# Effect of pad material and regenerative braking on brake wear emissions

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19.6.2025 28th ETH-Nanoparticles Conference

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# Background

**Air quality monitoring stations**

PM10, PM2.5,...

Chemical composition?
mix of emissions

Literature search

Brake particle physical and chemical properties, marker compounds?

<u>Laboratory study</u>
No other emissions producing interference

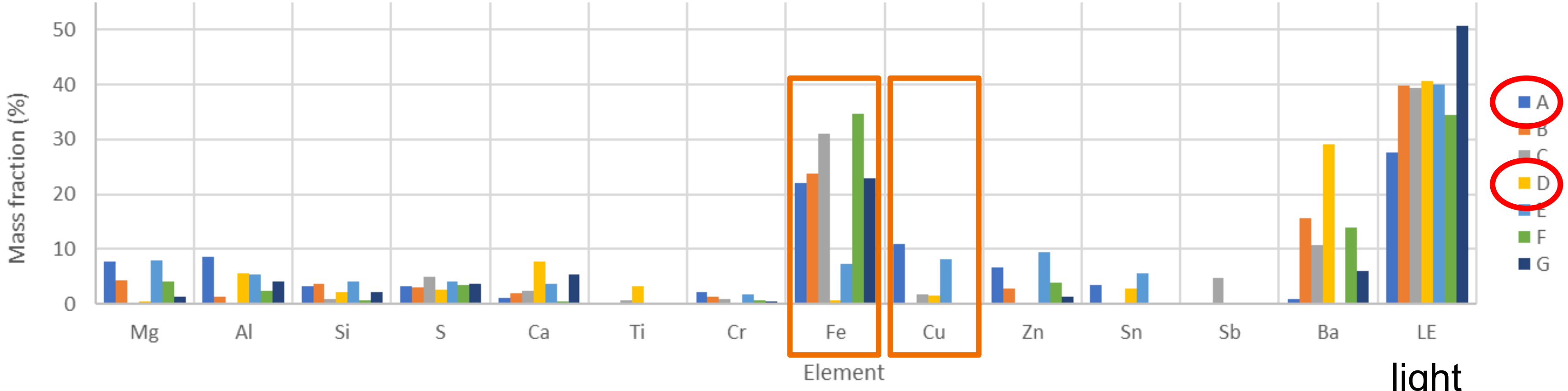
**Amount of brake wear particles in urban environment?**

# Preliminary screening of brake pad elemental composition

Preliminary screening of commercial brake pads

- Purchased from car part dealers in Finland (EU), 7 different pads
- Pads from well-known brake component manufacturers
- Elemental composition from unused pads (Olympus Vanta XRF, Geochem Method)

# XRF of commercial pads

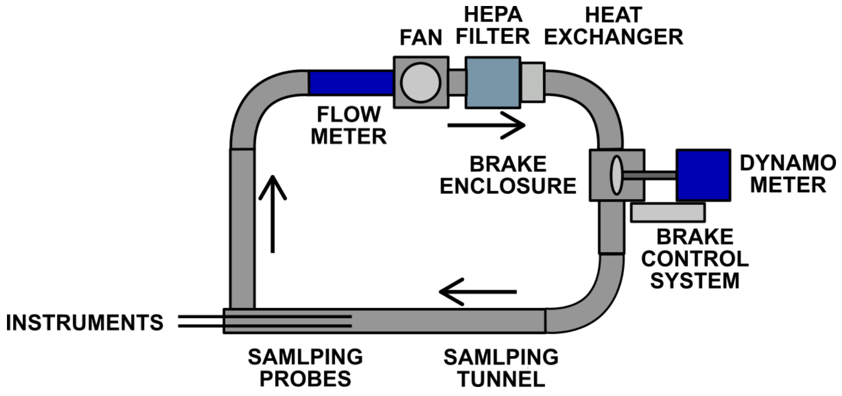


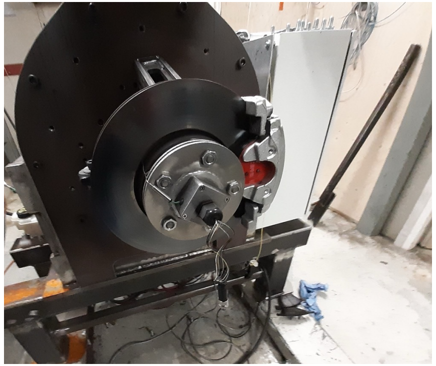

light elements

- Relatively high differences in elemental composition
  - Note that elements may be ionic compounds
- Two pads selected for further testing:
  - A containing Fe and Cu (low metallic, semi-metallic)
  - D very low Fe and Cu (organic, non-asbestos organic "NAO")
    - but "high" Ca, Ti, Ba

