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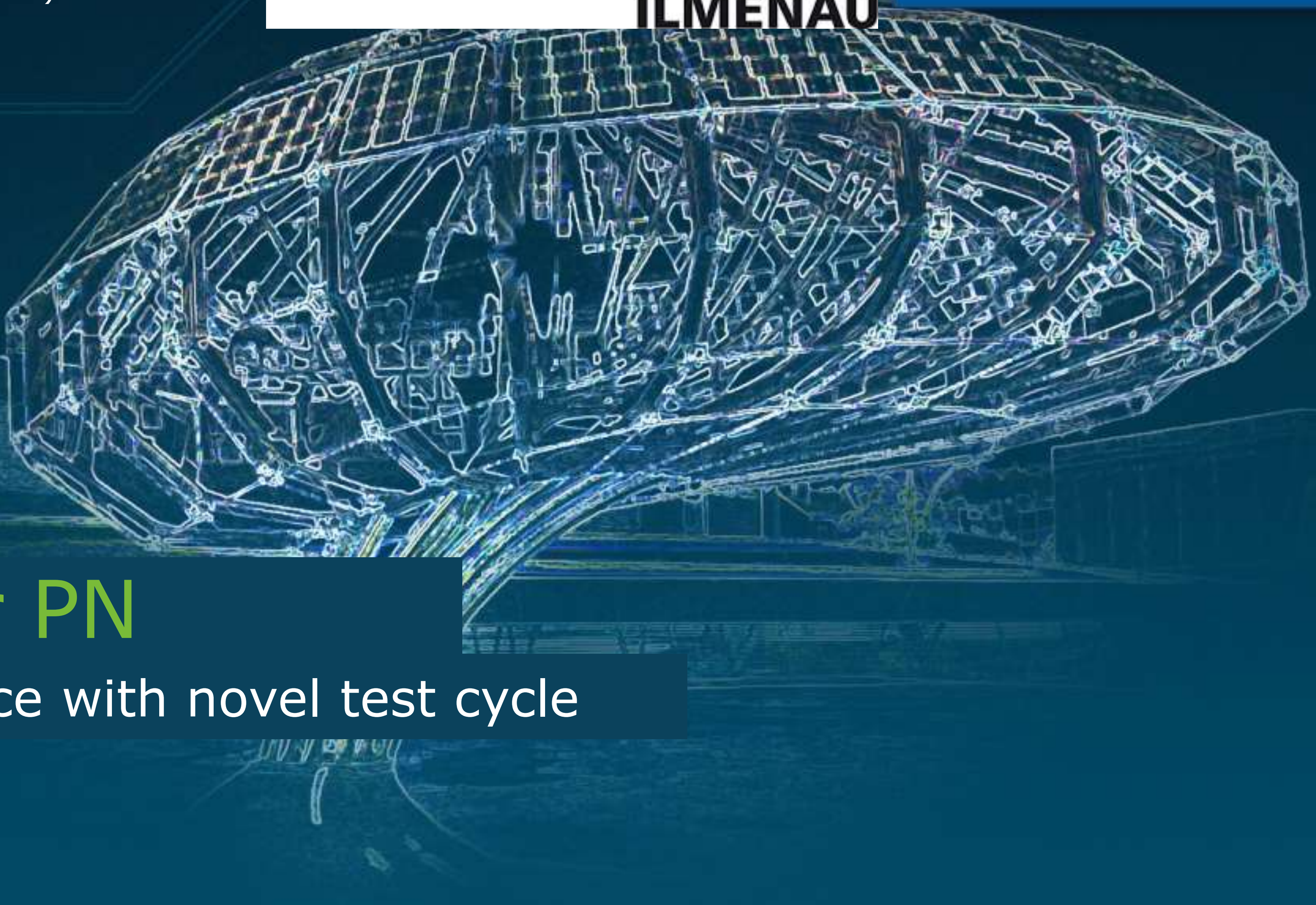
AVL List GmbH (Headquarters)



Brake-wear PN

AVL/TUI experience with novel test cycle

Confidential

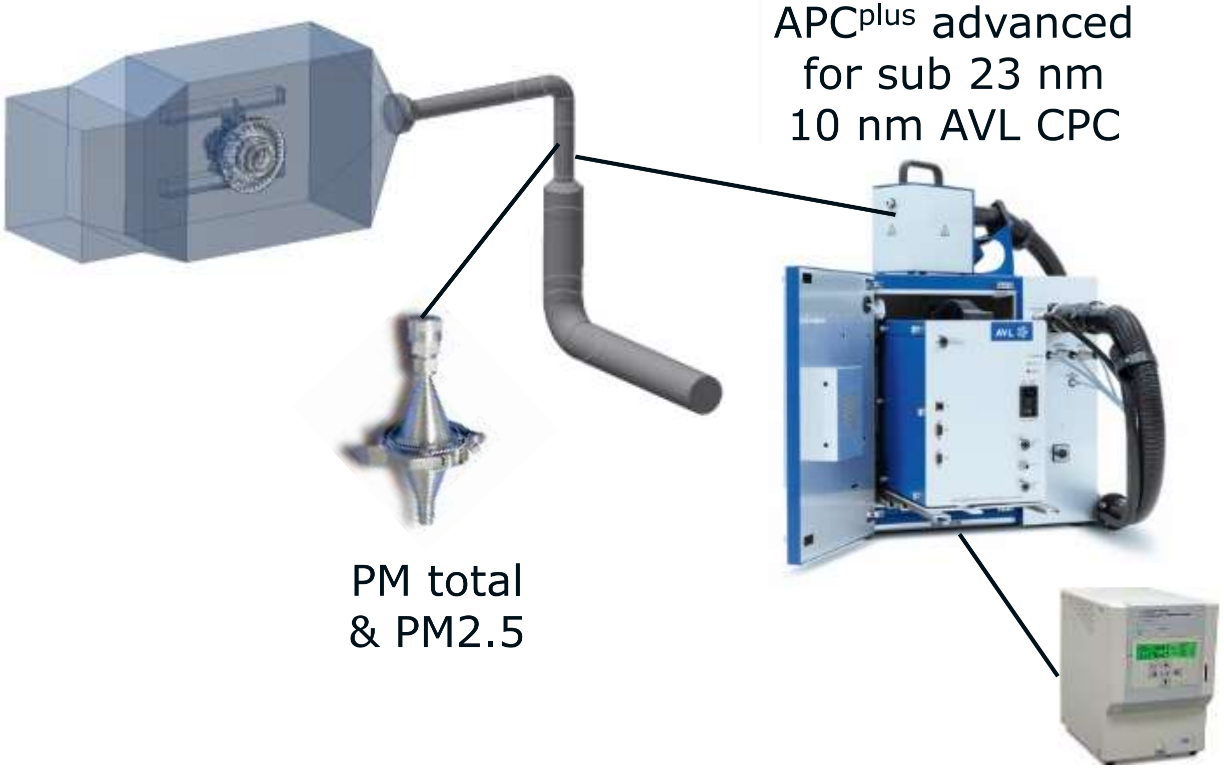
Experimental

Tests were performed at TUI on their PM10 tunnel. Tunnel flow: 170 m^3/h

Measurements included PM total (on 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 35C before the start of each trip.

All tests were performed with the brake pads supplied from the task force.

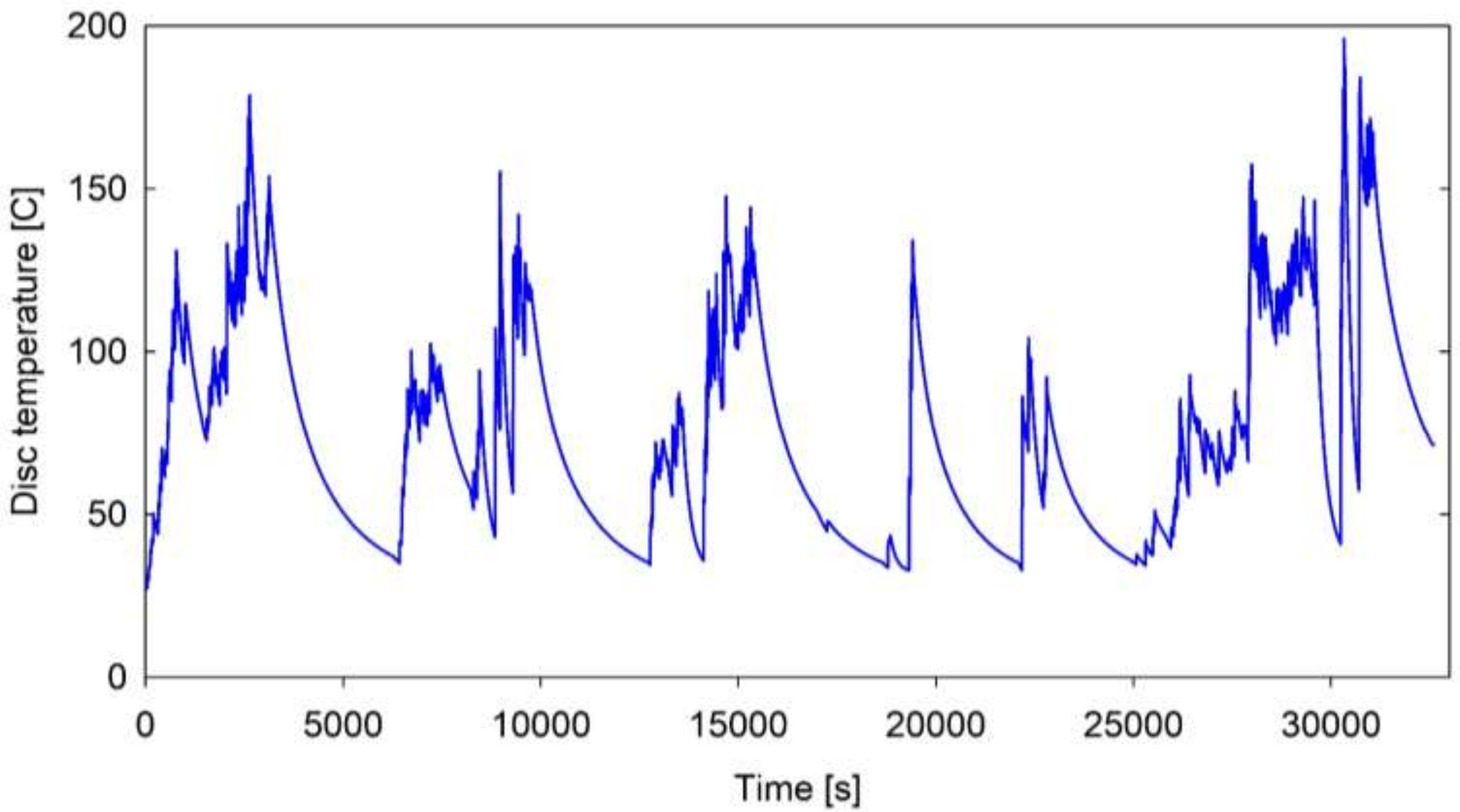


APC^{plus} advanced
for sub 23 nm
10 nm AVL CPC

PM total
& PM2.5

TSI 3790
23 nm

Temperatures



Trip	max T [°C]
1	131
2	179
3	102
4	155
5	148
6	52
7	134
8	104
9	51
10	196

Temperatures were generally higher from what we observed with other brake-pads we have tested in our previous campaigns.

