AVL List GmbH (Headquarters)

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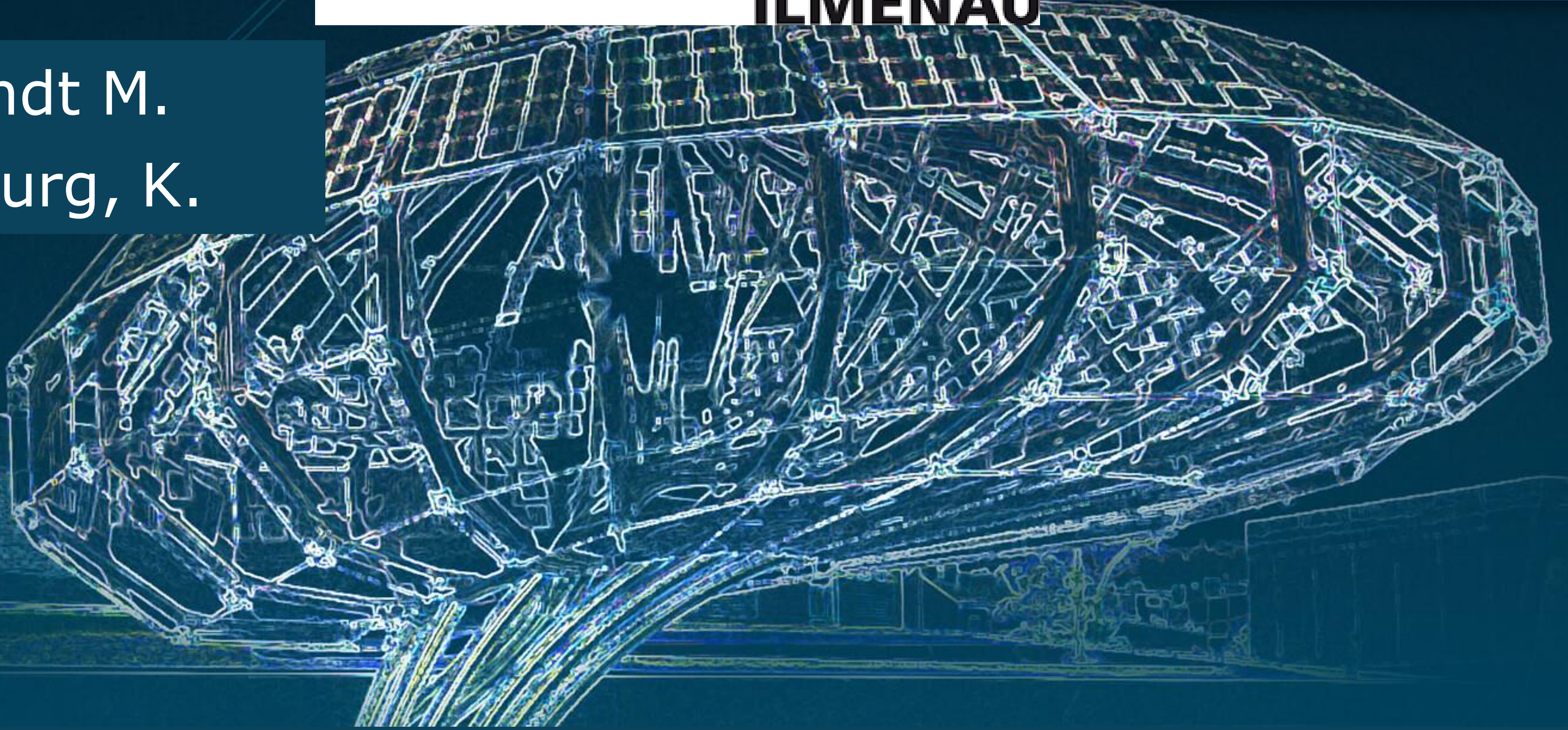

Challenges in brake-wear PM/PN measurements over the WLTP test cycle

Public

Experimental

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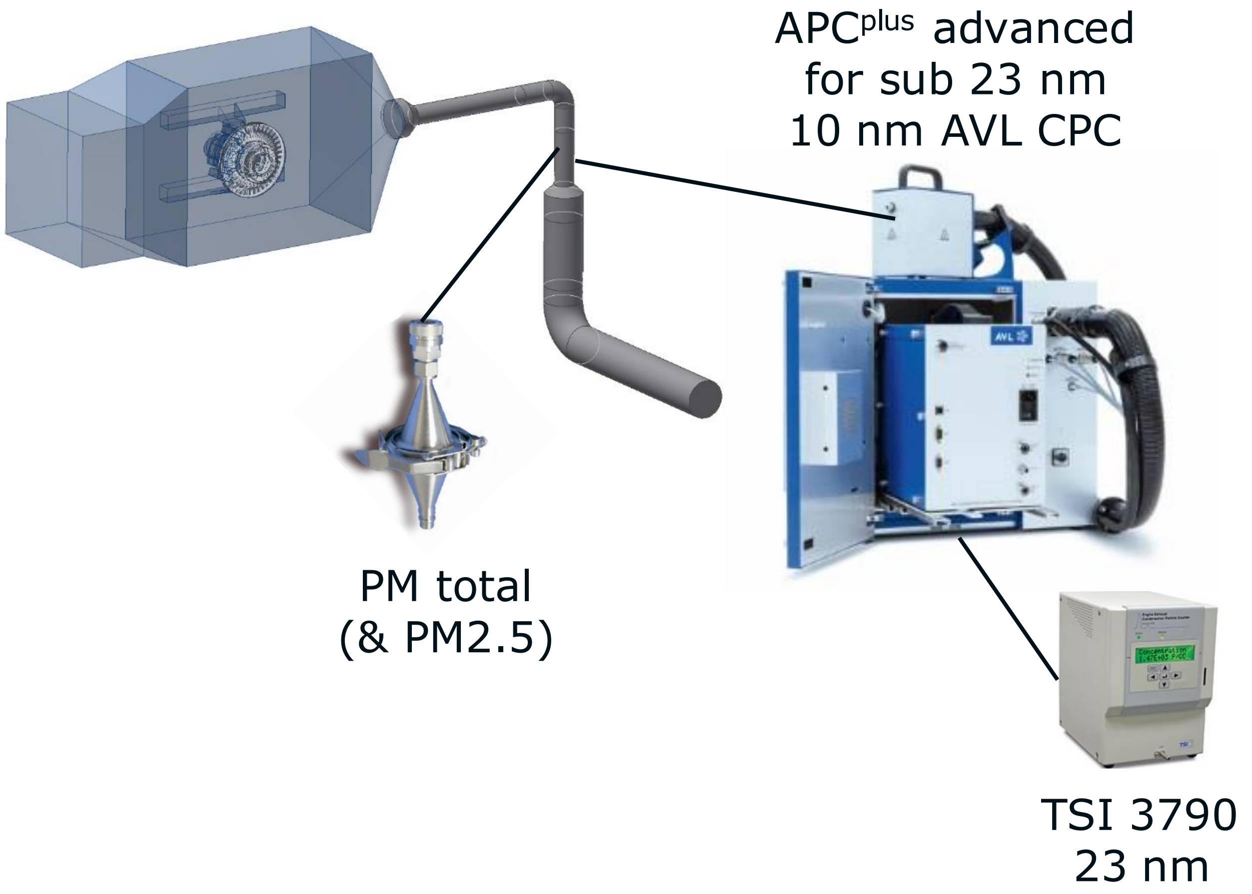
Tests were performed at TUI on their PM10 tunnel
Tunnel flow: 270 m^3/h

Measurements included PM total (with a gravimetric filter box) and non-volatile PN with 10 nm and 23 nm CPC using two separate isokinetic probes.

