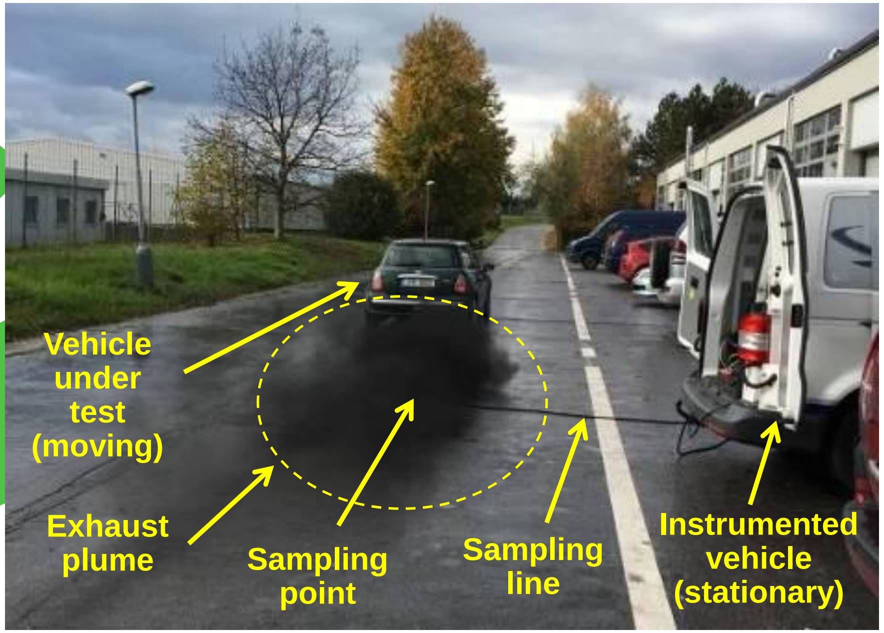
Roadside detection of excess particle emitters: practical limits & potential for "garage-grade" instruments



Michal Vojtisek-Lom[1,2], Martin Pechout[1], Martin Kotek[1], Michal Fleischhans[3], Libor Fleischhans[3]

[1] Czech University of Life Sciences in Prague
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L-vehicles Emissions and Noise mitigation Solutions

CARES

26th ETH Nanoparticles Conference
Zurich, June 20-22, 2023

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Czech (Prague) real driving emissions group

Czech Technical University (CTU) – Automotive Engineering

Czech University of Life Sciences (CZU) - Dept of Vehicles and Ground Transport

Key competences: engines, fuels, combustion, emissions, air quality

real driving emissions – testing and instrumentation

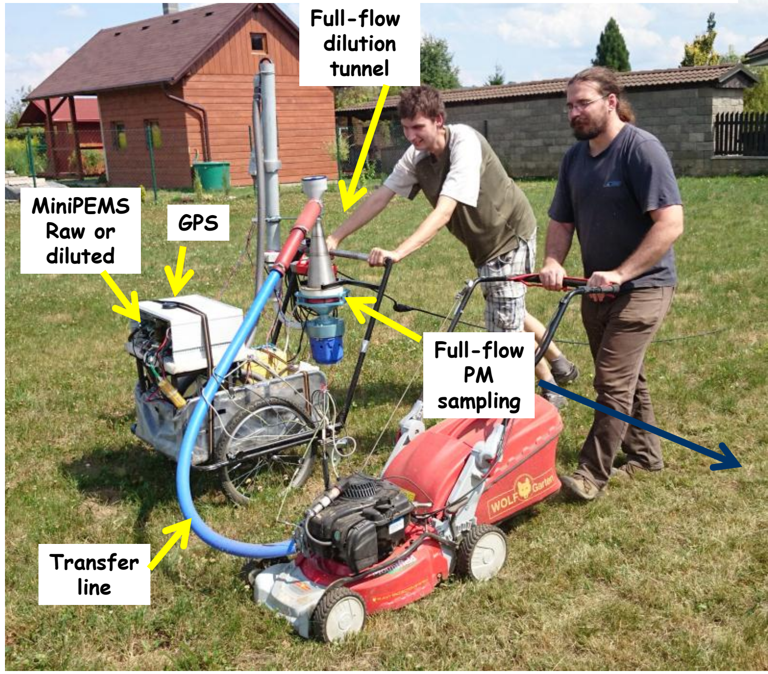
advisory group to City of Prague & Czech Ministry of Environment

in the area of vehicle & engine emissions and related air quality and health issues

