Solid and volatile brake-wear nanoparticles under real-world operating conditions

Mamakos, A.; Arndt. M. – AVL List GmbH

Kolbeck, K.; Schröder, T.; Bernhard, M. – BMW

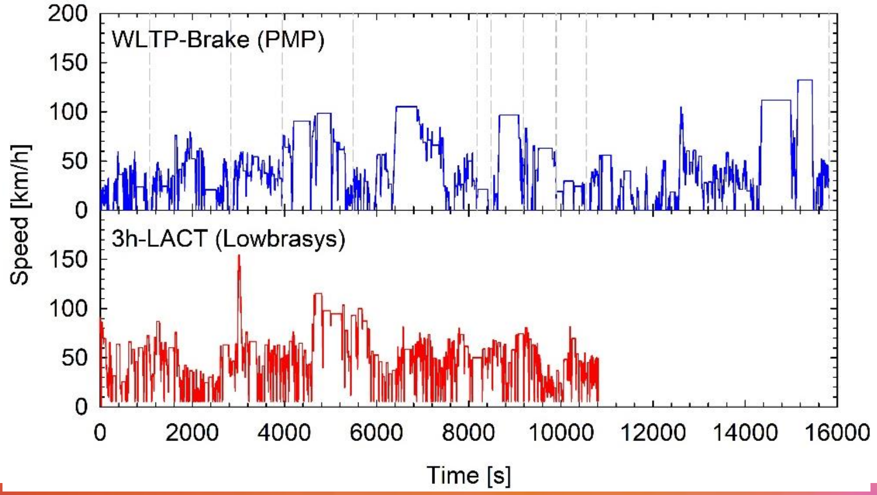
Hesse, D.; Hamatschek, C.; Augsburg, K. – TUI

d_{duct} = 80 mm

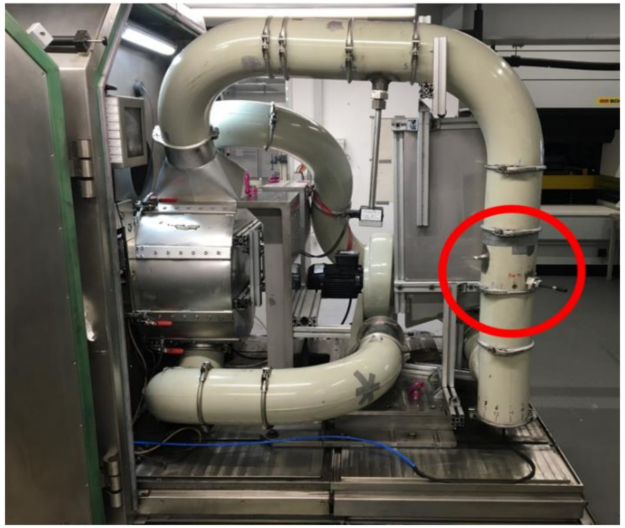
Q_{duct} = 170 & 270 m^3/h

Experimental

- Brake system:
  - Floating caliper
  - 133.5 mm effective friction radius
  - 9 kg disc
  - Copper-free ECE pads
  - 73.3 kg/m^2 inertia
  - 332 mm rolling radius
- Test cycles:



