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Applying lessons learned from diesel exhaust to brake wear nanoparticle measurements and regulation

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Automotive friction brakes

Friction brakes are used to dissipate (convert into heat) excess vehicle kinetic energy.
In disc brakes, rotating cast iron disc is squeezed by brake pads.
In drum brakes, brake shoes are expanded against the inside of a rotating brake drum.

https://en.wikipedia.org/wiki/Disc_brake

https://en.wikipedia.org/wiki/Drum_brake

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Particles produced during braking

Mechanical processes (abrasion):
Coarse particles several micrometers in diameter and larger

Thermal processes:
Nucleation of evaporated material or of compounds produced during its transformation
Ultrafine particles on the order of 10 nanometers,
agglomerates on the order of tens or even hundreds of nanometers in diameter

https://www.youtube.com/watch?v=QIc-9UuLSmg

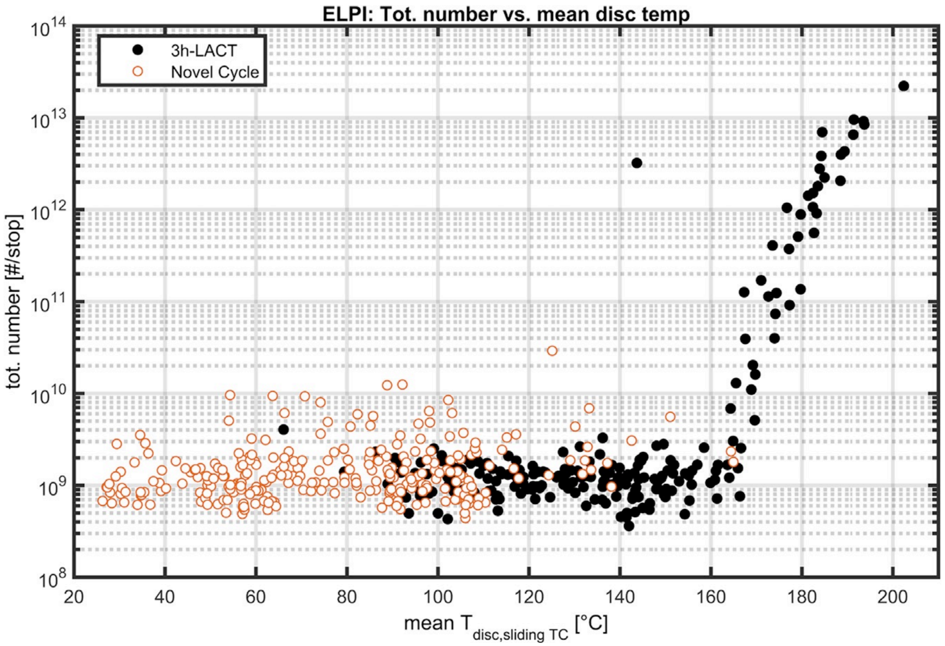
What is abraded: cast iron (rotors, drums) and friction materials (pads, shoes)
Materials: Binders, fibers, fillers, lubricants, abrasives
Composition: top secret, usually metals, anorganic compounds, resins, carbon

How much of a problem are they?

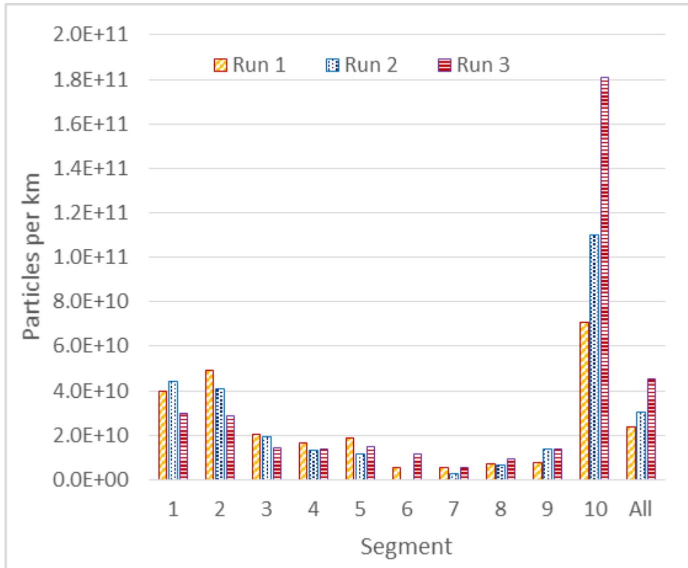
Brake wear particles:
~ 55% of non-exhaust PM emissions
Up to 21% of traffic-related PM_{10} emissions

Grigoratos, T. and Martini, G., 2015. Brake wear particle emissions: a review. *Environmental Science and Pollution Research*, *22*(4), pp.2491-2504.

Braking during conditions designed to mimic real world driving (WLTP braking cycles developed within the UN PMP group) are on the order of 10^9-10^{10} particles/stop
> order of magnitude less than Euro 6 exhaust limit $6 \cdot 10^{11}$ #/km



Mathissen et al., Wear 414-415 (2018) 219-226.



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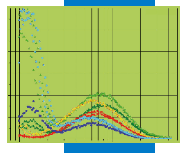

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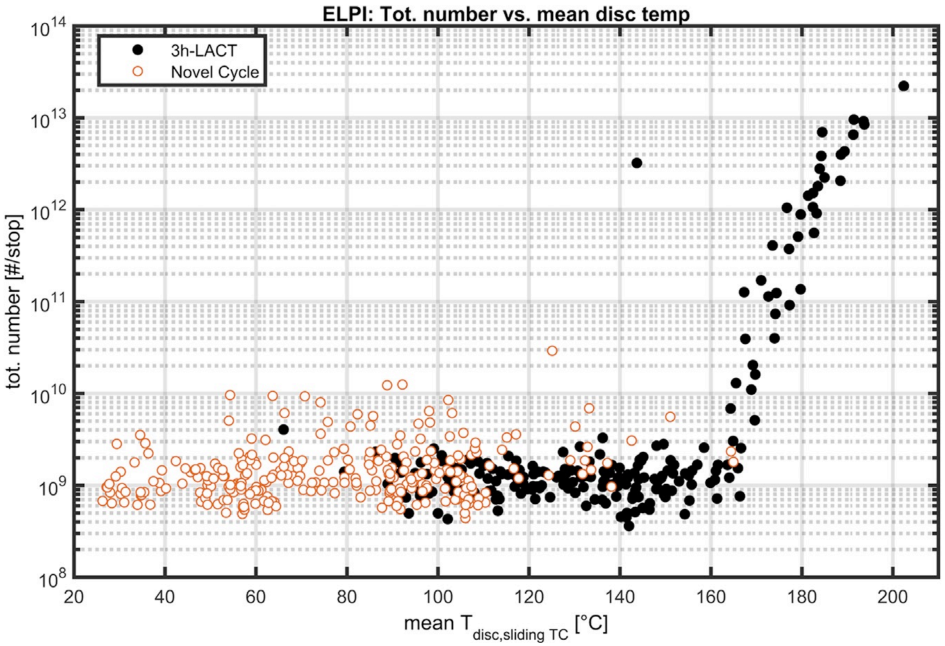