# Dynamometer testing of emissions

- In-house-made brake emissions test system
  - In-house-made dynamometer (eDyno), electric motor, inverter, control system
  - Electric ball-race screw actuator pushing brake main cylinder (brake pedal)
  - Ford Focus Mk3 brake system
- Closed loop cooling air system with HEPA H13 filter and temperature control system
- AVL Flowsonix Air ultrasonic flow meter



# Particle emission instrumentation

- PM measurements
  - Dekati Cyclone and filter collection (PM10)
  - Dekati DGI impactor (PM2.5)
- PN measurements
  - Dekati eDiluter Pro
  - Airmodus A20 CPC (10 nm)
- Size distribution and PN & PM (real-time)
  - Dekati ELPI+
  - Dekati HT-ELPI+
- Chemical composition
  - Malvern Panalytical Epsilon 4 (XRF-analysis from 47 mm  PM10 filters)
- Other instruments not covered in this presentation

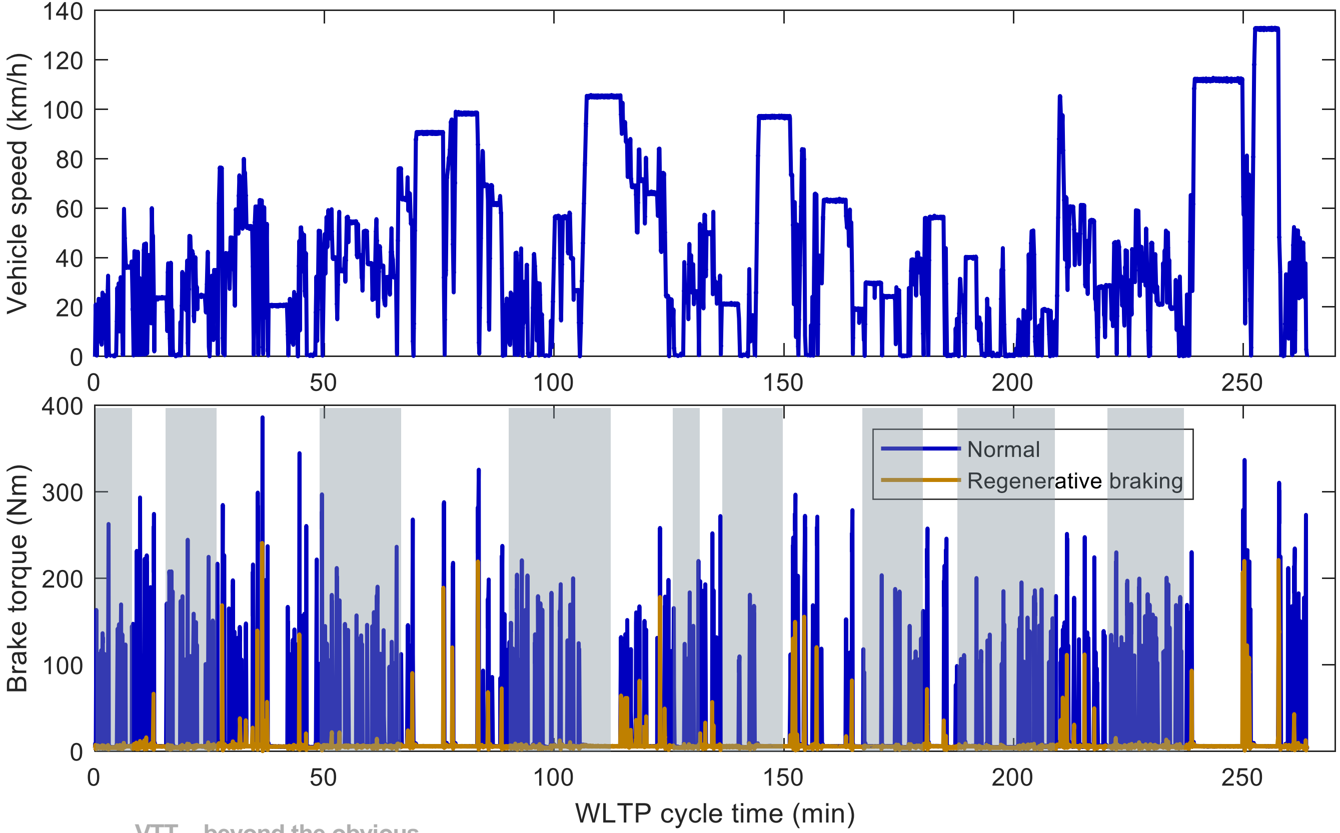
# Measurement matrix

- Two pad materials
- WLTP brake cycle
  - Normal car ~ 1450 kg total mass
  - Normal car +300 kg extra mass
  - Plugin hybrid/electric car (regenerative braking and +300 kg)
    - Regenerative braking difficult to realize in laboratory conditions
    - Effect depends on vehicle, battery charge state, environmental conditions and driver (in real driving conditions)
    - Relized as braking power of 20 kW, which reduced required brake power and consequently torque
    - More accurate model for current vehicles, see Hagino (2024)

