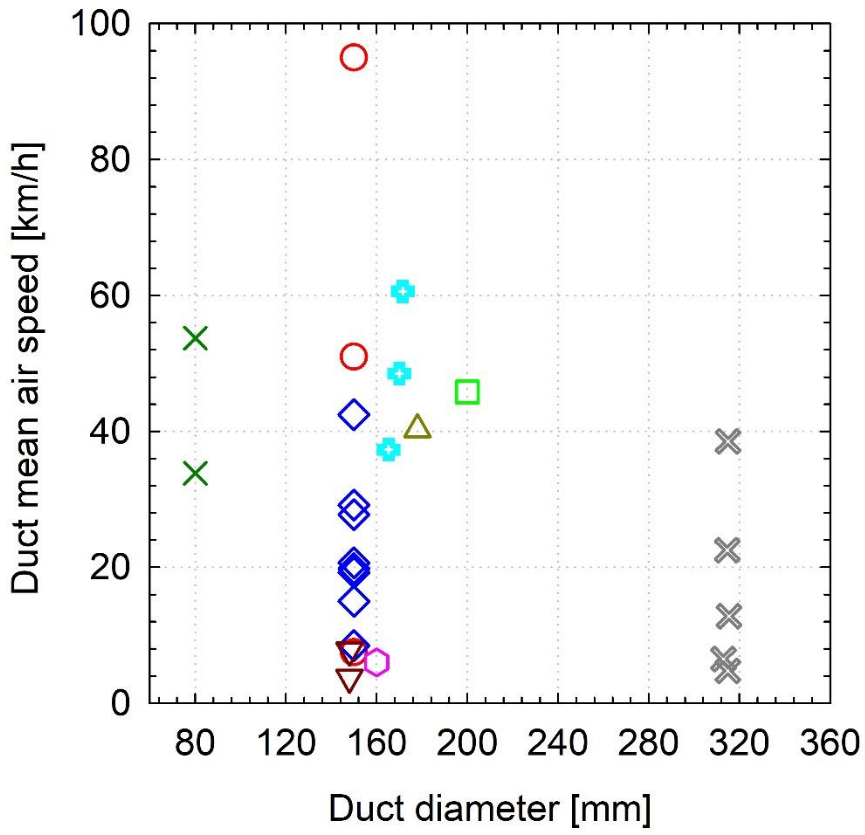
Assumed range of operating conditions

- Tunnel velocity is a critical input for the calculations (i.e. iso-kinetic sampling etc.).

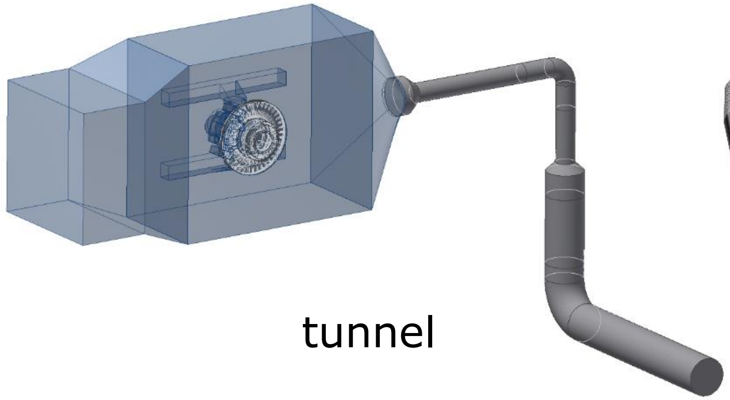
- Similarly, duct tunnel diameter is relevant for particle penetration in the ducts. These losses are not the focus of this work, but merely serve as a reference to assess the importance of losses in the PM sampling train.

- A range of values was derived from the “Cooling Data PMP Method.xlsx” file as representative of available tunnels.

- For the analysis it was assumed that:
  - Tunnel diameter can range between 80 and 320 mm
  - Duct mean velocity can range between 4 and 100 km/h.



Brake-wear particle odyssey


tunnel


nozzle


probe


tubing

Transport & extraction

Cyclone / filter holder


Cascade impactor

Classification

Weighing

Extraction

- Volumetric flow of extracted sample is dictated by instrumentation or inertial size classifier and should in maintain constant at a given setup.

- To achieve isokinetic conditions, nozzles must be installed at the sampling tip.

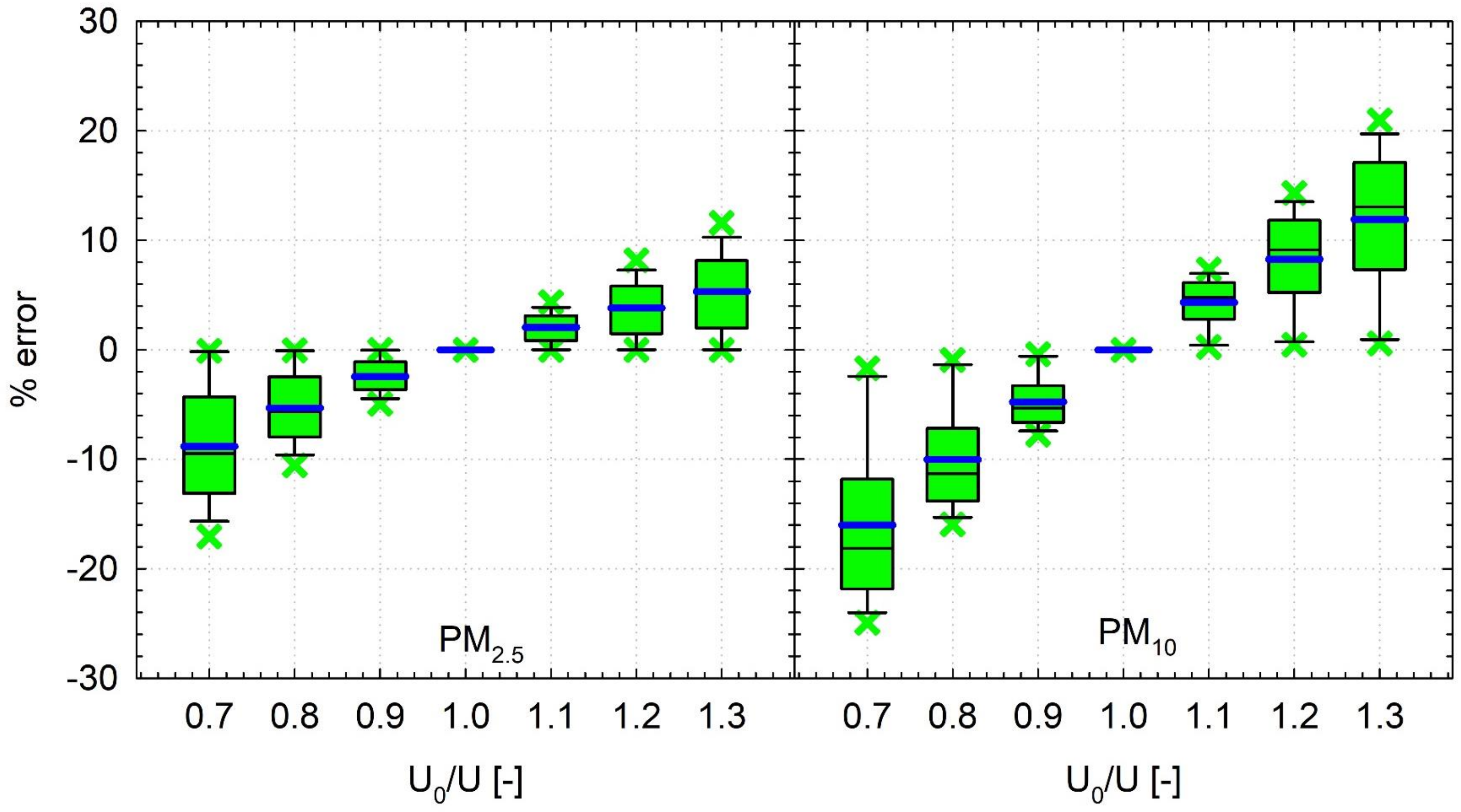
- Thin-wall nozzles are the most appropriate for extraction through ducts to minimize distortion of flow.