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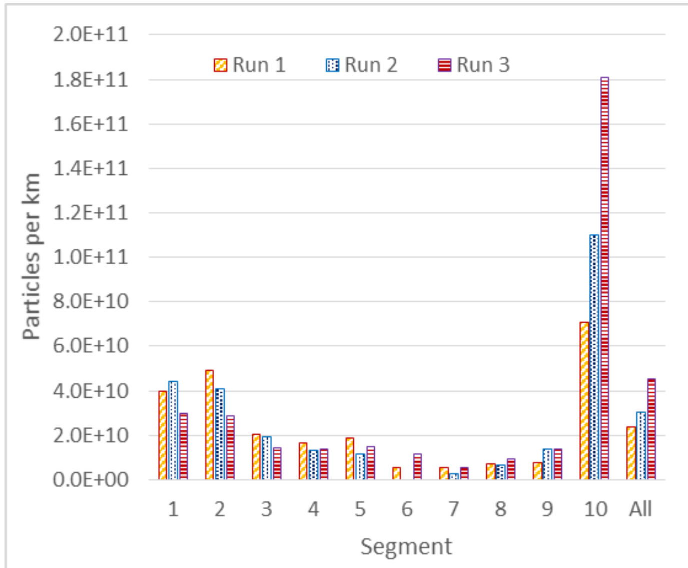

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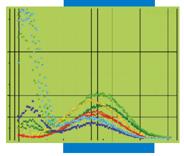

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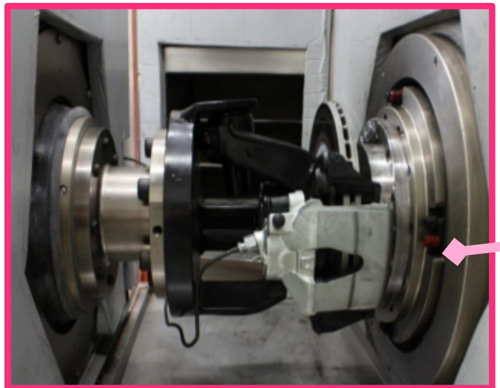
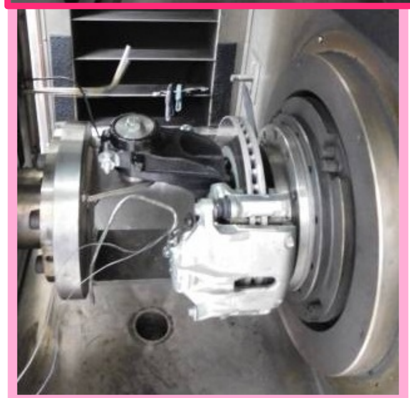
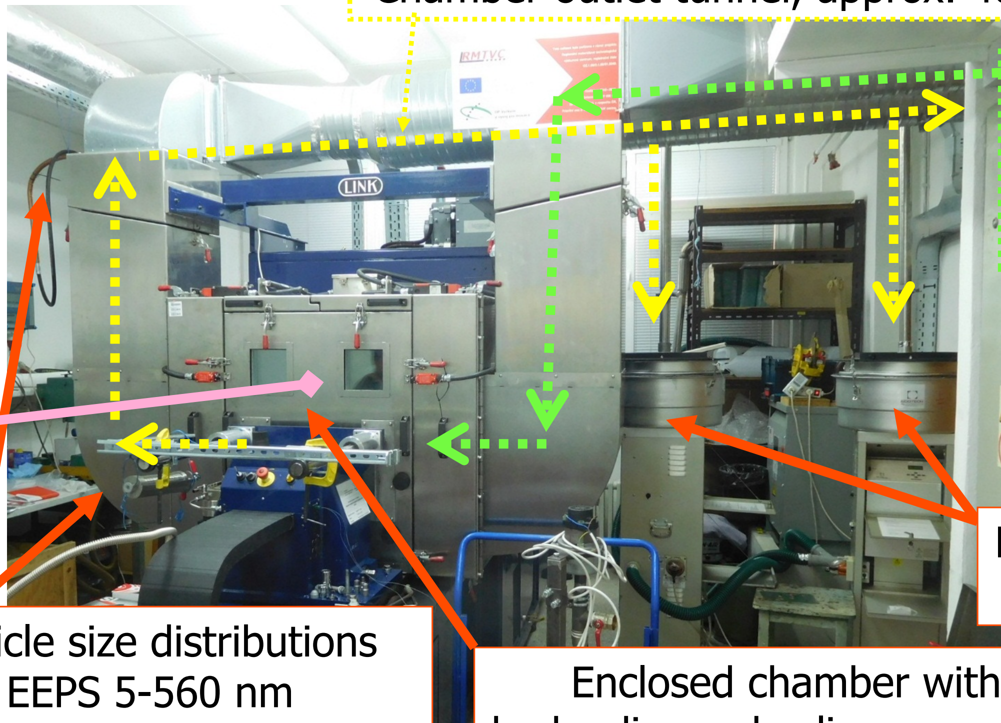
Brake wear particles measurement setup (TU Ostrava, CZ)

Tunnel and instruments analogous to engine exhaust measurements



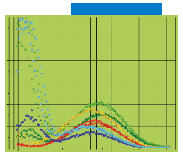




Chamber outlet tunnel, approx. 40 m^3/min flow

Filtered cooling air approx. 40 m^3/min

PM$_{2.5}$ samplers 2 x 68 m^3/h



Particle size distributions
EEPS 5-560 nm
electric mobility
ELPI 10 nm – 10 um
& Optical counter 0.5-10 um
aerodynamic diameter

Enclosed chamber with brake disc and caliper assembly (typical passenger car) coupled with asynchronous dynamometer