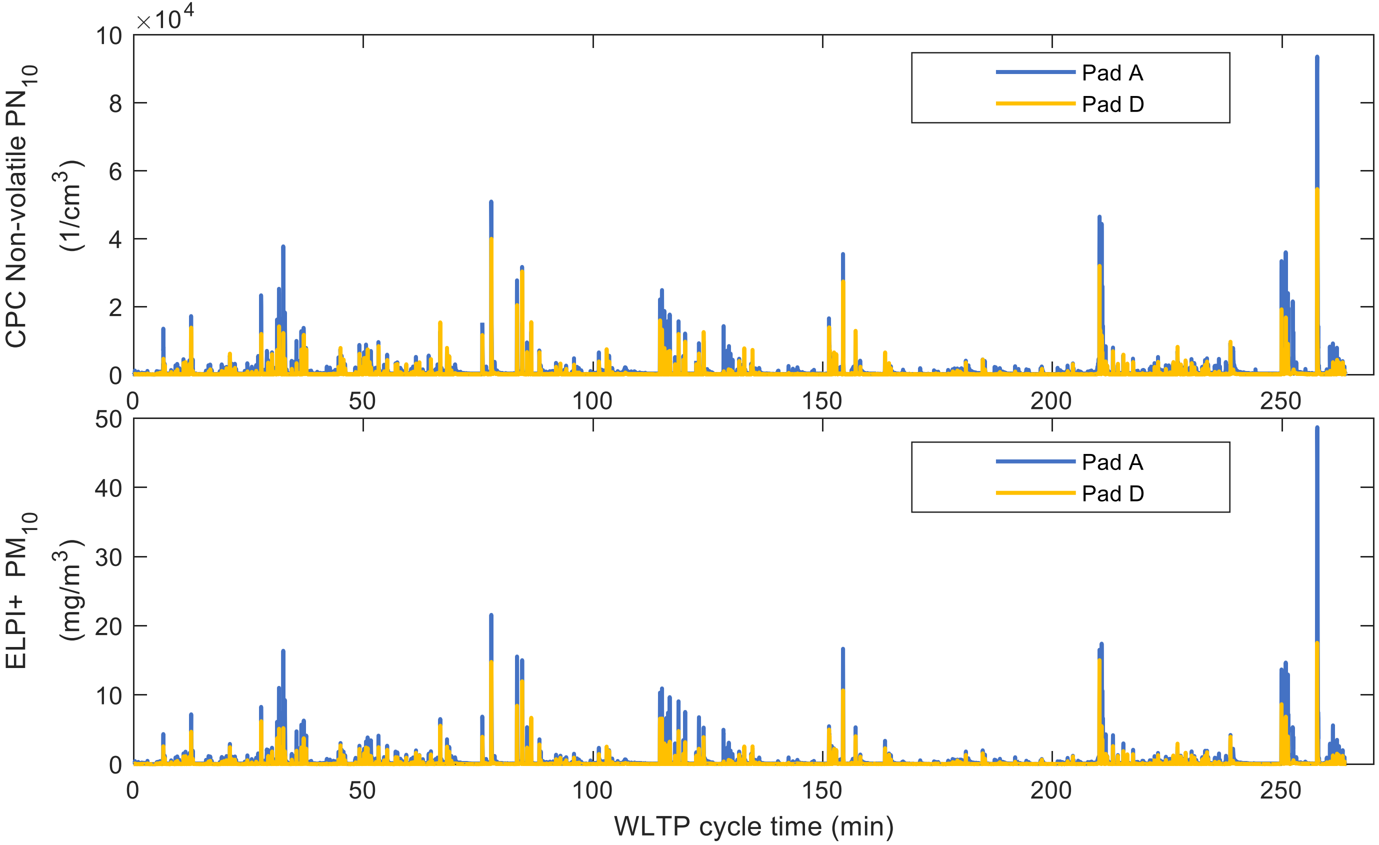


Hagino (2024). Atmosphere, 15, 75. https://doi.org/10.3390/atmos15010075

# WLTP cycle and regenerative braking



# PN and PM



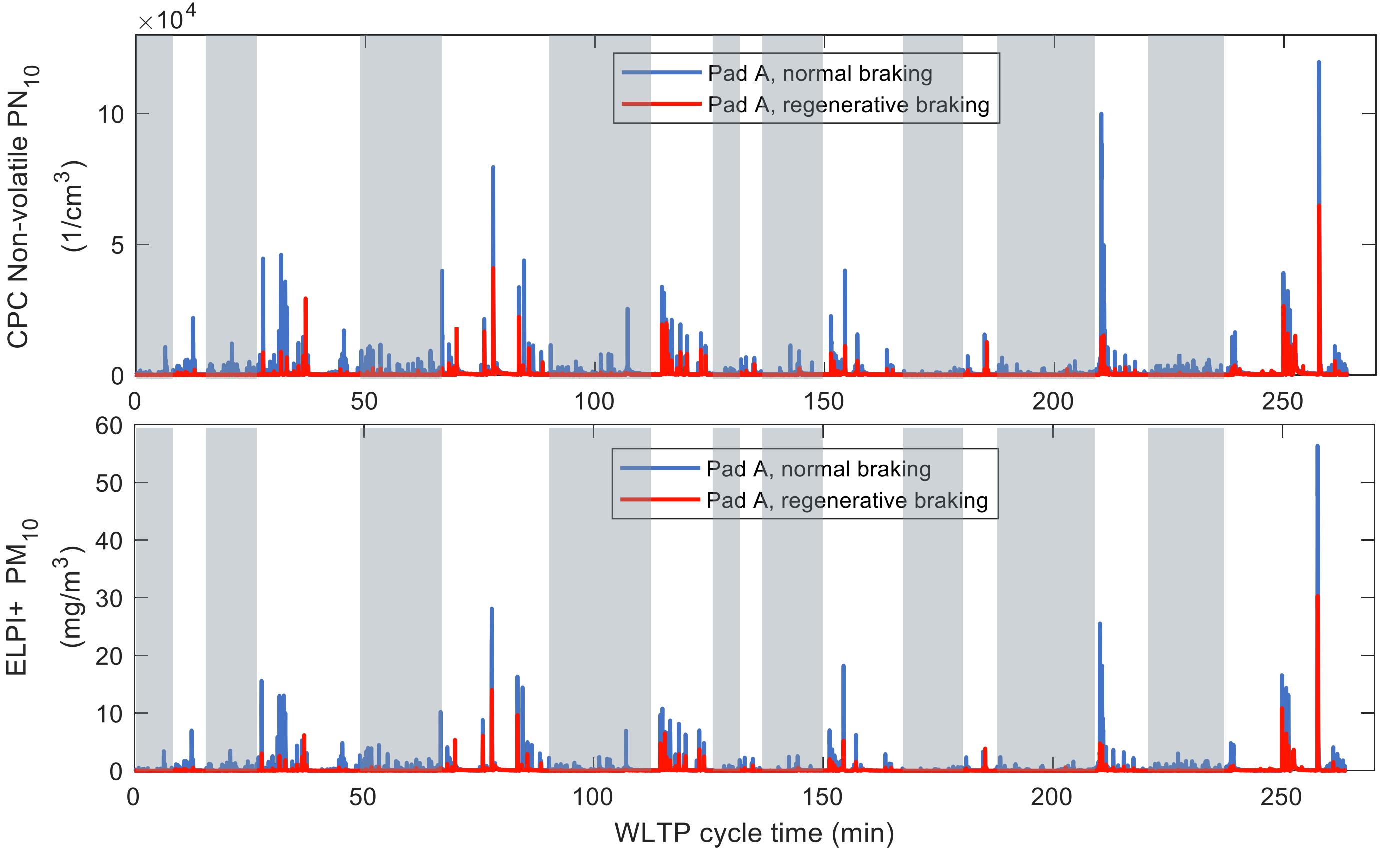

**Per brake**

nvPN10
→ ~ -60%
Mathiessen et al. (2023) ~ -50%

Filter PM10 (mg/km)
Pad A: 4.5
Pad D: 1.9
→ ~ -60%
Grigoratos et al. (2023)
-37...-89%

Mathiessen et al. (2023). Atmosphere, 14, 424. https:// doi.org/10.3390/atmos14030424
Grigoratos et al. (2023). Atmosphere, 14, 498. https:// doi.org/10.3390/atmos14030498

