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Doprava, zdraví a životní prostředí
CDV, Brno, 17. 10.2022

Vliv stylu jízdy na emise nanočástic z automobilových diskových brzd

Effects of driving style on nanoparticle emissions from automobile disc brakes

Michal Vojtíšek, Martin Pechout, Srinath Penumarti, Alden Fred Arul Raj, Praneet Ayyagari

Center for Vehicles for Sustainable Mobility, Faculty of Mech. Eng., Czech Technical University in Prague, CZ
michal.vojtisek@fs.cvut.cz, michal.vojtisek@tul.cz +420 774 262 854

Miroslav Vaculík
Nanotechnology Center, VSB Technical University of Ostrava, Ostrava, CZ

František Hopan, Jiří Smokeman Horák
Energy Reserch Center, VSB Technical University of Ostrava, Ostrava, CZ

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Představení skupiny: Měření emisí za provozu
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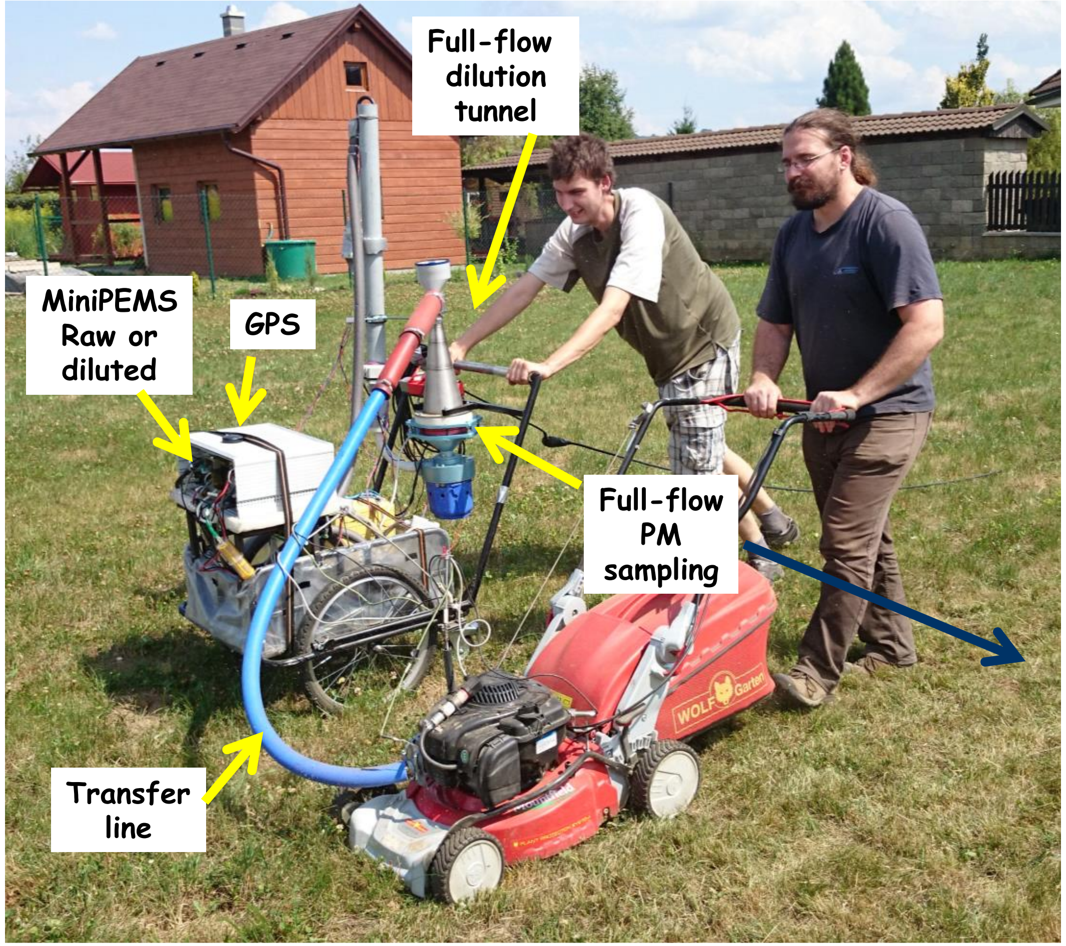
Přenosný systém s plnoprůtočným ředicím tunelem a vysokobjemovým vzorkováním částic pro malé motory



Miniaturní a nízkonákladová přenosná zařízení pro měření emisí za provozu
Mini-PEMS & Poor man's PEMS

NO, NO_2
CO, CO_2
orientační PM
orientační PN
orientační HC
výpočet toku výfuk. plynů
9 kg
3 hr výdrž

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Mobilní FTIR analyzátory

Pro měření emisí za provozu

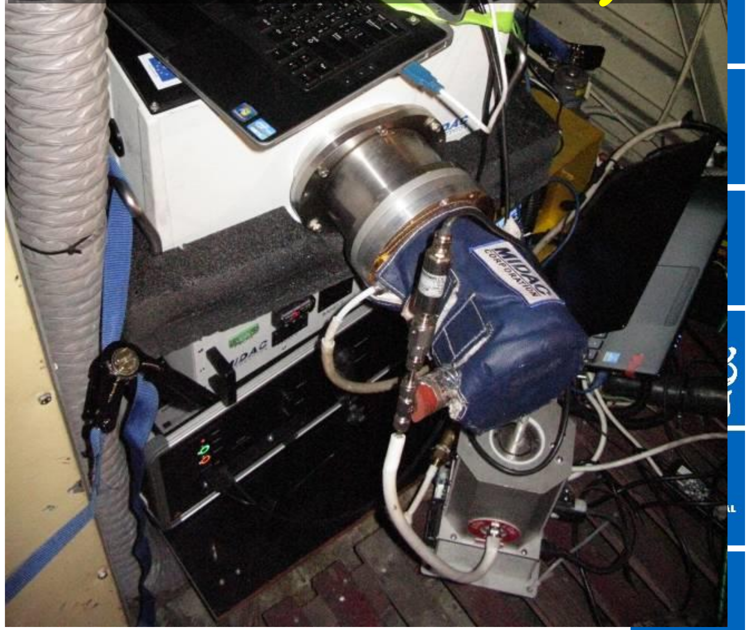
Skleníkové plyny CO_2, CH_4, N_2O

Reaktivní sloučeniny dusíku NO, NO_2, NH_3, ...

... a další látky absorbující ve střední oblasti infračerveného spektra

Nicolet Antaris IGS
5 m optická dráha
0.5 cm^{-1} / 1 Hz

Midac I-series, 30 kg
6 m cell length,
2.5 s resolution
(TU Liberec,
www.medetox.cz)



Suarez-Bertoa, R., et al. (2017). *Atmospheric Environment*, *166*, 488-497.
Pechout, M., et al. (2019). *Science of the Total Environment*, *696*, 133748.
Suarez-Bertoa, R., et al. (2020). *Atmosphere*, *11*, 204.
Vojtíšek-Lom, et al. (2018), *Science of the Total Environment* 616, 774-784

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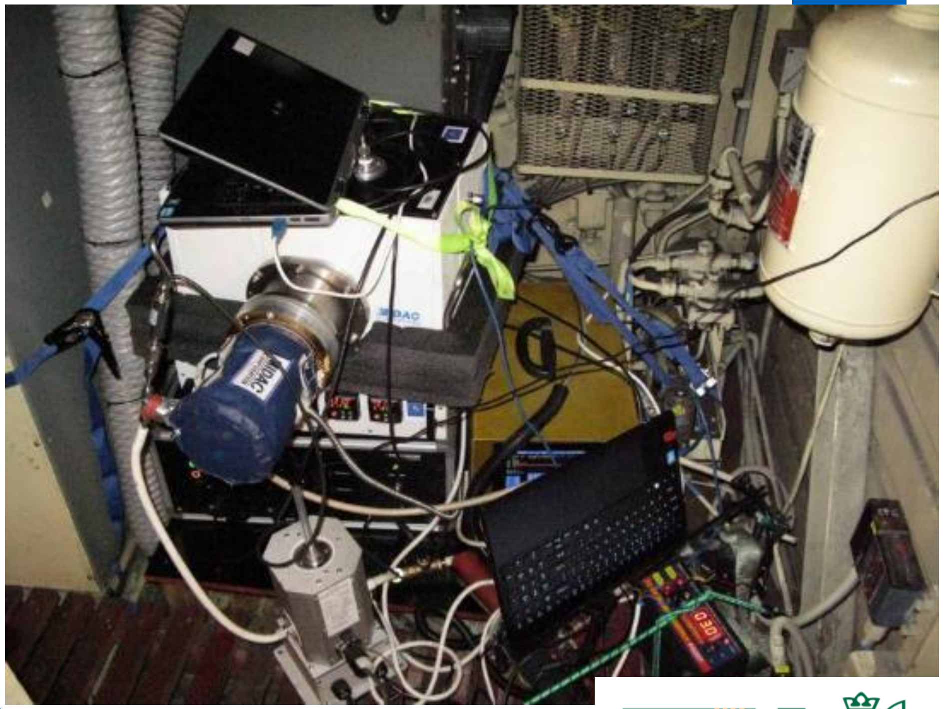
Mobilní FTIR analyzátory pro měření emisí za provozu

Skleníkové plyny CO_2, CH_4, N_2O, reaktivní sloučeniny dusíku NO, NO_2, NH_3,
... a další látky absorbující ve střední oblasti infračerveného spektra

Měření emisí drážních vozidel za provozu



Vojtíšek-Lom, et al. (2020), *Atmosphere, 11, 582.*

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Představení skupiny: Měření emisí za provozu
Dálkové měření emisí vozidel (a dalších zdrojů)

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Vojtíšek-Lom, et al. (2020), *Science of the Total Environment*, 738, 139753.

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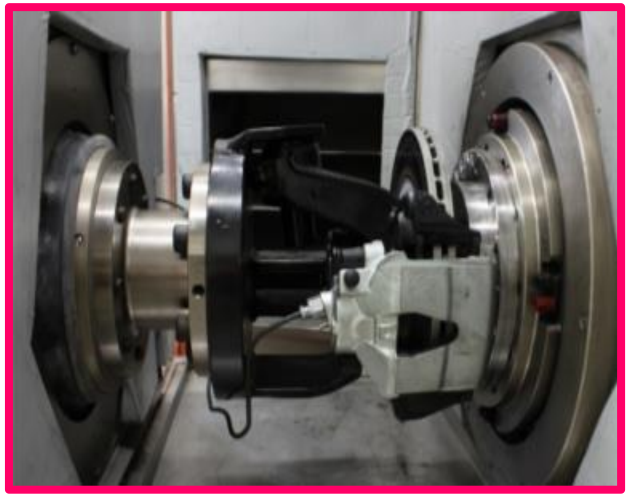
Představení skupiny: Měření emisí za provozu
Měření částic z otěrů třecích brzd – laboratoř VŠB TU Ostrava



Vojtíšek-Lom, et al. (2021), *Science of the Total Environment, 788, 147779.*

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Představení skupiny: Měření emisí za provozu
Charakterizace emisí ze spalování alternativních paliv v laboratoři a za provozu

Vojtisek-Lom, et al. (2015). *SAE Intl. Journal of Engines*, 8(5), 2338-2350.
Vojtíšek-Lom, et al. (2018), *Science of the Total Environment*, *616*, 774-784.

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Expozice buněčných kultur výfukovým plynům (air-liquid interface)

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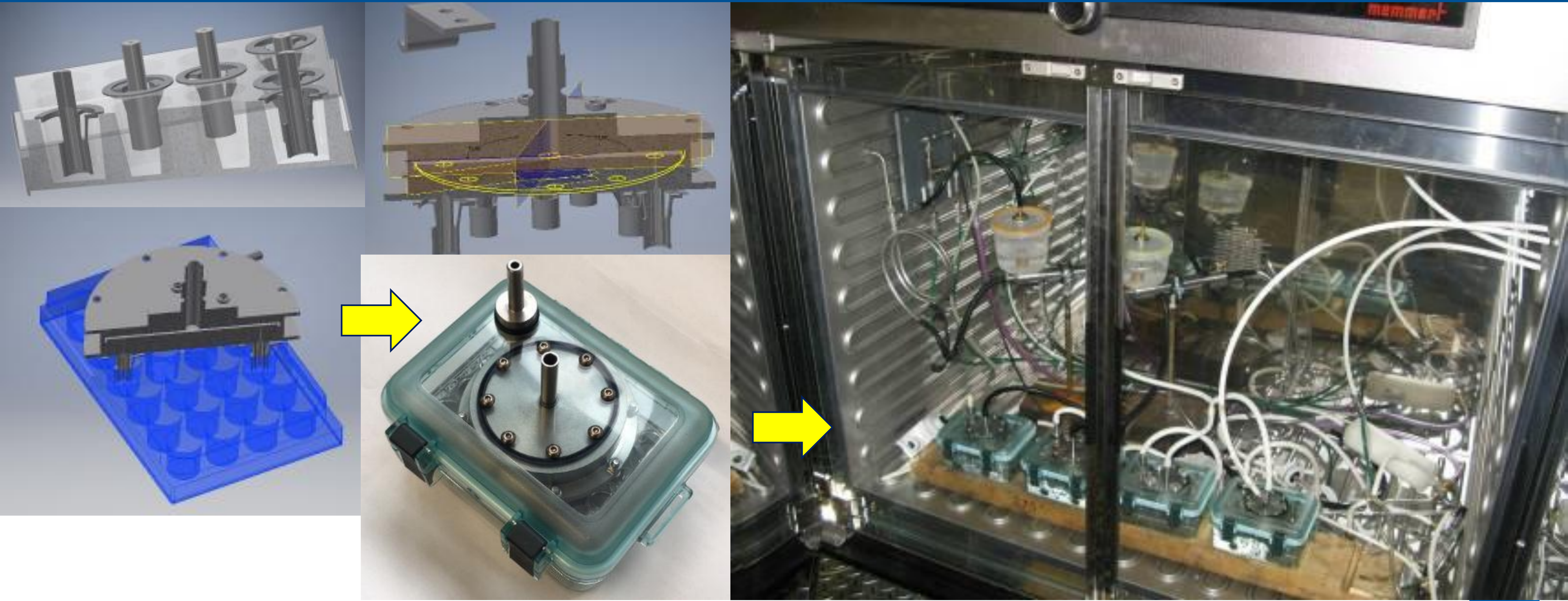

Vojtisek-Lom, M., et al. (2019). *SAE International Journal of Advances and Current Practices in Mobility*, 2(2019-24-0050), 520-534.
Rossner, P., et al. (2019). *International journal of molecular sciences*, 20(22), 5710.
Rossner, P., et al. (2021). *Chemosphere*, 281, 130833.