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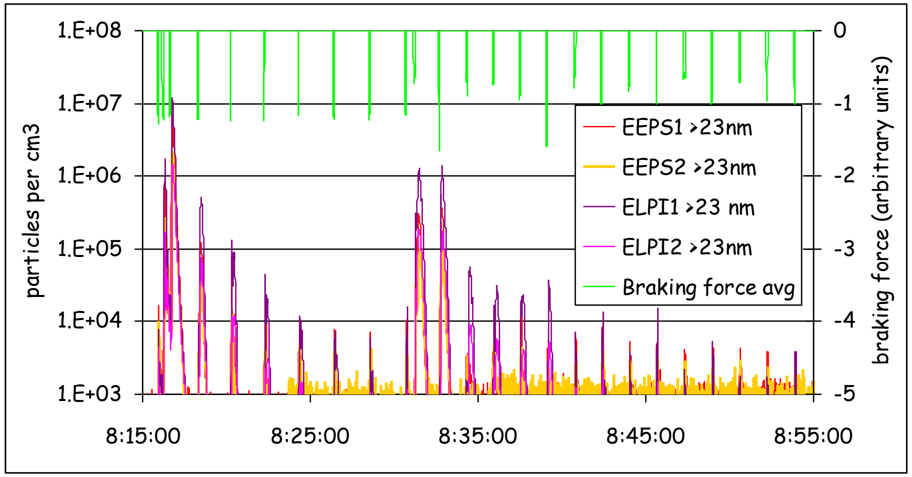
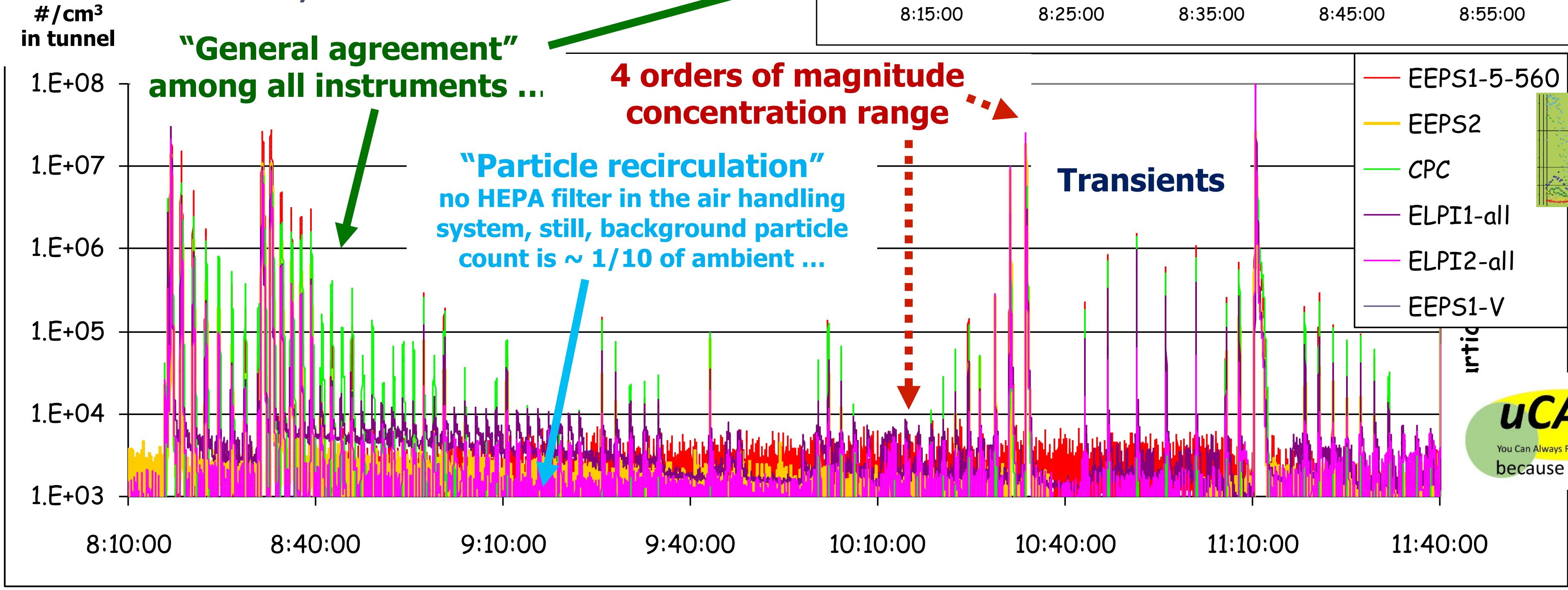
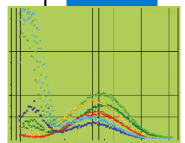
Sampling location effects
Instrument effects

Simultaneous
CPC, EEPS, ELPI, APS at box outlet and EEPS, ELPI from tunnel







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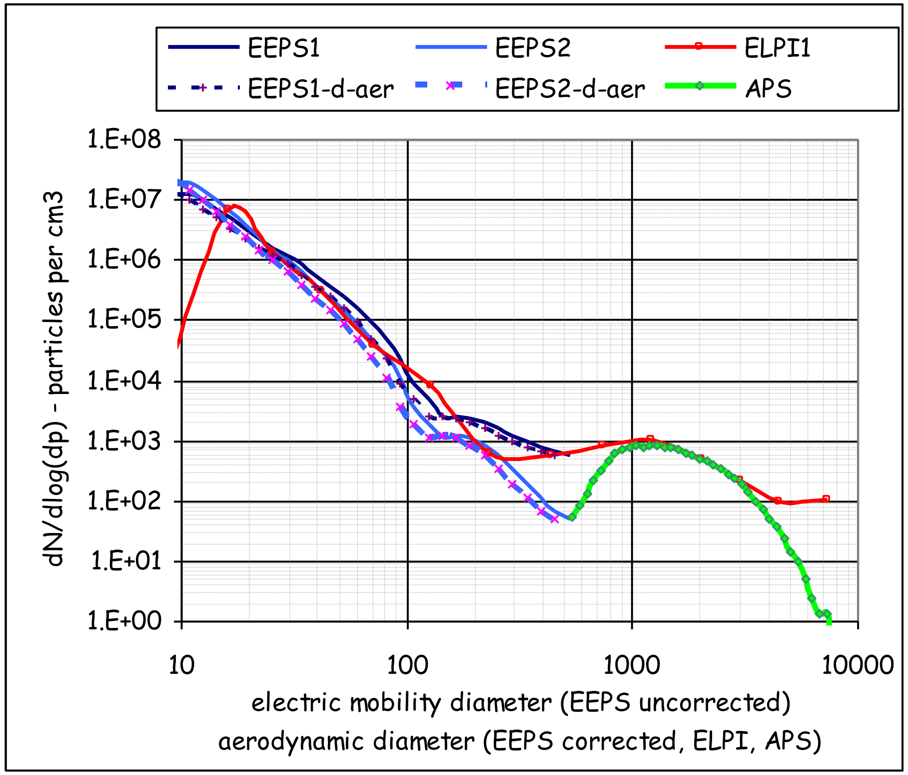
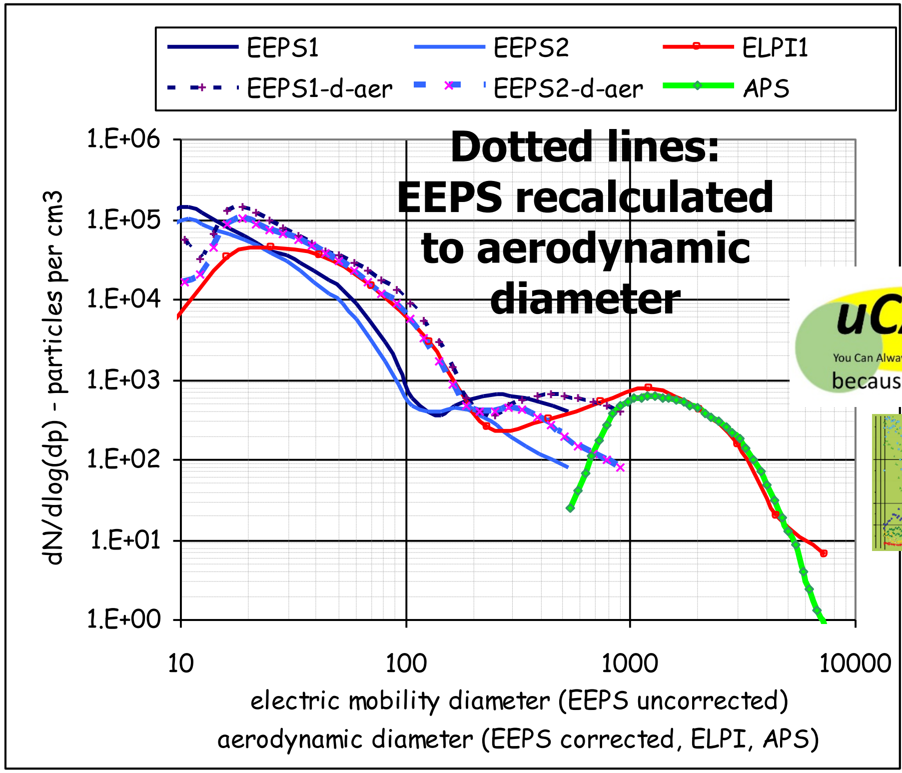
Matching electric mobility (EEPS) vs. aerodynamic (ELPI, APS) diameter