Repeatability

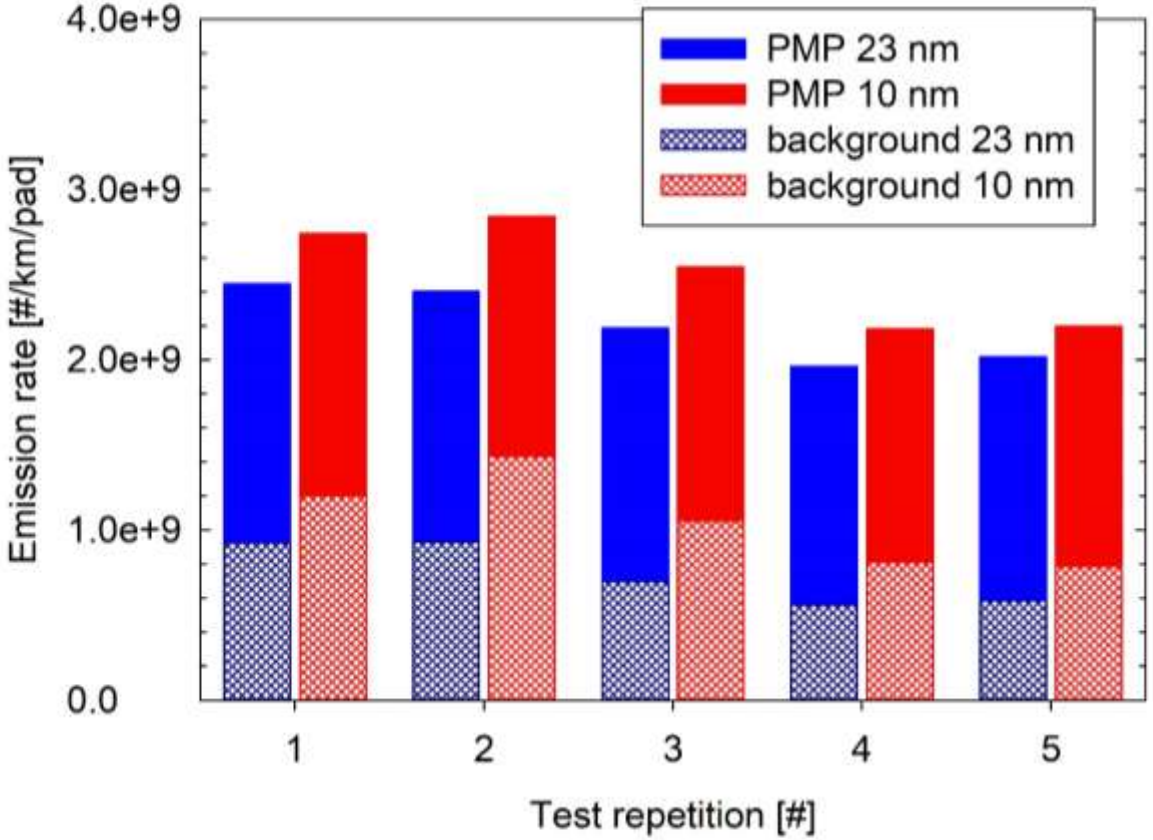
Brake-pads were preconditioned with 12 repetitions of trip10.

<u>For calculations cooling periods were discarded</u>.

PN emissions < 3×10^{9} #/km/pad i.e. more than 200 times below the current exhaust PN limit (6×10^{11} #/km).

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.



Repeatability

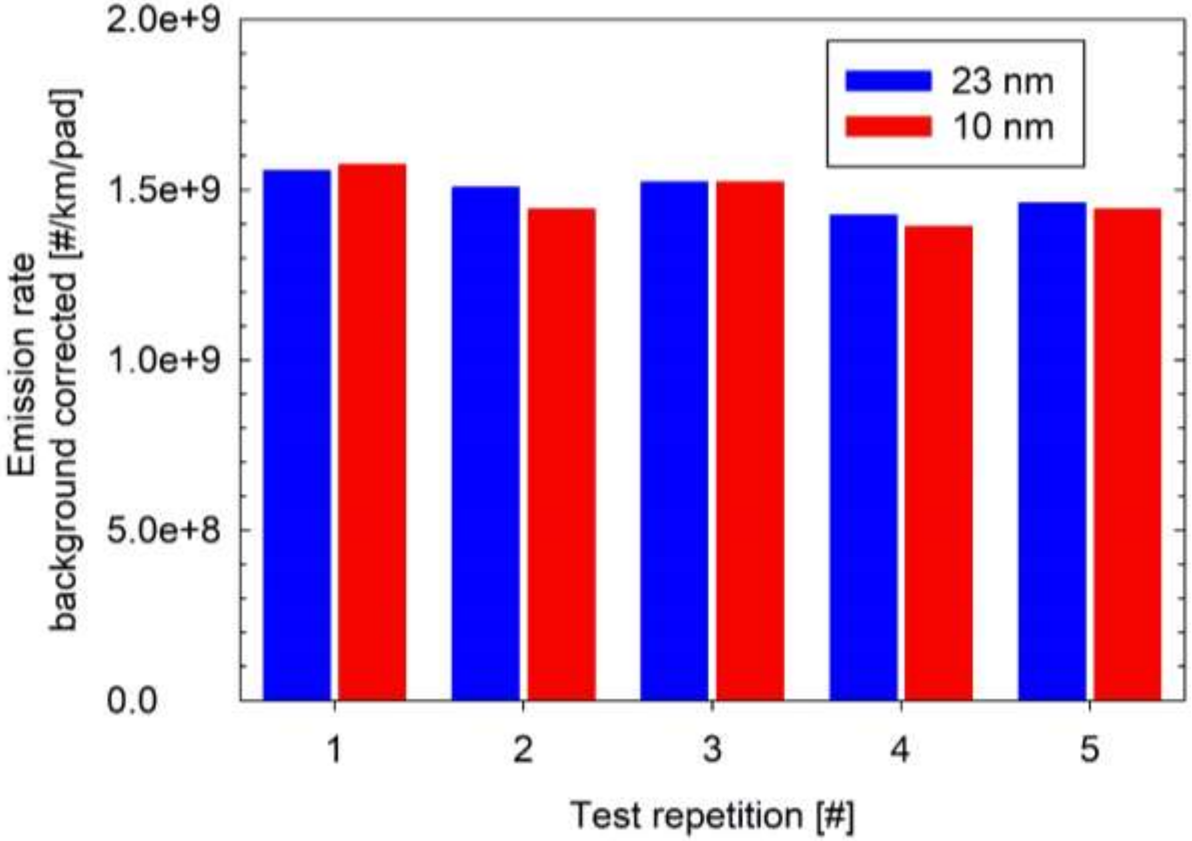
Number concentrations were too low for coagulation to have an effect (peak concentrations of 40000 #/cm^3) so number emission rate should be conserved:

$$C_{bck}\left[\frac{\#}{m^3}\right]Q_{in}\left[\frac{m^3}{s}\right]+N_{emitted}\left[\frac{\#}{s}\right]=C_{meas}\left[\frac{\#}{m^3}\right]Q_{out}\left[\frac{m^3}{s}\right]$$