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Outreach & citizen science:
Nanoparticles in the air & small engine emissions

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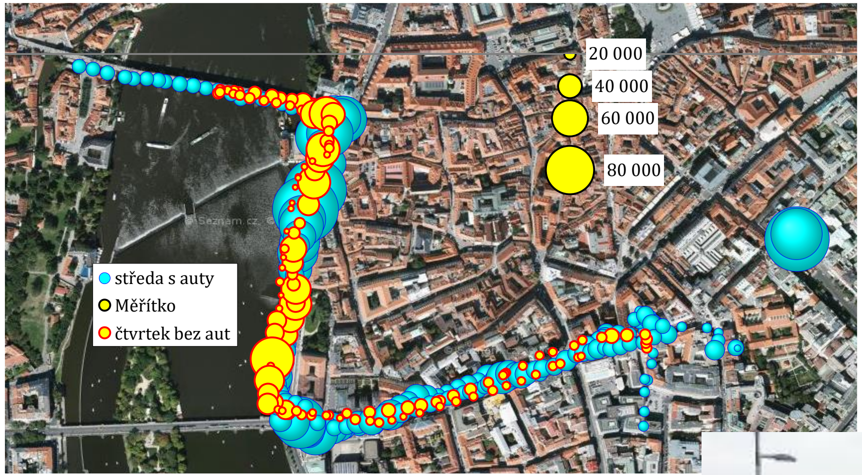

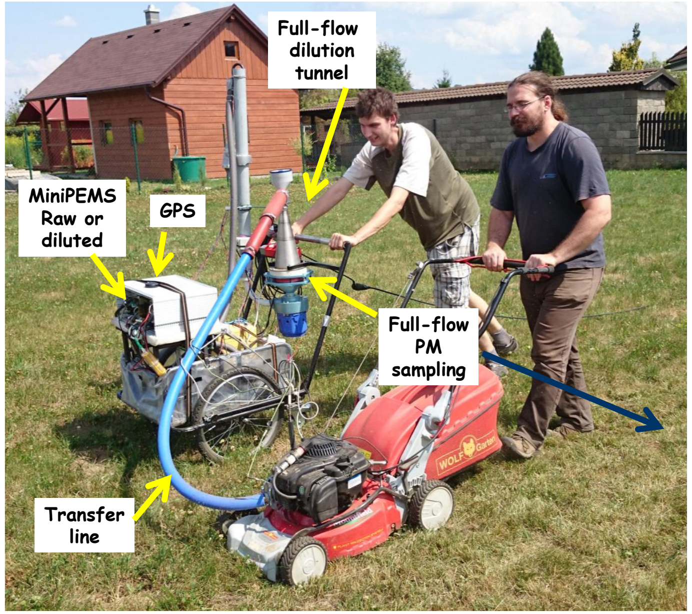

Stolcpartova, J., et al. (2015). *Atmosphere*, *6*(11), 1714-1735.

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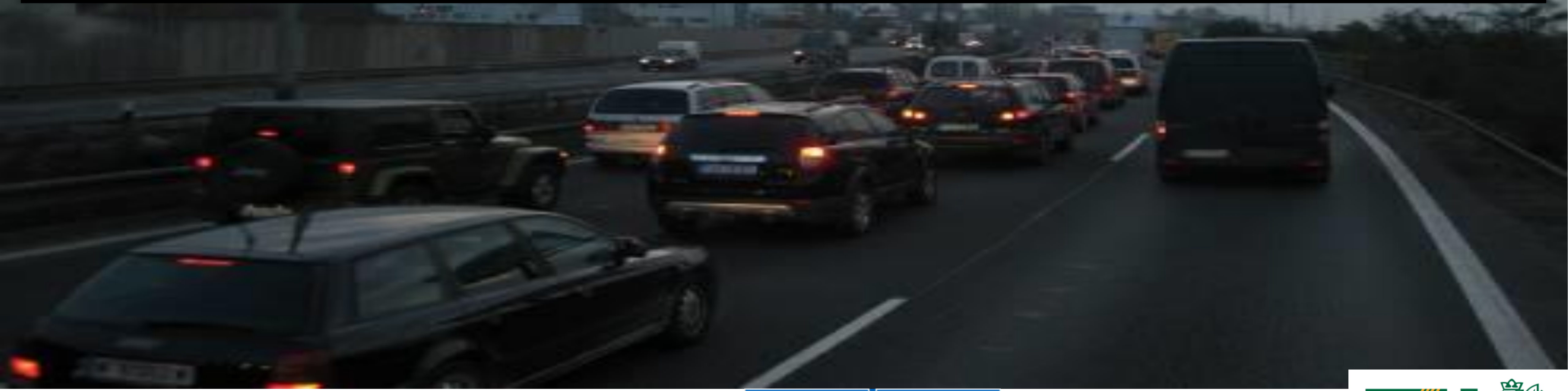
Motivace: Proč měříme a snižujeme emise

Dlouhodobá expozice částicím ($PM_{2.5}$), oxidům dusíku a přízemnímu ozonu ve venkovním ovzduší je příčinou předčasného úmrtí řádově jednoho promile populace ročně

(Evropa/EU: PM2.5 - 422/391 tis., NOx – 79/76 tis., O3 – 18/16 tis.; EEA Air Quality Report 2018)

dopravní nehody v EU v roce 2015 „jen“ 26 tisíc (EU Annual Accident Report 2017)



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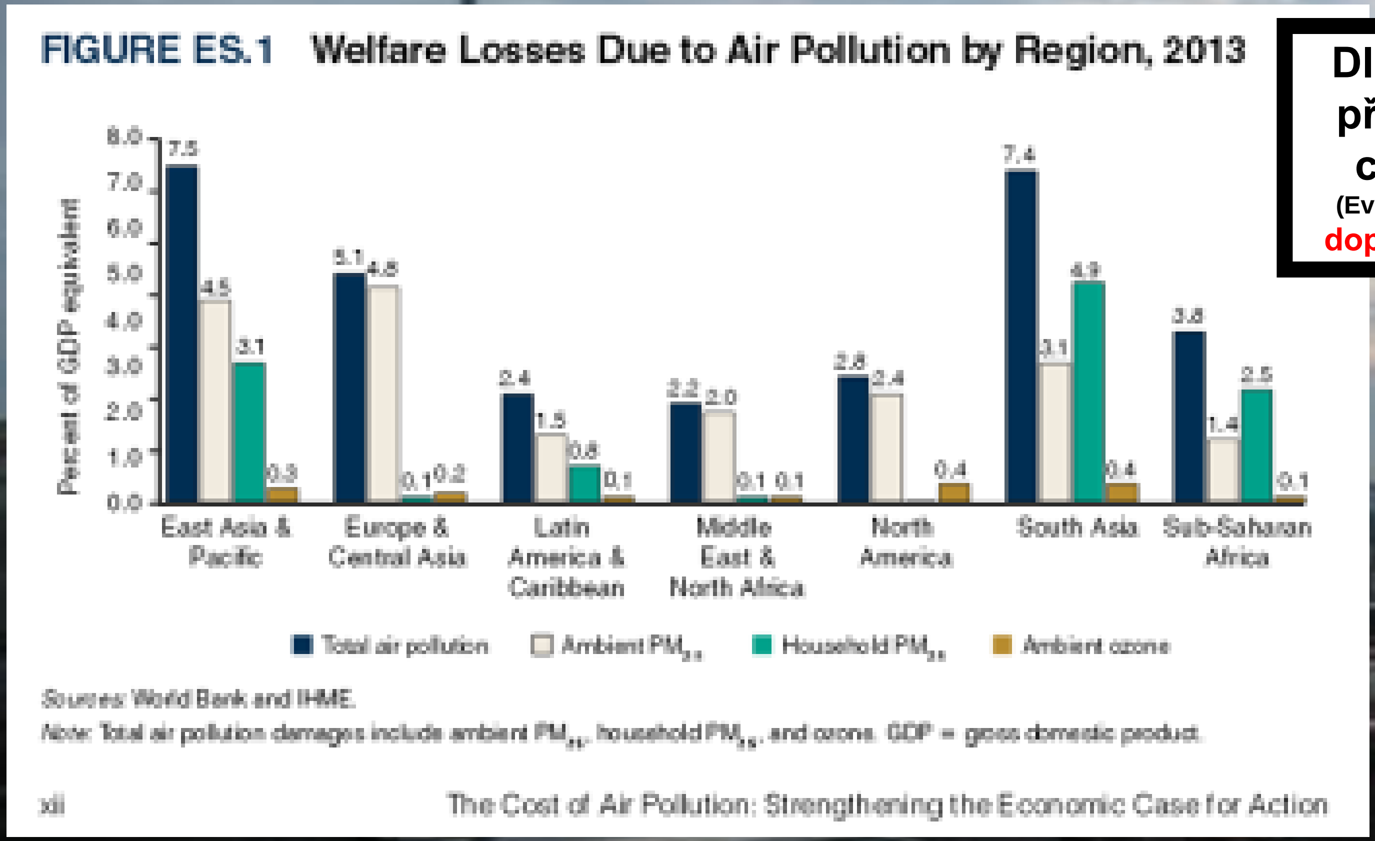

Dlouhodobá expozice částicím ($PM_{2.5}$), oxidům dusíku a přízemnímu ozonu ve venkovním ovzduší byla příčinou cca 518 tisíc předčasných úmrtí v Evropě v roce 2015

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dopravní nehody v EU v roce 2015 „jen“ 26 tisíc (EU Annual Accident Report 2017)

Světová banka odhaduje ekonomické škody v EU způsobené znečištěním venkovního ovzduší na 5 % HDP.

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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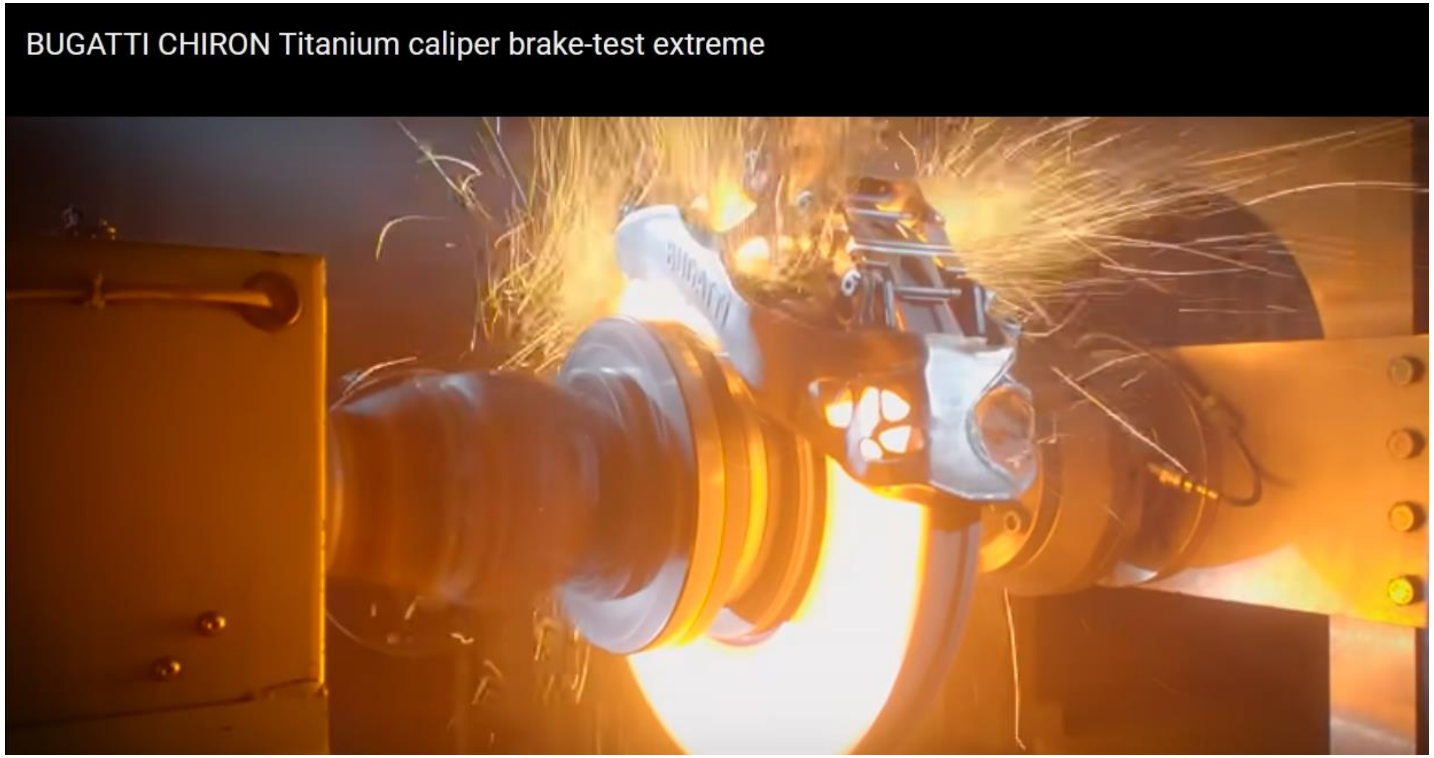
Particles produced during braking