From ISO26867 cycle, 16 bar
Brake pad temperature 256 → 262 C
Assumed eff. particle density of 0.75

Metal oxides vs. resins
Particle effective density varies !!!



Final stop of the NEDC cycle, 14 bar
Brake pad temperature 155 → 303 C
Assumed eff. particle density of 3.0

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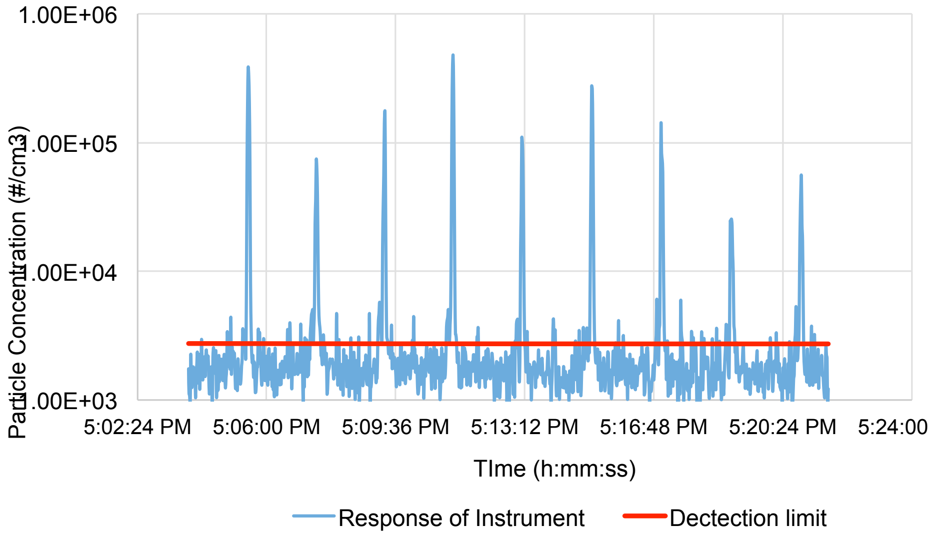
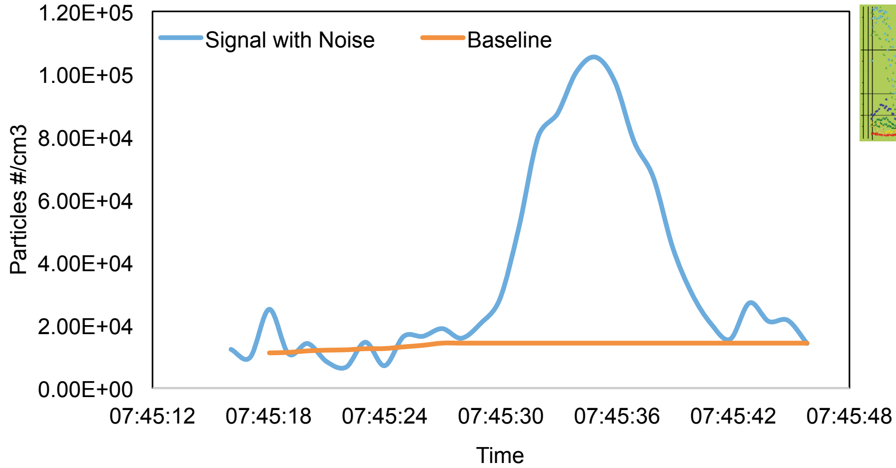
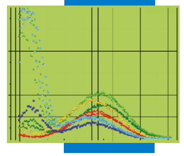
Quantifying emissions from short peaks

Similar to remote sensing exhaust emissions measurement

- Different strategies, but typically, a numerical integral of values (or a fitted curve) above the background noise
- Synchronizing time between various instruments using, i.e., brake line pressure signal or rotor rotational speed signal







Test cycles and brake pads used in the study

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- One brake rotor for a typical midsize passenger car
- One set of OEM and 3 sets of aftermarket brake pads
- 3 x WLTP brake cycle developed within the PMP group
  (Mathissen et al., Wear 414-415 (2018) 219-226.)
- Sections of ISO 26867 and SAE J2522 standard tests selected to still fall within the realm of real driving

Traditional standard brake cycles are used to test performance, safety, durability and focus on covering extreme events.