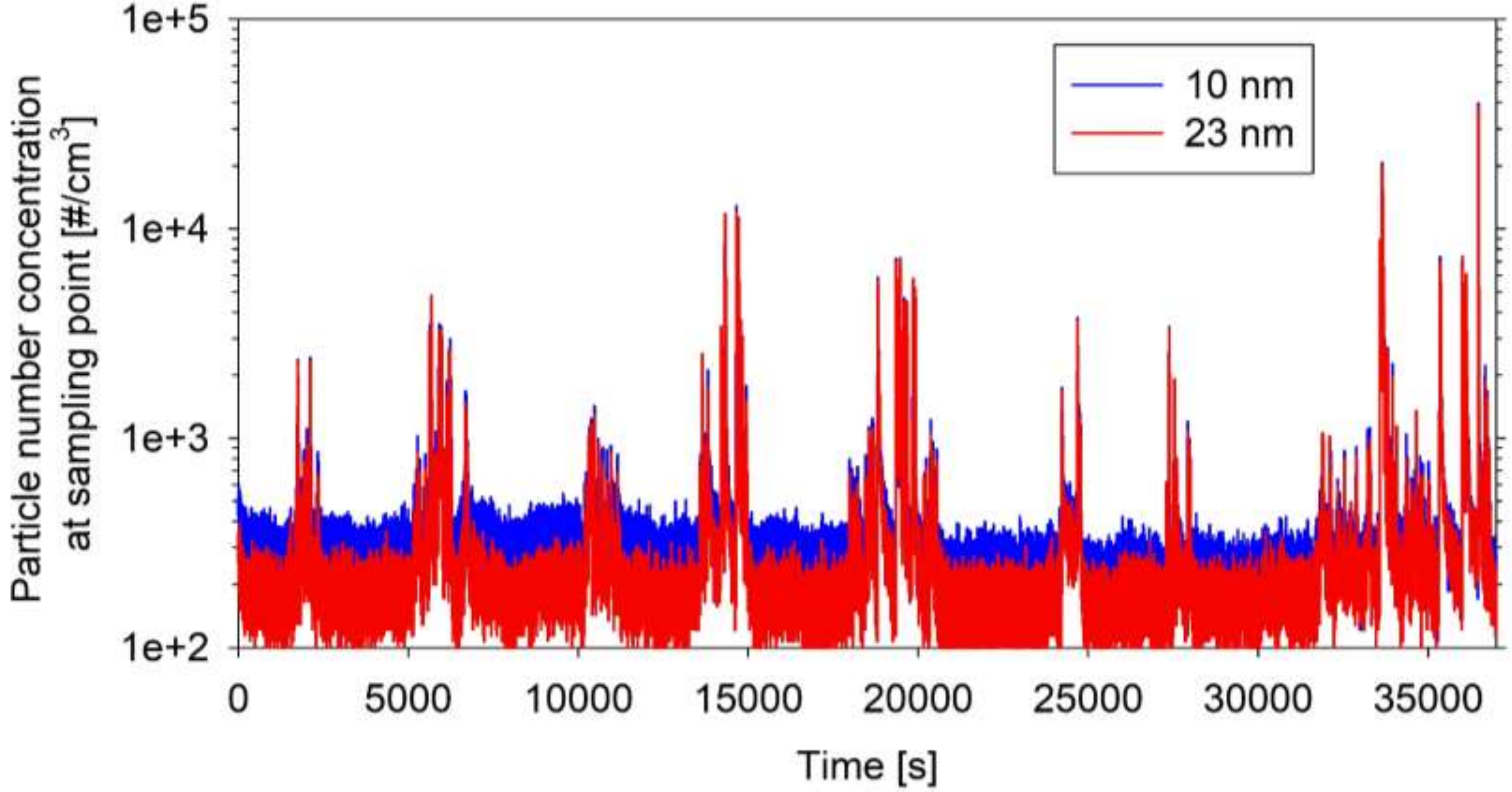
$$N_{emitted}\left[\frac{\#}{s}\right]=\left\{C_{meas}\left[\frac{\#}{m^3}\right]-C_{bck}\left[\frac{\#}{m^3}\right]\right\}Q_{tunnel}\left[\frac{m^3}{s}\right]$$

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

Also CoV improved to ~4% for both CPCs.



Background levels



Trip	PN23 [#/cm³]	PN10 [#/cm³]
1	306	374
2	400	440
3	279	328
4	772	809
5	587	637
6	165	231
7	388	449
8	344	399
9	186	244
10	649	687
bck	**153**	**207**

Background concentrations were in the order of 200 #/cm^3 for 23 nm and 300 #/cm^3 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.

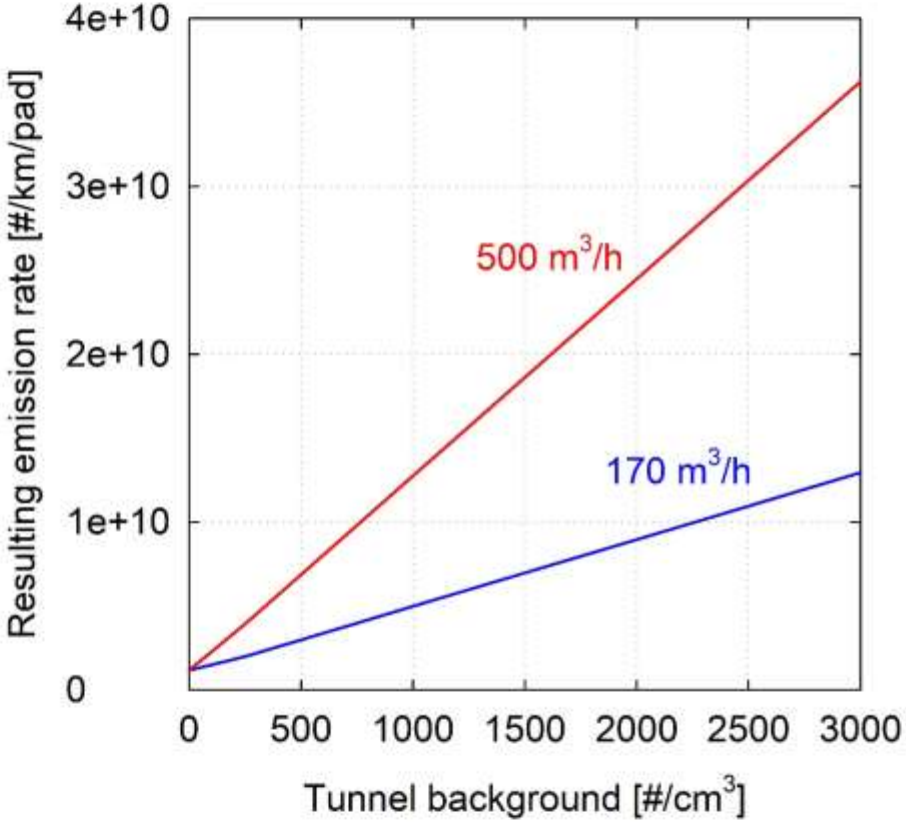
Effect of background

Background can have a significant effect on PN emissions ➔ should be kept as low as possible (background level should be reported).

Contribution of background on measured concentrations will increase as tunnel flow increases (emitted particles are further diluted).

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



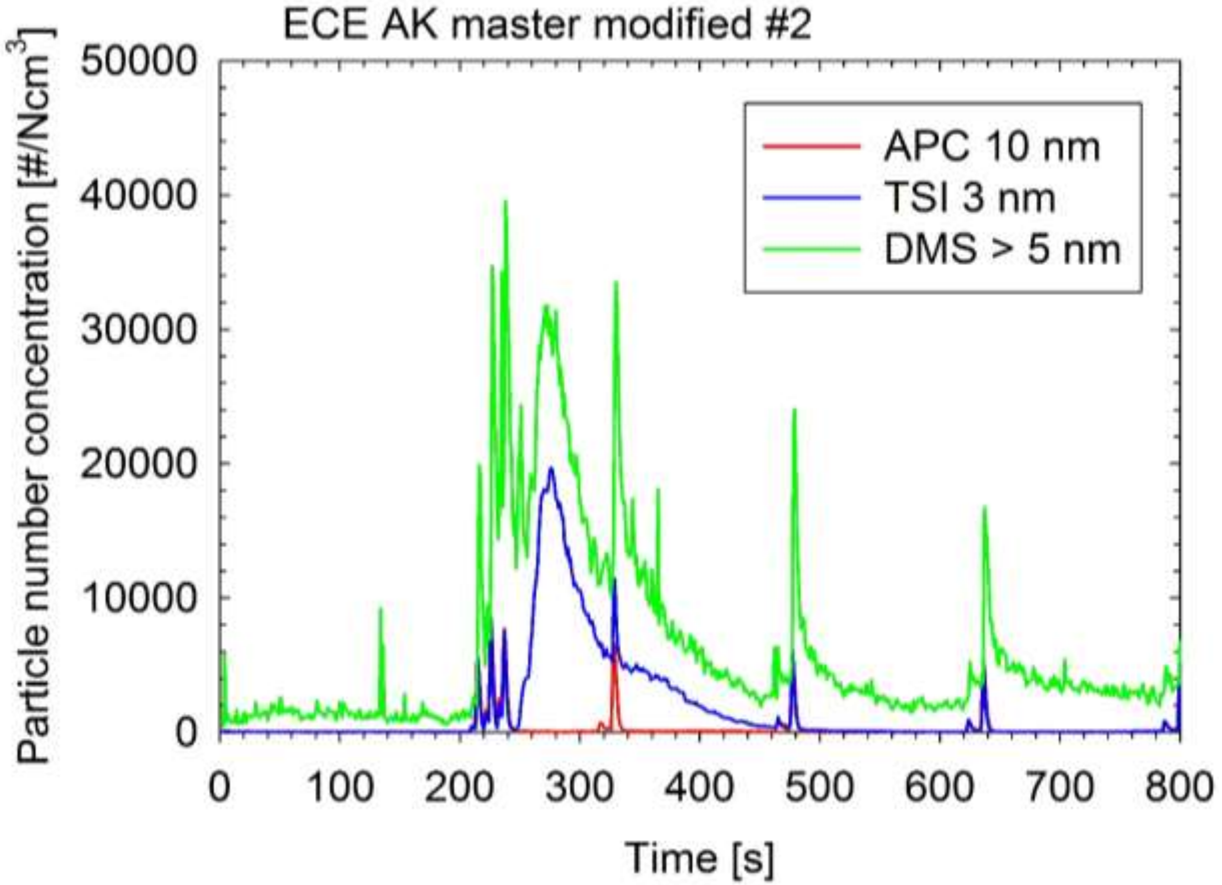
Background – treatment & electrical techniques

Special care needs to be taken when measuring total particles to:

- Carefully clean the tunnel (with no alcohol).
- Ensure that bearings do not release volatile particles.
- Brake pads/discs are properly handled.

Electrical size classification techniques have inherently higher noise level (i.e. 1680 #/cm^3 for EEPS/DMS):

- which increases with decreasing size (i.e. 240 #/cm^3 at 6.04 nm bin, to 60 #/cm^3 at 23 nm)
- can drift over time (especially after high emission events)



How would nucleation events contribute to cycle average emissions?