- Potential sources of bias during extraction at nozzle include:
  - Anisokinetic sampling
  - Anisoaxial sampling
  - Inertial impaction
  - Gravitational deposition

Anisokinetic sampling effect (including inertial losses on tip)

- Anisokinetic sampling can have a strong effect on both PM_{10} and $PM_{2.5}$.

  ➔ Confine U_0/U in the 0.9 to 1.1 range.



Anisokinetic effect – reference velocity

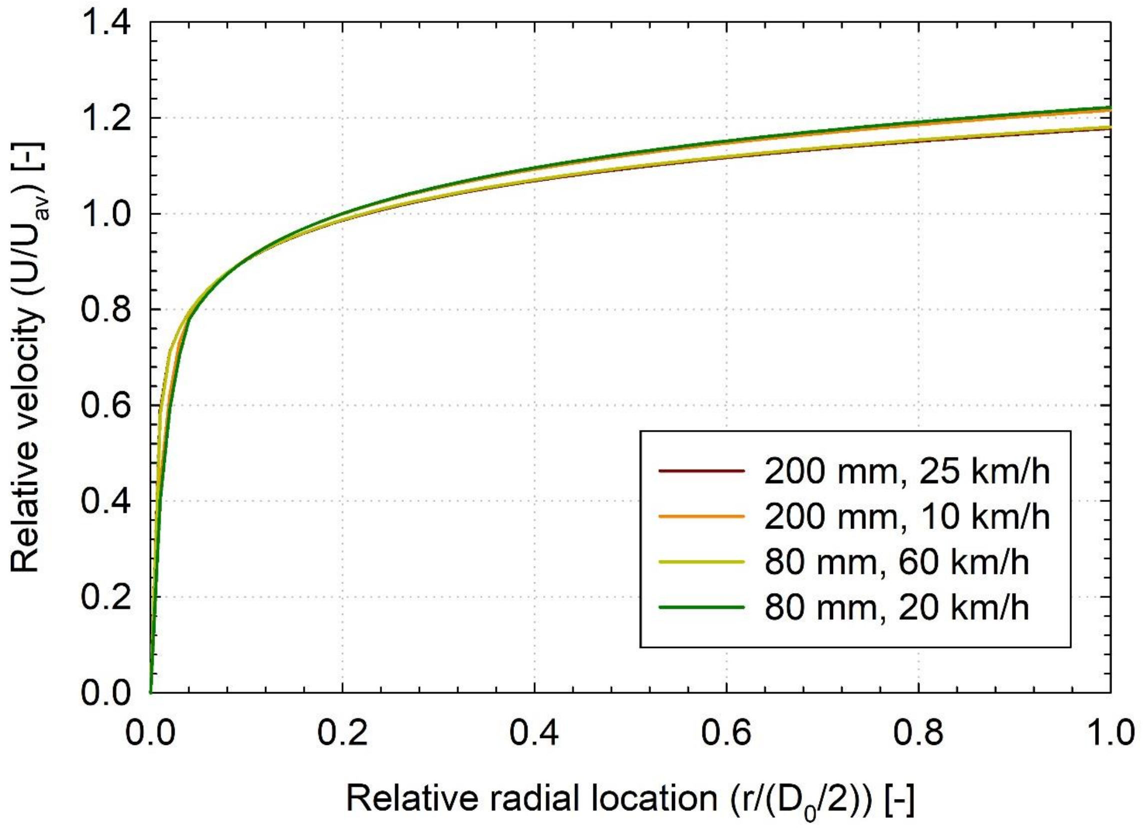
- The Reynolds number in the ducts is in the range of 5×10^3 to 6×10^5, i.e. flow is always turbulent.

- Provided that sufficient length is provided for the flow to stabilize, i.e. at least 7 diameters downstream any flow distortion, a fully developed velocity profile can be assumed.

- Velocity at tip of thin-wall nozzles can be considered uniform.

- The fully developed turbulent velocity profile can exhibit 5 to 20% deviations from average velocity.