ISO characteristic section (#)	Initial speed (kph)	Final speed (kph)	Initial Disc Temp (°C)	Average Pressure (Bar)	Repetitions
A (ISO 1)	80	30	150	30	10
B (ISO 2)	80	30	200	15-50	32
C (ISO 3)	80	30	150	30	6
D (ISO 5)	80	30	150	30	6
E (ISO 8)	80	30	150	30	18

SAE characteristic section (#)	Initial speed (kph)	Final speed (kph)	Initial Disc Temp (°C)	Average Pressure (Bar)	Number of brake events
F (SAE 4.1)	40	5	100	10, 20, …… ,80	8
G (SAE 4.2)	80	40	100	10, 20, …… ,80	8
H (SAE 4.3)	120	80	100	10, 20, …… ,80	8
I (SAE 6)	40	5	40	30	1
J (SAE 7)	100	5	50	50	1
J (SAE 7)	180	100	50	60	1
K (SAE 11)	80	30	100	10, 20, …… ,80	8

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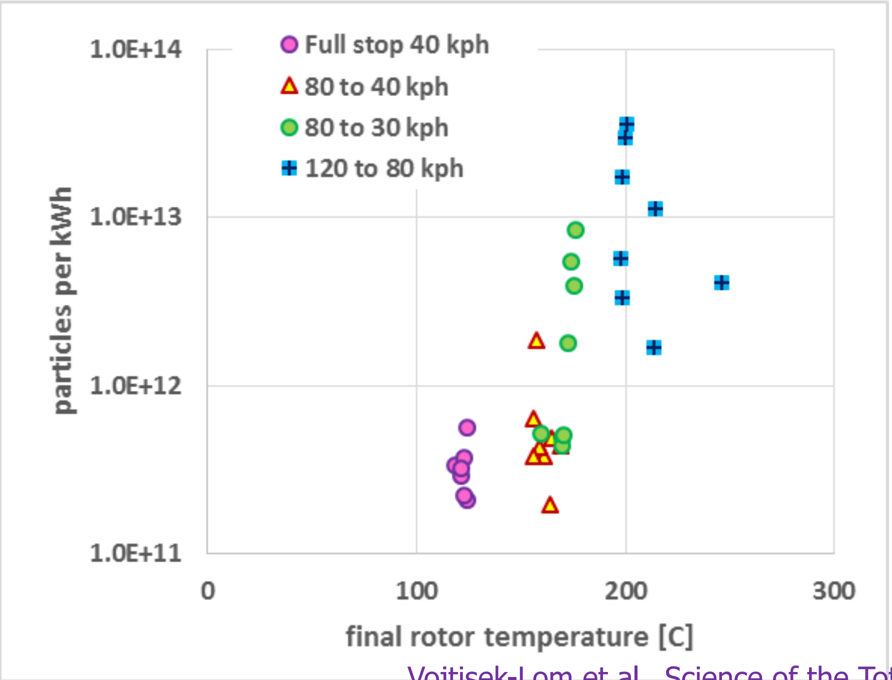
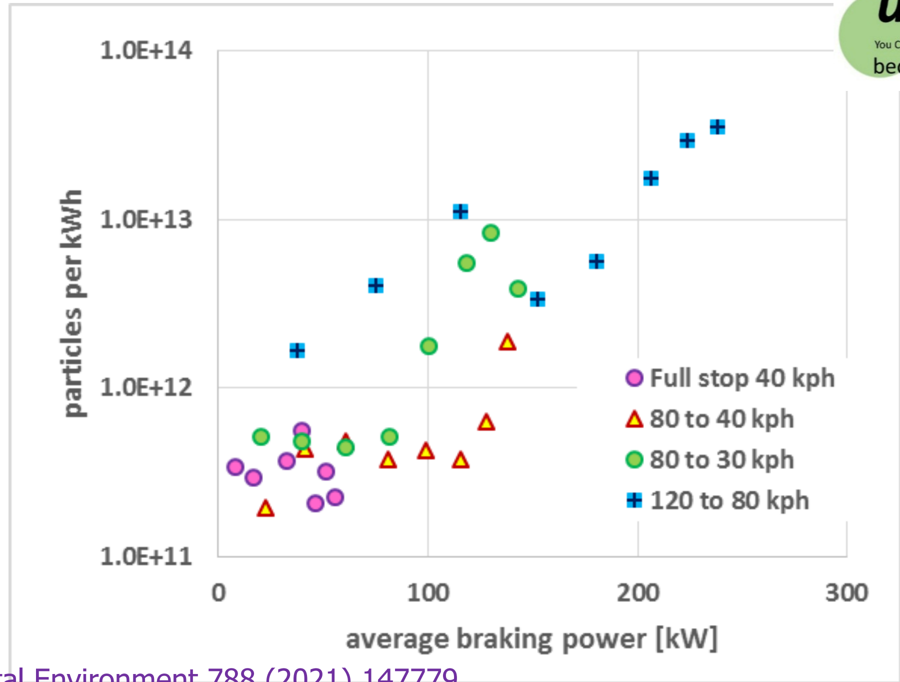
Original („OEM") pads and rotor, typical mid-size passenger car 1840 kg test weight, 35% braking power on left front wheel

- Data normalized to kWh dissipated (energy dissipated proportional to the square of speed)
- Not a straight-forward temperature-emissions dependence ... non-linearity, memory effects …
- What is „brake temperature"?
- The driver definitely can do something: Speed deceleration rate, temperature matter
- Is there „acceptable level" of emissions, and what is it?





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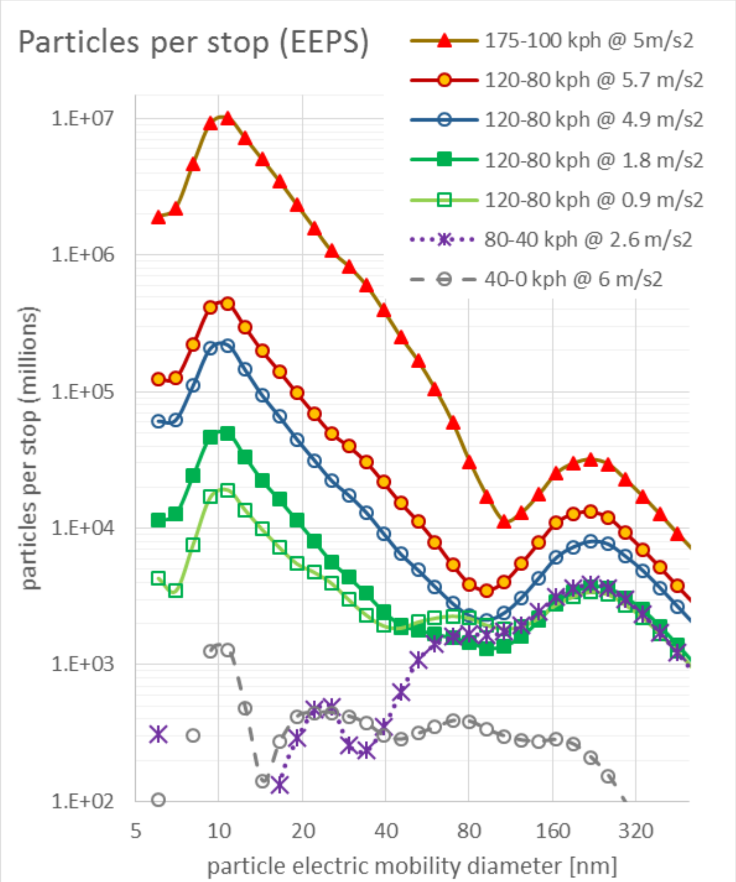
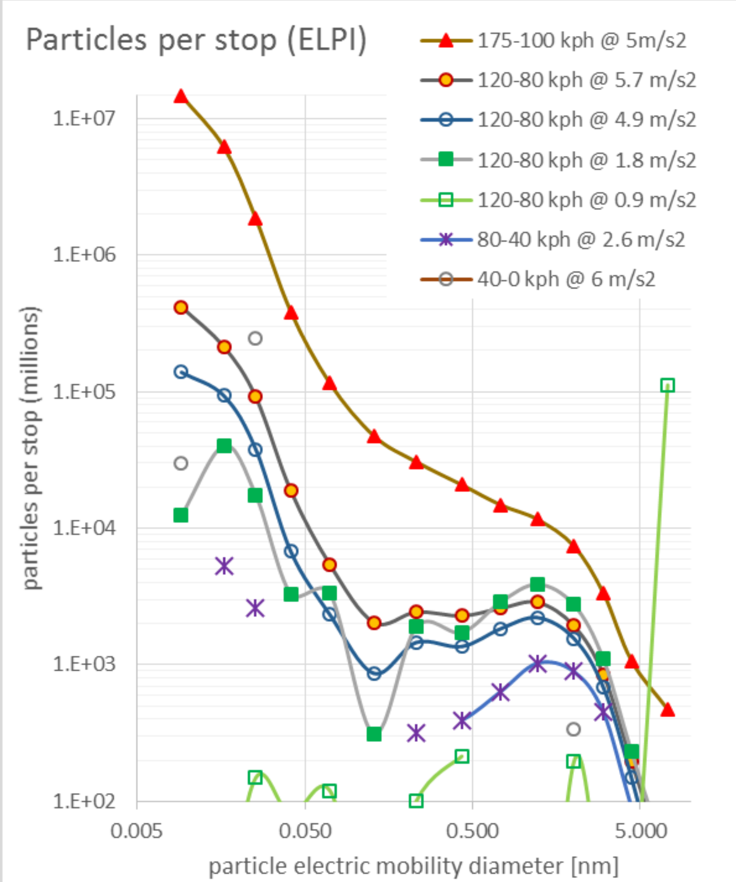
- The particle count is dominated by ultrafines
- Ultrafines are also most sensitive to operating conditions