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

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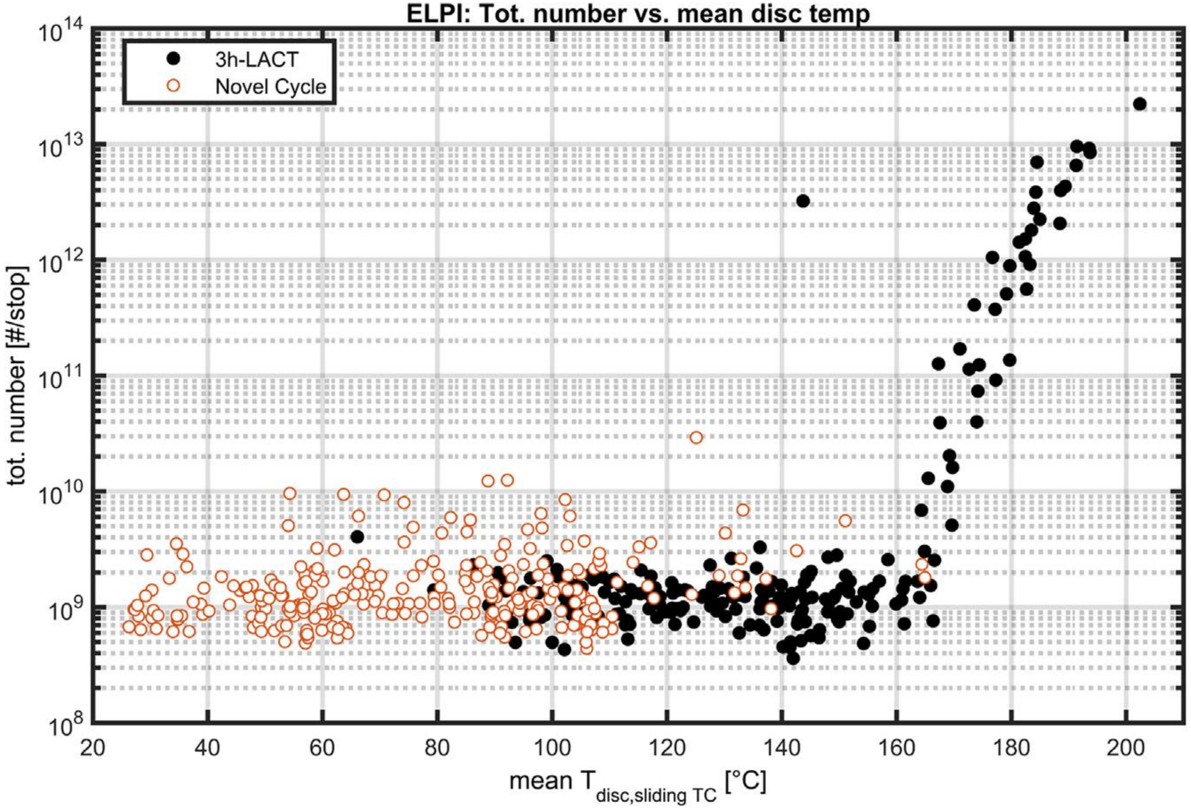
How much of a problem are they?

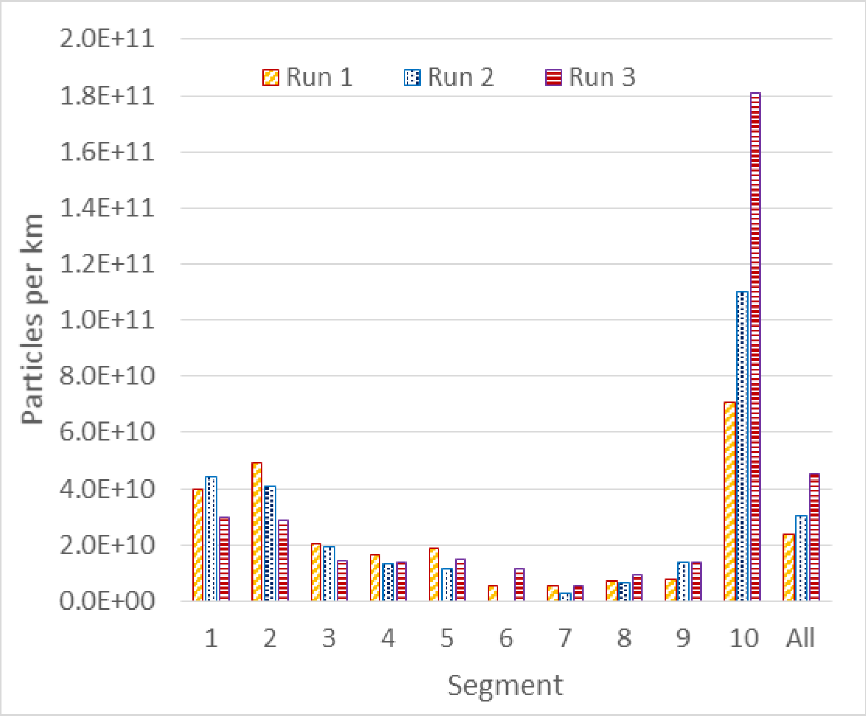
Brake wear particles:
~ 55% of non-exhaust PM emissions
Up to 21% of traffic-related PM_{10} emissions

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

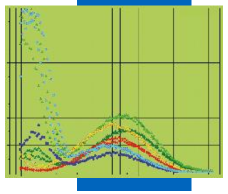
Braking during conditions designed to mimic real world driving (WLTP braking cycles developed within the UN PMP group) are on the order of 10^9-10^{10} particles/stop
> order of magnitude less than Euro 6 exhaust limit $6 \cdot 10^{11}$ #/km



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



Vojtisek-Lom et al., Science of the Total Environment 788 (2021) 147779



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How much of a problem are they?

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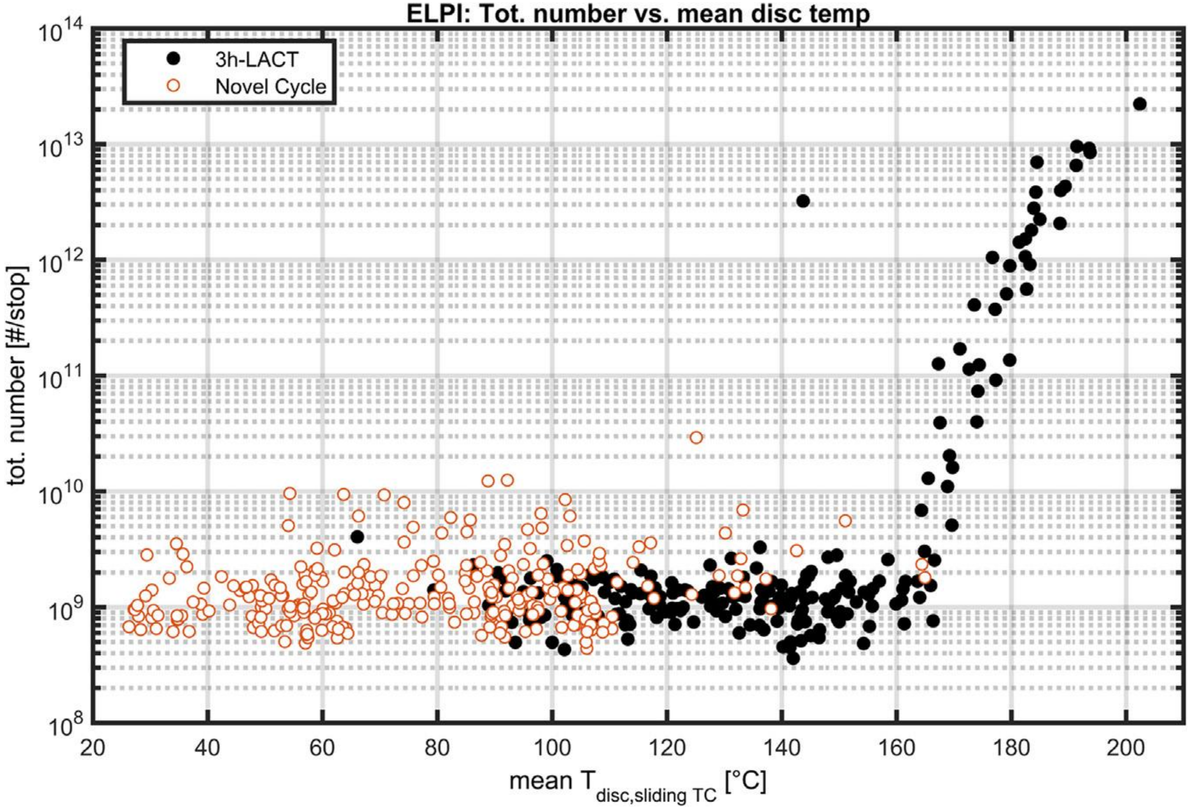
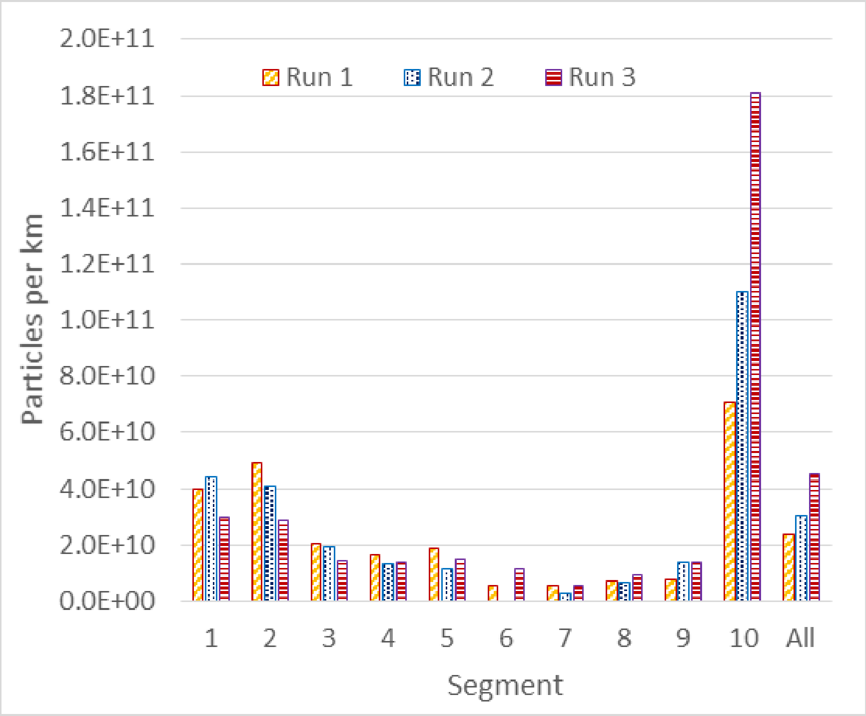
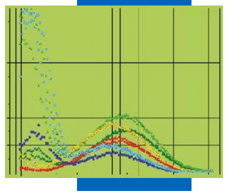


Mathissen et al., Wear 414-415 (2018) 219-226.



Vojtisek-Lom et al., Science of the Total Environment 788 (2021) 147779



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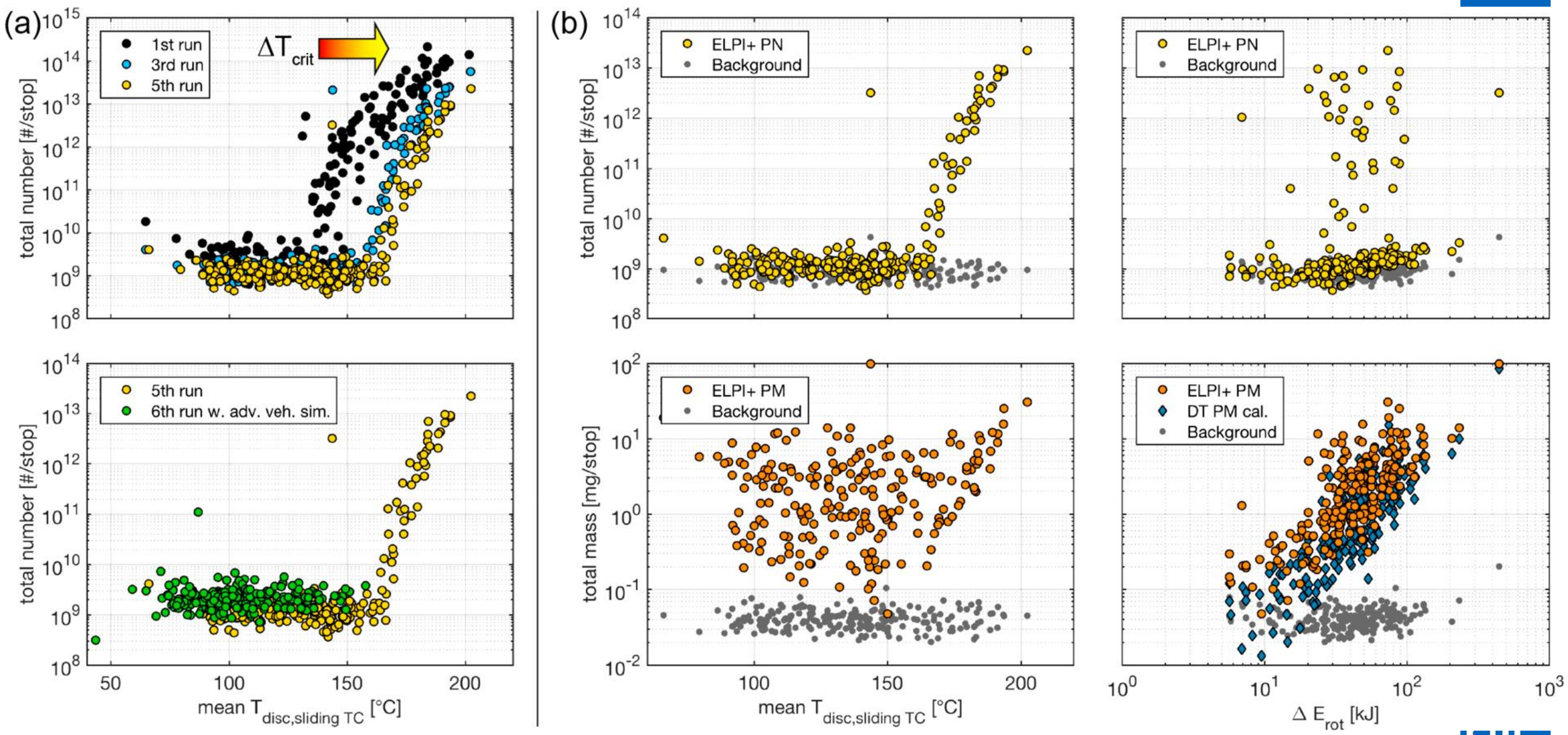
Effects of braking conditions