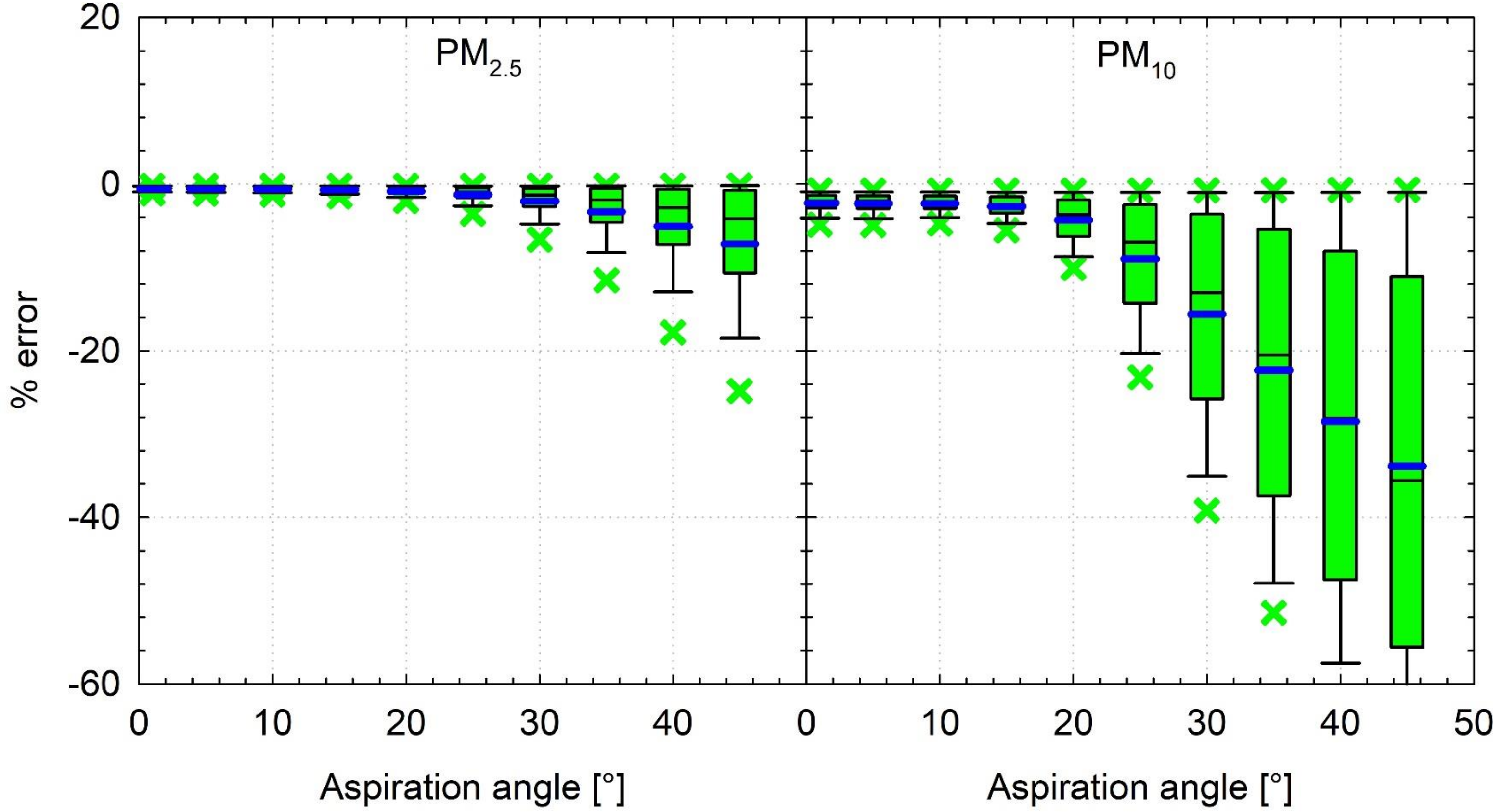
  → What should be the reference velocity for isokinetic calculations?



Anisoaxial sampling

- Effect of anisoaxial sampling was evaluated for isokinetic sampling.
- For aspiration angles smaller than 15°, the effect can be neglected.

➔ A minimum requirement of less than 15° aspiration angle is recommended. Manual alignment of probe should be still feasible.

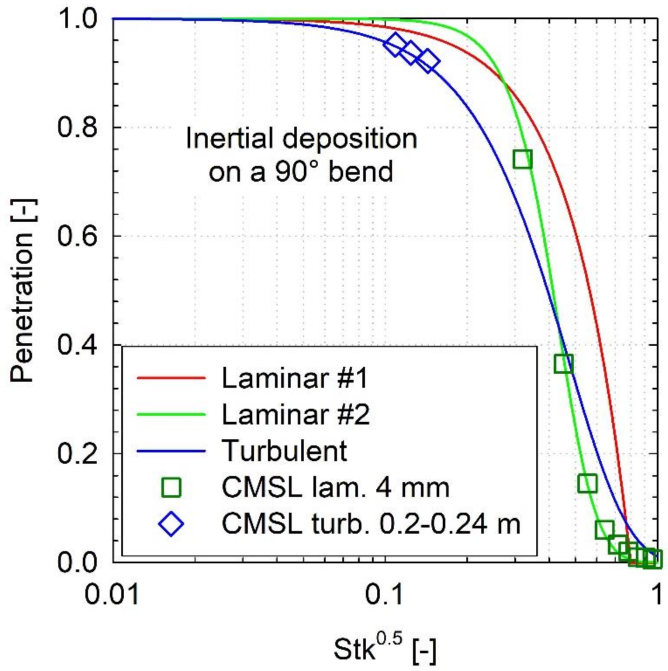


Particle transport

- The two most relevant loss mechanisms for super-micron particles are:
  - Inertial deposition → relevant parameter being the square root of the Stokes number:

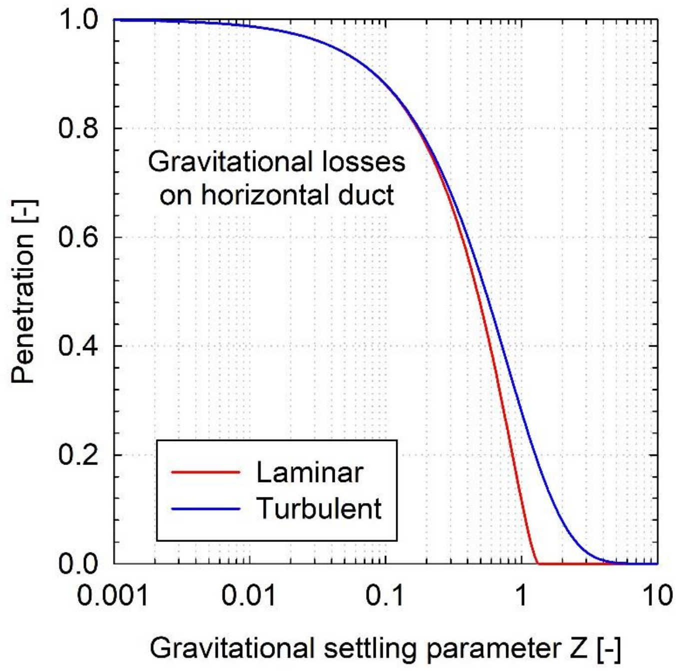
$$Stk^{0.5} = \sqrt[2]{\frac{\rho_0 d_a^2 C_C V_0}{18\eta d_c}} < 0.1$$

  - Gravitational settling → relevant parameter being the gravitational settling parameter:



$$Z = \frac{L}{V_0}\frac{V_s}{D} = \frac{\rho_0 d_a^2 C_C g L}{18\eta V_0 D} < 0.01$$