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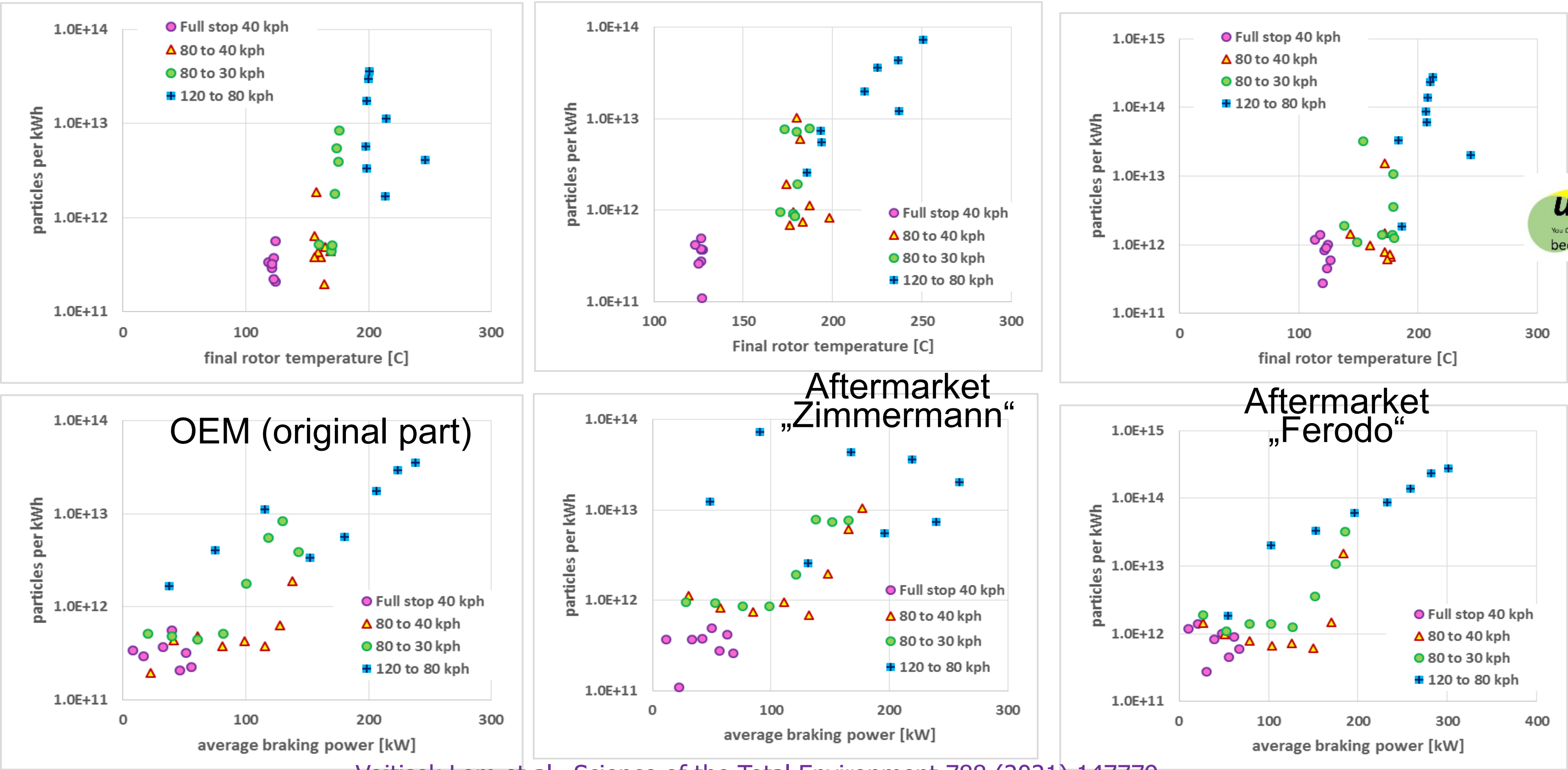
Original („OEM“) pads and rotor, typical mid-size passenger car
1840 kg test weight, 35% braking power on left front wheel