# PN and PM regenerative braking



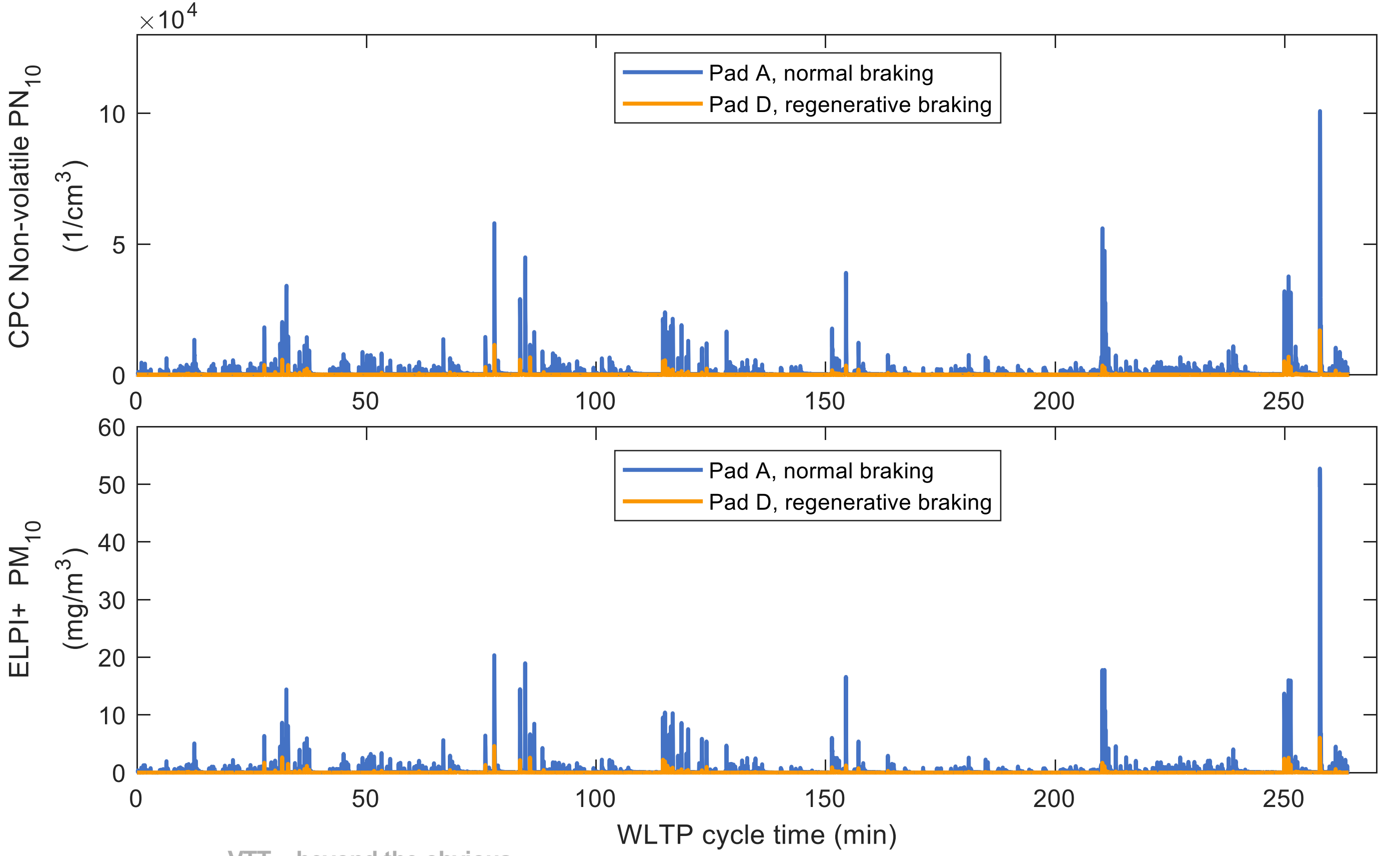

**Per brake**

nvPN10
→ ~ -70%
Hagino et al. (2024)
~ -87%

Filter PM10 (mg/km)
Norm.: 4.8
Regen.: 1.6
→ ~ -70%
Hagino et al. (2024)
~ -85%

Hagino (2024). . Atmosphere, 15, 75. https://doi.org/ 10.3390/atmos15010075