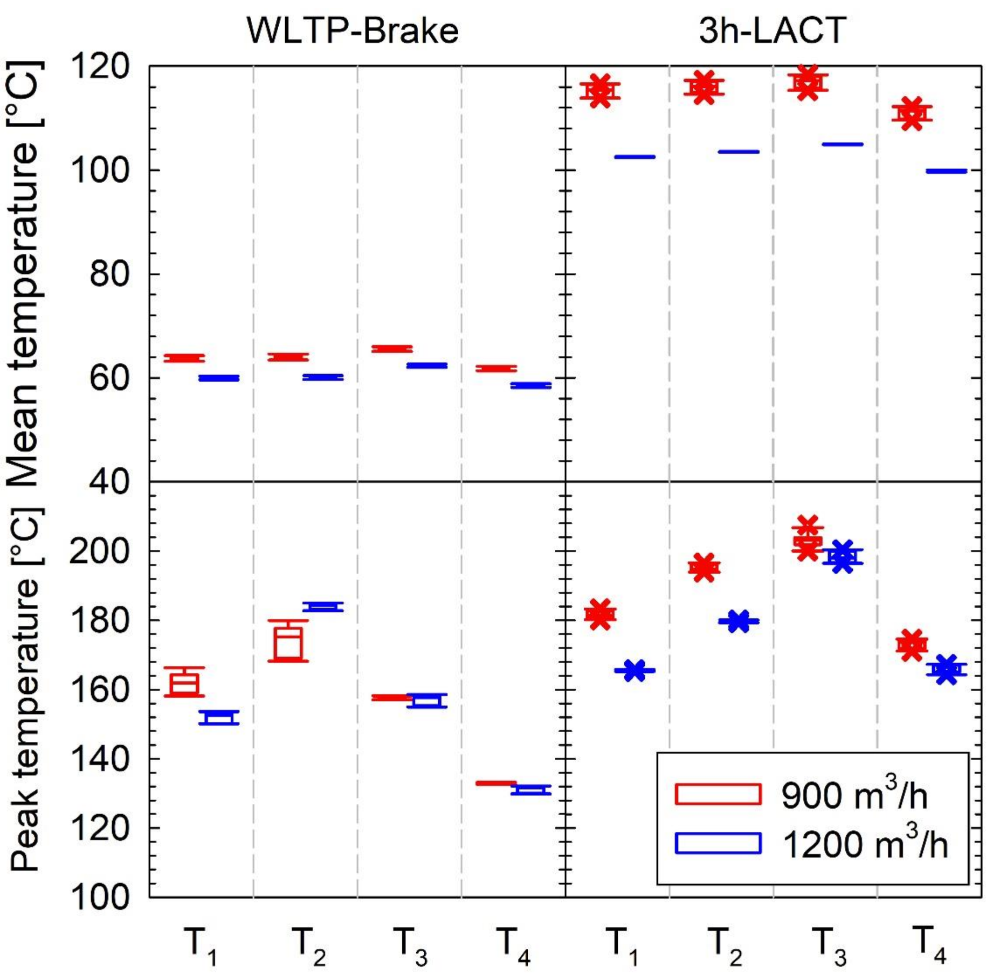
- Instrumentation:
  - Particulate Matter (TX40)
    - $PM_{2.5}$ @ 5 lpm (URG-2000-30EHS)
    - PM_{10} @ 7 lpm (Mesa SCC2.345)
  - Particle Number (PN):
    - Untreated (TSI 3776 UCPC 2.5 nm)
    - R83 10 nm (APC xApp 10 nm):
      - Catalyst @ 350°C
      - PCRF 100
      - 10 nm full flow CPC
  - PN size distribution
    - TSI EEPS 3090 (5.6-560 nm)