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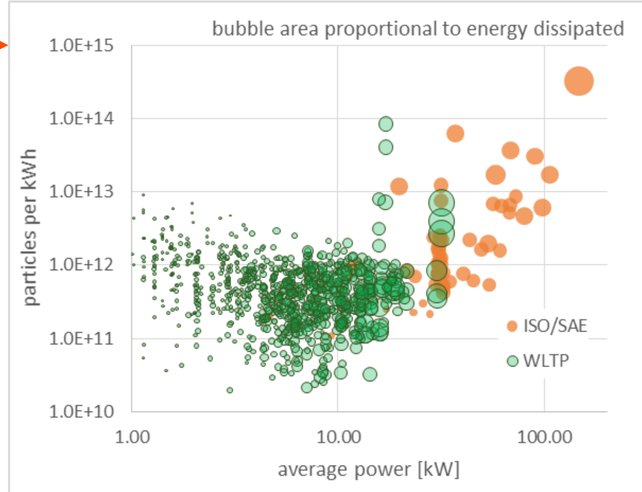
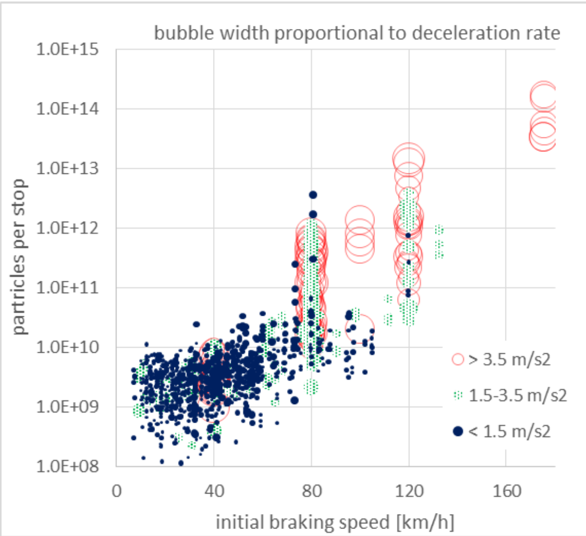
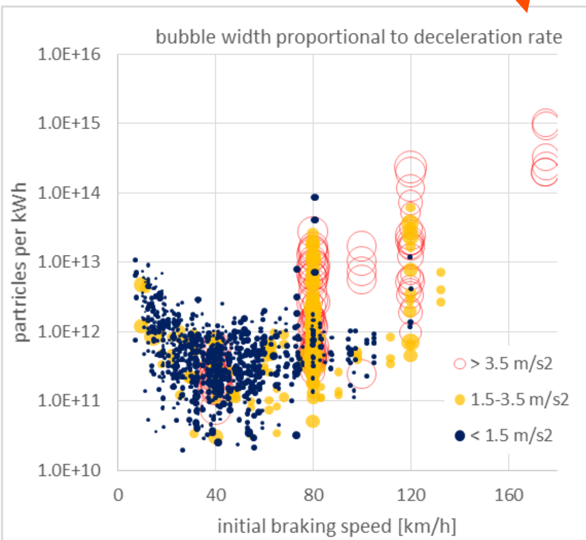
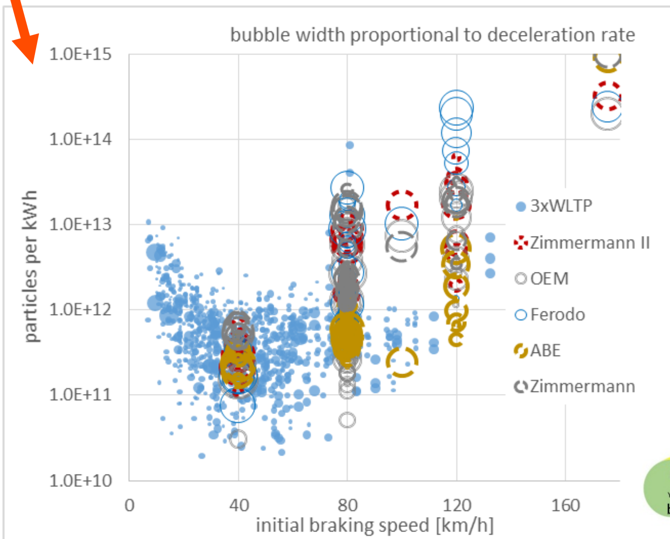
"Off-cycle" emissions
Differences among makes/models
Effect of operating conditions



Units: particles/stop ->
particles/kWh dissipated
particles/km







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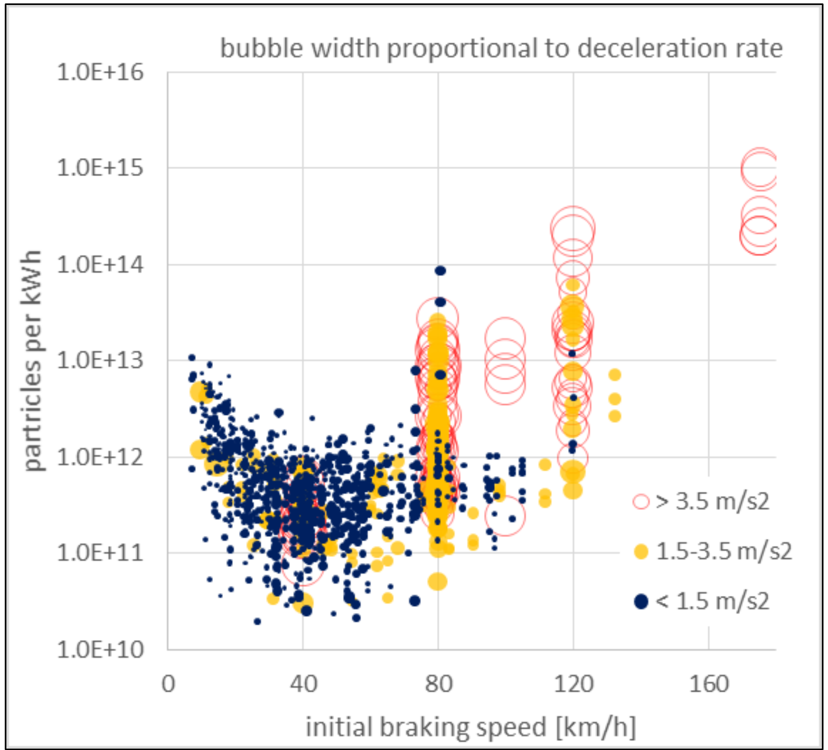
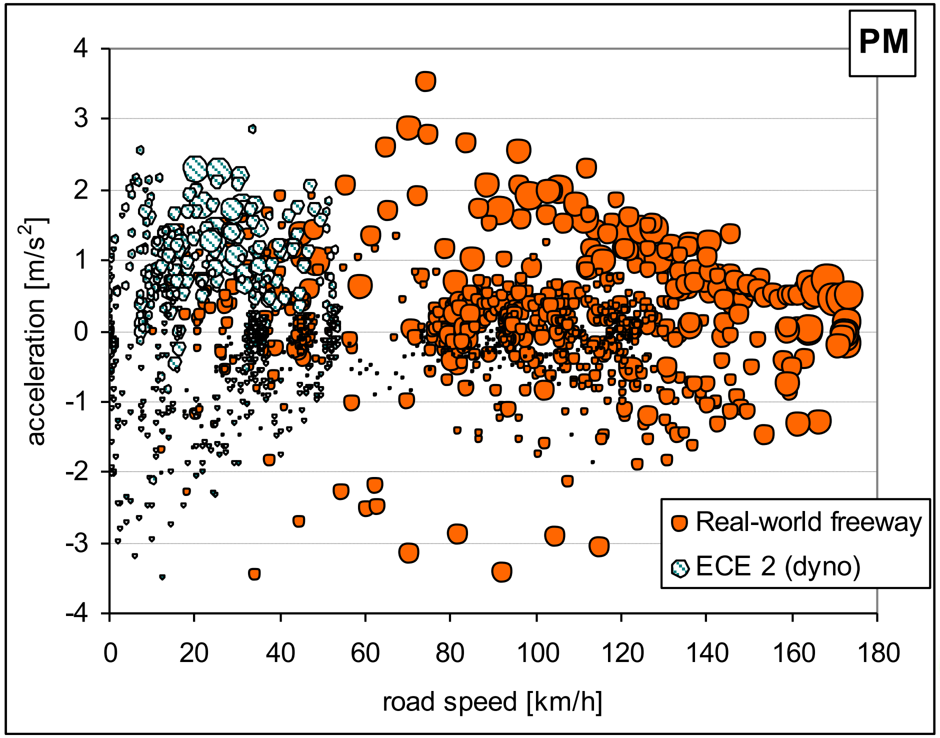
High-speed, high-power driving -> high emissions