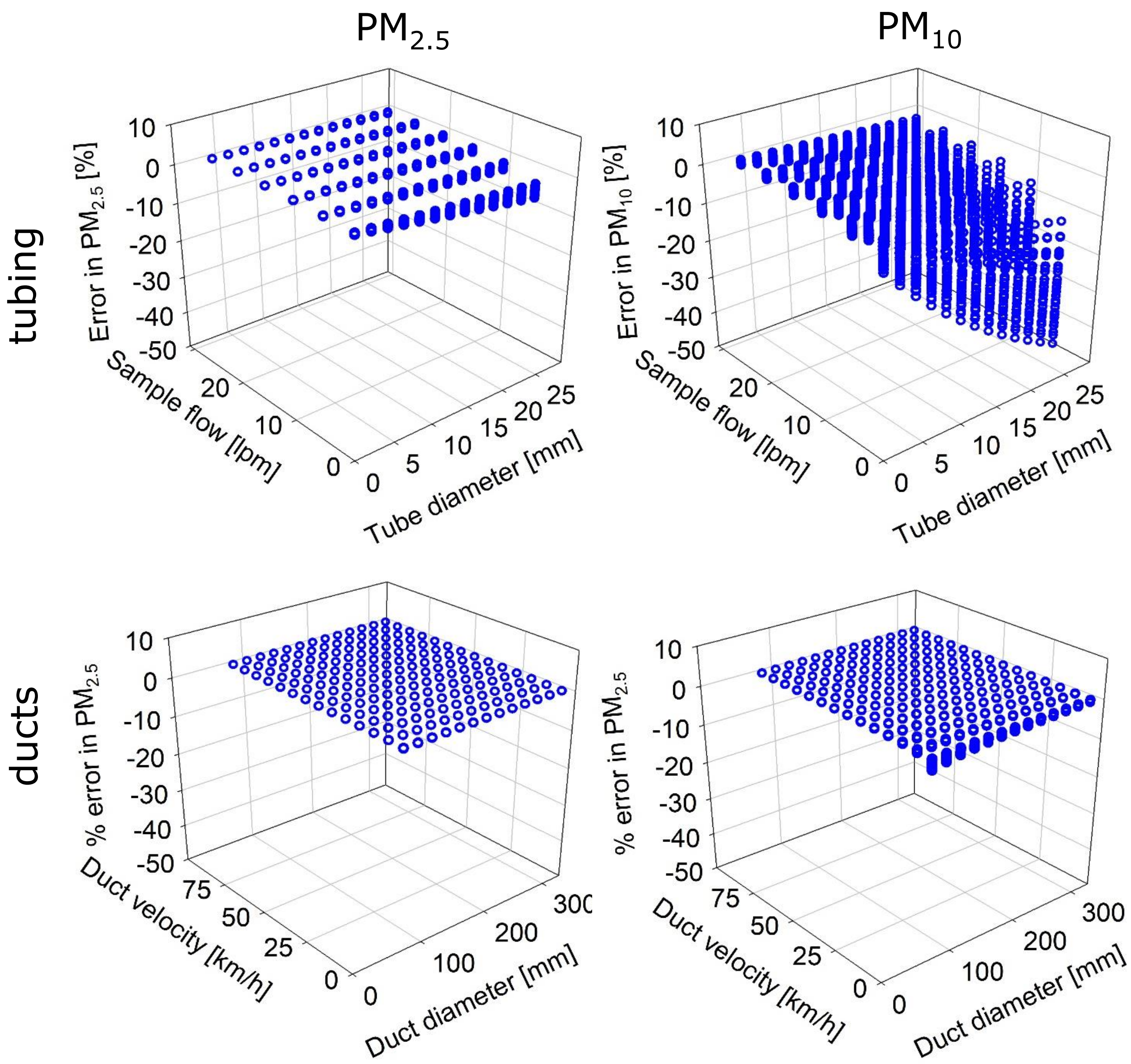
Empirical expressions for inertial deposition are based on experimental data on 1-8.5 mm ID, but COMSOL simulation verified that they can be extrapolated to ducts at least for curvature ratios larger than 4.



Relative importance of losses on tunnel and tubing - #1
Gravitational losses per meter

- Gravitational losses in horizontal tubing can be significant at large diameters and small flows.
  - ➔ Maintain horizontal sections of tubing as short as possible, and ideally below 1 m.
  - ➔ Avoid flows lower than 10 lpm, or restrict tube diameters below 15 mm.

- Gravitational losses on tunnel ducts are not that critical.