5 repetitions of the novel test cycle were performed with the criteria of 35°C before the start of each trip.

All tests were performed with the brake pads supplied from the task force 1, employing the recommended dyno settings.

Pads were preconditioned by running 20 repetitions of the R83 WLTC cycle.



Repeatability

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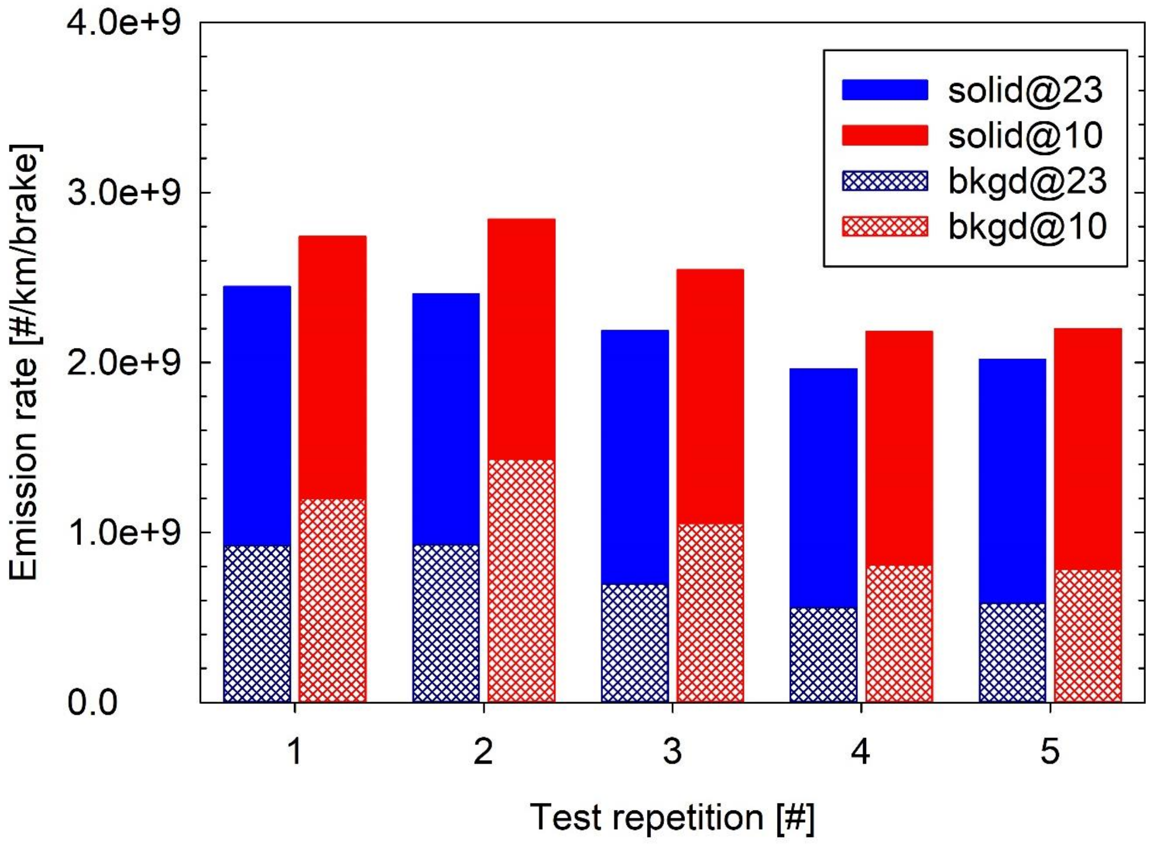
The cool-down periods were discarded from calculations.

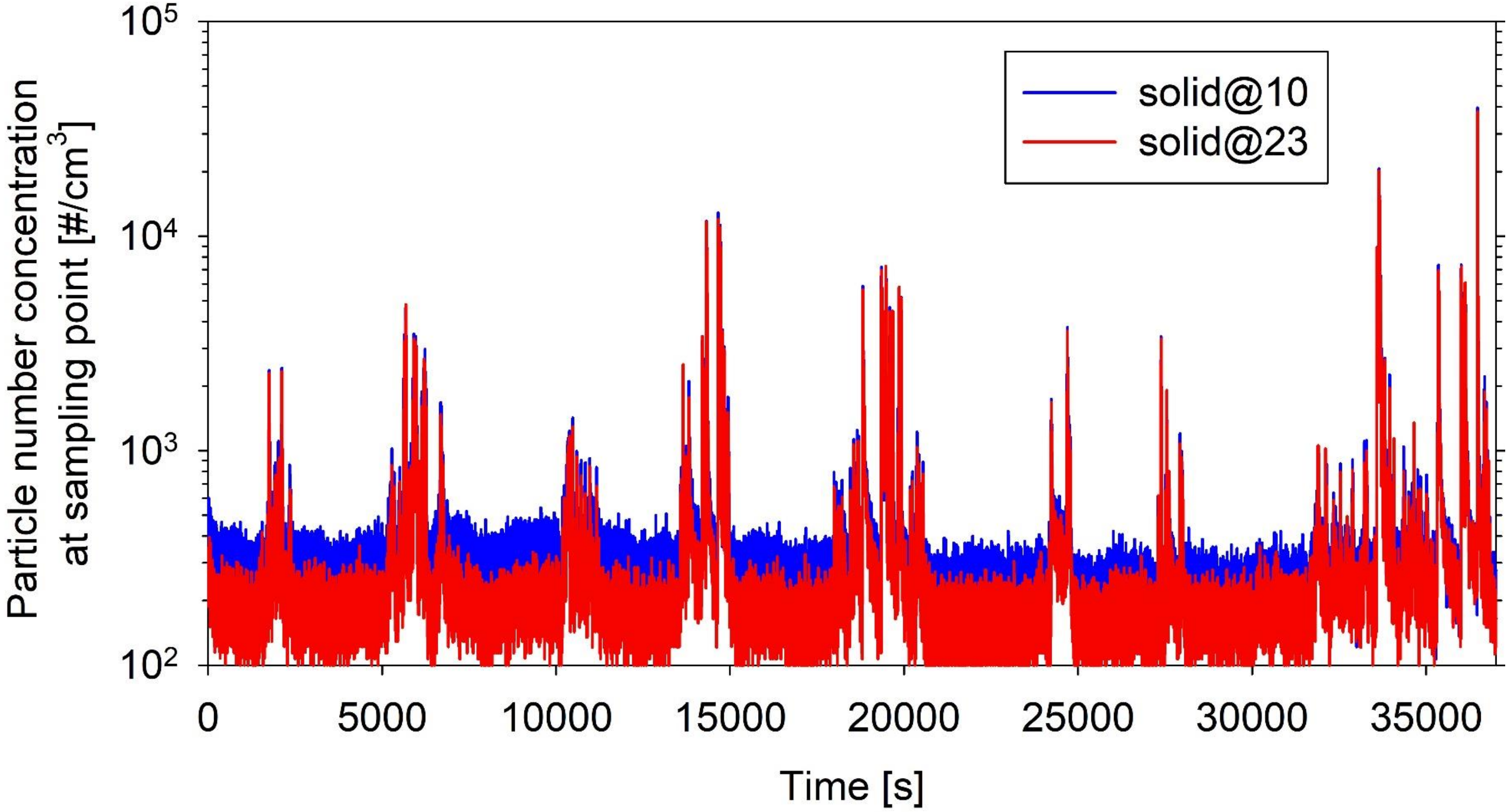
PN emissions in the 2 to 3×10^9 #/km/brake range.