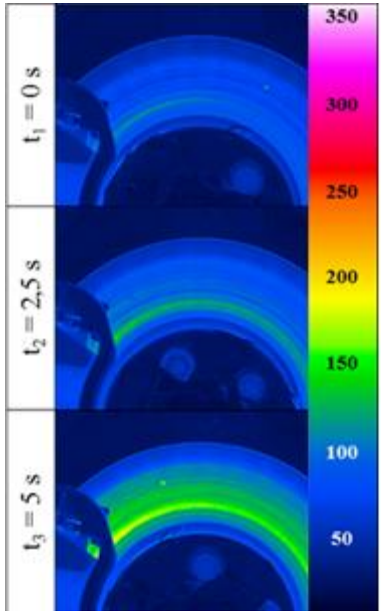
d_{duct} = 175 mm

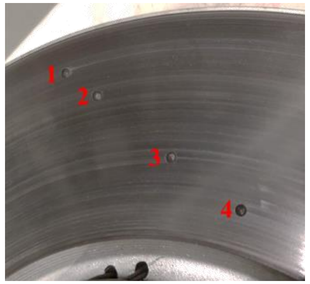
Q_{duct} = 400, 900 & 1200 m^3/h

Disc temperatures - spatial distribution



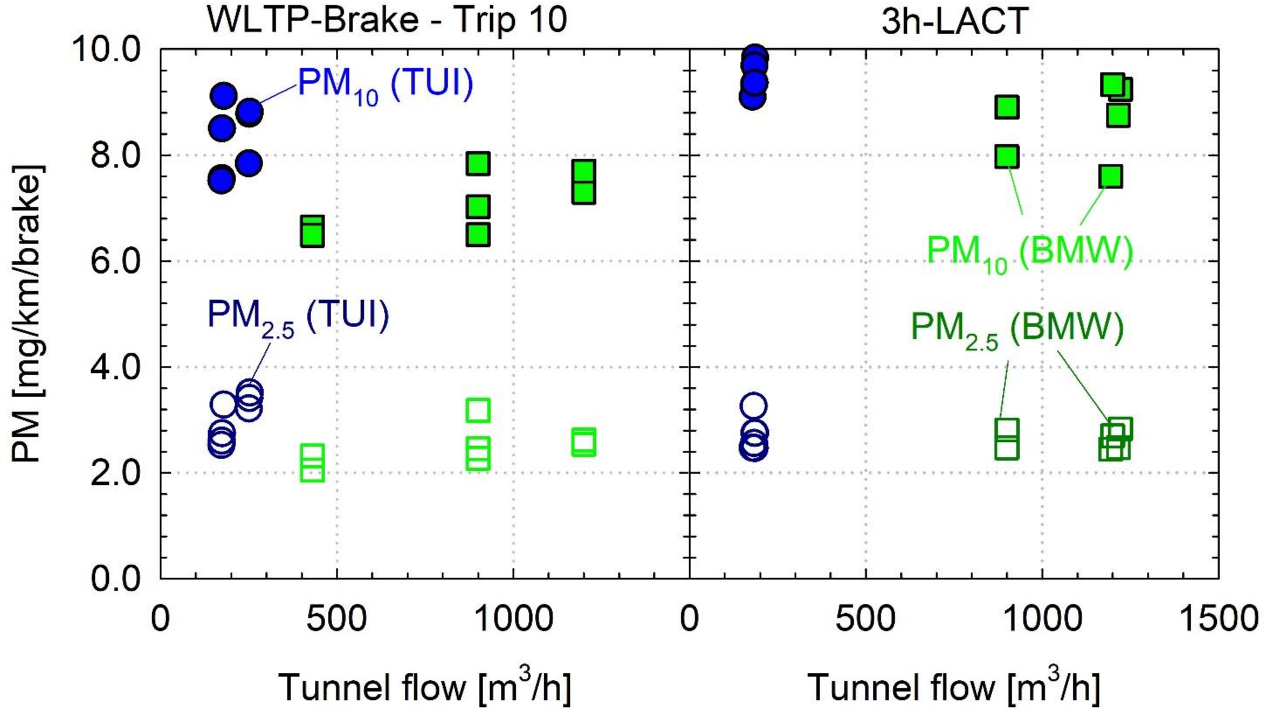
120→80 km/h
(20 bar)