# Worst and best case: PN and PM

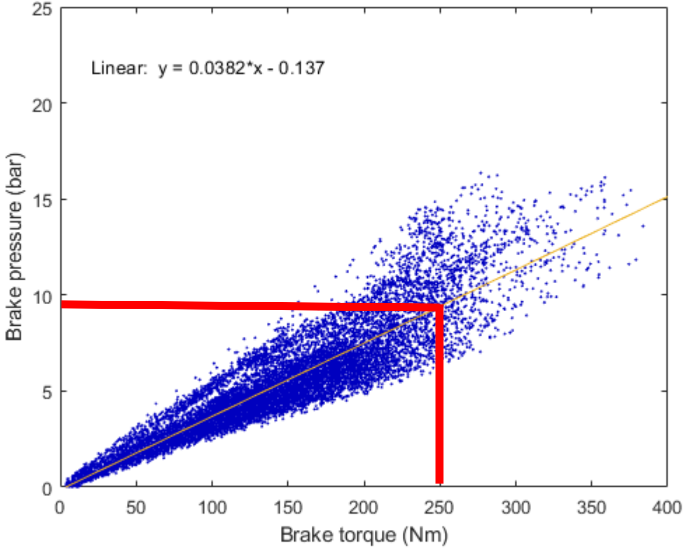



Avg. nvPN10
-90%

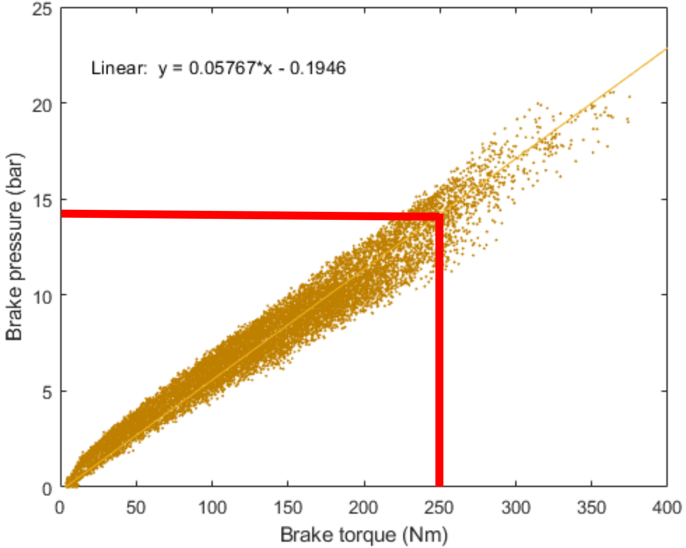
Filter PM10
-93%

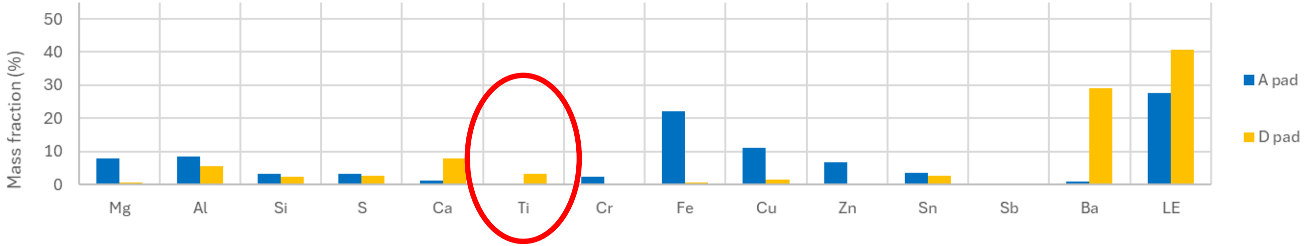
# Pad D produces less emissions, but...