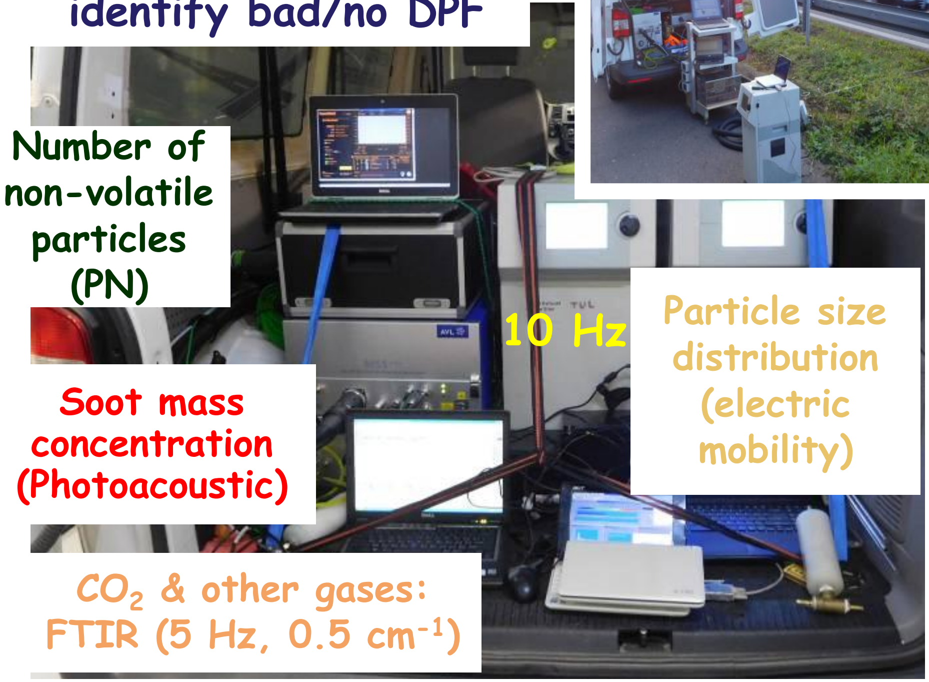
interdisciplinary cooperation – nanoparticles, toxicology,

air quality, sustainable transport

„Real gardening emissions“ measurement with „off-board“ system with full-flow dilution tunnel



Roadside PN & soot measurement to identify bad/no DPF



Poor man's PEMS & Mini-PEMS

NO, NO2, CO, CO2

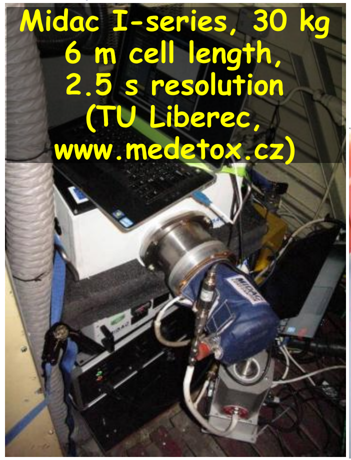
qualitative: PM, PN, HC

calculated exhaust flow

9 kg, 3 hr run time

Portable on-board FTIR analyzers

(NO, NO2, NH3, ..., CO2, CH4, N2O)



Nicolet Antaris IGS, 70 kg

5 m cell length, 1 s resolution

Goal: Practical, affordable measurement. Variances among engines and magnitude of excess emissions are much higher than instrument uncertainty

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We drive cars (trucks, locomotives, …) to show that driving cars is bad for the environment.