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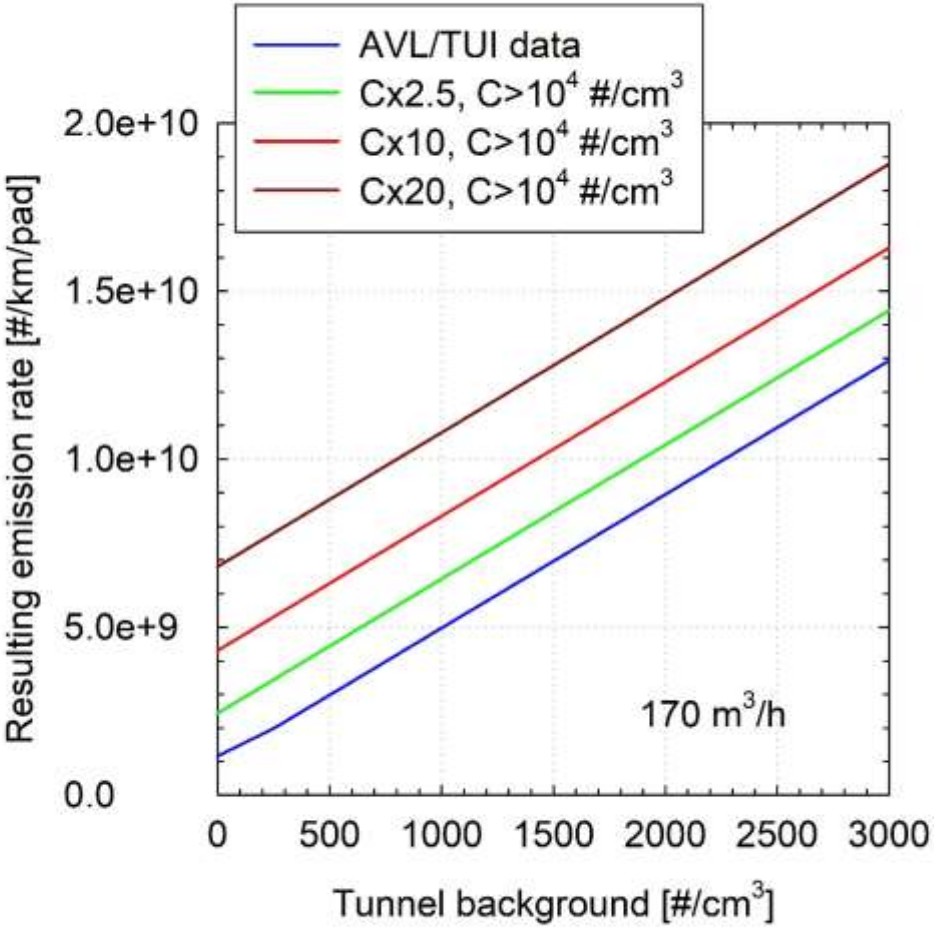
Potential for nucleation is limited to some specific events.

Assuming for example that these are the events on which we observed tunnel concentrations above 10000 #/cm^3, we performed some simulations to investigate what would be the effect on calculated emission rates if these events were associated with 2.5, 10 and 20 times higher concentrations.

Even a 20-fold increase in emissions over these events and with zero background will lead to just a 6-fold increase in the cycle average emissions owing to the short duration of these events.

As background level increases, the effect on cycle-average emission drops with a 3-fold increase at background levels of 500 #/cm^3 background and 45% increase at 3000 #/cm^3 background.



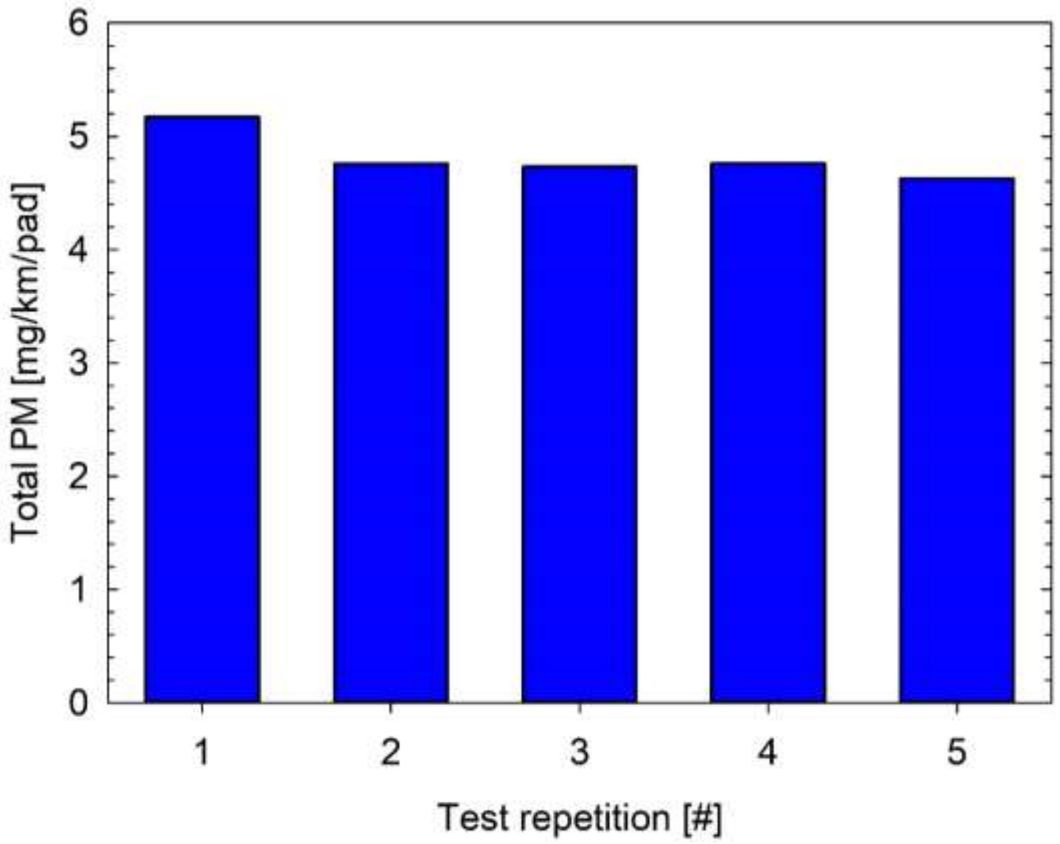
Total PM results

In lack of a clearly defined recommendation the main evaluations were performed without cyclone.

Great care was taken to ensure isokinetic sampling and 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%.

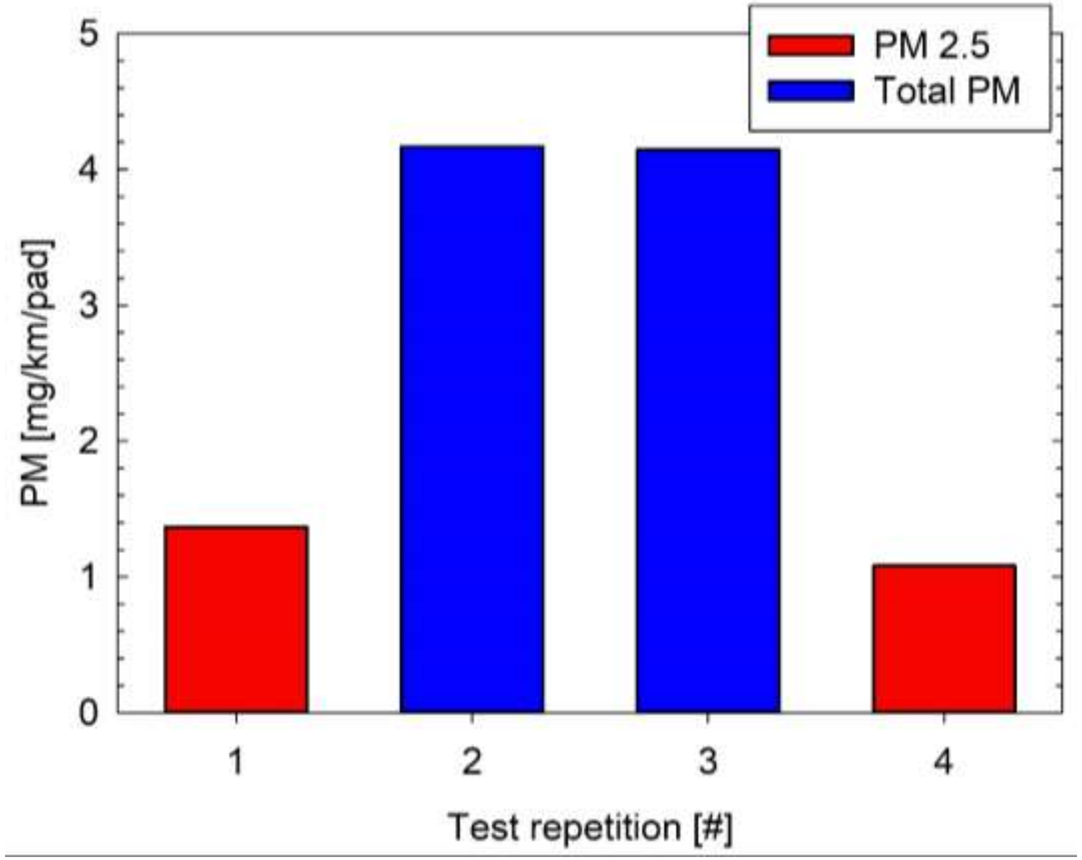


Total PM vs PM2.5

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

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

Visual inspection of cyclone after two repetitions of trip 10 showed visible coarse particles but also a trace of deposits on the side walls of the cyclone.