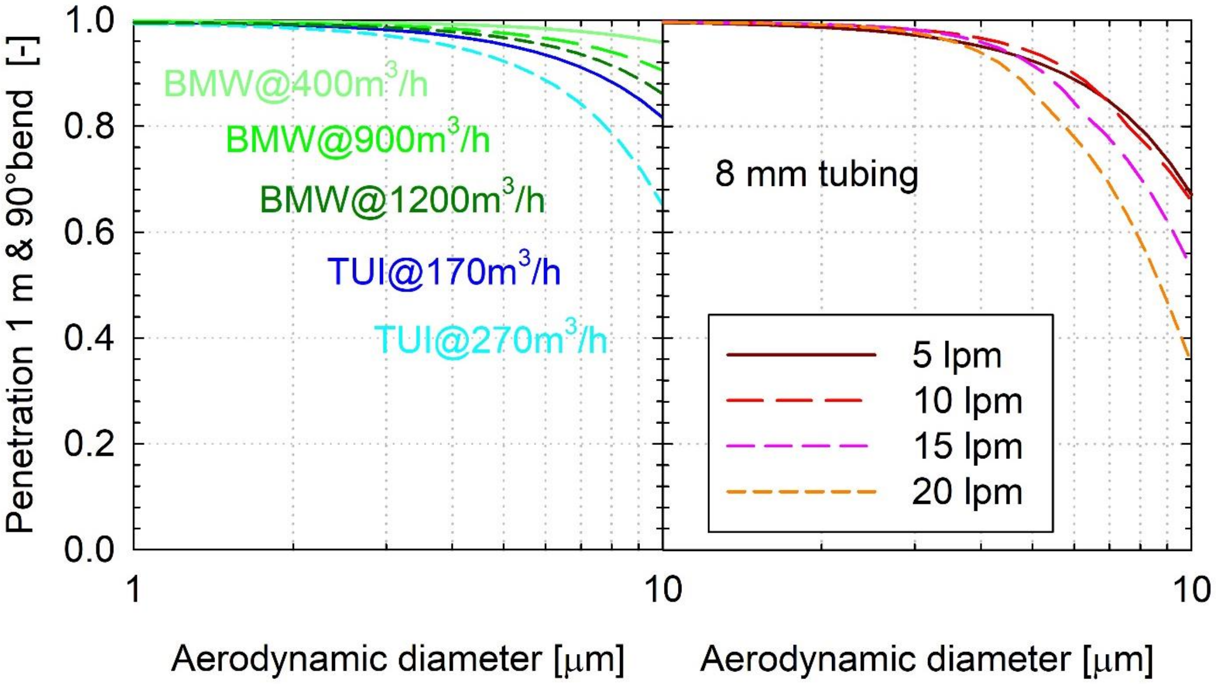




- Disc temperature exhibits large spatial distribution over individual braking events.
- Temperature profile depends on operating conditions (e.g. different deformation of pads).
- Radial location of hot rings changes dynamically as the microstructure in the contact area changes with use.
- Averaging over the cycle reduces spatial effects and variability introduced by the development of hot rings.

PM emissions

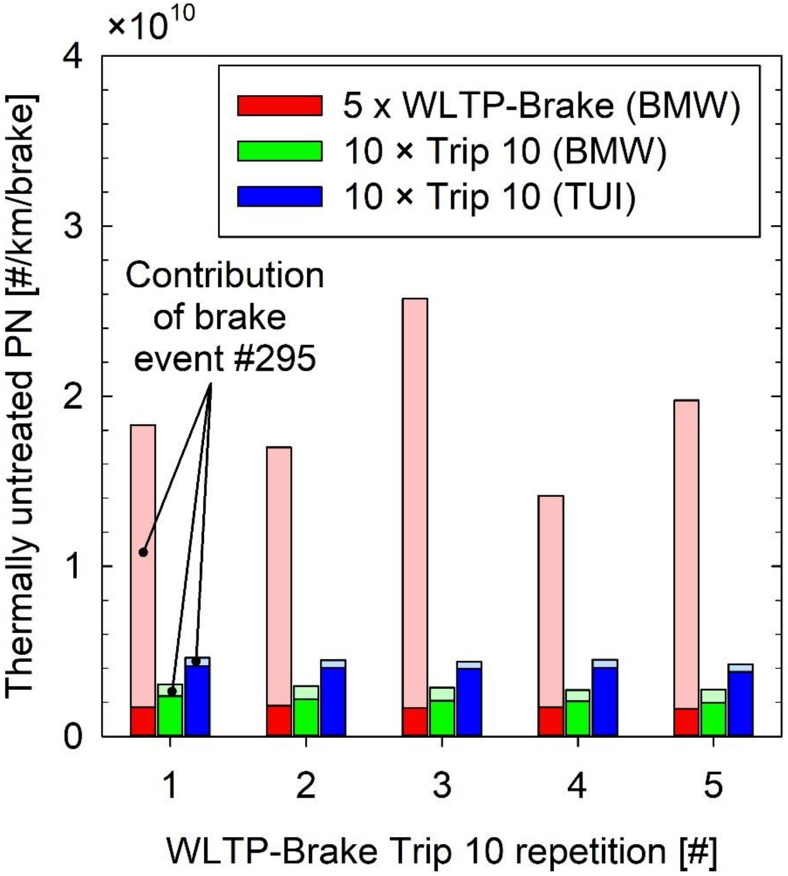




- Repeatability was in the order of 20% for both PM_{10} and $PM_{2.5}$ and at both facilities.
- No statistically significant effect of tunnel flow, tunnel design or test cycle:
  - 2.7±0.4 mg/km/brake $PM_{2.5}$
  - 8.4±1.2 mg/km/brake PM_{10}

- Most of super-micron particle losses occur on the tubing of the PM train, owing to the much smaller diameter (increasing Stokes number).
- The use of low PM sample flows and the same arrangement (cyclones/tubing) helped improve the reproducibility of PM measurements.