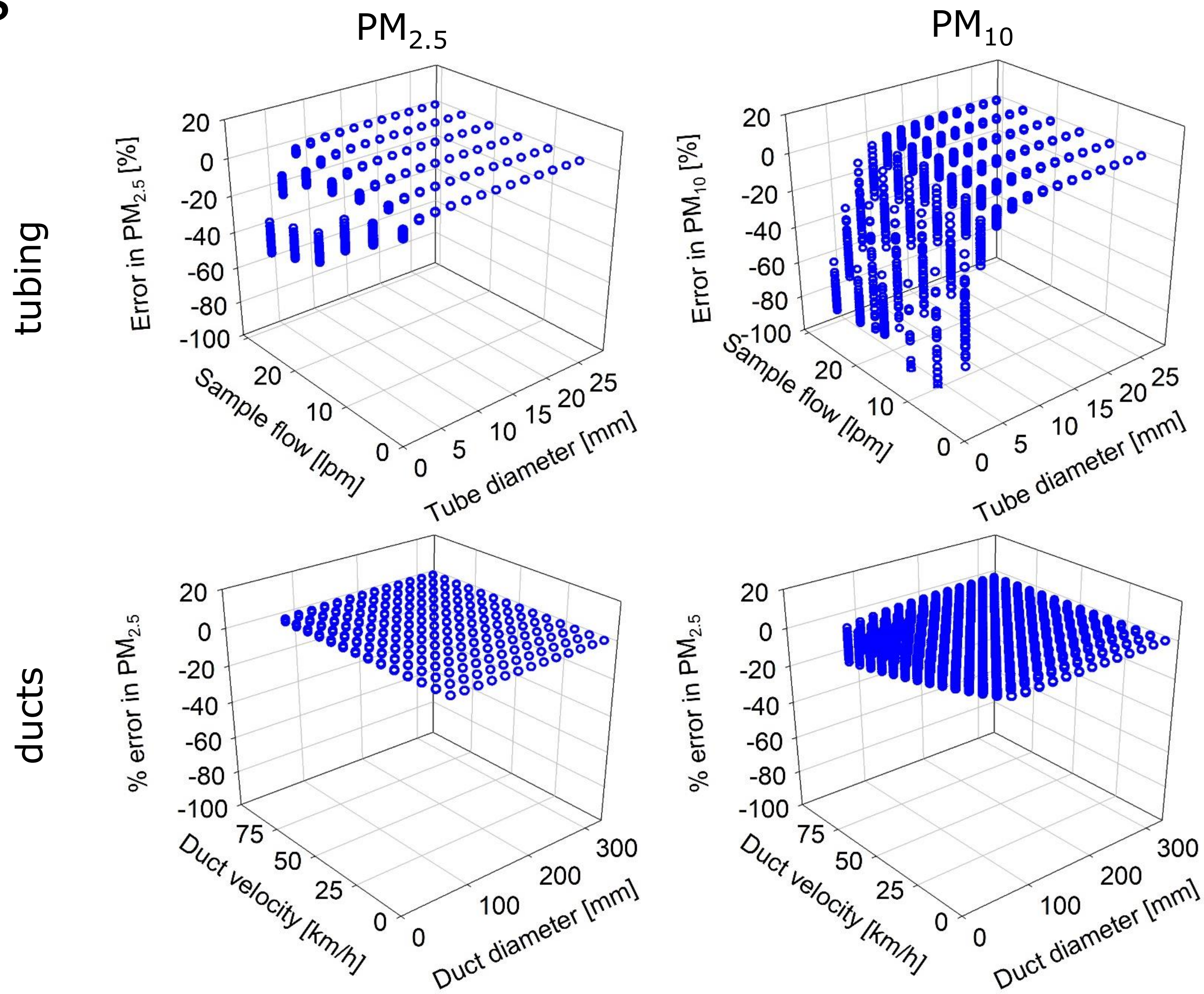


Relative importance of losses on tunnel and tubing - #2 Inertial deposition on bends

- Inertial losses in bends can be excessive on transport tubing.

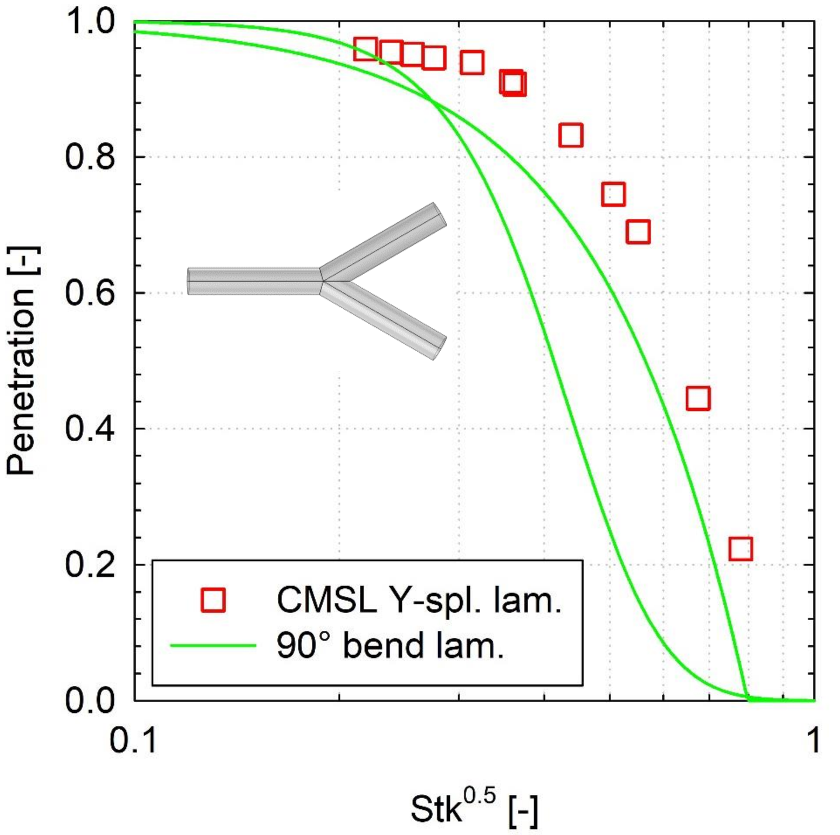
➔ If bends are unavoidable, (i.e. sampling probes, cyclones):
  - inner diameter of the tubing must be larger than 10 mm.
  - sample flow should preferably be confined to less than 20 lpm.

- Inertial deposition on tunnel ducts are relatively less critical. Still can become relevant at high duct velocities (>50 km/h).



Losses in flow dividers

- Flow splitting can lead to inertial deposition and complex velocity profiles that further enhance losses.
- In lack of analytical expressions for particle losses in such flow dividers we have performed simulations in COMSOL, for different designs.
- As can be seen in the example case illustrated here, losses can be comparable to those in bends → Avoid such flow splitting for PM measurements.



Inertial classification

- Different technical solutions are available for size classifications:
  - Cyclones
  - (Cascade) Impactors
  - Virtual impactors
  - Others?