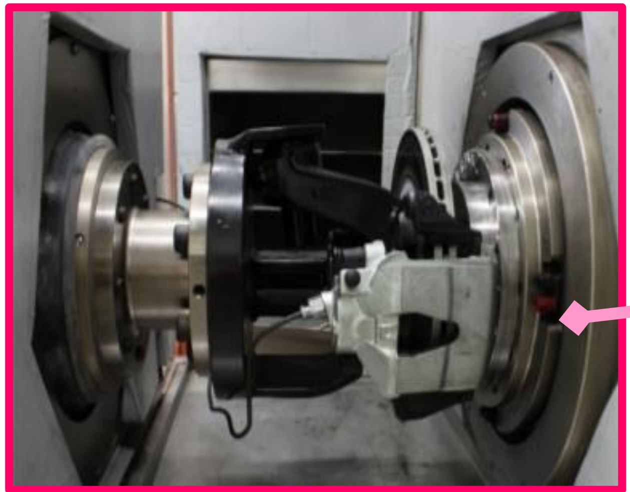
Zum Hagen et al., Environ. Sci. Technol. 2019, 53, 5143−5150

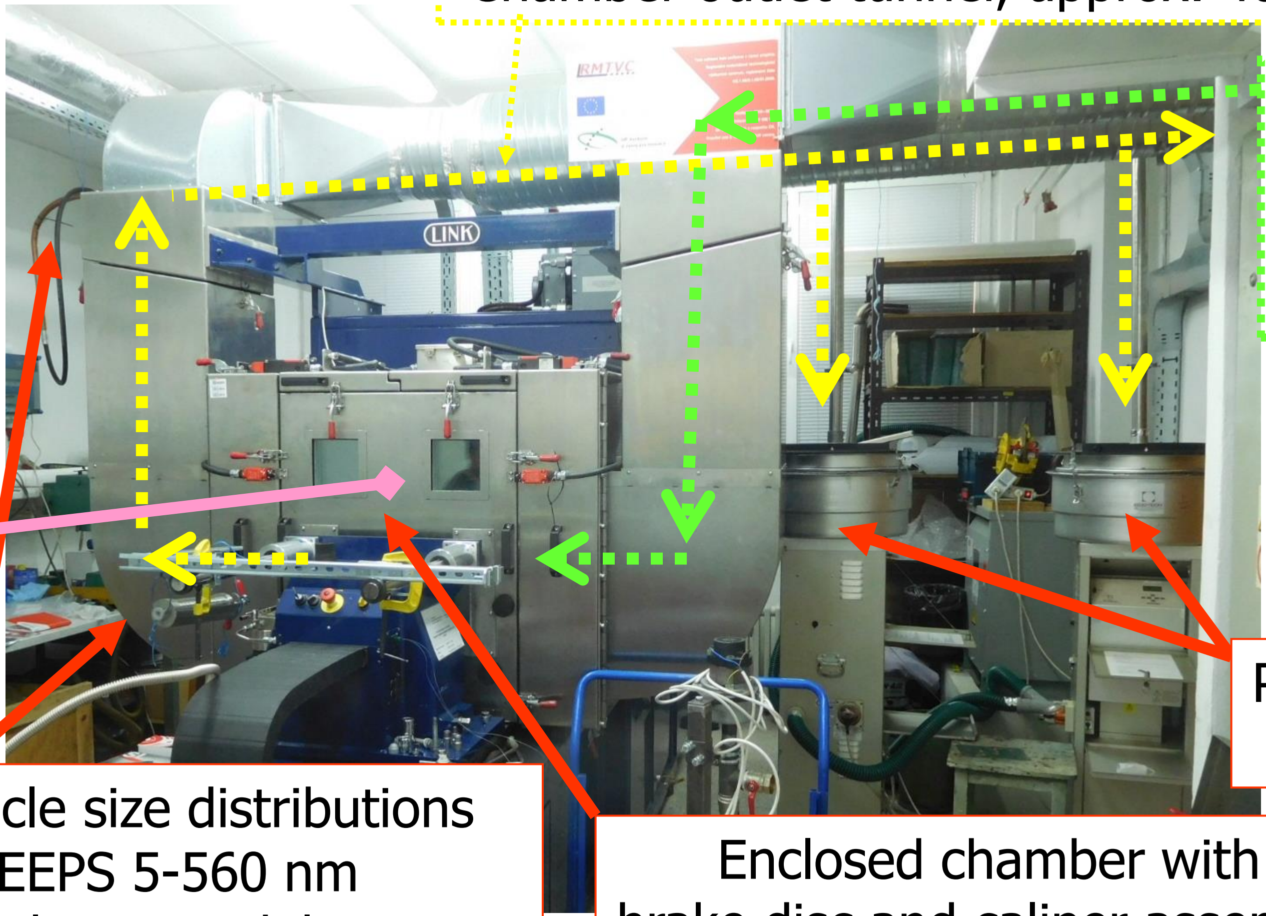
Particle mass - non-linear increase with energy dissipated

Particle number - Steady and low until a given threshold temperature, then increases expponentially with temperature

Brake wear particles measurement setup (TU Ostrava, CZ)

Tunnel and instruments analogous to engine exhaust measurements





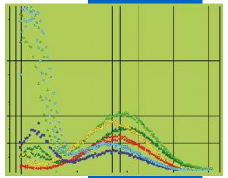
Chamber outlet tunnel, approx. 40 m^3/min flow

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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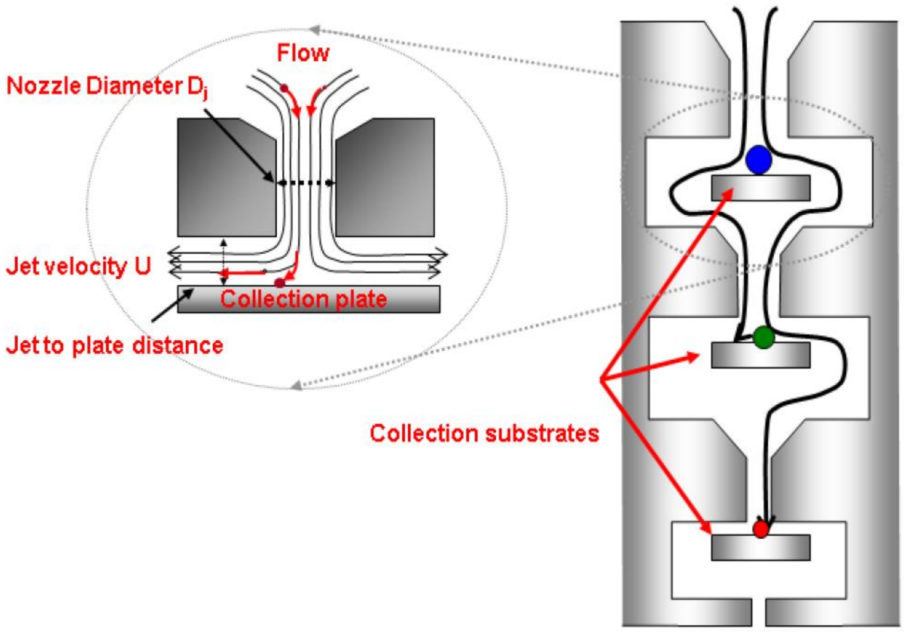
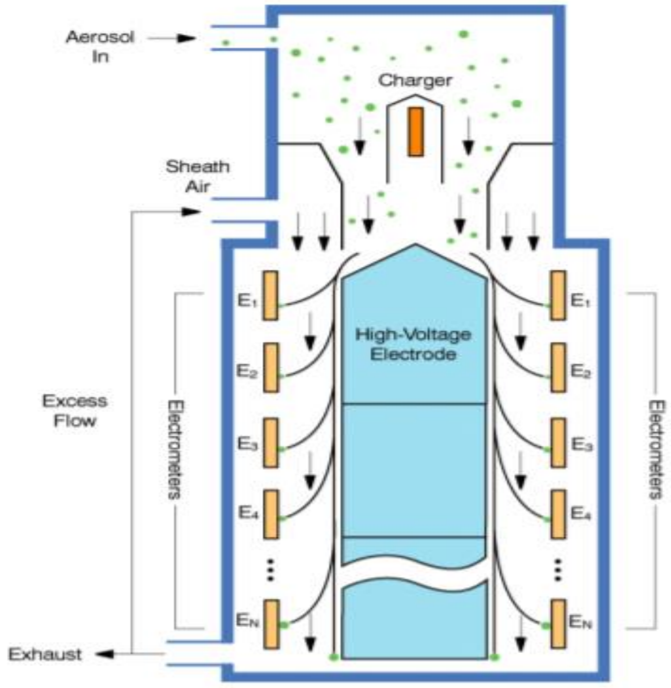
Vojtisek-Lom et al., Science of the Total Environment 788 (2021) 147779

- Rotor and brake assembly enclosed in airtight enclosure.
- Flow rate of 2400 m3/h to provide cooling and remove brake wear particles.
- Part of the outlet duct was replaced by a 30 cm diameter, approximately 5 m long pipe, serving as a dilution tunnel for particulate matter sampling by online particle size classifiers, EEPS and ELPI.



Schematic of ELPI



Schematic of EEPS

Sampling points

Matching instruments

Dilution tunnel

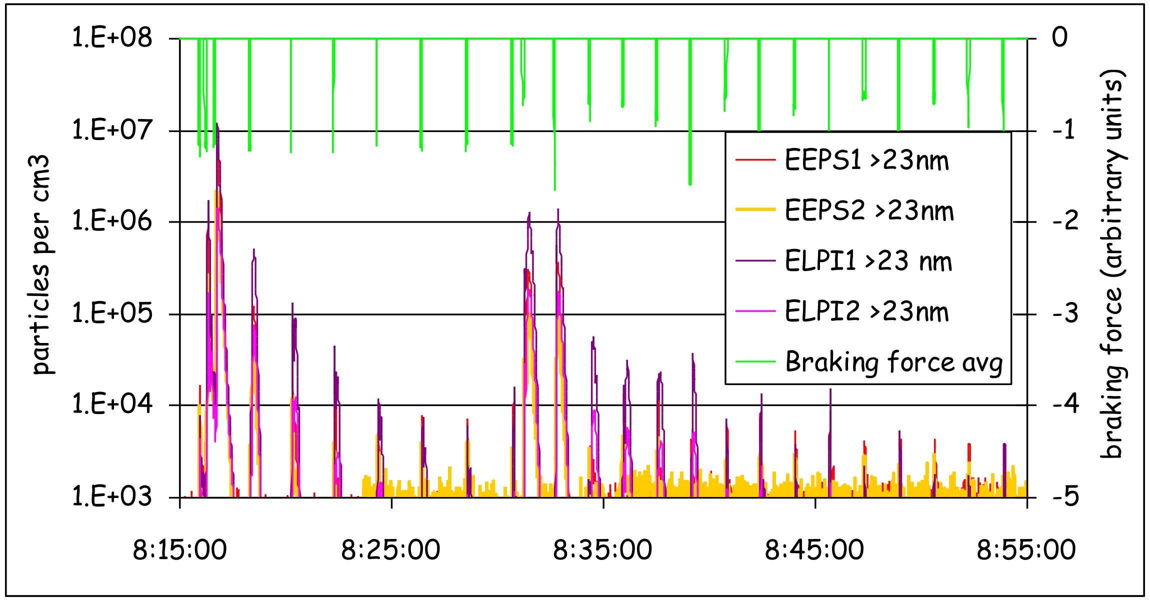
Brake enclosure outlet

Closest to source, low diffusion & settling losses, but is mixing homogeneous? Also, no isokinetic sampling…