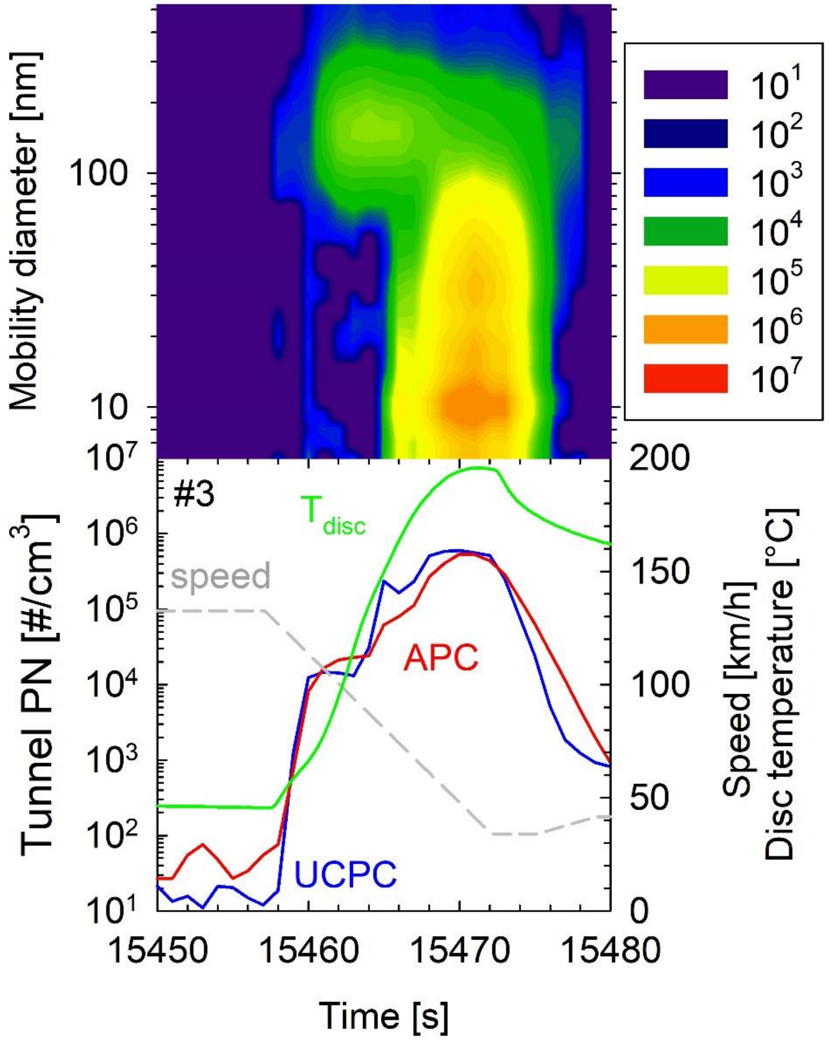
Effect of preconditioning on PN emissions



- When the brakes were preconditioned by running 10 repetitions of WLTP-Brake Trip 10, the PN results at the two facilities agreed within 30%.
- Preconditioning the brakes with 5 repetitions of the full WLTP-Brake cycle however, resulted in an approximately 1 order of magnitude higher PN emissions.
- The increase was solely attributed to elevated emissions over a single braking event from the top cruising speed.

Mamakos, et al. 2021; 10.3390/atmos12030377
Kolbeck et al. 2021; Eurobrake EB2021-EBS-003