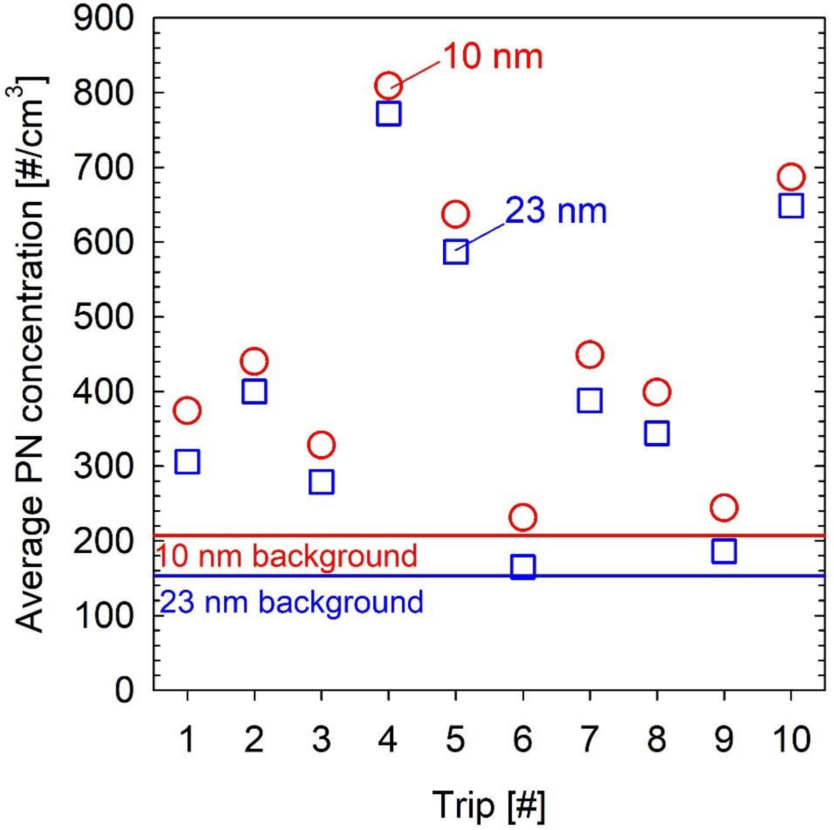
Emissions exhibited a downward trend but still coefficient of variation (CoV) was only 10% for 23 nm and 12% for 10 nm, with the latter measuring on average 13% higher concentrations.

However, the background also exhibited a downward trend and was at levels of up to 38% (23 nm) and 50% (10 nm) of the average cycle emissions.



Background levels





Background concentrations were in the order of ~150 #/cm³ for 23 nm and ~200 #/cm³ for 10 nm.

These were true tunnel background as APC was measuring absolute zero through HEPA filter.

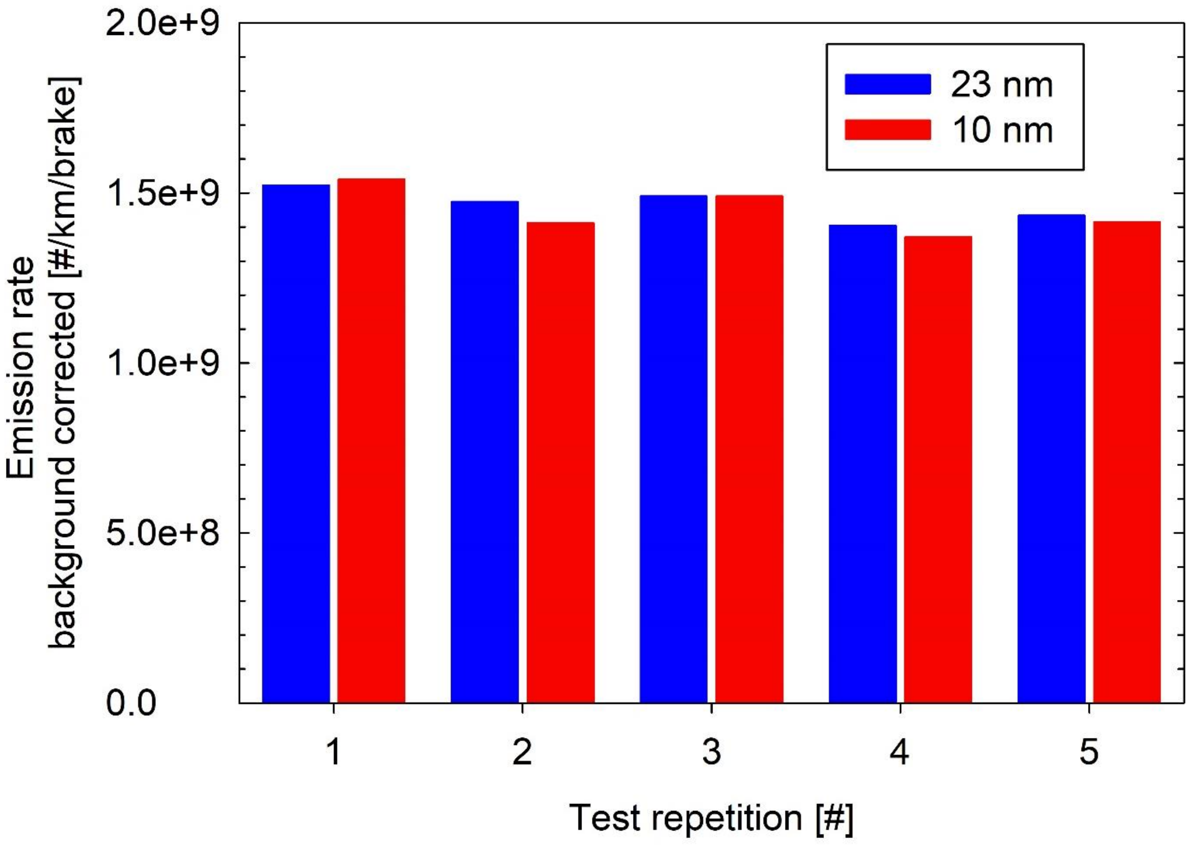
Emission events ~20 s per brake, with some of them at or close to background levels ➔ emissions during more than 60% of the cycle at background.