Measured & reasonably constant flow
Isokinetic sampling

Sampling location effects
Instrument effects

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

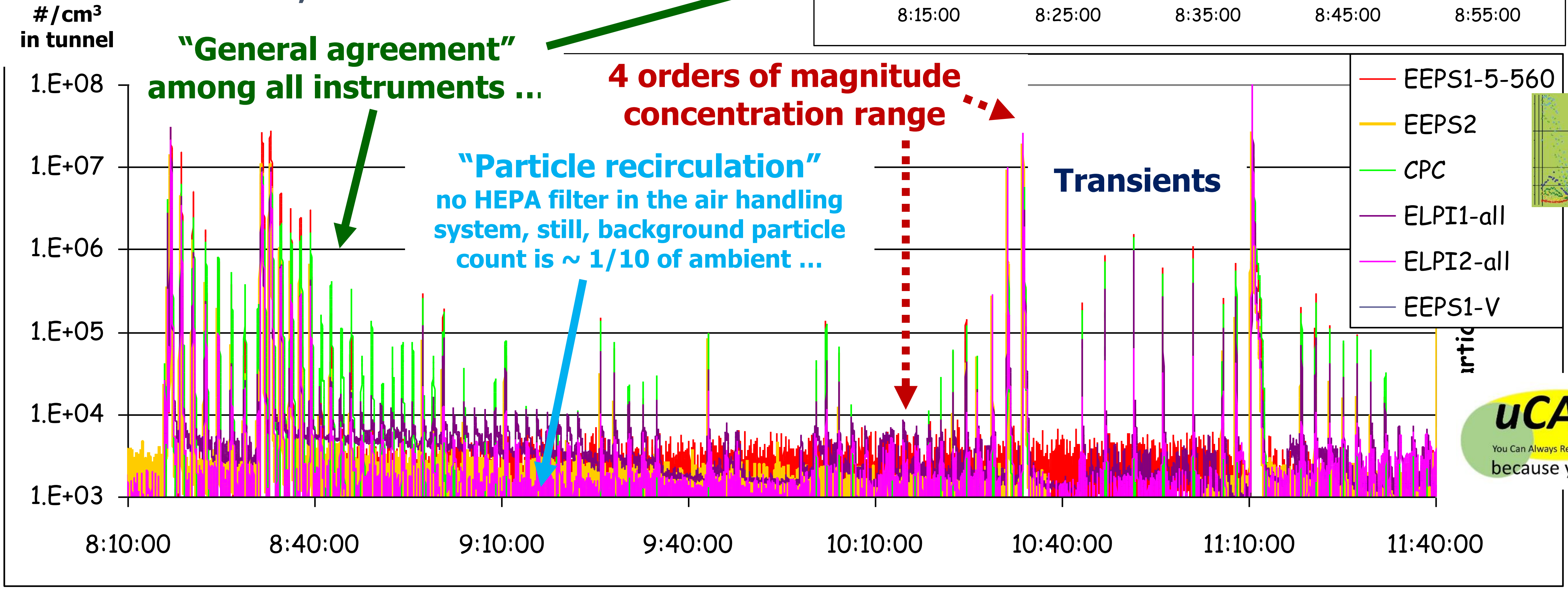


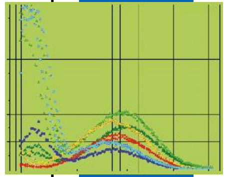
"General agreement" among all instruments …

4 orders of magnitude concentration range

"Particle recirculation"
no HEPA filter in the air handling system, still, background particle count is ~ 1/10 of ambient …

Transients





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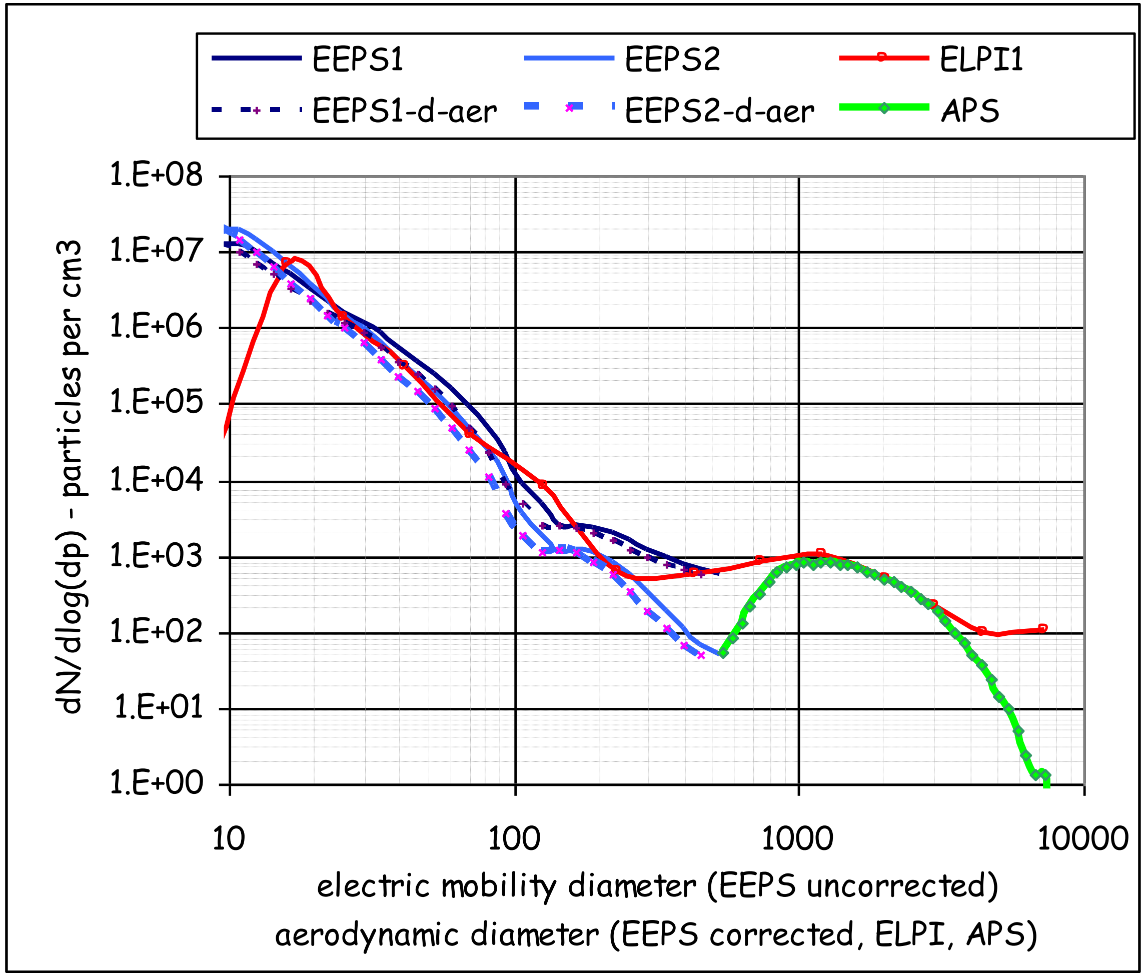
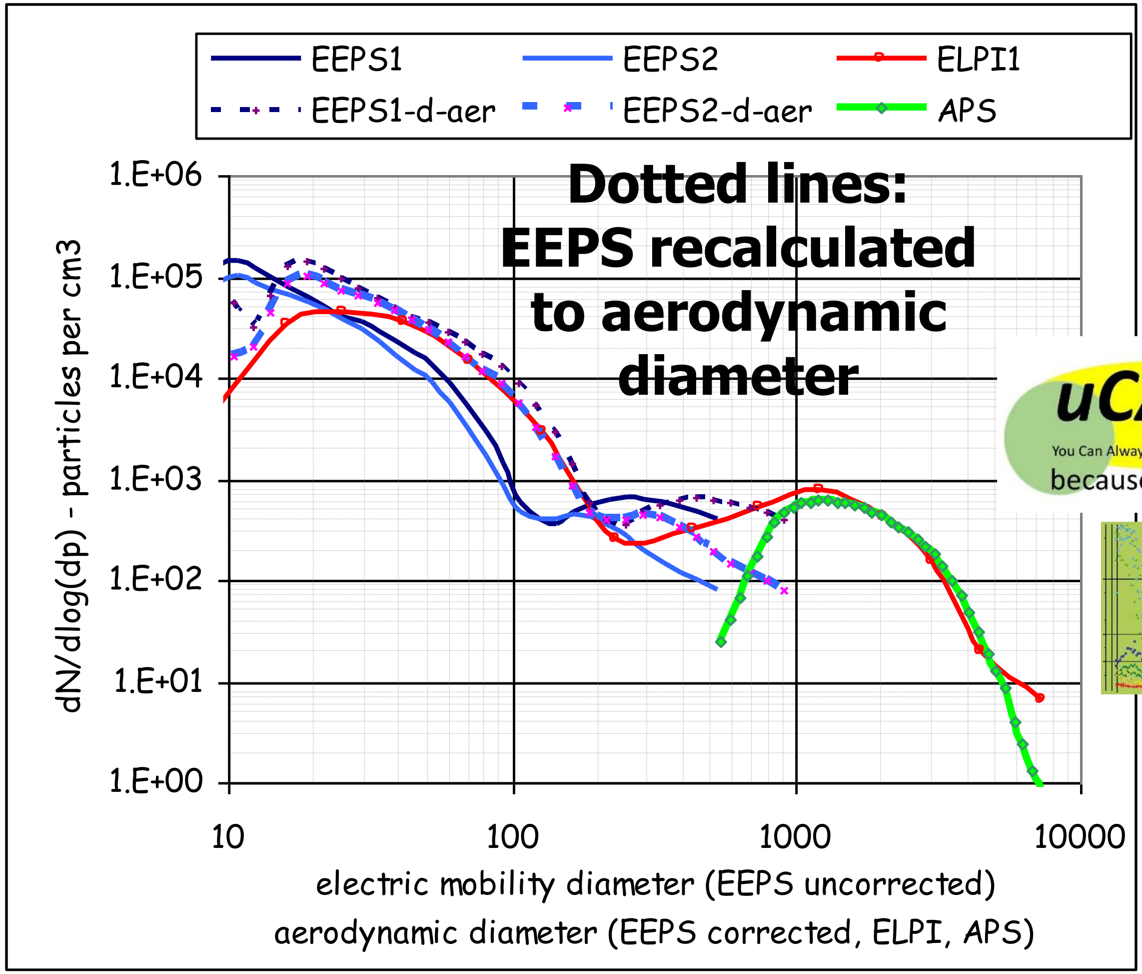
Matching electric mobility (EEPS) vs. aerodynamic (ELPI, APS) diameter





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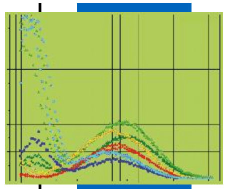

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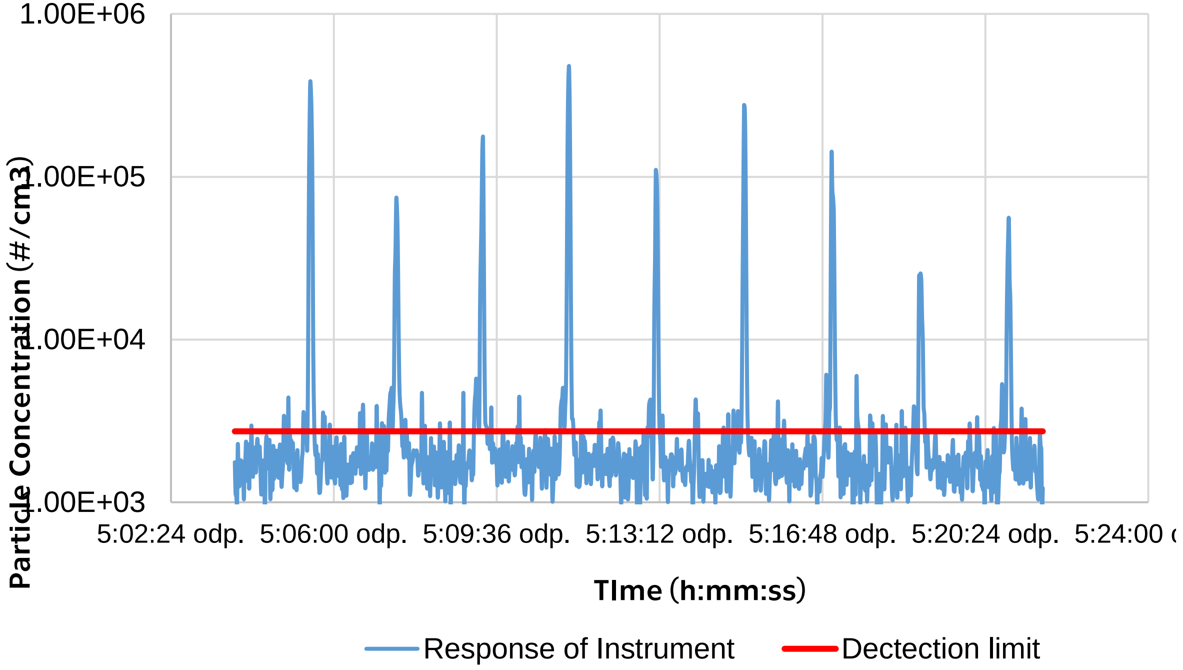
From ISO26867 cycle, 16 bar
Brake pad temperature 256 → 262 C
Assumed eff. particle density of 0.75

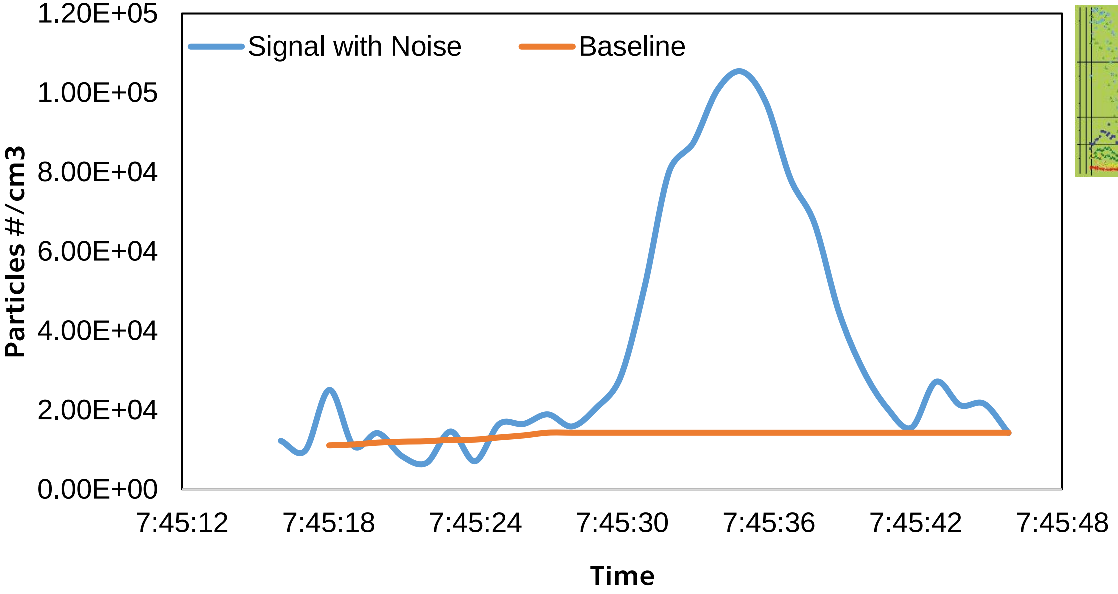
Metal oxides vs. resins
Particle effective density varies !!!