Thermally stable nanoparticles

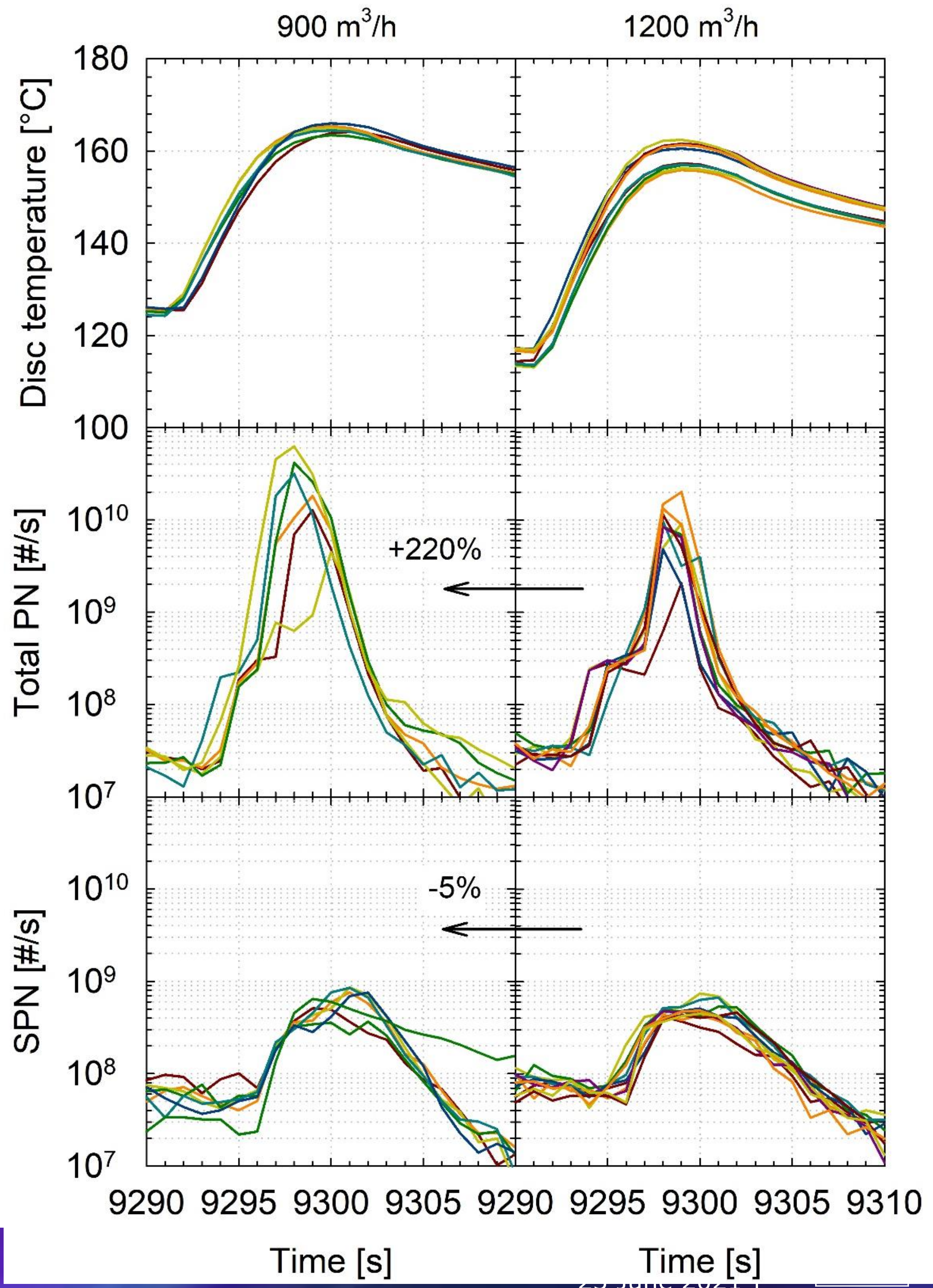


- Size distributions measured with the EEPS revealed the formation of a distinct mode peaking at 10 nm.
- These nanoparticles survived thermal treatment at the catalyst operating at 350°C, with the APC reporting similar levels with the UCPC measuring untreated samples.
- This approximately 10 s duration event led to cycle-average emission levels at 20-25% the proposed Euro 7 exhaust PN limit of 10^{11} #/km.

Mamakos, et al. 2021; 10.3390/atmos12030377

Volatile nanoparticles

- Volatile nanoparticles were observed over specific braking events of the 3h-LACT cycle.
- In contrast to solid PN, their concentration strongly depended on the tunnel flow.
- This behaviour is consistent with the homogeneous nucleation theory, since increasing tunnel flow reduces the concentration and thus supersaturations of gas precursors in such full flow tunnels.
- It is well established (Khalek et al. 1998, Khalek et al. 1999) that full flow tunnels are not suitable for such volatile PN measurements. Assessment of the volatile particle formation potential of commercial brake pads requires the development of dedicated sampling methodologies.



Conclusions

- Brake-wear $PM_{2.5}$ and PM_{10} emissions of the same brake system were tested at two facilities following the recently established PMP methodology and were found to agree within the ~20% repeatability levels, despite the ~1 order of magnitude difference in the operating tunnel flows.
- Calculation of losses indicated the PM sample train as the most critical section, and the use of low sampling flows (5-10 lpm) beneficial.
- PM emission levels (2.7±0.4 mg/km/brake $PM_{2.5}$ and 8.4±1.2 mg/km/brake PM_{10}) are considerably higher compared to exhaust PM of modern vehicles.
- Thermally stable nanosized brake-wear particles were observed over both the WLTP-Brake and the 3h-LACT, although their formation was found to depend on the conditioning of the brakes.
- Their concentration over a single braking event was sufficient to increase the 4.5 h cycle-average PN emissions by an order of magnitude, reaching at 20 to 25% the proposed Euro 7 limit of 10^{11} #/km.
- Volatile nanoparticles were found to strongly depend on the employed tunnel flow in good agreement with the homogeneous nucleation theory. Full-flow tunnels are not suitable for number concentration measurement of thermally untreated brake-wear particles.