Pad A




Pad D



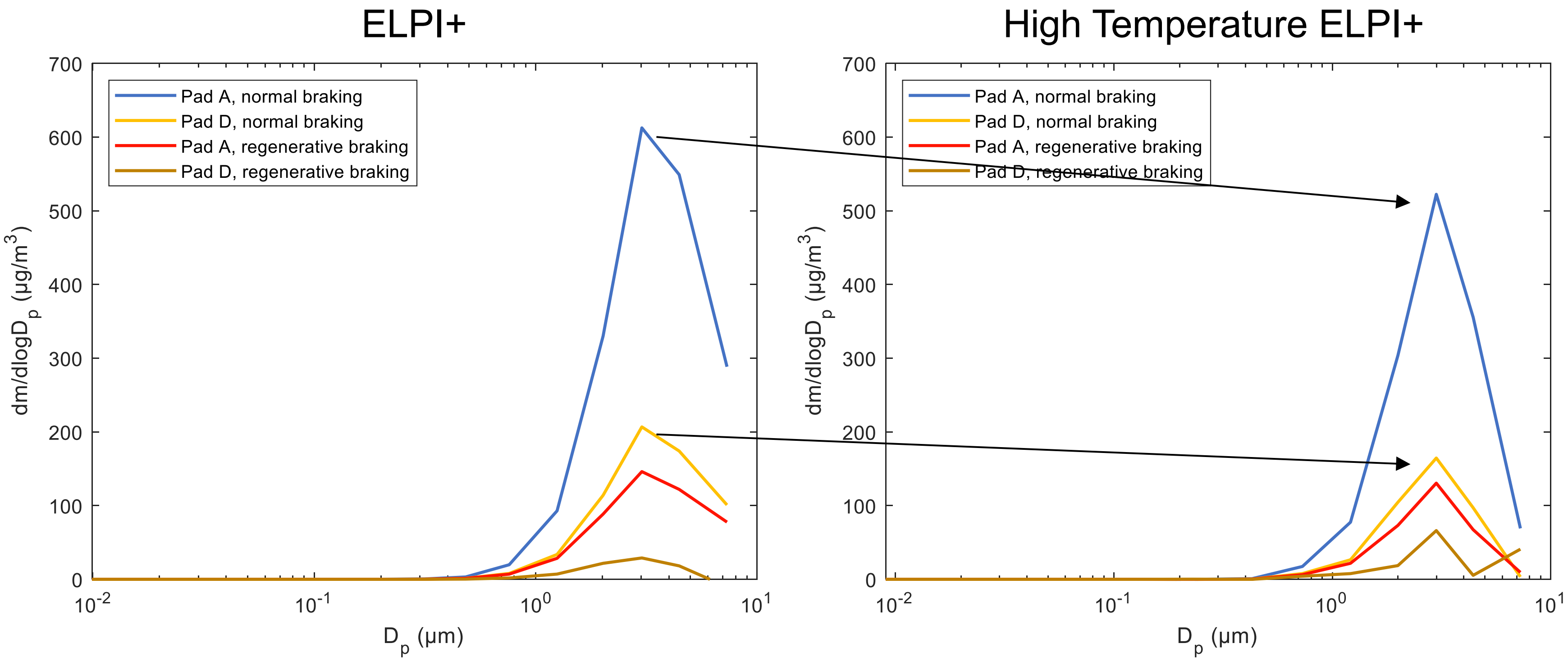

**Pad A has higher friction coefficient "A is better"**

**Barosova et al (2018): NAO pads (D) cause adverse effects in vitro studies, pads contained anatase. Low metallic (A) no effects.**

**Pad D contains Ti, anatase?**

Barosova et al. (2018). Archives of Toxicology, 92:2339–2351 https://doi.org/10.1007/s00204-018-2218-8

# Size distributions



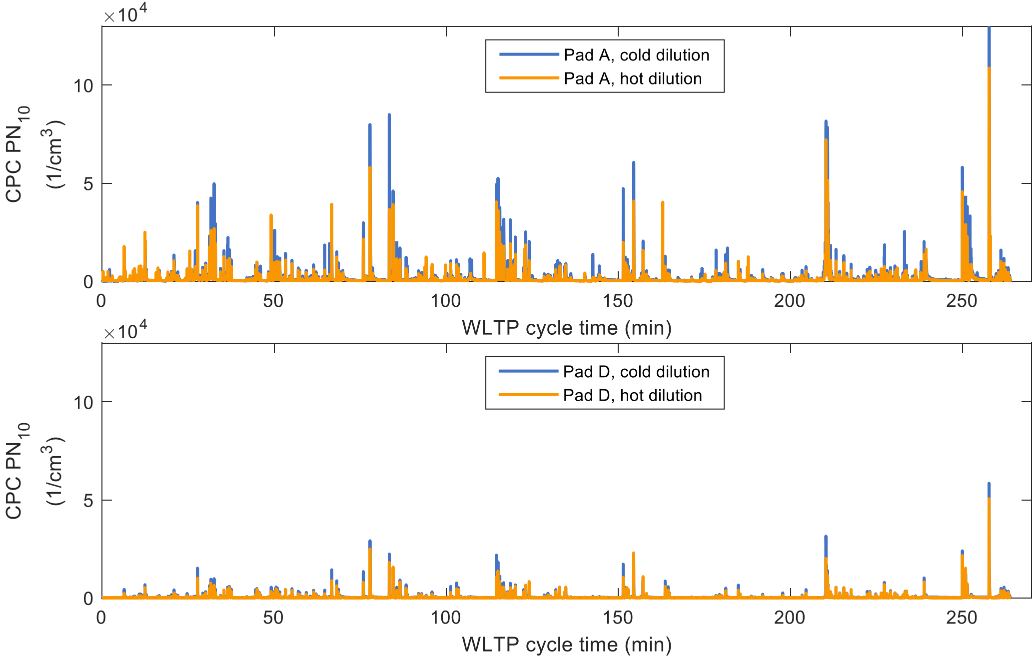

**Concentration decrease:**
**Something semi-volatile?**

# Volatility of brake wear particles

CPC measurement
(after eDiluter Pro)
- cold dilution ~25 °C "TPN"
- hot dilution 350 °C "SPN"

Both pads produced lower number emissions in case of hot dilution
**Something is evaporating**
Brake disc <160 °C