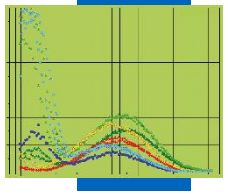
Final stop of the NEDC cycle, 14 bar
Brake pad temperature 155 → 303 C
Assumed eff. particle density of 3.0

Quantifying emissions from short peaks

- 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







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Test cycles and brake pads used in the study

Vojtisek-Lom et al., Science of the Total Environment 788 (2021) 147779

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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 (ºC)	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 (ºC)	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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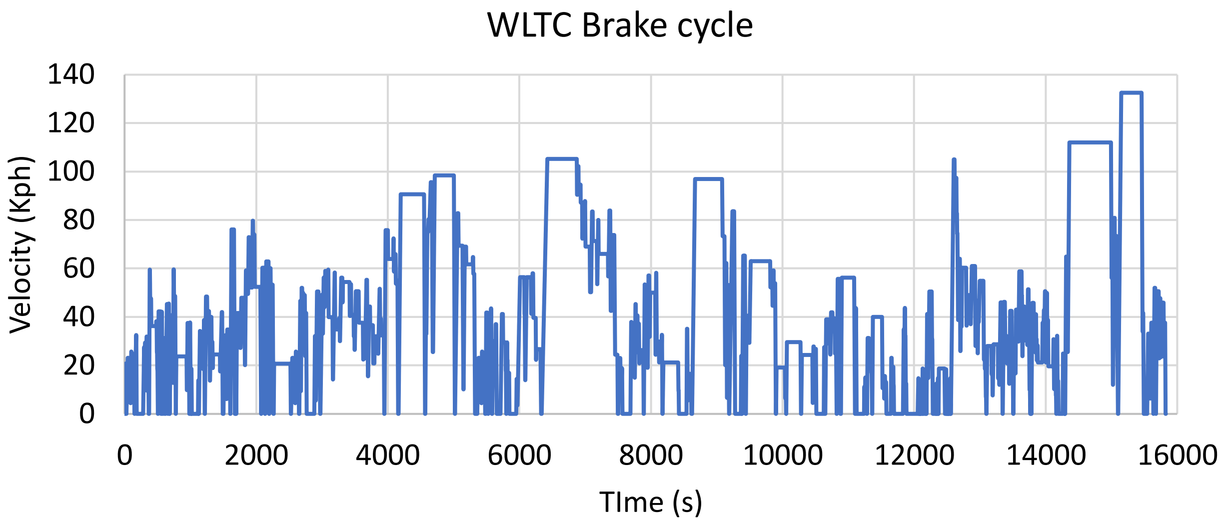
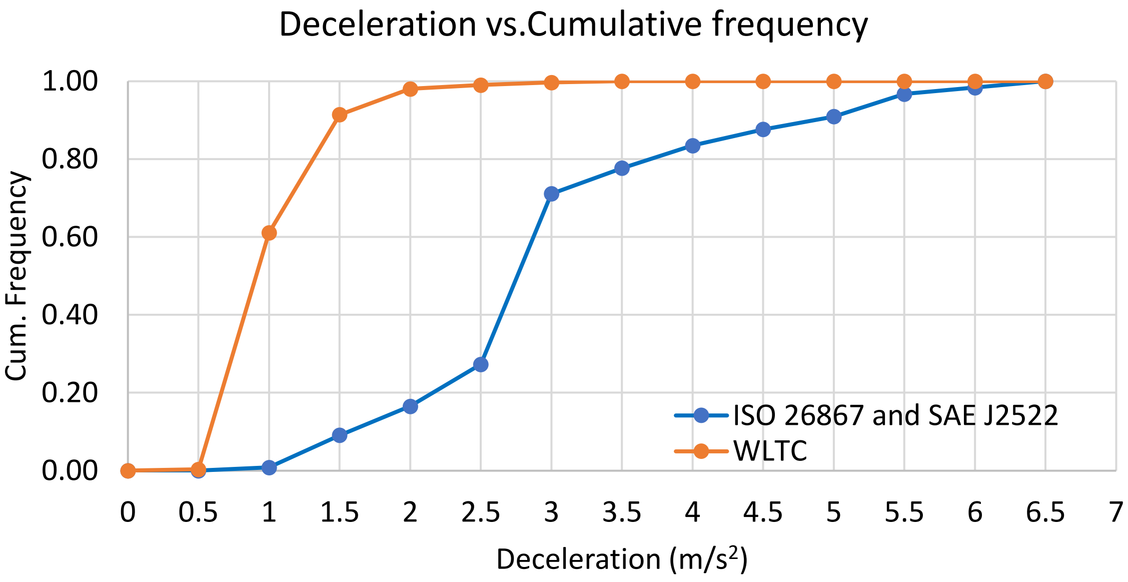
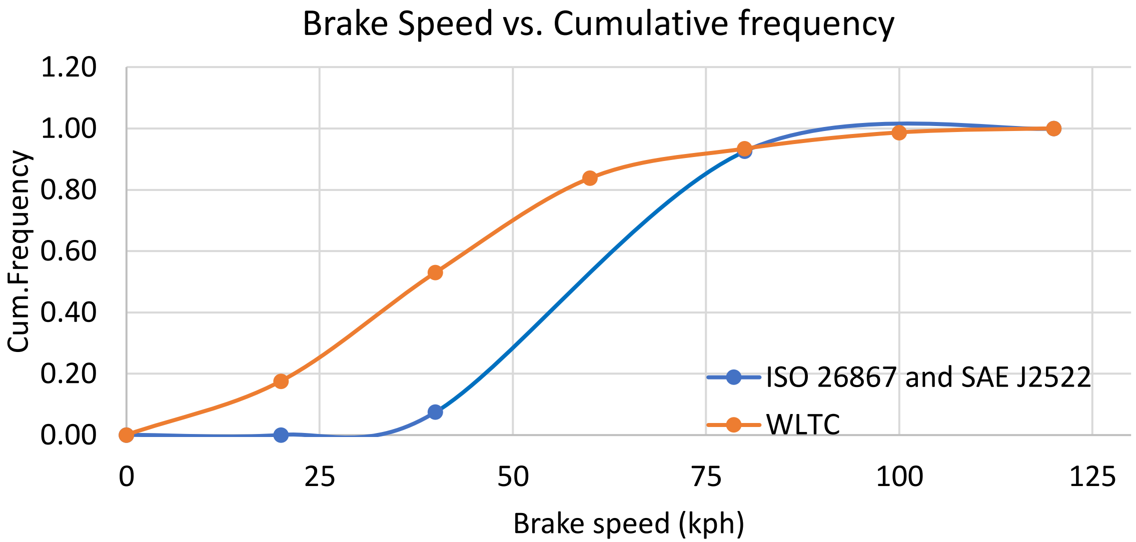
WLTC Brake cycle

- Developed aiming towards reflecting real world braking patterns for brake wear particles sampling and measurement [1].
- 10 segments, distance of 192 km, 303 stops, with max braking speed of 132.5 km/h.

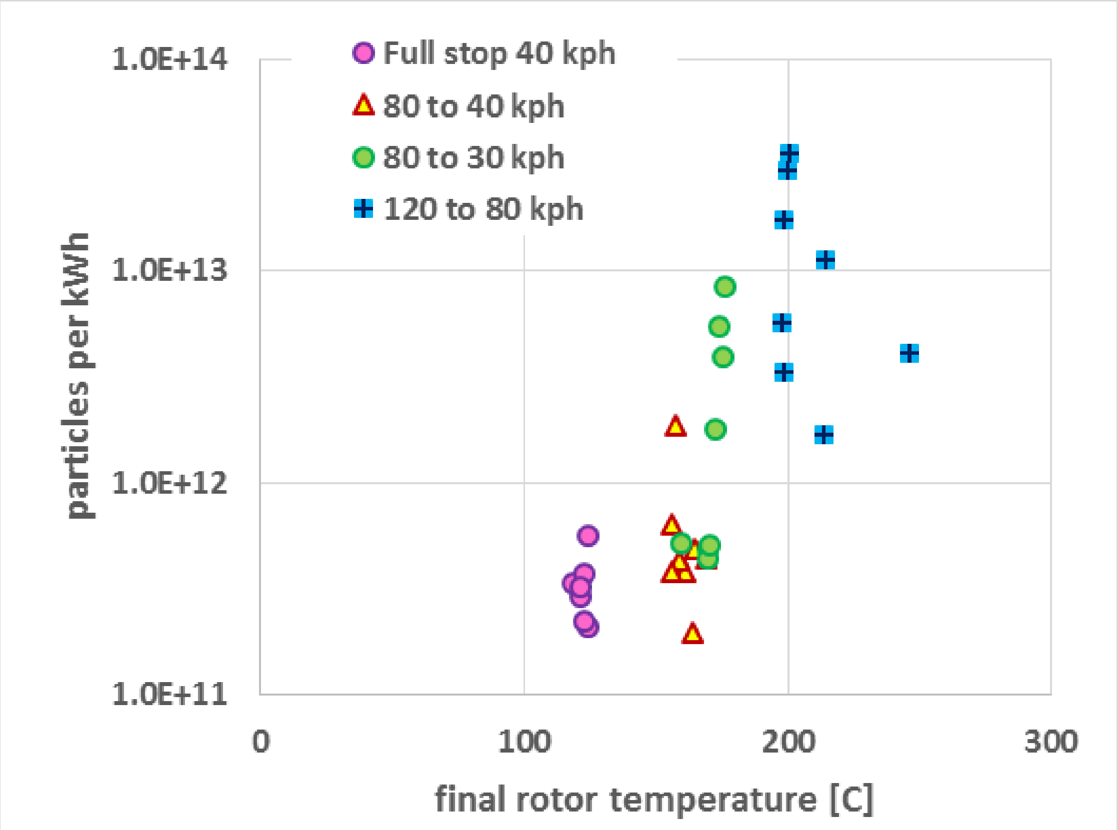


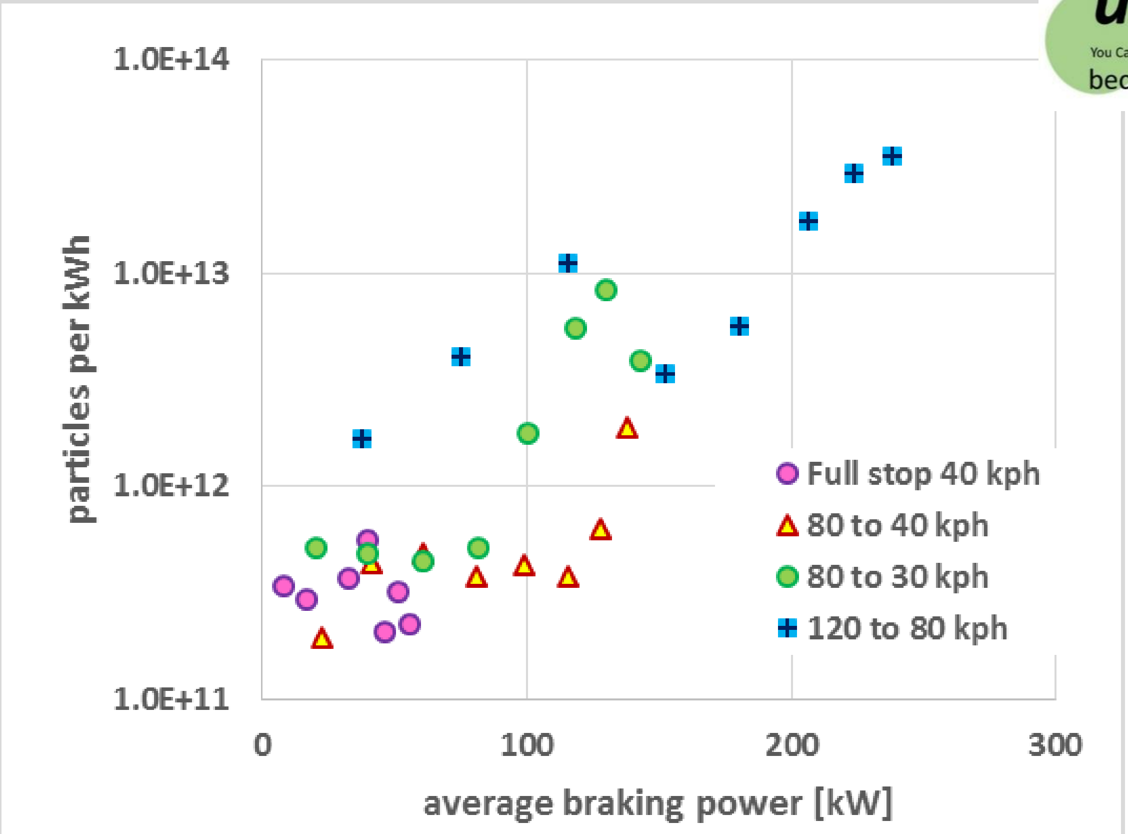




Original („OEM“) pads and rotor, typical mid-size passenger car 1840 kg test weight, 35% braking power on left front wheel

- 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?