Repeatability

Considering the relatively low peak concentrations measured (~40,000 #/cm^3), coagulation should be insignificant ➔ to a first approximation, direct background subtraction would be reasonable.

When background corrected, both 10 and 23 nm CPCs measured practically the same (difference of less than 1%±2%).

Also CoV improved to ~4% for both CPCs.



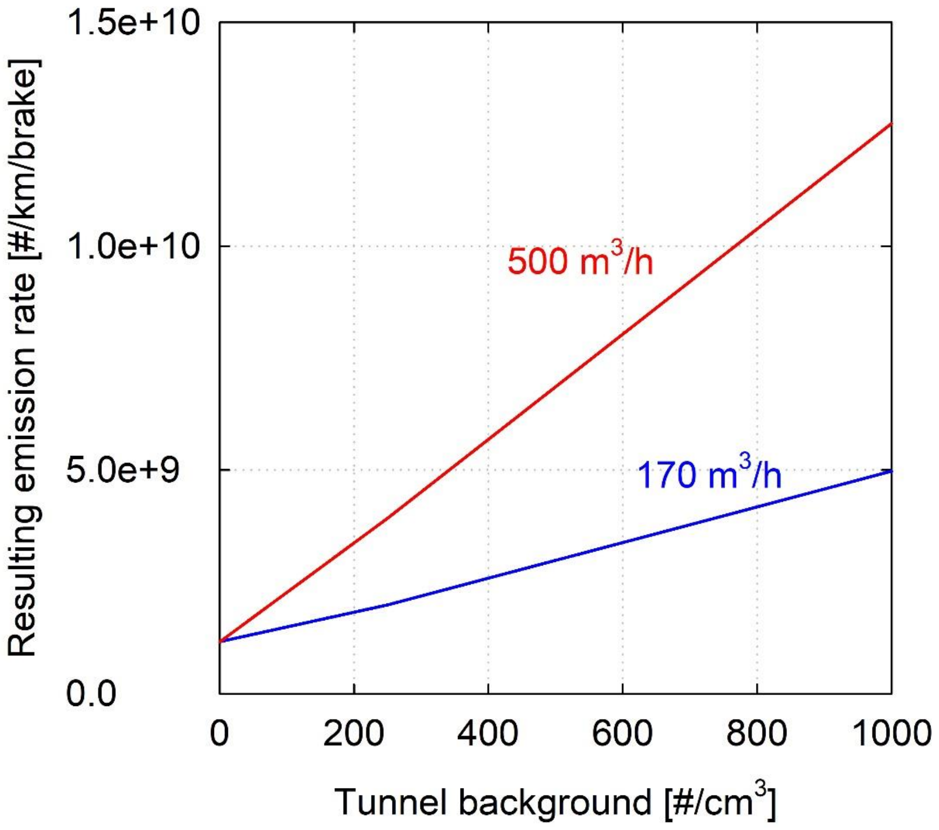
Simulated effect of background

Background PN concentrations are not expected to change much with change in tunnel flow.

However, the contribution of background on measured concentrations will increase as tunnel flow increases (emitted particles will be further diluted).

On the tested system, a 500 #/cm^3 background would result in:

- 150% overestimation of PN emissions at 170 m^3/h
- 500% overestimation of PN emissions at 500 m^3/h