PM recovery and losses

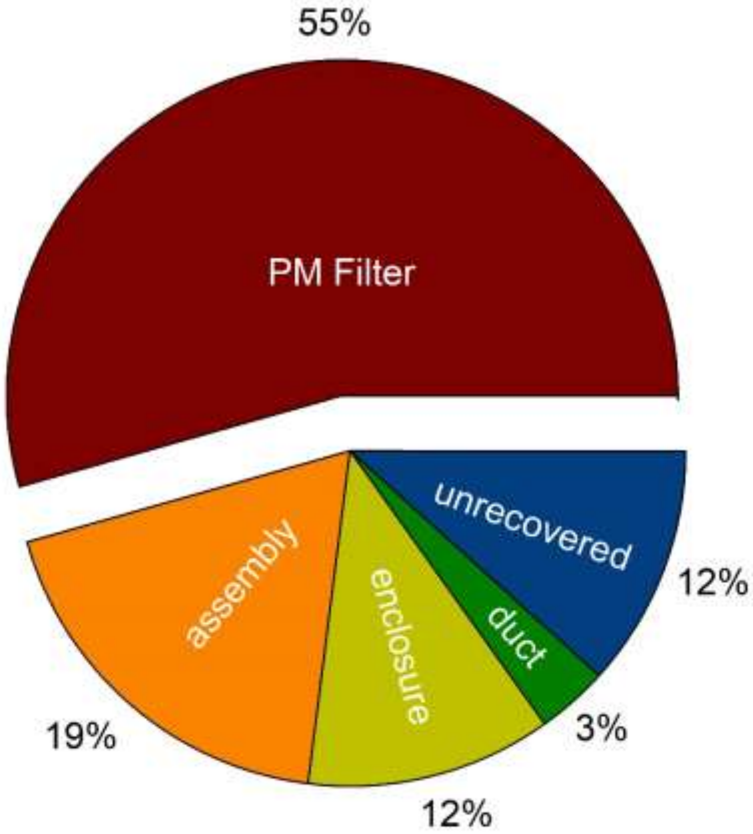
Weighing of different components took place to characterize the penetration of particles through different components.

9% of material lost, remained on pads/discs.

From the 91% of the remaining mass:

- 19% was lost on the assembly (shaft/mounting)
- 12% on the enclosure
- 3% on the ducts

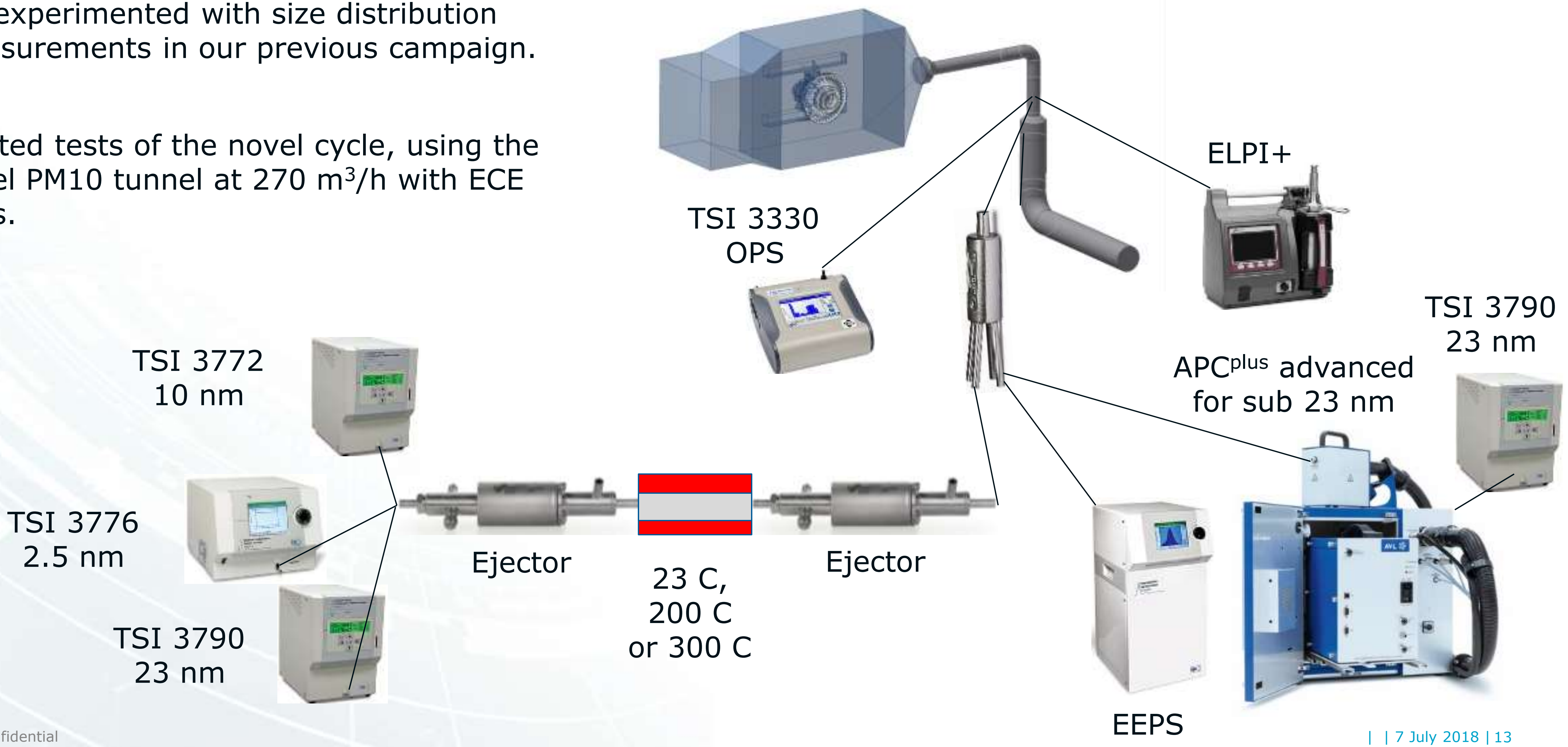
➔ Simple models for particle losses in tubing/bends are not reflecting the true penetrations.



Size distribution measurements

We experimented with size distribution measurements in our previous campaign.

Limited tests of the novel cycle, using the novel PM10 tunnel at 270 m³/h with ECE pads.



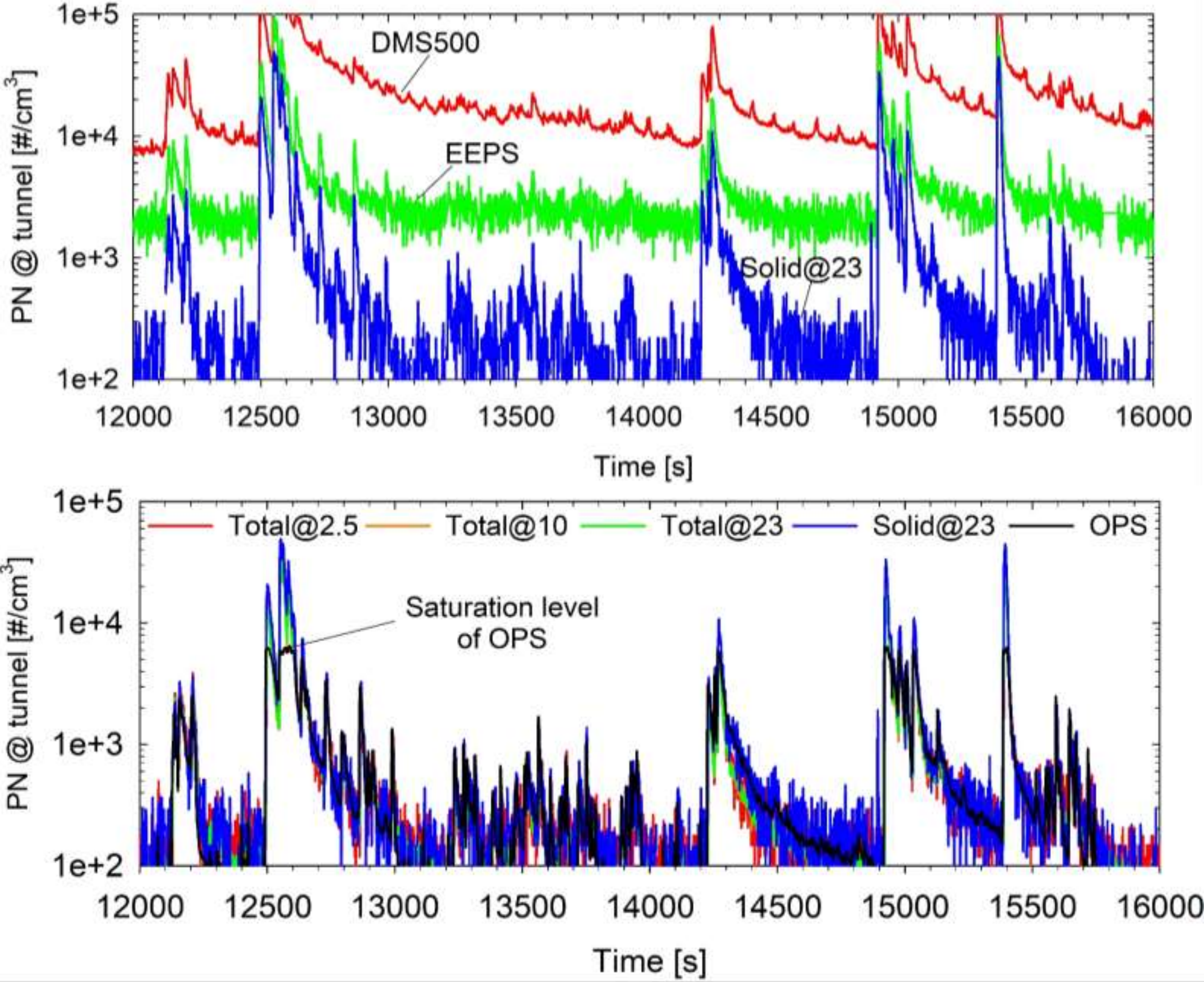
Size distribution measurements

Example results over the last 4000 s of the novel cycle (run continuously) with ECE.

Noise levels of EEPS (~2000 #/cm³) and especially DMS (>8000 #/cm³) well above the background levels of the tunnel (100-200 #/cm³) and concentration spikes during braking events overestimated substantially true particle number emissions.

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.

Interestingly, OPS that should detect particles with optical diameter > 300 nm matched well the CPCs up to ~6500 #/cm³ where it seems to got saturated.