Vojtisek-Lom et al., Science of the Total Environment 788 (2021) 147779

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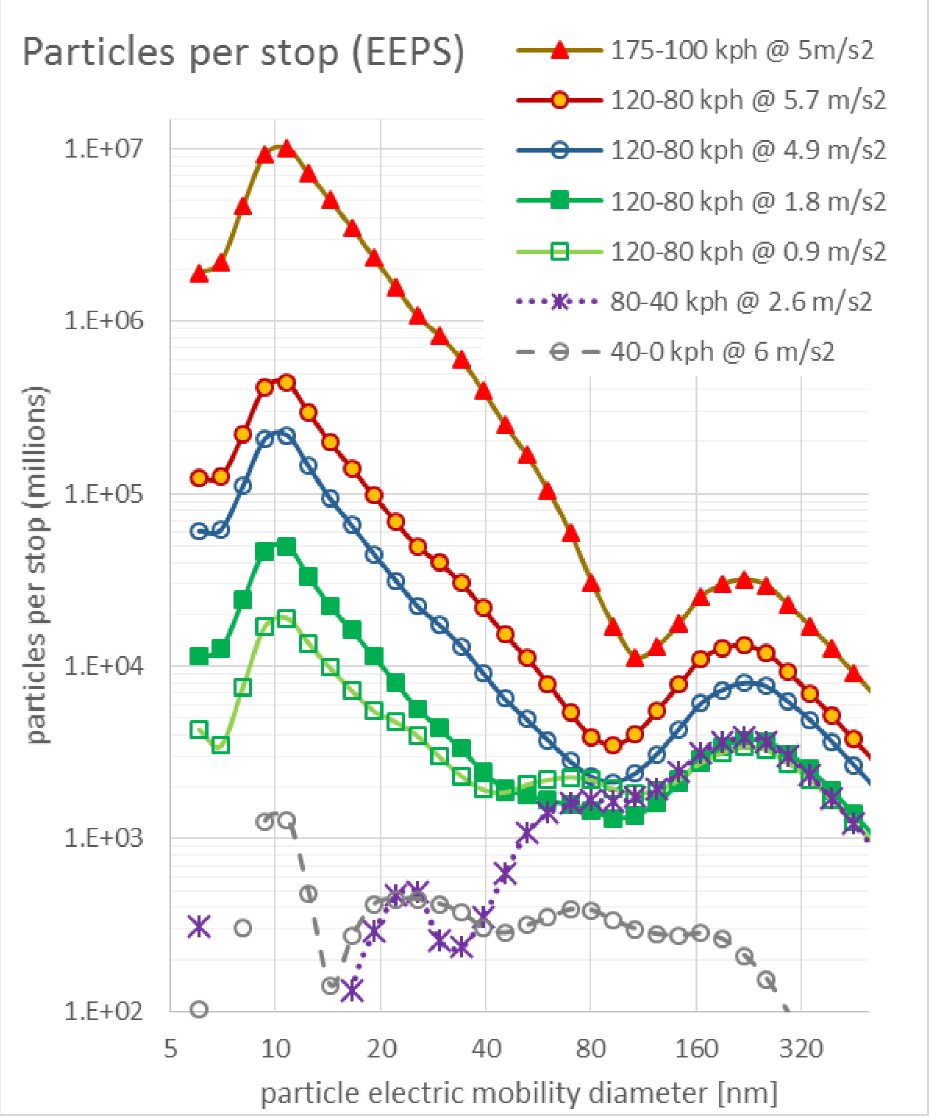
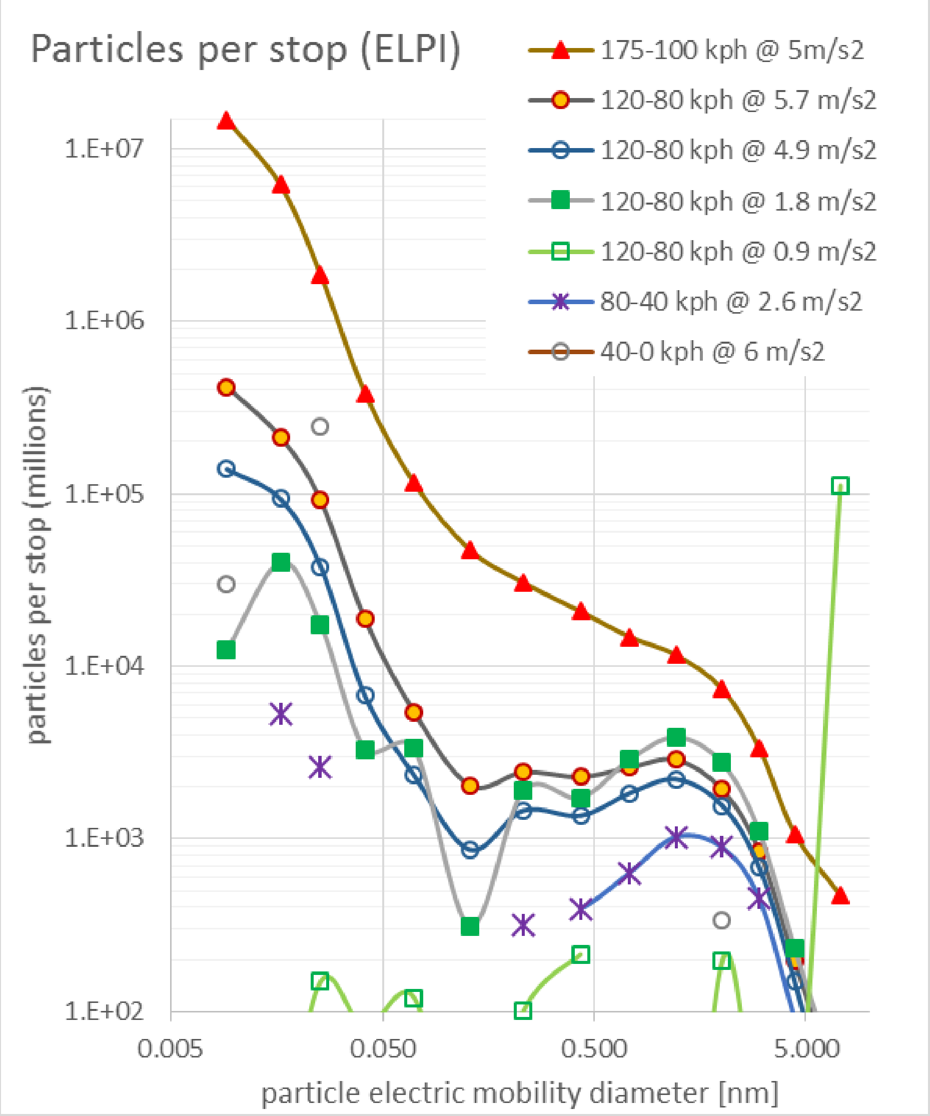
Original („OEM") pads and rotor, typical mid-size passenger car 1840 kg test weight, 35% braking power on left front wheel

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





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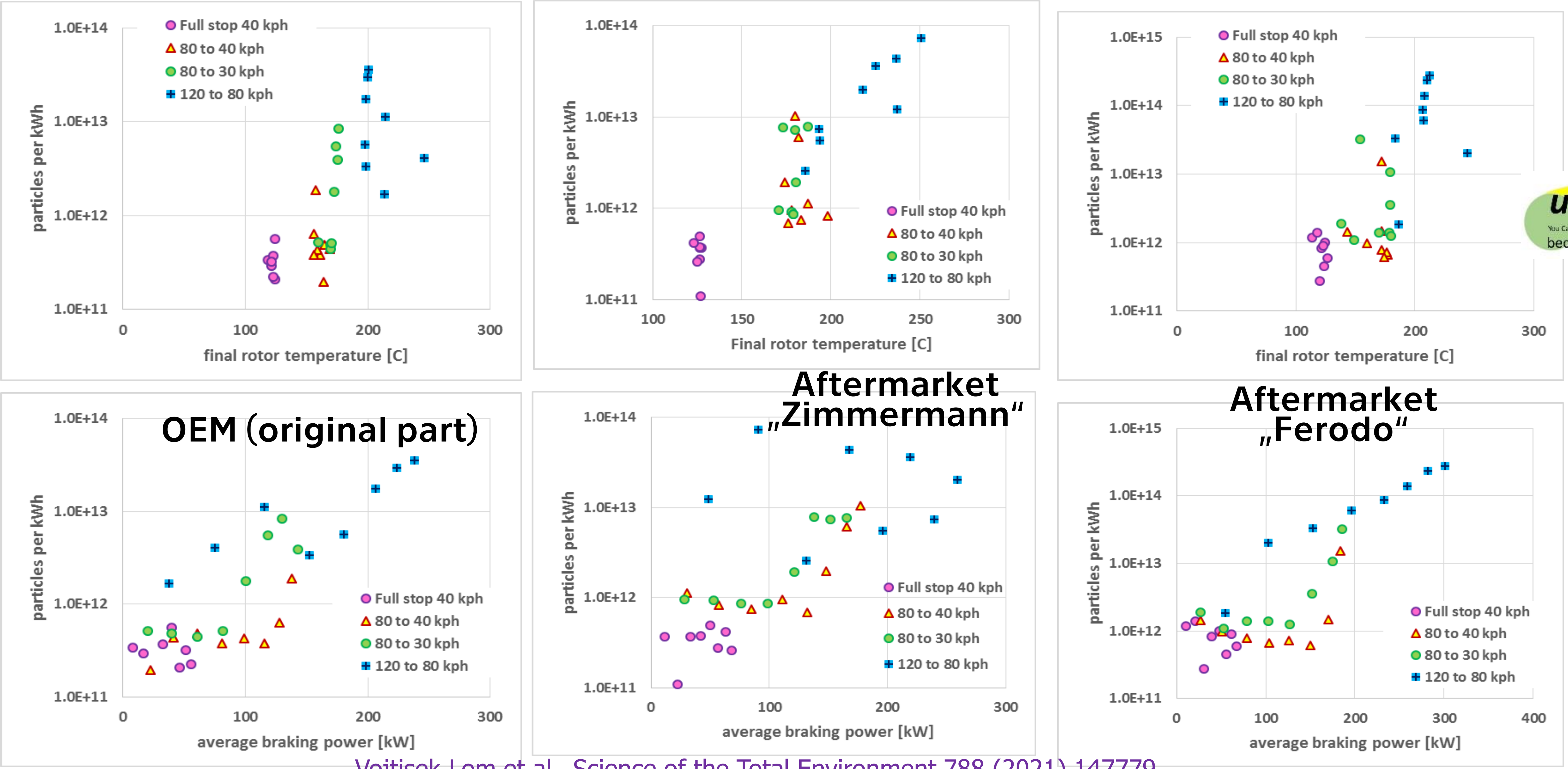

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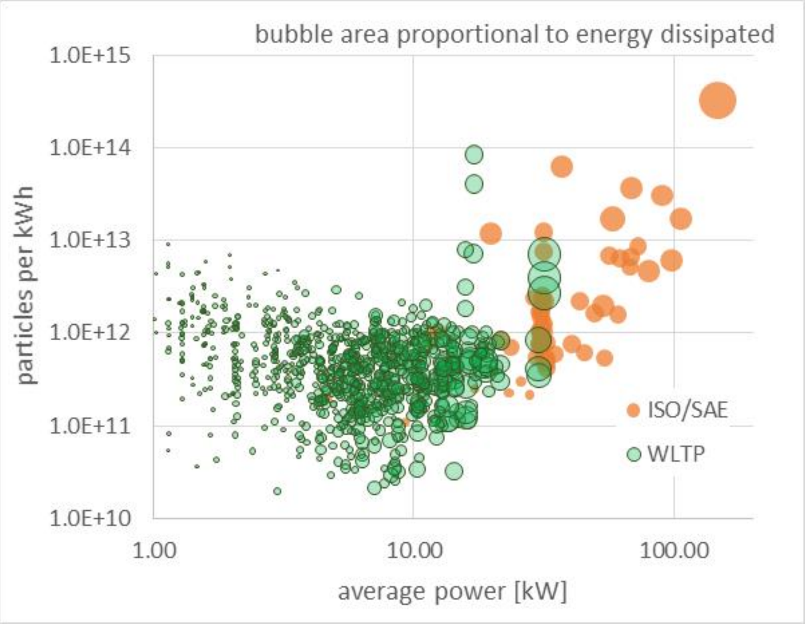
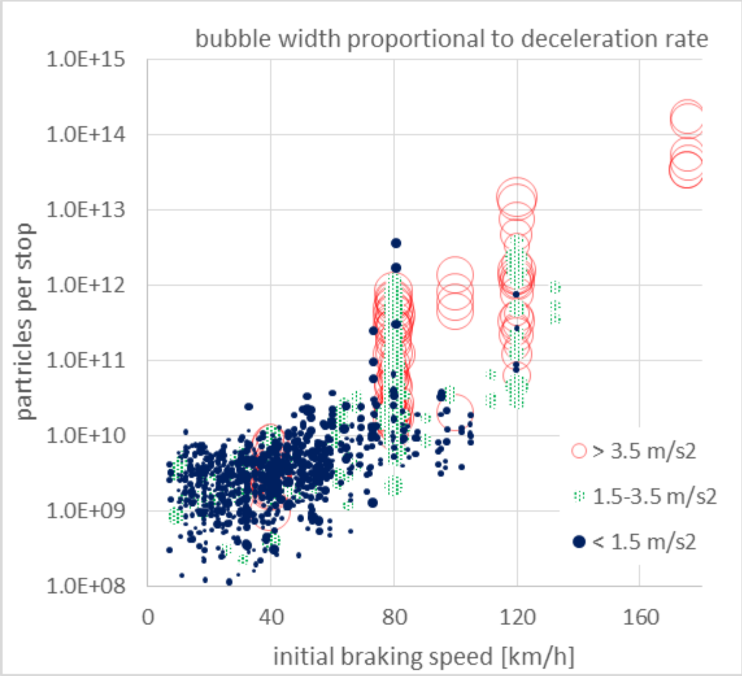
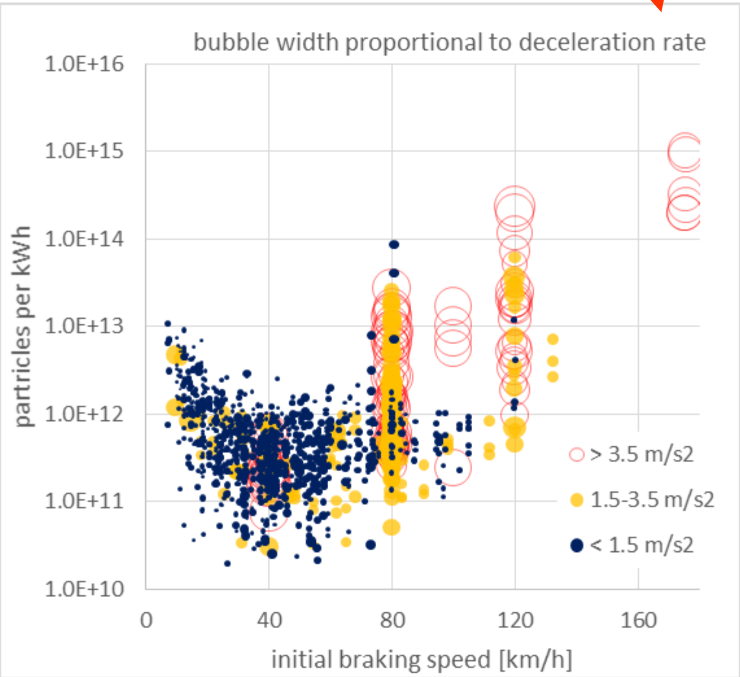
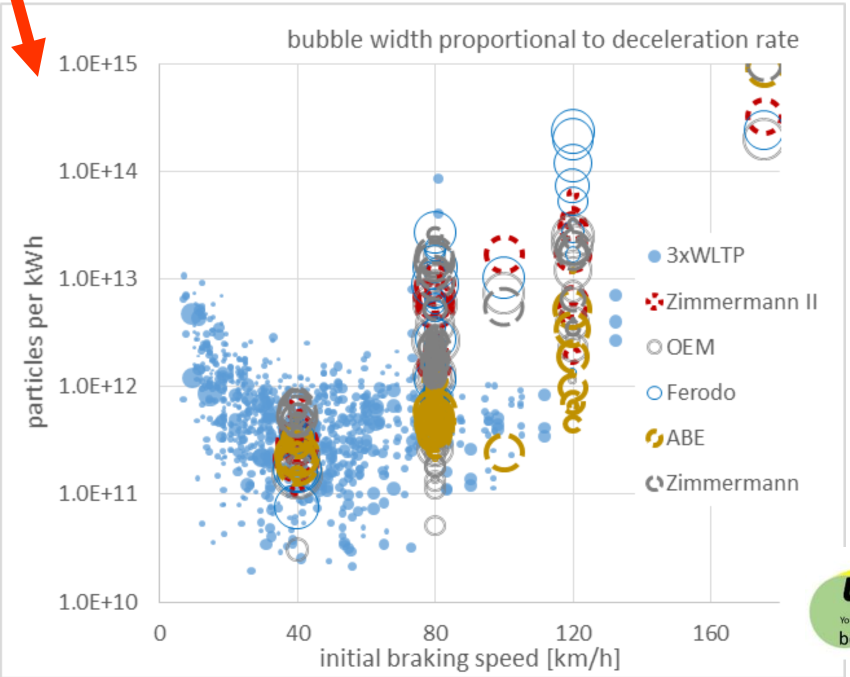
"Off-cycle" emissions
Differences among makes/models
Effect of operating conditions