- Hard decelerations (left) and accelerations (right) lead to high emissions of exhaust (non-DPF diesel) and brake particles
- Additional reason to consider a speed limit (or enforcement of an existing one)
  - **Is high speed travel on autobahn in Germany, de-facto, a constitutional right?**



Vojtisek-Lom et al., Sci. of the Total Env. 788 (2021) 147779



Vojtisek-Lom et al., SAE techical paper 2009-24-0148

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High excess emissions due to “extremes”

- **Disproportionate distribution of emissions (both exhaust and brake wear):**
- **Small part of operating time ~ large part of total emissions**
- **Small fraction of vehices ~ large part of fleet emissions**
- **Similar to distribution of income/wealth (Lorenz curve, Gini coefficient)**

Lorenz curve: Atkinson, A.B. "On the Measurement of Inequality”. Journal of Economic Theory., Vol. 2, 1970.

https://www.carthrottle.com/post/when-your-brakes-glow-red-youre-driving-a-ferrari-599xx-evo-right/

Czech Univ of Life Sciences high emitter detection experiment (this car driven daily, tested as-recruited, without modifications)

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Are extreme events
- infrequent but heavily contributing to the total emissions – outliers to be excluded or important part of the emissions inventory to be investigated, included, quantified and targeted???

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Source apportionment based brake emissions factors

Brake wear emissions factors:

Rough calculation from the loss of mass of pads/linings and rotors/drums and frequency of replacement and/or total sales of parts

Rough calculation from analysis of roadside/urban particulate matter

Contributing factor	Engine exhaust	Brake wear
• Base emissions over a cycle tests on a few well maintained vehicles	included	included
• “Off-cycle” emissions	limited inclusion	included
• Deterioration beyond “statutory” useful life	limited inclusion	included
• Excess emissions due to bad condition – malfunction, tampering, …	limited inclusion	included
• Resuspension of settled particles	not included	included in source apportionment

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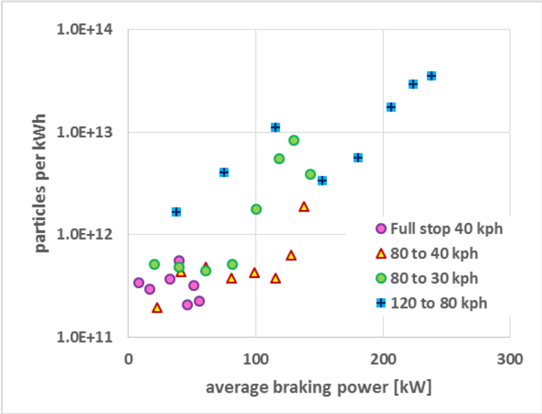
Practical recommendations to reduce brake wear particles



Drive gently, including braking

- Lower speeds – help (lower power at the same decel. rate)
- Lower deceleration rates – help (less braking power)
- Use air drag and engine braking – helps (less braking power)
- Less frequent braking – helps (more time to cool)

Synergy with fuel consumption, exhaust emissions, and tire wear

- Avoid extreme: accelerations (exhaust PM and CO, tire wear), cornering (tire wear) and braking (brake PM)
- Avoid high speeds (non-linear increase in fuel, exhaust PM and NOx, tire and brake wear)
- Lower vehicle weight (CO_2, tire wear, brake wear, not uniform effect on exhaust)
- Anticipating, avoiding stops, maintaining speed

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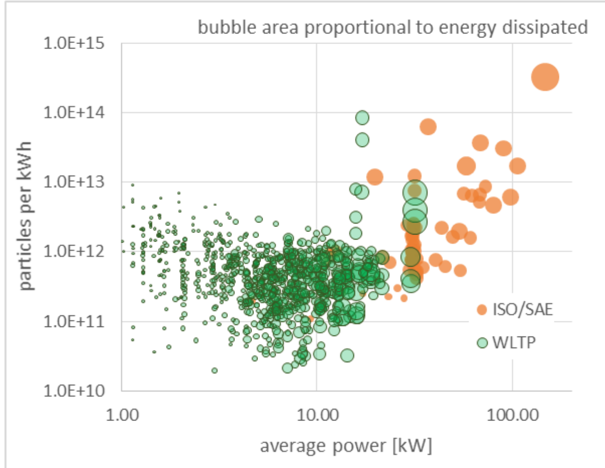
Discussion & implications for public policy



Traffic management & transportation planning

- Lowering the speed limits where heavy braking expected to reduce the need for high deceleration at high speeds
- Practices to enhance road safety tend to reduce braking
- “Eco-driving” practices to be included in driver training

Do electric vehicles have higher brake wear due to the battery mass?

- Higher mass -> higher average braking power and energy dissipated
- Nearly all electric vehicles use regenerative braking (dynamic braking) -> lower braking power and energy dissipated in friction brakes
- Regenerative braking typically limited to the rated electric motor power
  -> this depends on the driving style

Are brake wear particles a bigger problem than exhaust particles?

- Are your vehicles equipped with DPF and well maintained (i.e., Switzerland), or ….

Luckily not much tampering (brake removal, brake emulators)

Final thoughts

- Friction brakes produce both ultrafine (thermal origin) & coarse particles
- Transient dynamometers and pre-defined driving cycles used for testing
- Outflow of the chamber housing the brake mechanism has many analogies with diluted engine exhaust (constant volume sampling, particle sampling and measurement procedures, instrumentation, tunnel flows, particle concentrations)
- Emissions are low during "cycles developed to mimic real driving" but both exhaust and brake wear particles heavily contribute to the air pollution -> contribution of the high emission episodes/vehicles to be included, investigated, targeted
- "RDE" (or RBE – real braking emissions?) important (high emissions during extremes) but difficult to measure (no tailpipe)

Funding: Czech Science Foundation GA 19-04682S (testing) & H2020 project 815002 uCARe – You can also reduce emissions

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