Portable NDIR and FTIR for real-world emissions tests
@ Czech Univ of Life Sciences, Czech Tech Univ, TU Liberec

NO, NO_2, CO, CO_2, qualitative PM, PN, HC
calculated exhaust flow, 9-15 kg, 3 hr run time

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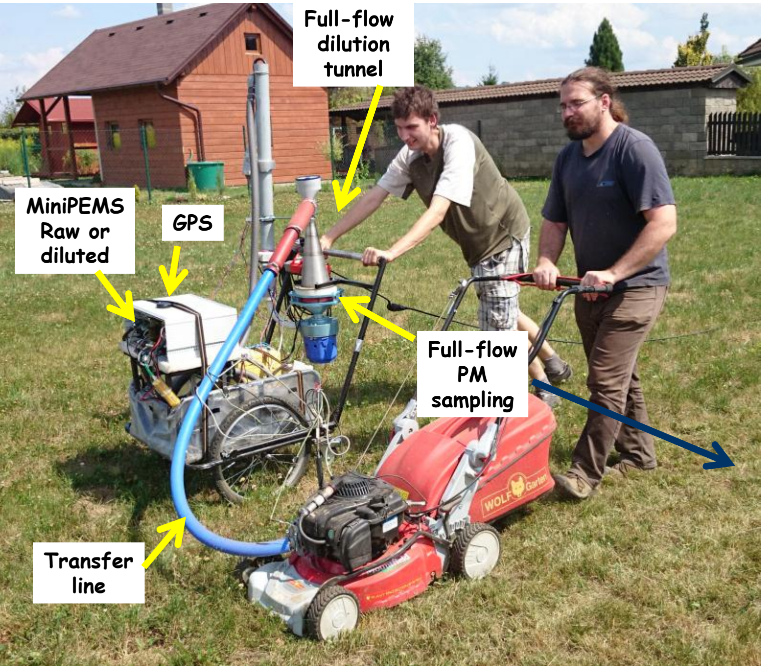
Goal: Practical, affordable measurement.
Variances among engines and magnitude of excess emissions are much higher than instrument uncertainty

„Real gardening emissions“ measurement with „off-board“ system with full-flow dilution tunnel



On-board FTIR analyzers – regulated & unregulated gaseous pollutants: NO, NO_2, NH_3, CH_4, N_2O, CO, CO_2, …

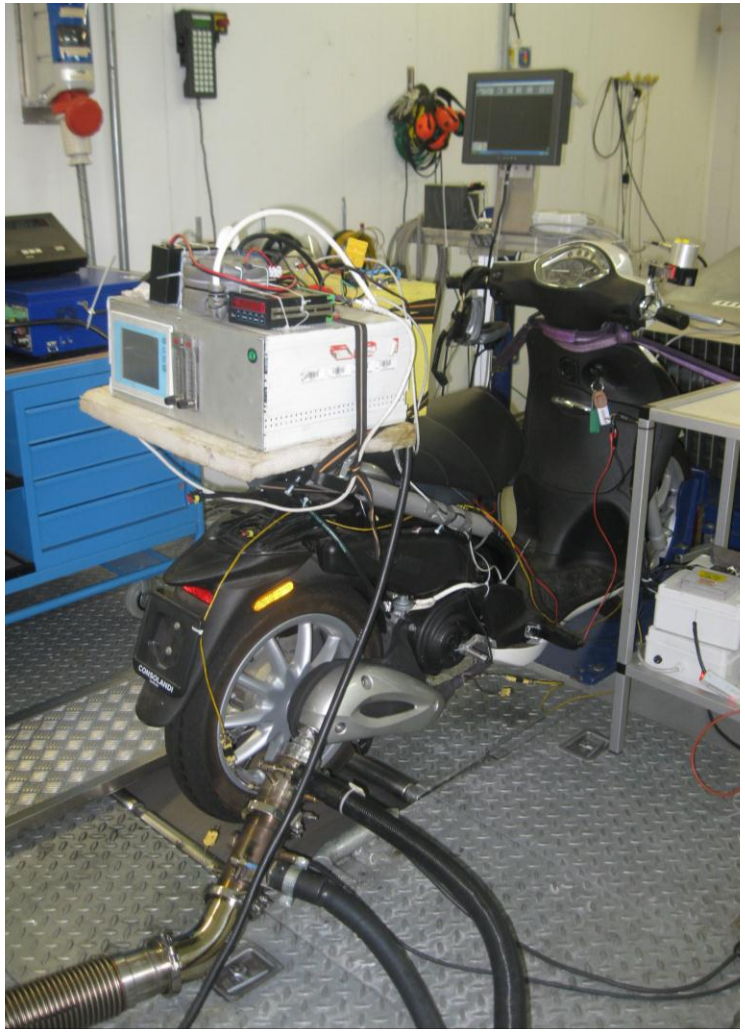
Nicolet Antaris IGS, 70 kg
5 m cell length, 1 s resolution