Thank you

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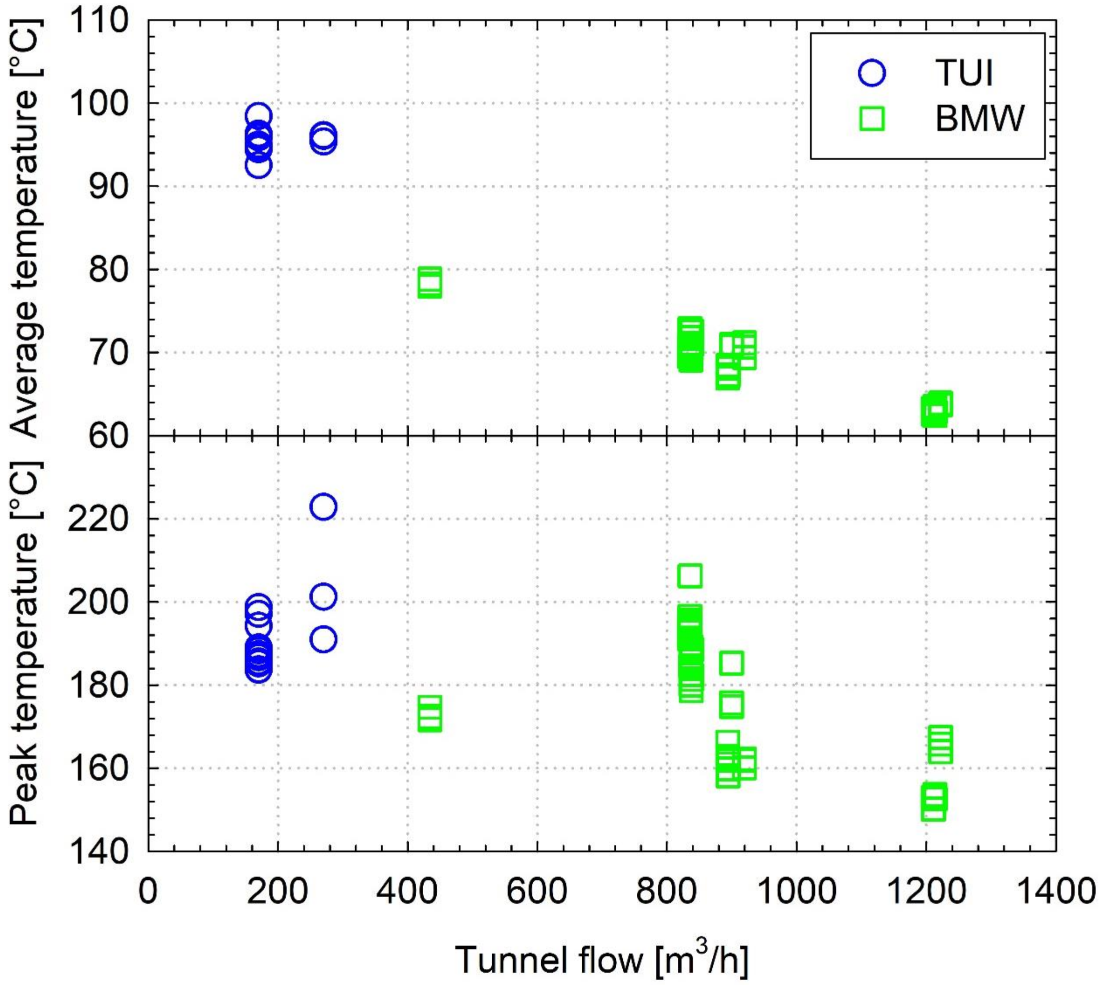
Disc temperatures – effect of tunnel flow



- Tunnel flow had no consistent effect on peak disc temperatures.
- Increase of tunnel flow resulted in a modest reduction in mean disc temperature ~2°C per 100 m³/h.

Tunnel flow affects convective cooling when brakes are not engaged.