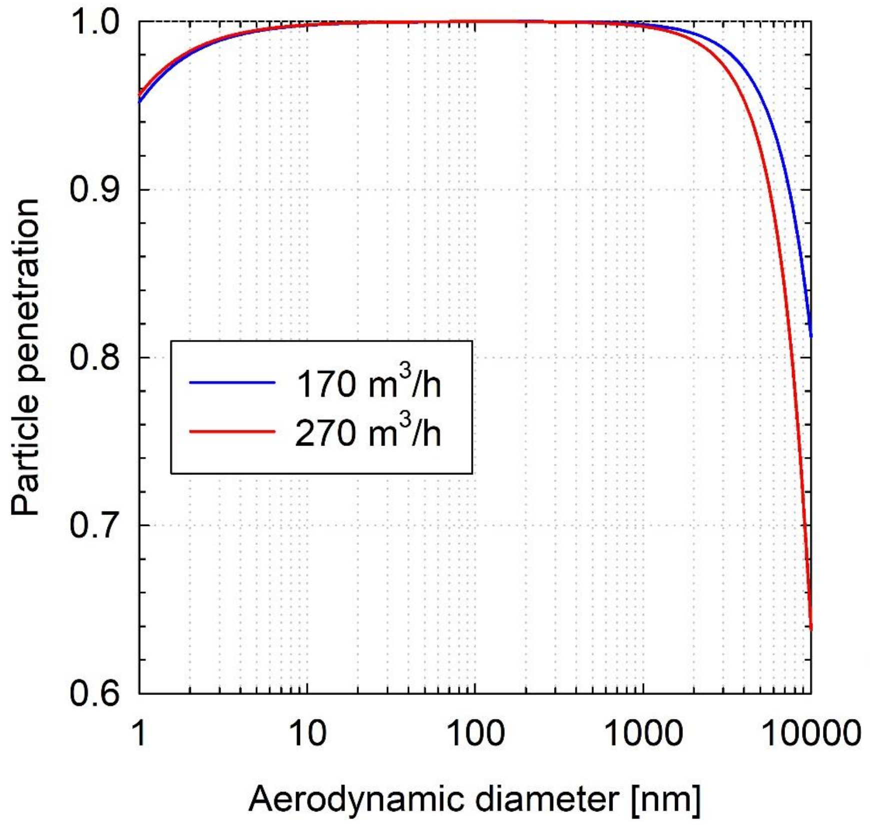
Total PM results

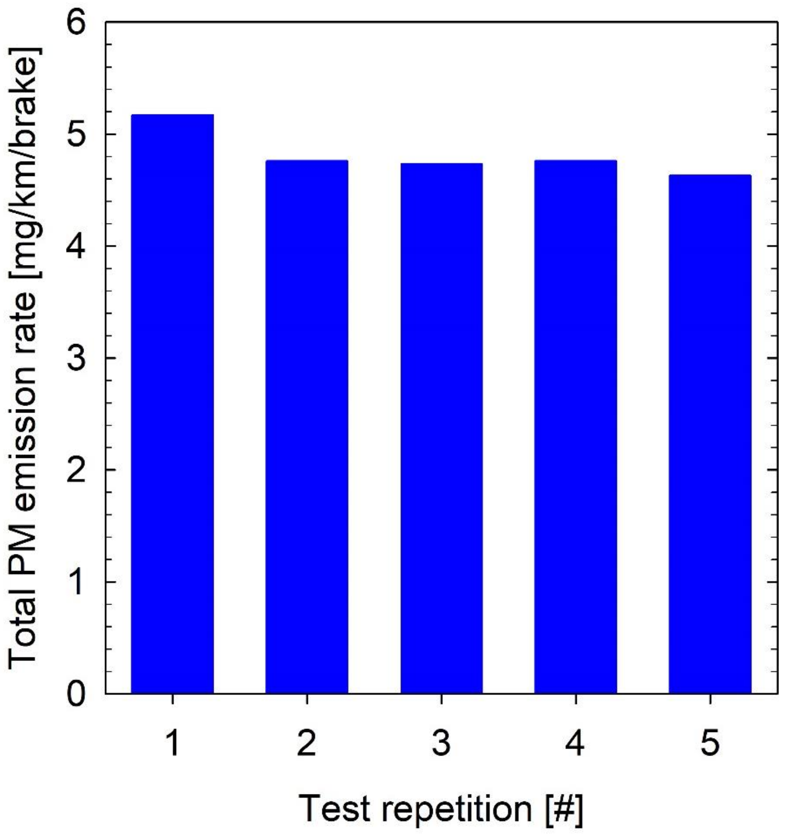
The majority of PM measurements were performed without cyclone. Losses in ducts are expected to result to ~65% penetration at 10 µm.

Great care was taken to ensure isokinetic sampling. Sample flow intentionally remained low (5 lpm) to minimize potential impaction losses in bends.

Average PM total emission levels for a single brake around 4.5 mg/km.

Repeatability was similar to background corrected PN results, with a coefficient of variation of 4.3%.



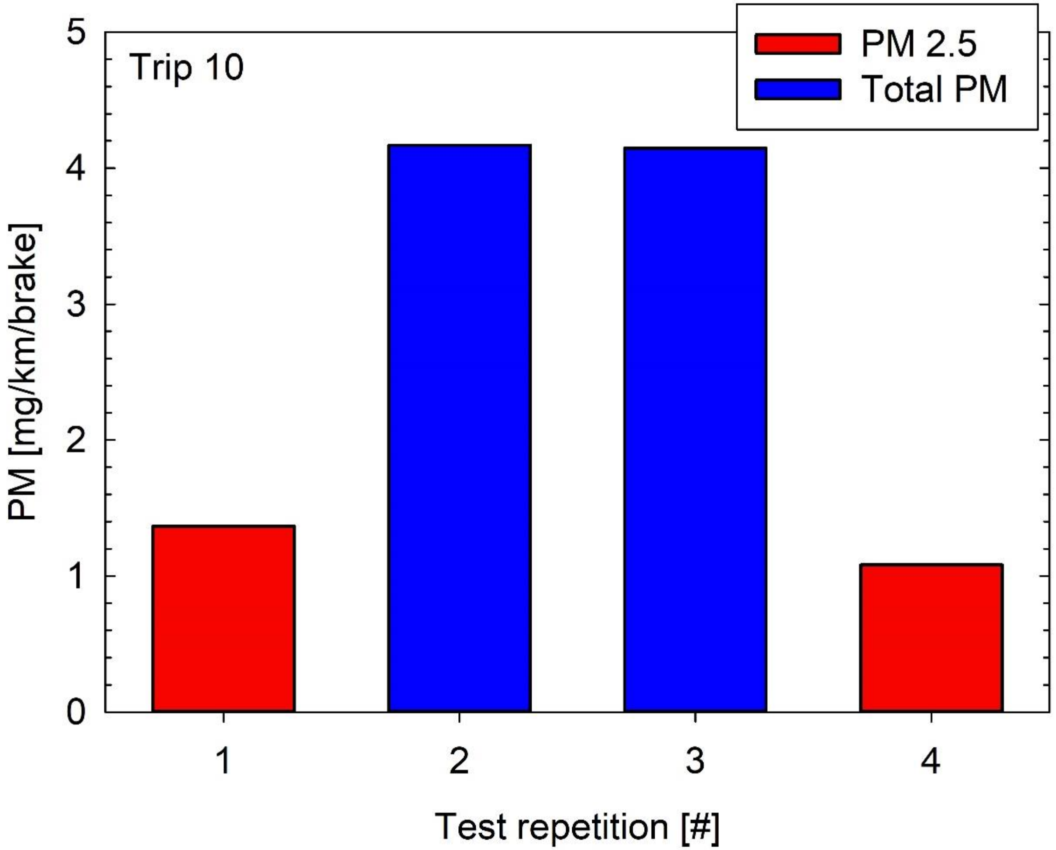


Total PM vs PM2.5

Some dedicated investigations were performed on trip 10 with a 2.5 µm cyclone.

PM2.5 was 3-4 times lower than total PM.

Visual inspection of cyclone after two repetitions of trip 10 showed in addition to the trace of deposits on the side walls of the cyclone the collection of visible coarse particles.