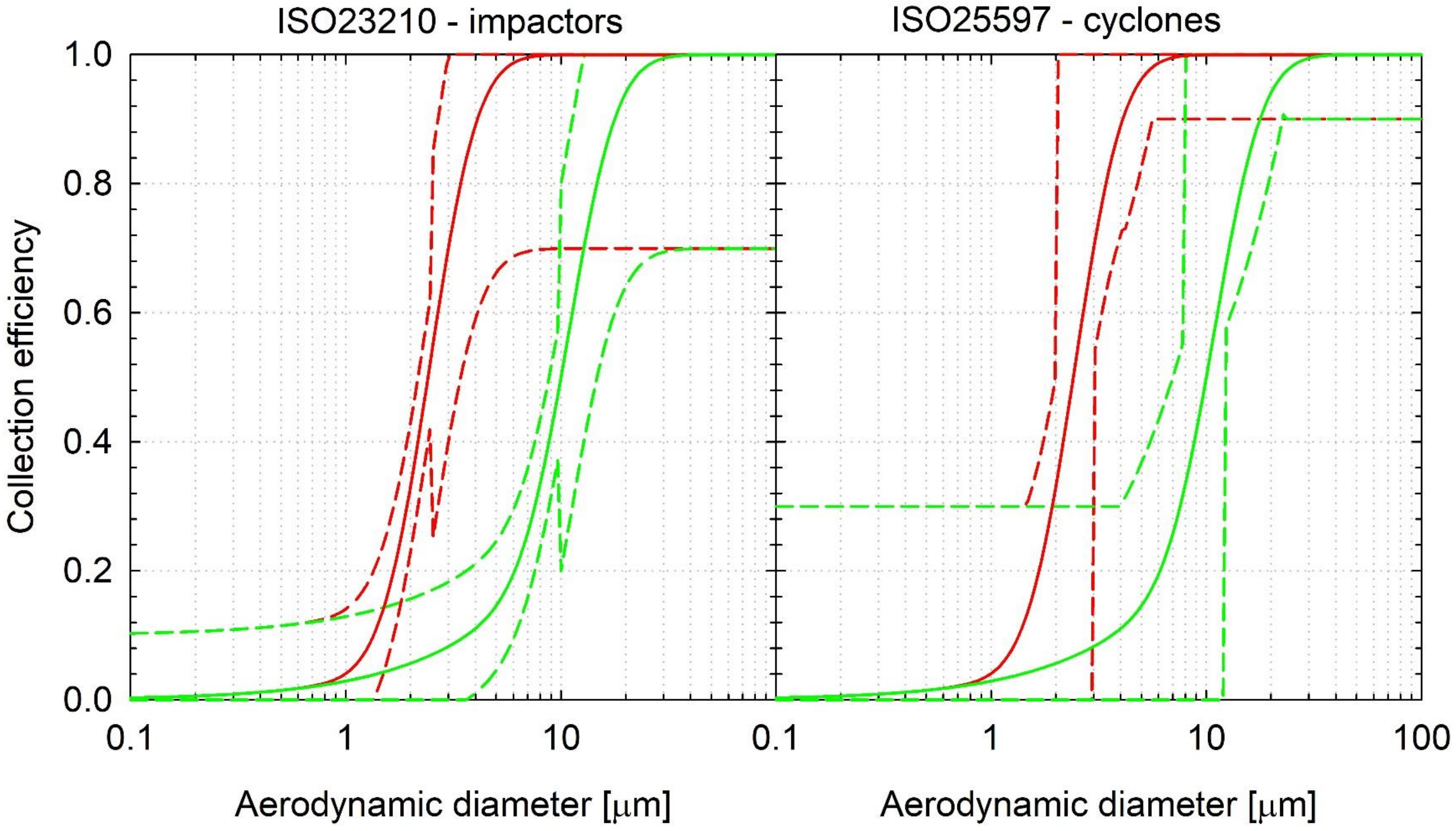
- The associated efficiency curve strongly depends on the volumetric flow, which thus needs to be maintained constant.

- ISO Standards exist specifying the envelop of allowed efficiencies.

- As size-dependent efficiency curves data are scares, some Monte Carlo simulations were performed to assess the effect of different commercial solutions on brake-wear PM measurements.

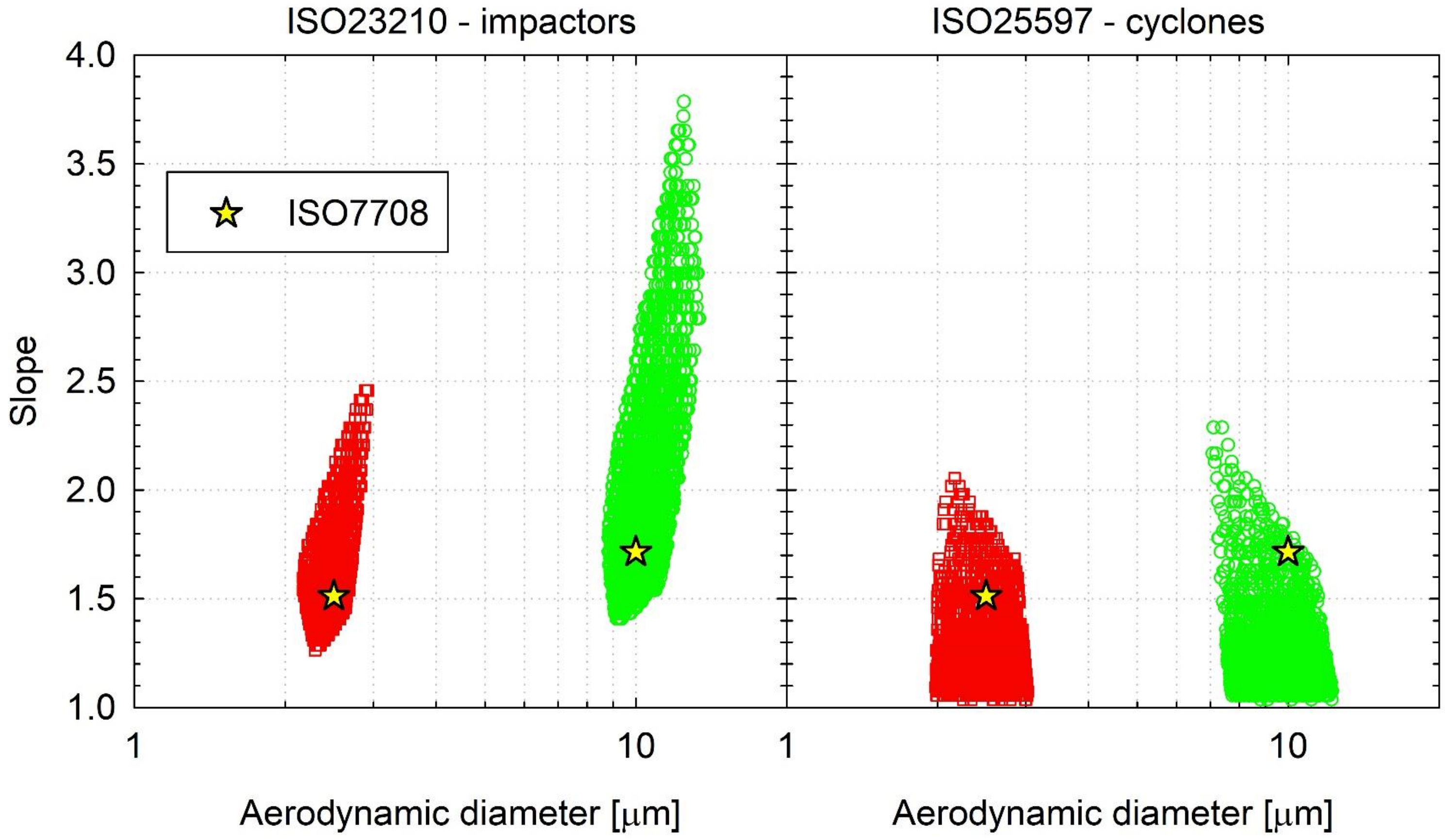
Inertial classifiers – ISO specifications

- ISO23210 and ISO25597 specify acceptable deviations from the target efficiencies, for impactors and cyclones, respectively.