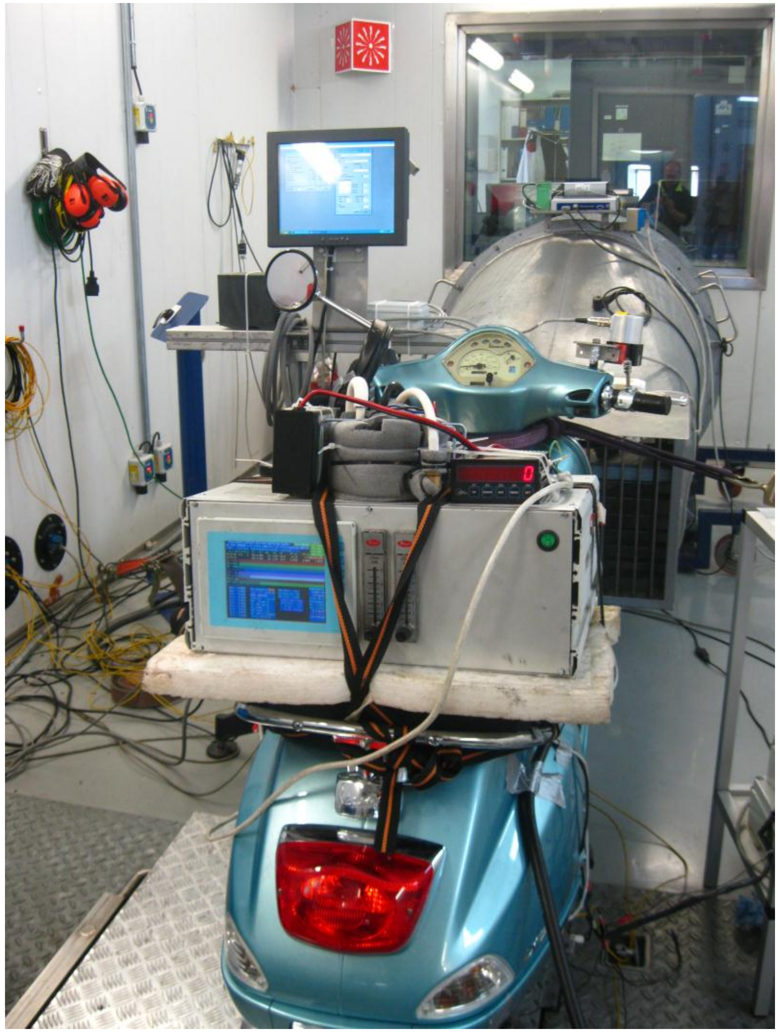
Bruker Matrix MG-5. 5 m cell length.

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

This work in general: Moped, motorcycle (L-cat vehicle) emissions

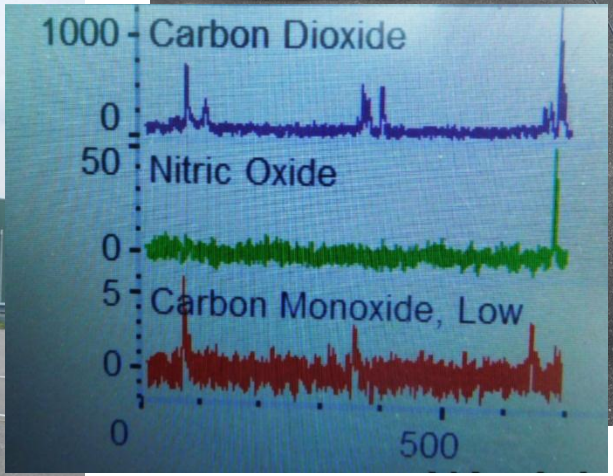
* measurement of exhaust flow: see poster P-27 *





VOJTISEK-LOM, Michal, et al. *Atmospheric Measurement Techniques*, 2020, 13.11: 5827-5843.