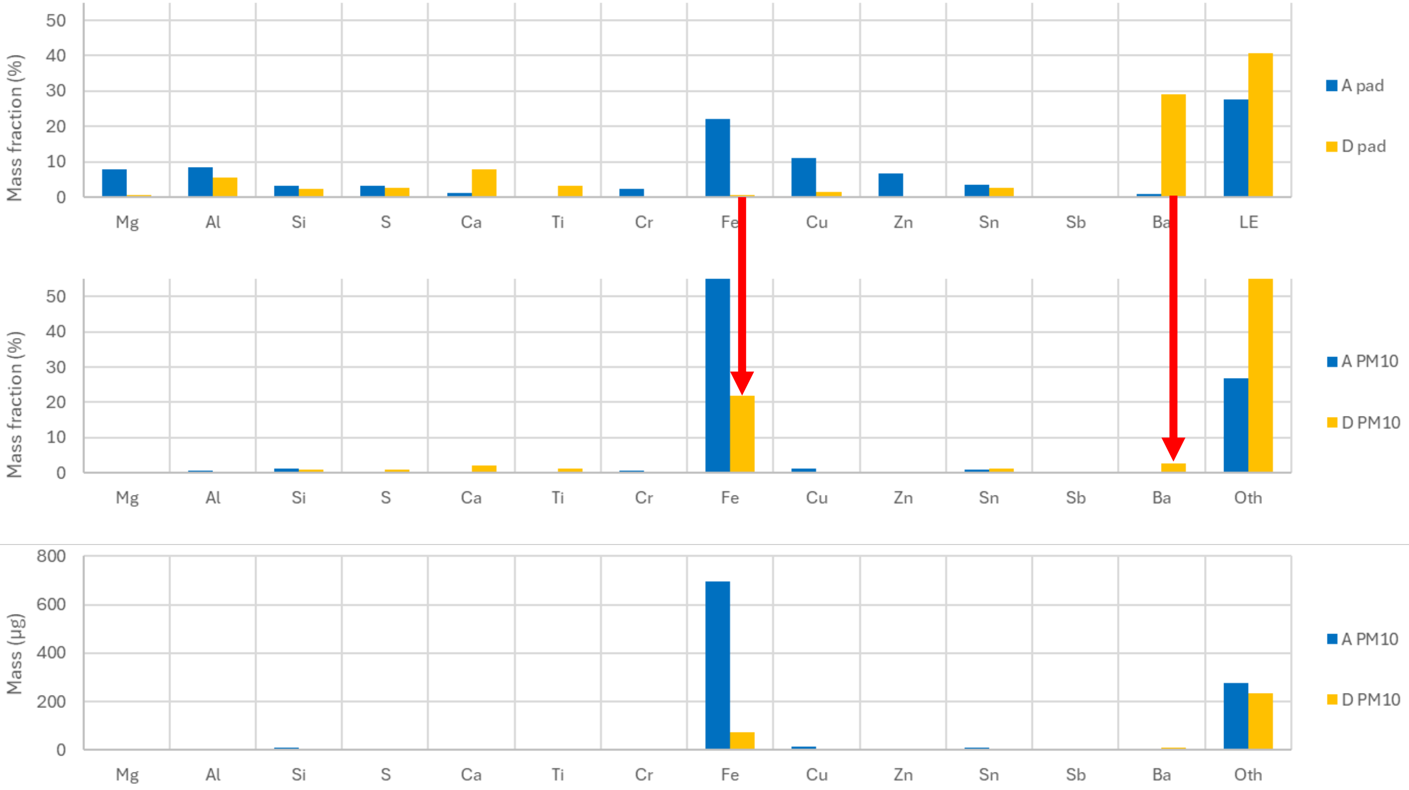
Fraction of semi-volatile particles:
- Pad A ~30%
- Pad D ~20%




**Hagino 2025: "CO2 and nucleation-mode particles with particle diameters of <20 nm are emitted at mild brake temperatures (40−90 °C)"**

Hagino (2025). ACS ES&T Air, 2 (6), 1055-1068 https://doi.org/10.1021/acsestair.4c00350

# XRF results from WLTP cycles




XRF from pads

XRF from PM10 filter

Absolute filter mass

**Fe significant emission compound (even if not in pad)**
**Pad D (low Fe and Cu) produces less Fe emissions**

# Conclusions

Particle number and mass emissions

- Brake pad material affects significantly, Pad D with very low Fe and Cu content produces **-60...-70 % less PN and PM** emissions than Pad A with Fe and Cu.
- Regenerative braking (PHEV / EV) can reduce emissions **over -60 %**
- When combining less emitting pad and regenerative braking, reduction ~ **-90 % possible**.
- Incresed vechicle mass +300 kg provided varied results, sometimes larger, sometimes lower emissions.
- 20-30 % of PN10 is semi-volatile

Elemental composition

- Brake emission particles contain components from **pad and disc**
- **Fe present due cast iron** disc although not in Pad D
- No single marker element for brake wear emissions except Fe

**Toxicological studies needed to choose least harmful compounds to pads**

# THANK YOU !

**Acknowledegements:**
VTT staff participating the project
Dekati for supplying instruments and providing support
Supporting companies

This work received funding from Business Finland (Grant. 7806/31/2022) and Finnish companies through NEX-EL-project and from RePowerEU RRF.

Funded by
the European Union
NextGenerationEU

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