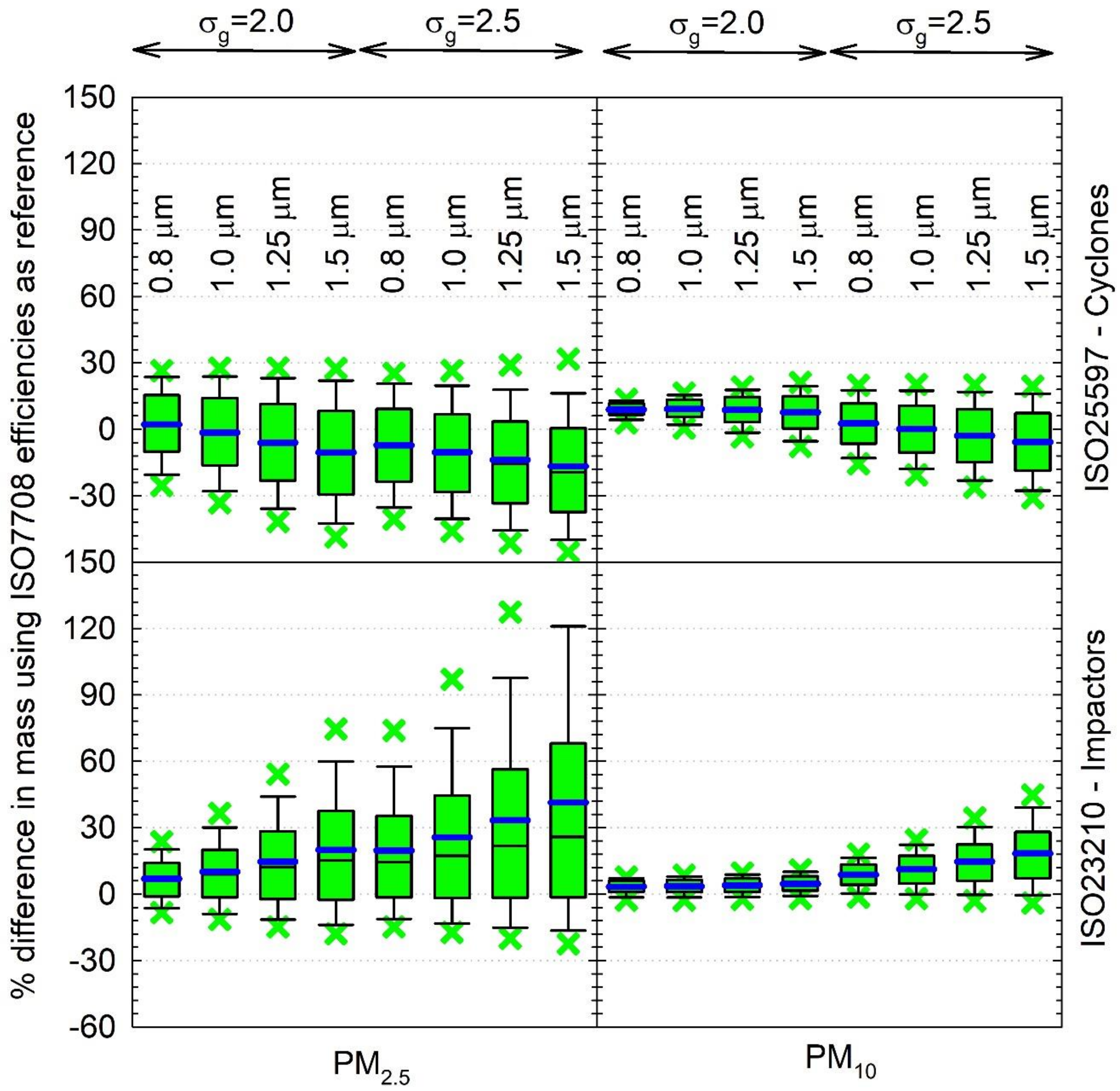
ISO-compliant inertial classifiers

- Fits of the generalized Lapple equation, $\eta(d_a) = \left(1 + (d_{50}/d_a)^{\beta}\right)^{-1}$, widely used to fit experimental data, allowed for the identification of allowed variation in slopes and cut-off sizes



Anticipated uncertainties in $PM_{2.5}$, PM_{10} from different ISO-certified inertial classifiers

- The effect of pre-classifier design is anticipated to be stronger in $PM_{2.5}$.
- The steeper impactor slopes allowed in ISO23210 tend to results in a positive bias (overestimations) and larger differences from ideal ISO7708 performance, compared to ISO25597 which promotes blunter collection efficiency curves.