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







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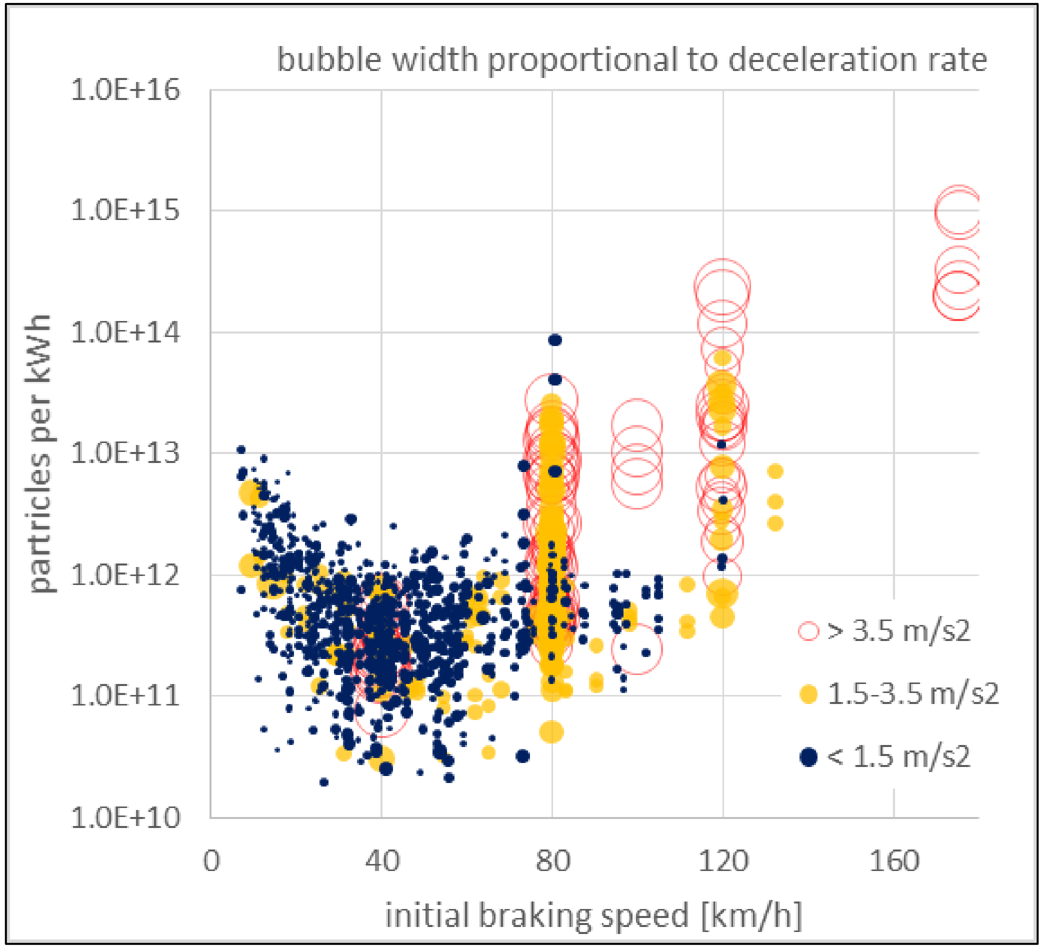
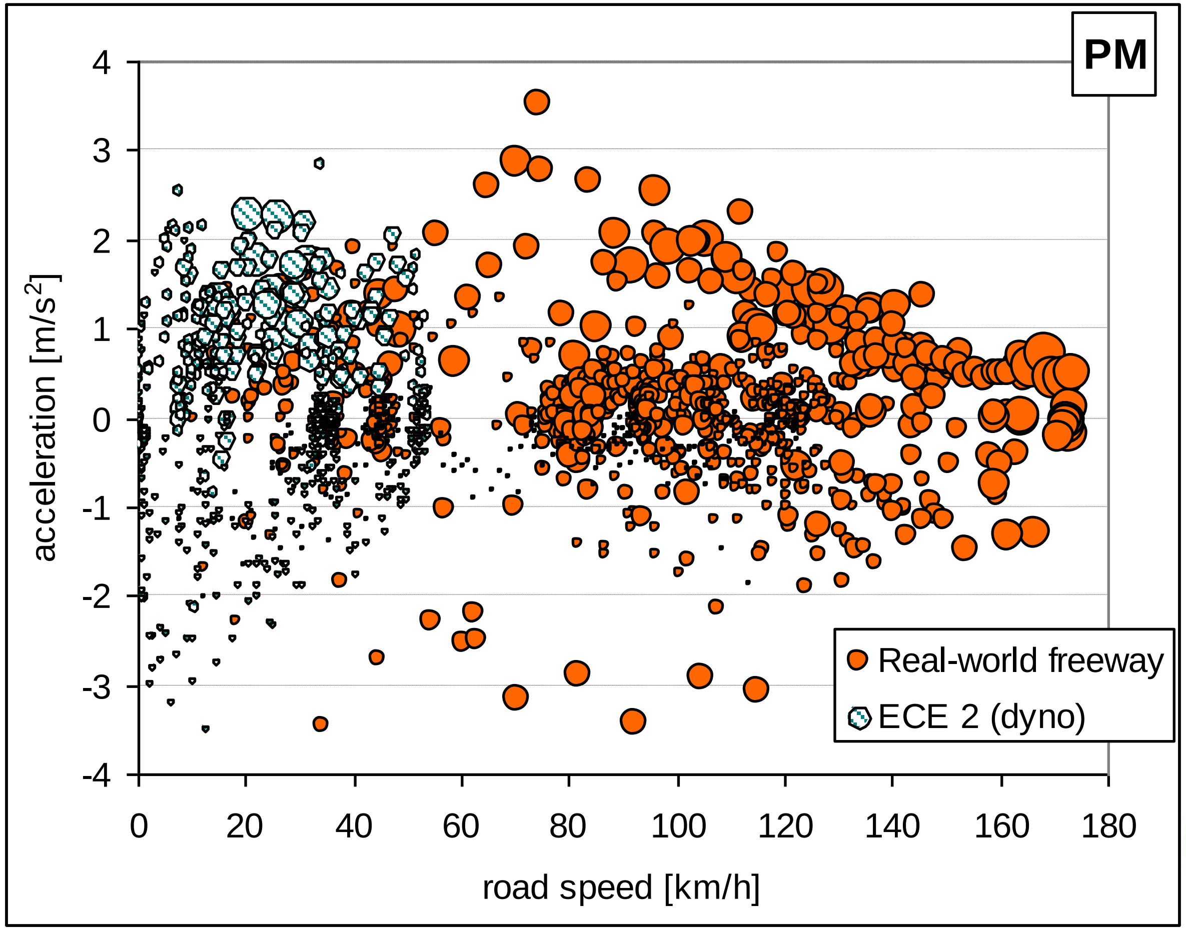
High-speed, high-power driving -> high emissions

- 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???

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

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Source apportionment based brake emissions factors

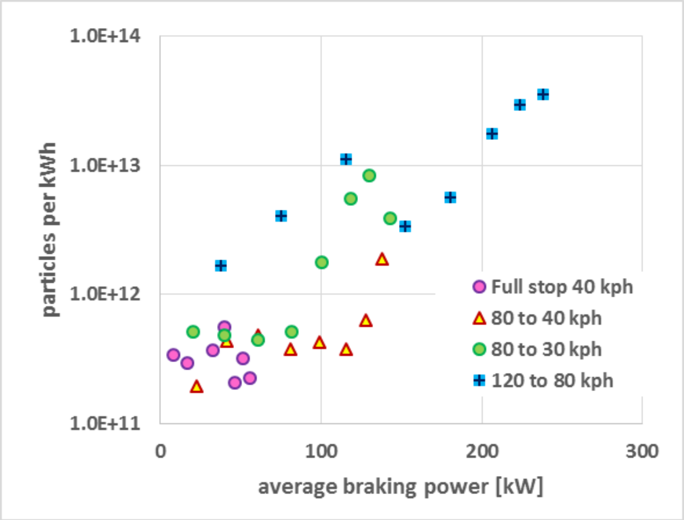
Brake wear emissions factors:

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

Practical recommendations to reduce brake wear particles



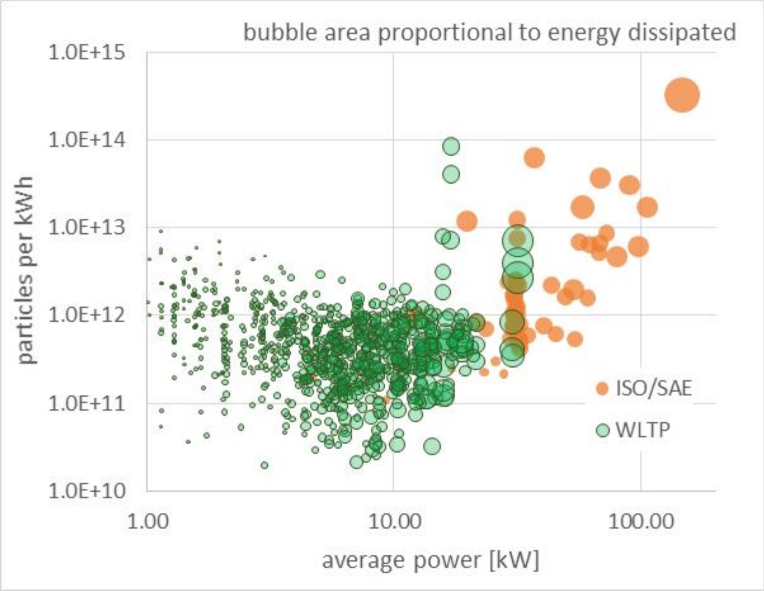
Drive gently, including braking

- 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

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 always reduce emissions
Contact: prof. Michal Vojtisek, +420 774 262 854
michal.vojtisek@fs.cvut.cz, michal.vojtisek@tul.cz

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Souhrn

- Třecí brzdy produkují velmi jemné částice z vysokoteplotních procesů i hrubé částice z mechanických jevů (tření).
- Emise nanočástic jsou značně a nelineárně (převážně exponenciálně) závislé na teplotě, brzdném výkonu, celkové energii převedené na teplo, a dalších; jsou vyšší při vyšších rychlostech a zpomaleních.
- Zatímco emise jsou nízké během WLTP brzdového cyklu, razantnější decelerace z vyšších rychlostí produkují neúměrně vysoké množství nanočástic.
- Emise nanočástic z brzd závisí na stylu jízdy.
- Vysoké rychlosti, zejména na vytíženějších komunikacích, jsou spojeny nejen s vyššími výfukovými emisemi, ale i vyššími emisemi nanočástic z brzd.

Funding: Data získána v rámci GAČR 19-04682S (Biodostupnost antimonu a jeho interakce s prostředím v místech dopravních uzlů) a vyhodnocena pro vliv provozních podmínek v rámci H2020 815002 uCARe – You can always reduce emissions

Contact: prof. Michal Vojtíšek, +420 774 262 854
michal.vojtisek@fs.cvut.cz, michal.vojtisek@tul.cz