PM recovery and losses

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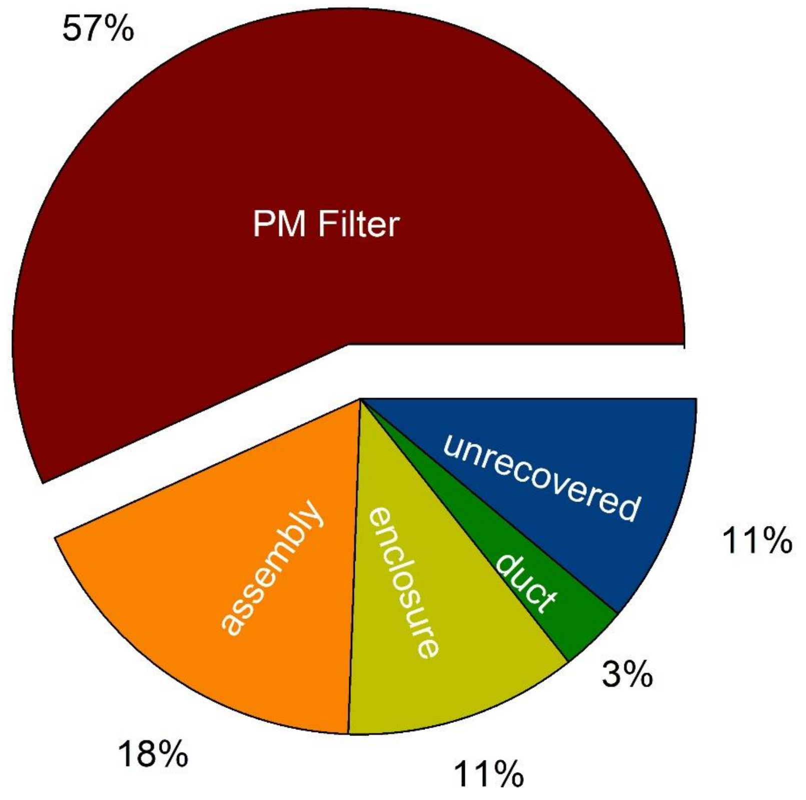
Weighing of different components took place to characterize the penetration of particles through different components.

From the total brake material lost:

- 57% reached the filter
- 18% was lost on the assembly (shaft/mounting)
- 11% on the enclosure
- 3% on the ducts
- 11% of material lost could not be recovered.

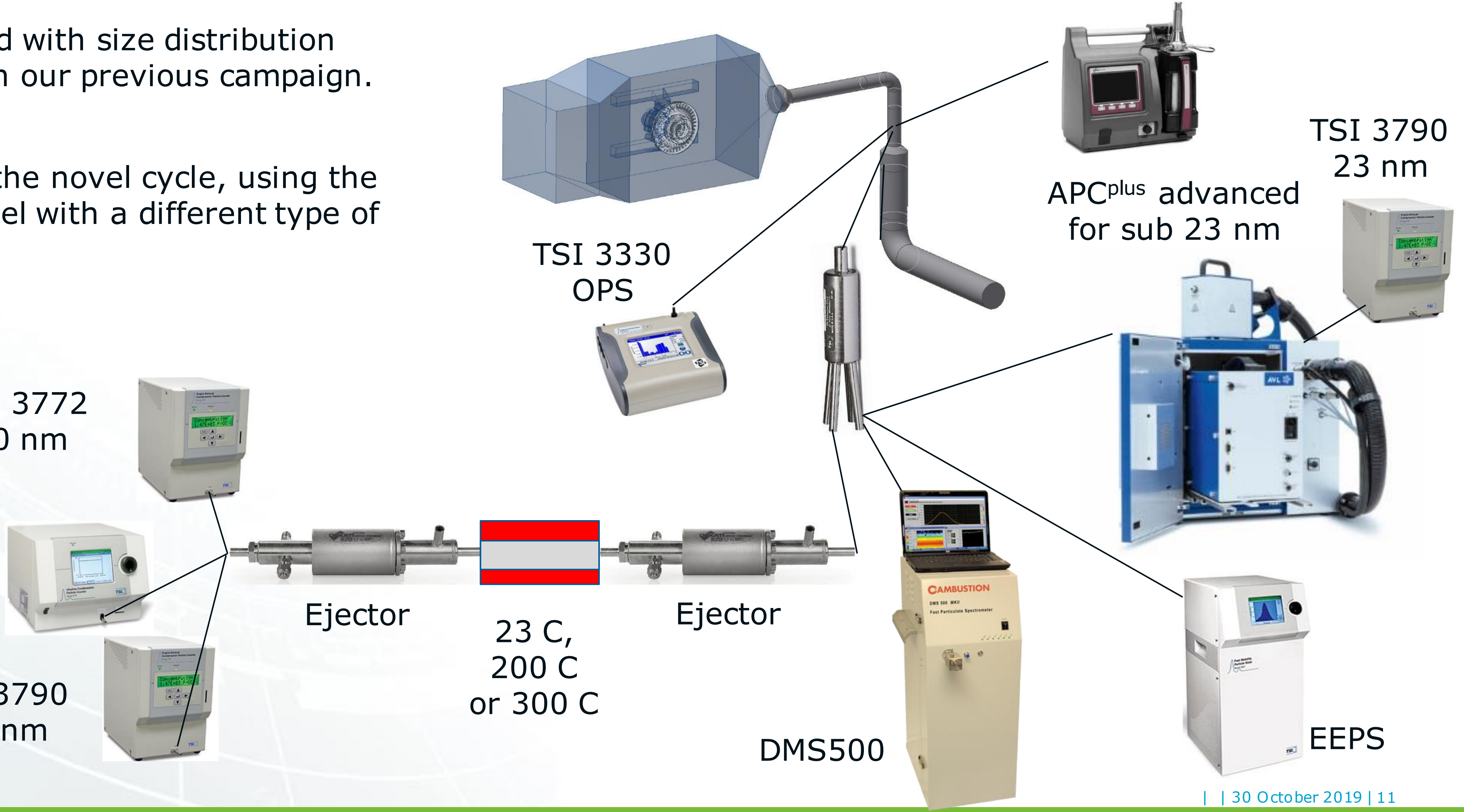
➔ Simple models for particle losses in tubing/bends are not reflecting the true penetrations.



Size distribution measurements

We experimented with size distribution measurements in our previous campaign.

Limited tests of the novel cycle, using the novel PM10 tunnel with a different type of ECE pads.