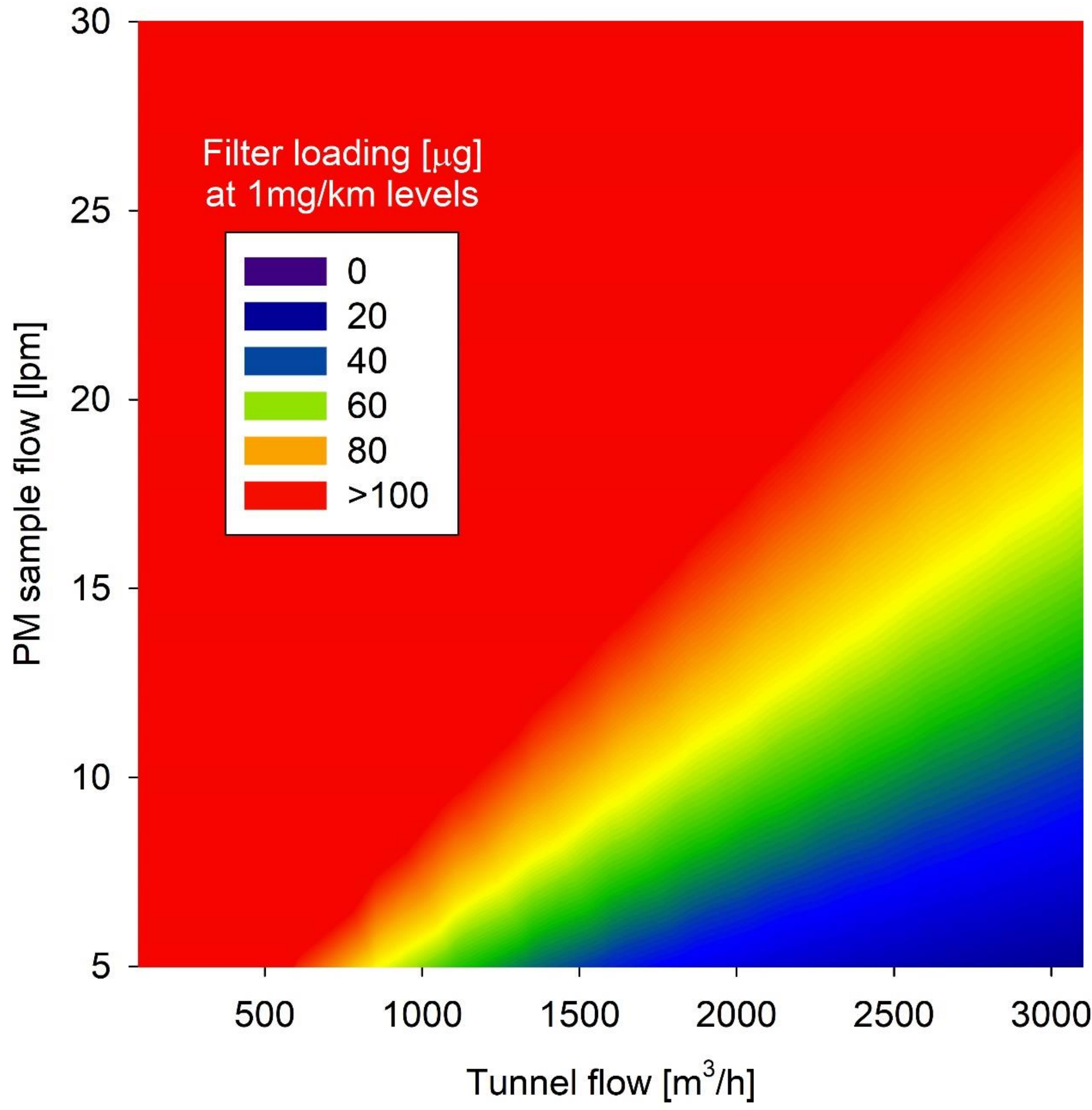


Filter types

- Two types of filters are specified for exhaust PM applications in recent technical regulations (40 CFR part 1065, R49, etc.), and in principle both can be recommended for brake dust sampling:
  - PTFE membrane filters with polymer support (i.e. Pall Teflo): Are also compliant with 40 CFR part 50. They do collect less gaseous background (gas adsorption artifact). This is an advantage when significant amounts of nitrous or carboxylic gases are present in the sample. However, this is not the case for brake dust sampling from a tunnel. The weighing procedure is more challenging, because these filters collect a significant amount of electrostatic charge. This charge must be neutralized, with Po^{210}-based neutralizers performing best. In Europe, it is extremely difficult to get approval for a radioactive neutralizer.
  - Teflon-coated glass fiber fabric (i.e. Pall EMFAB TX40): are much easier to handle. They are lighter (~100 mg compared to >200 mg of PTFE), less sensitive to damage and do not collect as much electrostatic charge. Neutralization is easier as no radioactive-based device is required. This makes them the preferred solution in European labs.
  - Other types (quartz, borosilicate, polymer fiber, etc.) are available but are typically used in special applications (i.e. quartz filters for OC/EC analysis)

Filter loading

- The front disc-brake systems we have tested over the WLTP emit in the range of:
  - 1 to 8 mg/km $PM_{2.5}$
  - 4 to 22 mg/km PM_{10}
- Rear-wheel (especially drum) brakes are expected to emit less, while regulation may bring further reduction.
- R49 regulation recommends a 100 µg filter loading, although currently exhaust PM levels lead to much lower levels. Based on our experience, the 30 µg of loading can be reliable measured when following the R49/ CFR part 1065 weighing procedures.
- At 1 mg/km emission levels and the 4.5 hours duration of the cycle, such levels should be feasible in all setups. At lower emission levels, excessive tunnel flows can lead to sensitivity problems.
- We observed extremely low pressure-drop: less than 15 mbar even at as high as 3 mg loading.



AVL’s approach for PM sampling

- On the basis of the aforementioned analysis, a dedicated industrialized solution was developed for brake-wear PM sampling.
- Two separate PM samplers will be employed for parallel measurements of PM_{10} and $PM_{2.5}$, both sampling at constant volumetric flow of 8 lpm, to minimize (competing gravitational and inertial) losses and ensure the same isokinetic conditions for both $PM_{2.5}$ and PM_{10}.
- Volumetric sample flow maintained constant (<2%) via the use of a precise Mass Flow Controller, and real-time compensation for pressure, temperature, humidity changes.
- Maintaining constant flow is essential for precise measurements. In addition to the direct effect on PM calculation, uncertainties in flow have an indirect effect through changes in inertial classifier efficiency curve.
- Size classification will be employed through a dedicated cyclone for each PM sampler.
- A dedicated probe was also designed for setups requiring a bend for the extraction from ducts, to minimize losses.
- Cyclones will be installed directly at the outlet of the probe, to allow for extraction of deposited material in the sampling train if required.

Recommendations for minimum requirements

- Avoid exchanging inertial classifiers if tunnel flows are adjusted. Use the same inertial classifiers and sample at constant volumetric flow ➔ defining limits on sample flow changes is very important.
- Use nozzles to ensure isokinetic sampling for both PM_{10} and $PM_{2.5}$ and maintain isokinetic ratios to a maximum (0.9, 1.1) range.
- Restrict aspiration angle to ±15°.
- Avoid use of flow dividers for PM measurements.
- Prudently report penetrations for the PM sampling train.
- Gas adsorption is not expected for brake-wear PM, and even if exists its contribution should be insignificant relative to the mass of abrasive PM.
- Weighing accuracy can become an issue, especially at large tunnel flows and/or future low-emitting brake systems ➔ Automotive regulation should form the reference for the weighing procedure. However, since adsorption is not relevant for brake-wear the associated requirements (specifically filter face velocity and temperature control of filters) should be discarded.
- Both TX40 and PTFE filters currently allowed in automotive exhaust regulation should be allowed. We recommend TX40 glass fiber Teflo filters for gravimetric PM measurements as they are easier to handle (sensitivity to gas adsorption is irrelevant while conditioning of charges is much easier than Teflo filters).

Points for clarifications

- What should be used as a reference velocity for isokinetic ratio calculations?
- Can we collect more detailed information on cyclone and impactor performance?
  - Collection efficiency curves and characterization uncertainties.
  - Are we to anticipate changes in efficiency curves with use (i.e. impactor nozzle fouling)?
  - Is there a need to extract deposited PM material in the sampling train upstream of the filter?
- Should sampling stop during cooling down phases?
- Will there be a provision for the calibration of the instruments/components?

Thank you

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