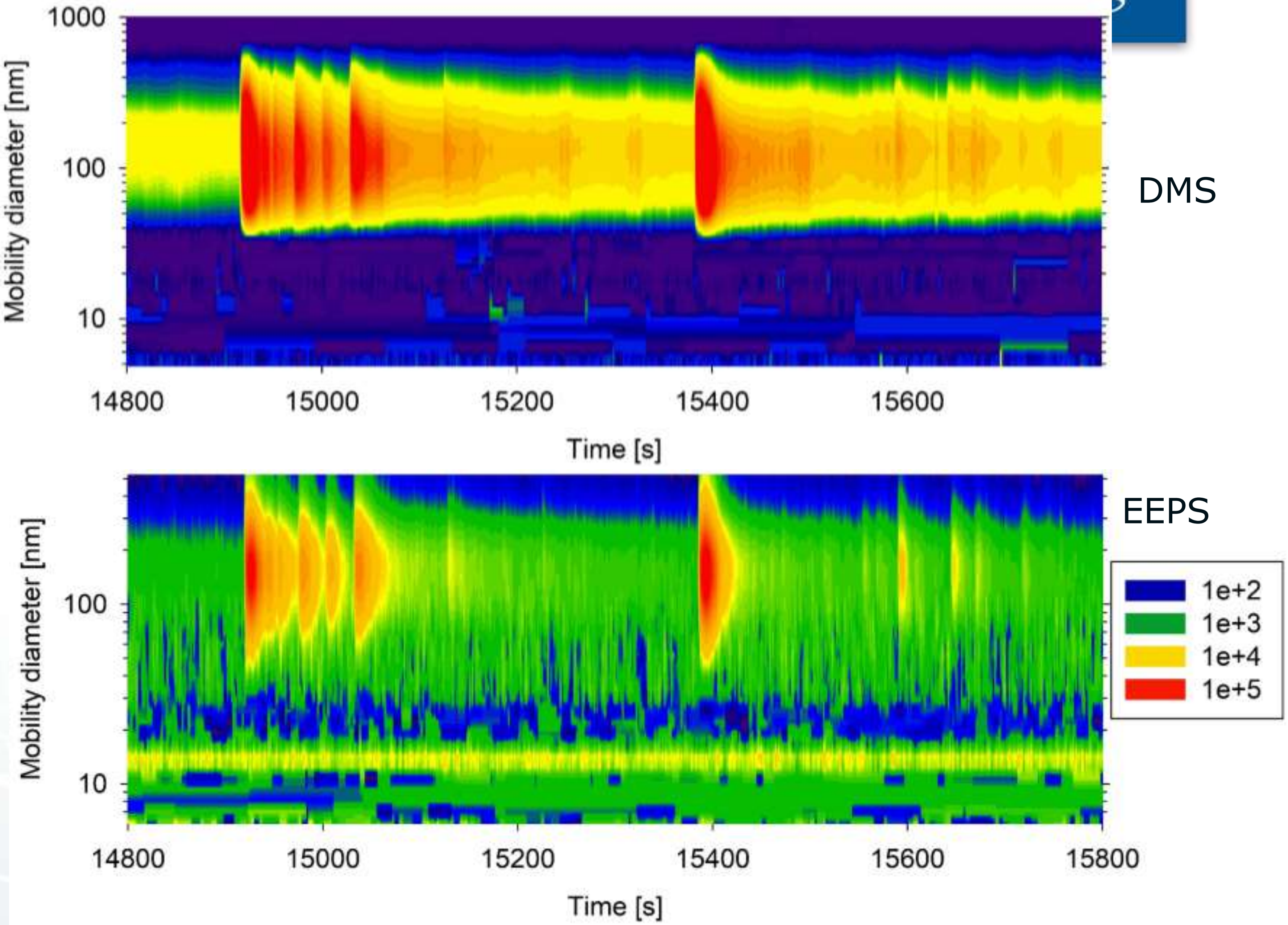


Real time size distributions #1

Cycle-average mode was 136 nm based on DMS and 92 nm based on EEPS.

However EEPS mode was affected by an artificial mode at 12 nm due to electrometer offset (no such indications from 2.5 and 10 nm CPCs, or DMS). By excluding sizes below 13 nm, the EEPS cycle-average mode increased to 123 nm.

The size distributions measured with EEPS and DMS had similar shapes although absolute levels differed by nearly one order of magnitude.



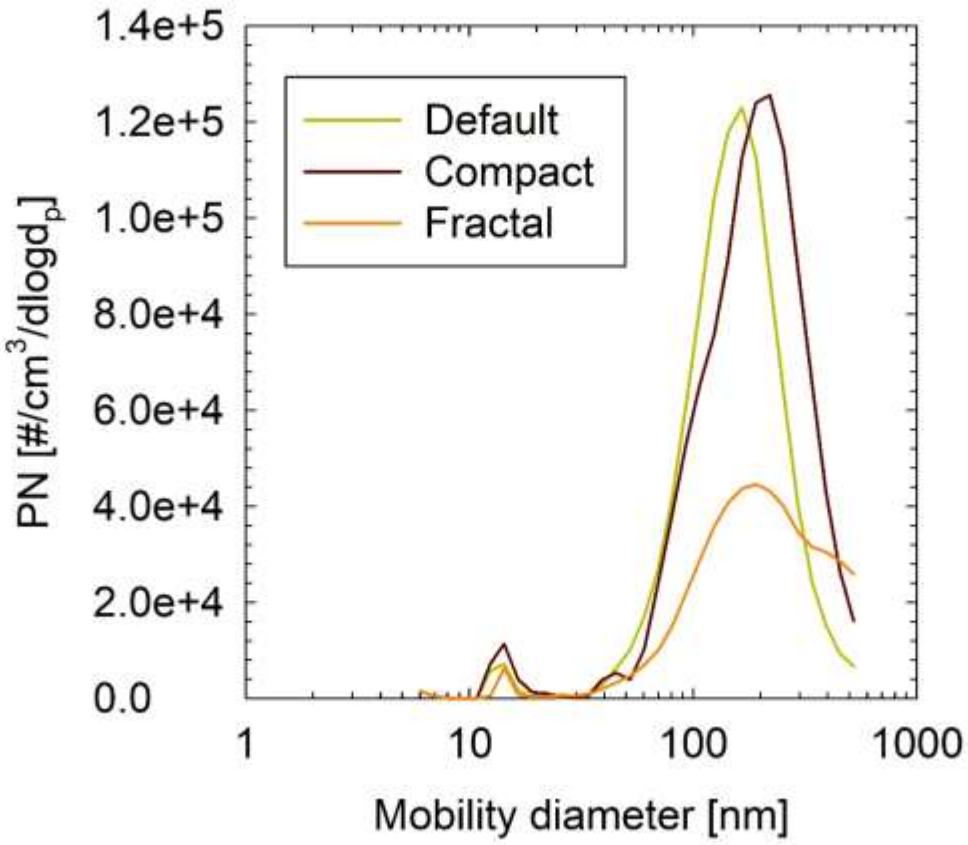
Real time size distributions #2

The inversion of EEPS & DMS data strongly depends on the assumptions on the particle morphology.

Different inversion matrices have been established for different types of particles for EEPS.

The effect can be substantial as can be seen on the figure for one example breaking event.

All calculations were performed with default model as no clear information is available for morphology of brake wear particles.



Real time size distributions #3

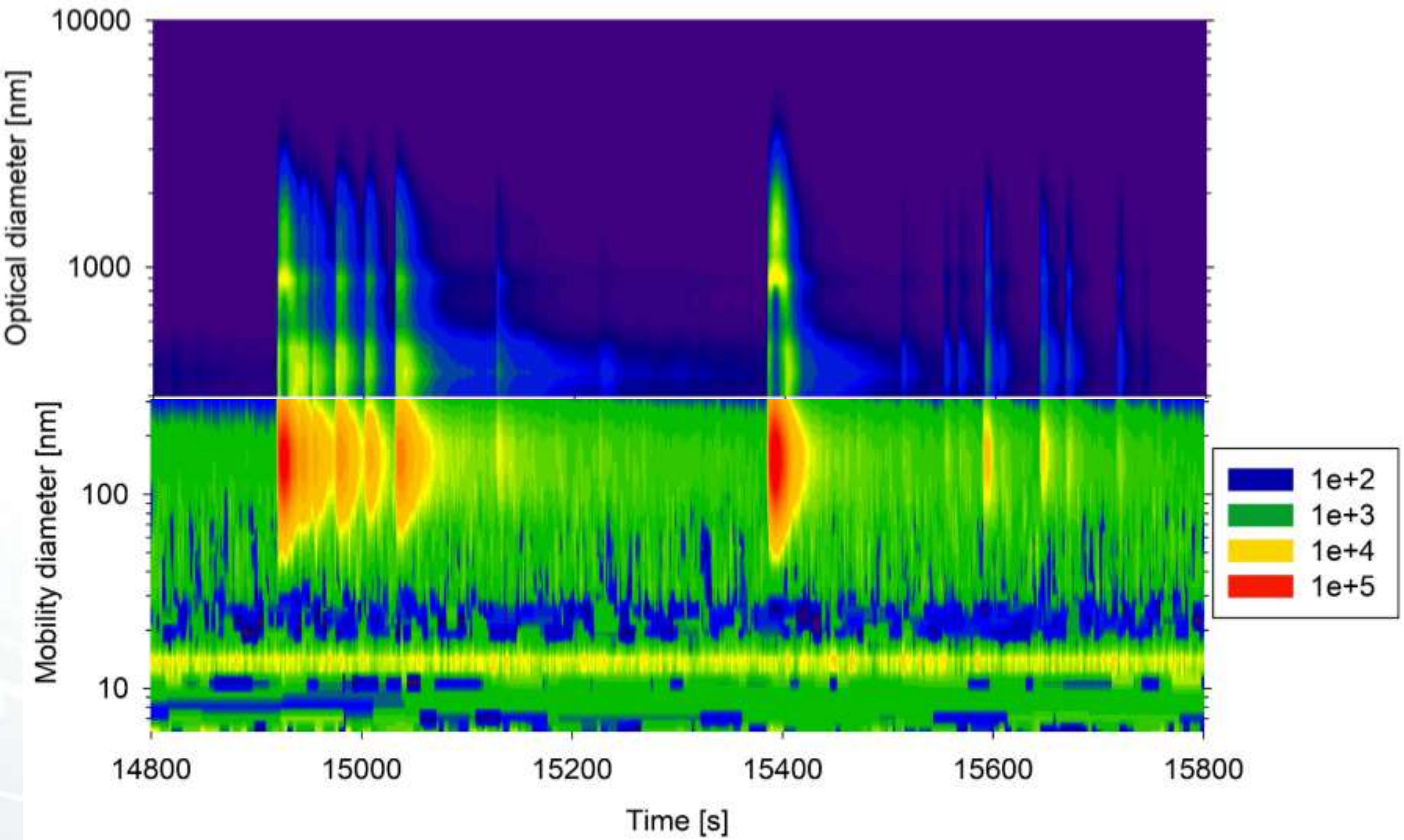
Corresponding real time size distributions:

Size distributions from OPS and EEPS do not match over the overlapping range due to:

- Different equivalent diameters
- Inversion algorithms

Note also an <u>artificial</u> mode in EEPS at 12 nm due to electrometer offset (no such indications from 2.5 and 10 nm CPCs)

➔ Great care needs to be taken in interpreting size distribution data

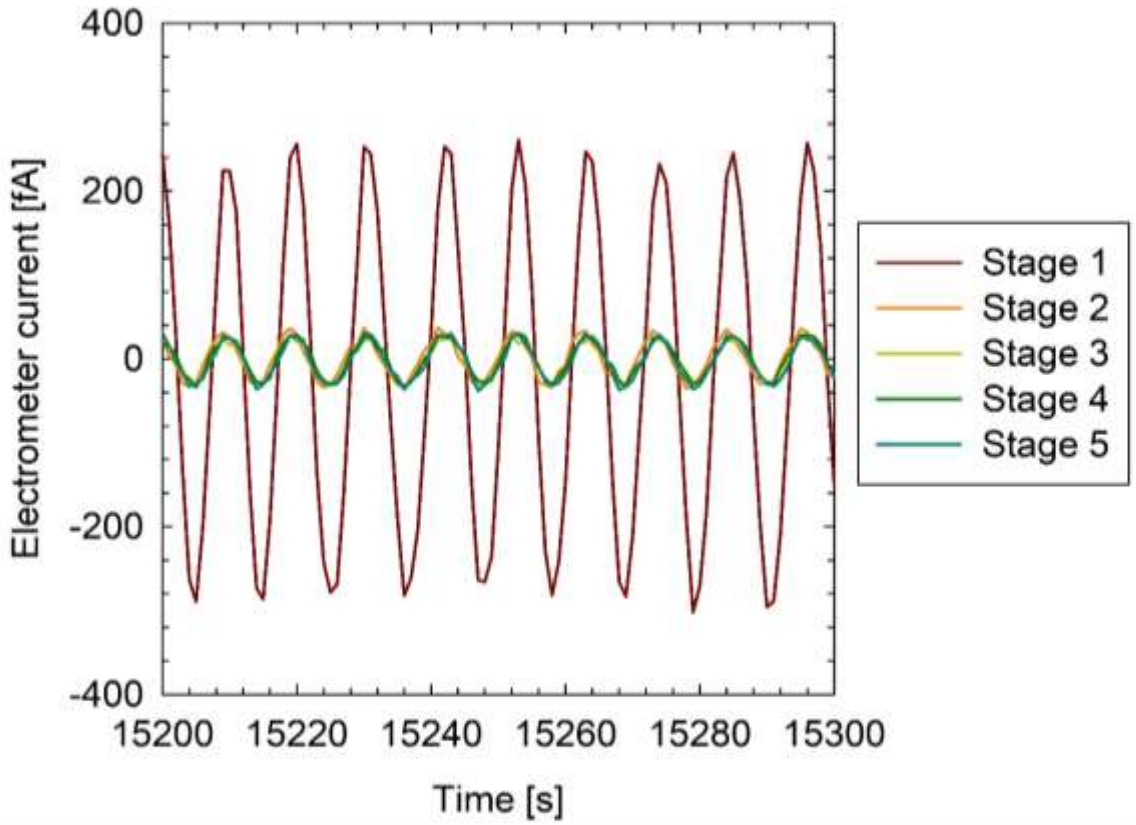


ELPI electrometer issue

ELPI electrometers were oscillating during most of the tests, especially for filter stage ➔

- True signal would be hidden within these oscillations
- Noise level increases

Due to the power-law dependence of charging probability on size, this severely affected PN calculation for small stages/sizes ➔ first 3 stages were excluded from calculations.

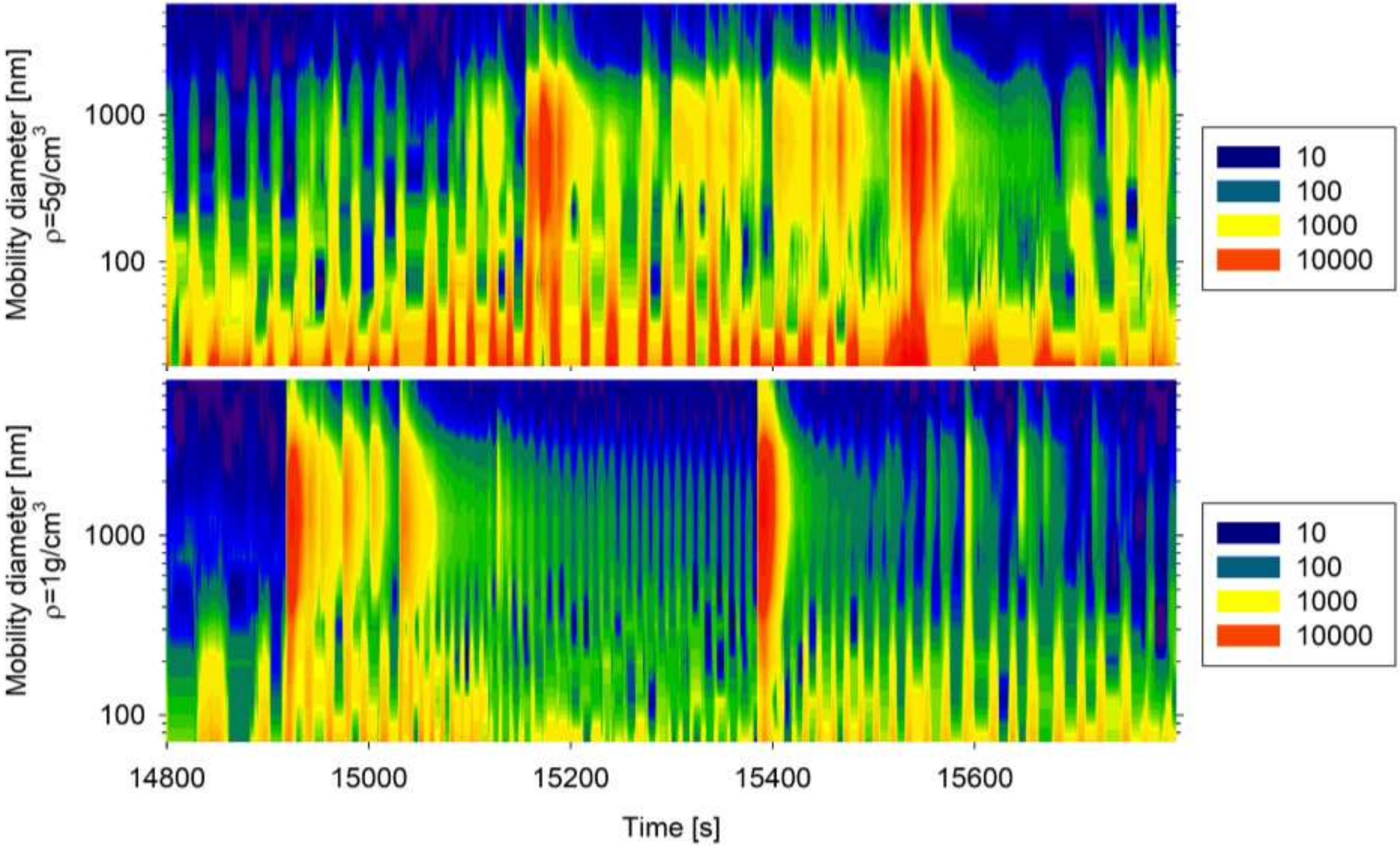


ELPI distributions for different effective densities

ELPI results depend on assumed effective particle density.

When shifting from the default 1 g/cm³ to a higher value of 5 g/cm³, the mobility size is shifting to smaller sizes and the number concentration increases. Electrometer oscillations have also more strong effect on number results.

Mode of ELPI distributions peaks at considerable larger mobility diameters than DMS/EEPS, even for effective density of 5 g/cm³.