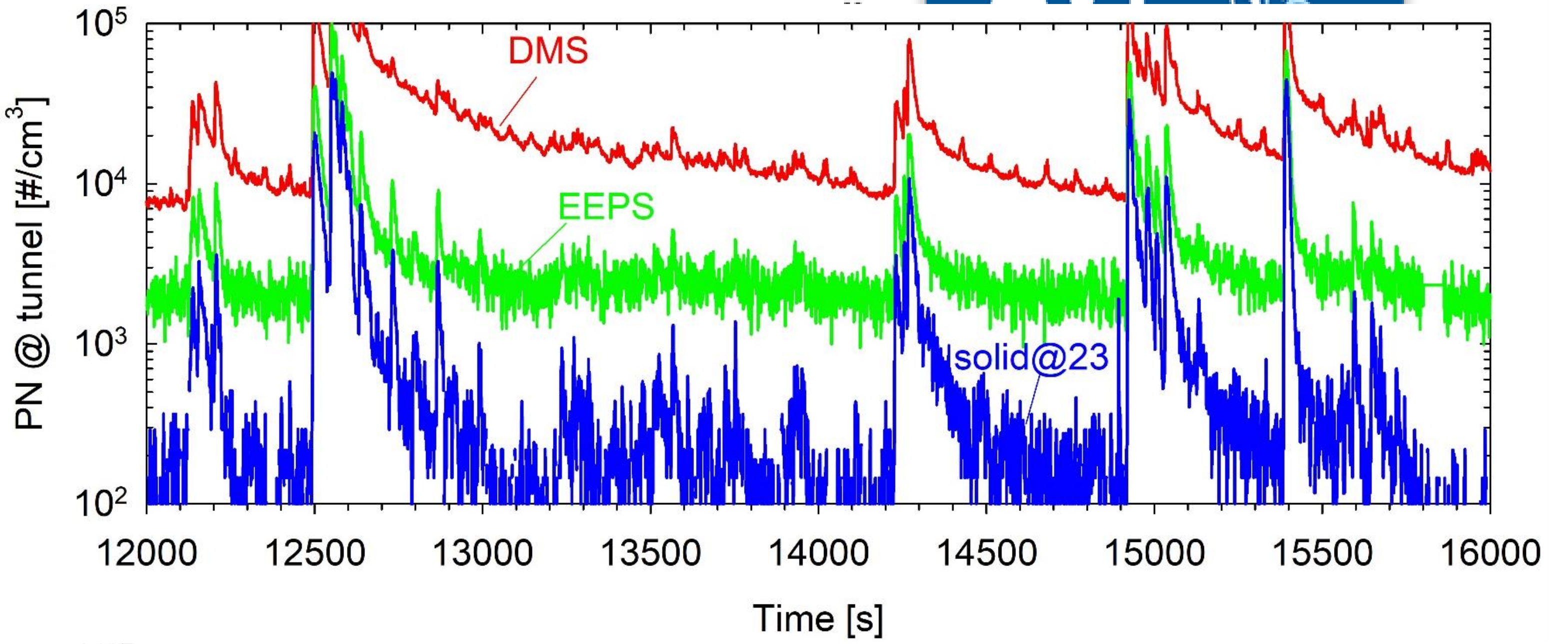


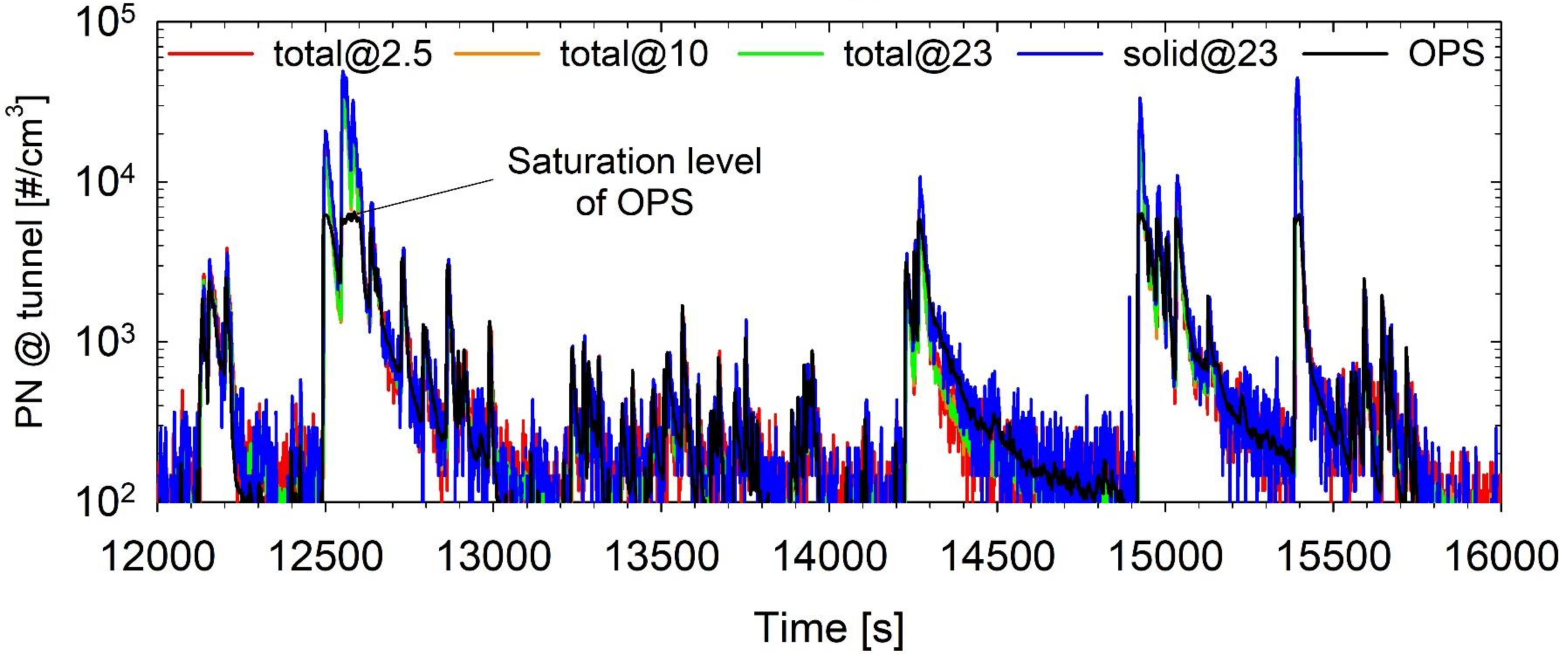
Counting vs sizing techniques (trip10)

Noise levels of EEPS (~2000 #/cm^3) and DMS (>8000 #/cm^3) were well above the background levels of the tunnel (100-200 #/cm^3).

All CPCs, measuring either total PN (23, 10 and 2.5 nm) from cold ejectors (DR 25) or solid (23, 10 nm) from APC gave practically identical results.

OPS (optical diameter > 300 nm) matched well the CPCs up to ~6500 #/cm^3, where it got saturated.





Solid vs total PN

Solid PN emission rates were ~4 times higher than those measured with the circulated pads from TF1, so background contribution was lower.

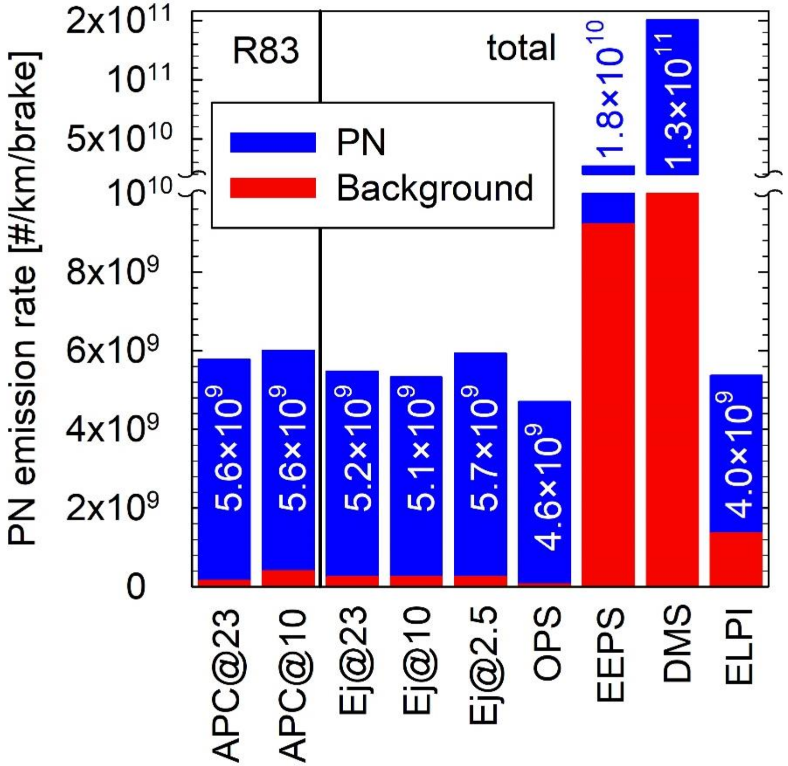
CPCs of different cut-off sizes agreed within ±5%, as did results with (APC) and without (Ej) thermal pretreatment.

➔ No evidence of sub-23 nm or volatile particles over the WLTP with the ECE pad.

Optical particle counter measured 80-90% of the concentrations measured with the CPCs, despite getting saturated over sections of the cycle, which is estimated to have led to 10% underestimation.

➔ Nearly all of the emitted particles appear to be larger than 300 nm (optical diameter).

PN emissions measured with electrical sizing techniques suffered from high noise levels, but even with noise subtracted, results differed considerably from reference techniques.



Inversion ambiguities in electrical sizing techniques

Data inversion from electrical sizing techniques requires some assumption on the properties of particles measured.

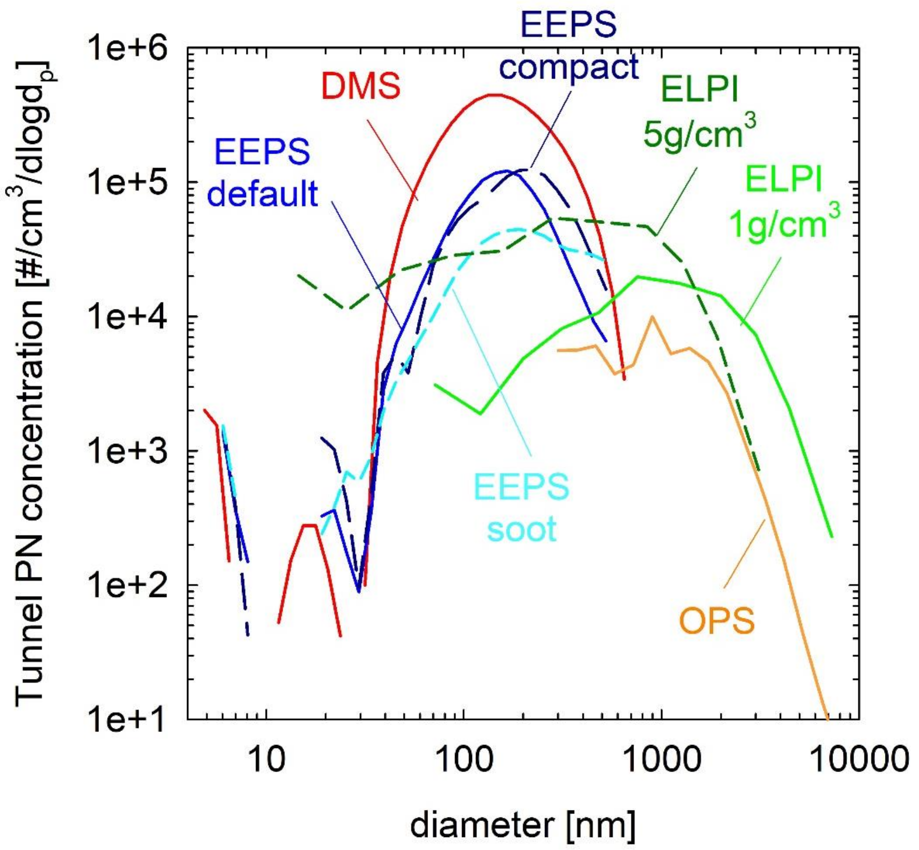
The charging efficiency is known to depend on particle morphology. Accordingly EEPS software provides different inversion matrices for different types of particles. The two alternative inversion matrices to default result in:

- A 40 nm shift of the mode towards larger sizes
- A +15% to -45% change in number concentration

The ELPI data inversion additionally requires an assumption on particle density. Assuming a constant 5 g/cm³ density instead of the default 1 g/cm³ (*Sanders et al. Environ. Sci. Technol. 2003, 37:4060-4069*), leads in:

- a 700 nm shift of the mode towards smaller sizes
- a 4-fold increase in number concentration

Distribution comparisons over the highest emission peak over trip 10



Conclusions

- The WLTP test cycle was evaluated on the dilution tunnel of TUI with the brake pads circulated from TF1.
- Measurement repeatability was better than:
  - ~5% for total PM
  - ~10% for solid PN >10 nm (following current PMP proposal)
- Background can be critical in PN measurements, with the contribution increasing with increasing tunnel flow. Only direct counting (CPC/OPC) techniques were found to exhibit sufficient sensitivity.
- A large fraction of PM mass > 2.5 µm (~70%) was measured. Precise specifications for tunnel / pre-separator is necessary for PM10 measurements.
- The lack of knowledge on particle morphology and density (with their potential dependence on size and operating conditions) do not allow for accurate PN quantification with indirect measurement techniques. Use of CPCs with different cut-off sizes is the most reliable technique for the identification of nano-sized particle formation.

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Outlook

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- Quantification of the measurement accuracy is an important element for any established methodology. Repeatability is only one component of the measurement accuracy. It is important to also establish the reproducibility of the proposed methodology.

- We would like to propose a round robin study for particle measurements, which should consider:
  - The use of at least two different types of brake-pads
  - At least one alternative test cycle (i.e. Los Angeles City Traffic)
  - Background concentrations reported and maintained below agreed limits
  - Two tunnel flows, with one being common at all setups
  - Weighing of pads to quantify PM recovery
  - Reference instrumentation for PN and PM:
    - Nonvolatile PN as the most repeatable methodology
    - Parallel measurement with 10 and 23 nm CPC
    - Parallel measurement of PM2.5 and PM10
  - Potentially also a reference dilution tunnel

Thank You

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