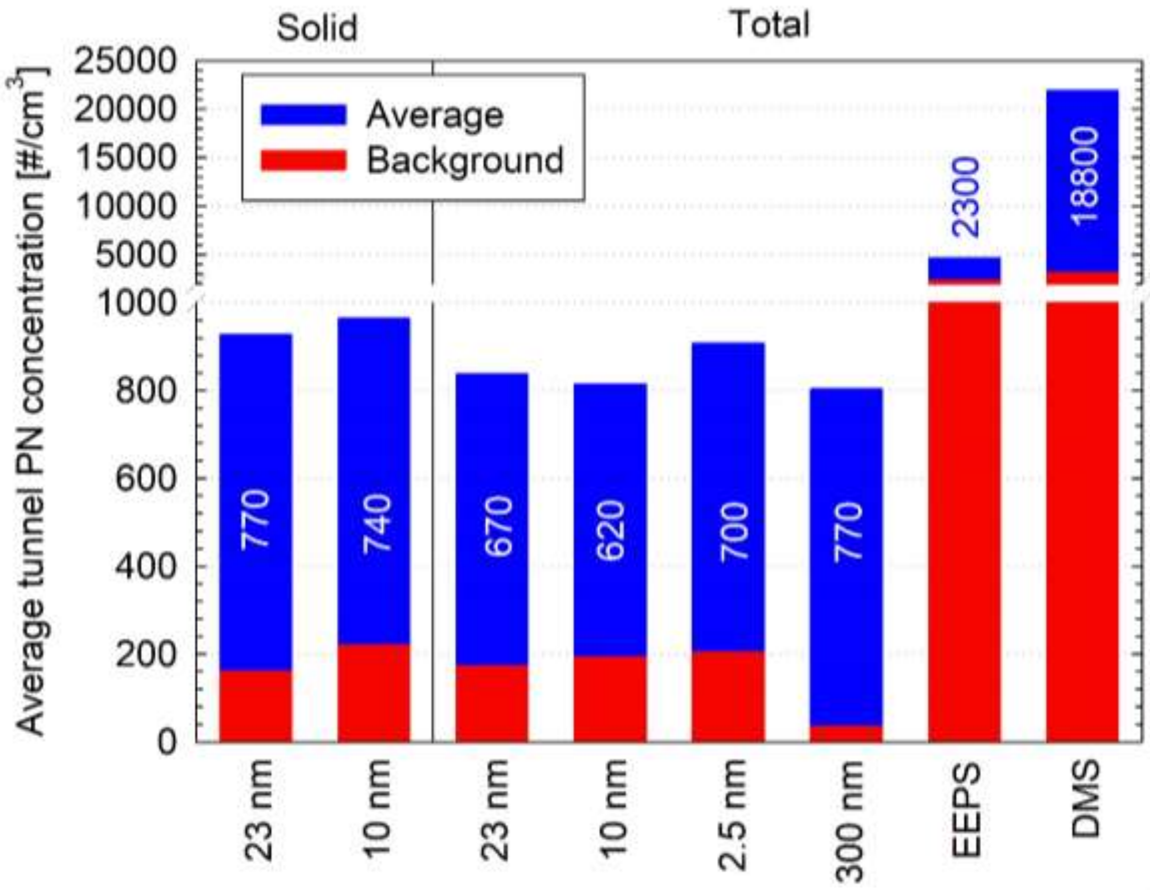
Solid vs total PN

CPCs of different cut-off sizes agreed within ±5%, with no evidence of sub-23 nm present.

Solid PN ~15% higher than total →

- Losses correction overestimated by taking the average at 30, 50 and 100 nm when particles peak above 100 nm: ~10%
- Ejector dilution changed over time due to contamination of the ejector nozzle with (large) particles.

➔ No indication of volatile particles over the novel cycle with pads tested.



Numbers on bars correspond to background corrected concentrations

Accuracy of size distribution techniques for PN

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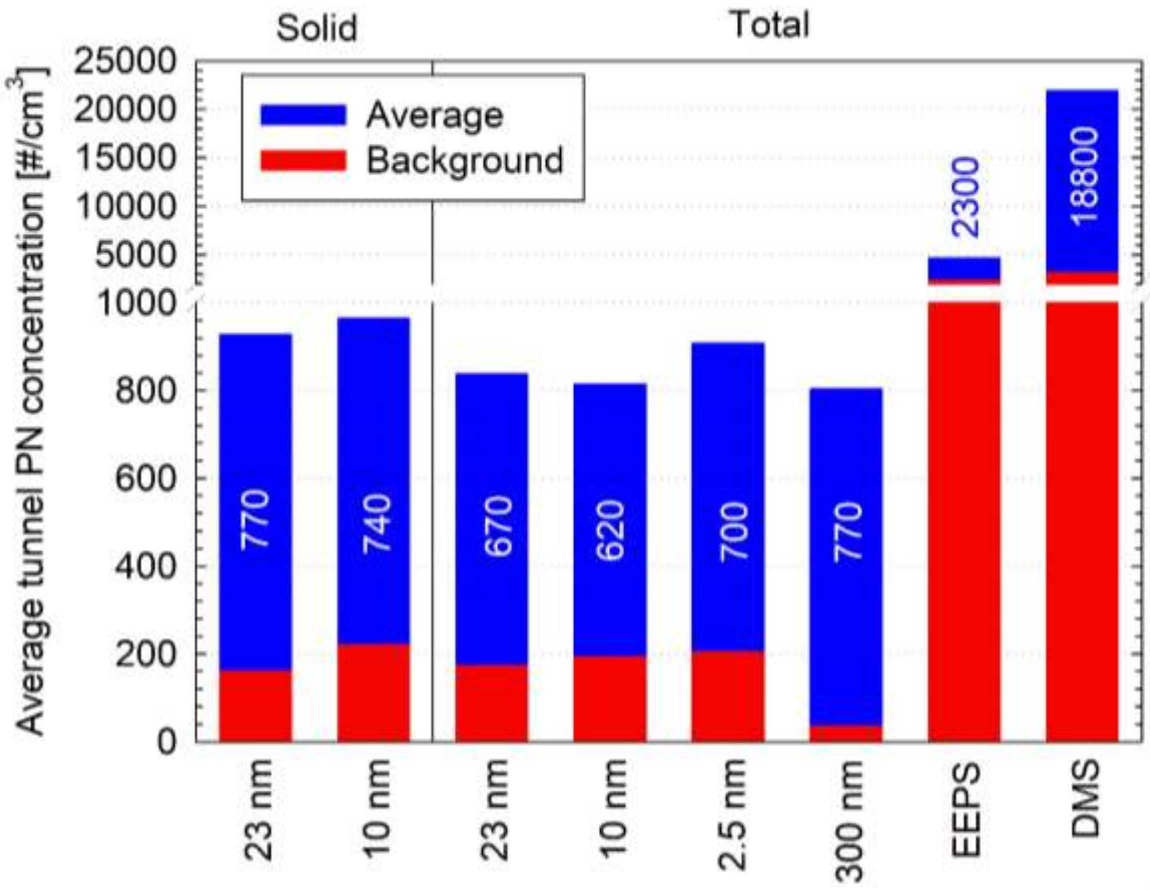
OPS total concentrations were rather high considering that it got saturated over segments of the cycle (~25% underestimation estimated) and that it should not detect sub 300 nm optical diameter:

- at what mobility does it correspond?

Electrical sizing techniques had noise level above the mean PN concentrations in the tunnel. Although manufacturer could not observe something wrong in raw data, we believe that there is something wrong with the specific DMS unit.

Even with background correction, calculated PN concentrations were 200 to 300% higher with the EEPS using the default inversion matrix.



Numbers on bars correspond to background corrected concentrations

Conclusions #1

- Particle number emissions over the novel cycle with the circulated pads, were found to be more than 2 orders of magnitude below the exhaust PN limit.

- At such low emission levels, background tunnel concentrations can have a significant effect on PN results.

- Peak concentrations exceeded though coincidence level of several commercial CPCs.

➔ <u>Maintaining background as low as possible is crucial for precise number measurements.</u>

➔ <u>Increase of tunnel flow will increase background contribution.</u>

➔ <u>Some type of dilution will be required for precice concentration measurements.</u>

Conclusions #2

- Non-volatile PN measurements exhibited a repeatability of better than 13% (over 5 repetitions)
- However, emission trends over different repetitions also followed the changes in background levels.
- Subtraction of background yielded an even better repeatability of <5%.

→ How reliable is background subtraction and up to what level?

Conclusions #3

- Previous experience with different type of ECE pads also suggested that emitted particles over novel cycle are much larger than 23 nm.
- There was also no indication of volatiles despite the relatively high disc temperatures, with the exception of sparse events resembling tunnel artifacts.
- The long duration of the cycle and the large contribution of background will weight down the contribution of any potentially formed sub-23 nm particles.
- Highest contribution of sub-23 nm particles came from background, the subtraction of which led to identical 23 and 10 nm recordings.

→ How should one deal with volatile background?

Conclusions #4

- Electrical techniques for size instrumentation exhibited a noise level several times above the average PN concentrations.

- Accuracy of inferred number concentrations was significantly affected by the assumptions in the inversion algorithm. Their performance depends on exact particle properties (effective density, shape of particles, etc.) which may differ for different pads.

- Complex morphology of particles does not allow a direct comparison between different sizing techniques.

- Their performance over transient concentration changes not clear.

→ Sizing instrumentation not sensitive enough to detect true PN emission levels.

→ Size information can only be treated as qualitative.

Conclusions #5

- Total PM emissions with the supplied pad over the novel cycle were at 4.8±0.2 mg/km/pad.
- 70 to 75% of the measured total PM was removed by a 2.5 µm cyclone.
- Visual inspection of cyclone revealed the presence of >>10 µm particles.

→ Cyclones with well defined specifications are necessary for both PM2.5 and PM10

Conclusions #6

- Based on weighing of the tunnel components, 91% of total PM became airborne
- 30% of total airborne PM were lost in the enclosure/assembly.
- Approximately half of total airborne PM reached the filter holder, with evident though penetration of coarse (>>10 µm) particles.

→ <u>Simplified models for the characterisation of particle penetration are not sufficient.</u>

Recommendations #1 Tunnel

- Given the relative PM / PN emission levels, tunnel design and operating parameters should focus on the optimisation of PM penetration.

- Weighing of components as a useful means of quantifying the actual penetrations of different designs.

- Recording of PM and especially PN background and maintaining it below an agreed level (ideally below 250 #/cm^3).

- The implication of high air velocities on particle losses should also be evaluated.

Recommendations #2 PM

- Parallel measurement of PM10 and PM2.5 with well prescribed cyclone specifications.

- Isokinetic sampling with velocity ratios confined within the DIN 13284 recommendations of -5% to +15% from 1.

- Use low sample flowrates (less than 10 lpm), and minimize bends in connecting tubes.

Recommendations #3 PN

- Accurate PN measurements require the use of full flow Condensation Particle Counters (CPCs).
- Additional dilution (with well characterised penetration) is anticipated to control coincidence errors.
- Parallel use of 10 and 23 nm CPCs in recommended to identify the potential formation of nanosized particles.
- The low PN emission levels on novel cycle with the tested pads do not justify the significant burden of establishing an entirely new PN measurement procedure.
- It would be desirable to establish the same measurement procedure for Heavy Duty applications and also allow measurements at more demanding conditions (at least CPCs should not saturate).
- PMP systems will also allow for a direct comparison of measurements with exhaust legislation.

Recommendations #4 Future steps

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- Not much progress can be made without a properly conducted round robin.
- For the best possible outcome, we consider important that we rely on first measurement principles, i.e. gravimetry with well defined cyclone specifications for PM and calibrated PMP systems for PN.
- Use of golden instrumentation would be beneficial.