Goal of this work: Remote sensing of L-category vehicle particle emissions



City Air Remote Emissions Sensing – CARES – project campaign at Lelystad, NL, July 2021

Moped and motorcycle were more challenging than larger vehicles …

LENS L-vehicles Emissions and Noise mitigation Solutions

CARES

www.cares-project.eu

26th ETH Nanoparticles Conference
Zurich, June 20-22, 2023

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The issue of high emitters

- The higher the emissions benefits due to advanced technologies, the higher is the potential for emissions increase due to tampering, malfunction, wear
- Small fraction of high emitters = large fraction of total fleet emissions
- DPF 99% efficient, 1% DPF broken => broken DPF double the fleet emissions
- DPF 99% efficient, 1% DPF removed due to excess (10x) engine-out PM emissions => broken DPF increase fleet emissions 10x
- TNO roadside study: 5% DPF on EU cars defective

What pollutants (out of regulated):

Diesel:

- PM (DPF, injection system)
- NOx (EGR, LNT, SCR)

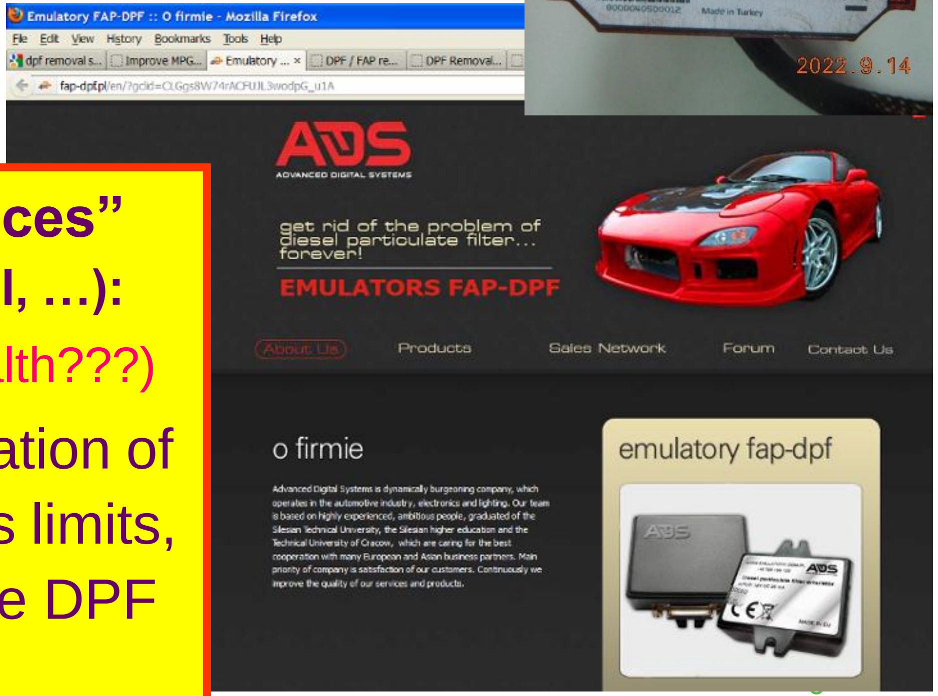
Positive ignition:

- HC, CO (TWC, air-fuel)
- NOx (TWC, EGR)

DPF, SCR "defeat services" (removal, emulation, rental, …):

(Organized crime against health???)

Do we mandate the installation of DPF through PN emissions limits, but then effectively tolerate DPF removal?



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Czech Republic periodic emissions inspection failure rates

All CZ LDV inspections on record in year 2018

2.27% CZ average fail rate (Germany: 6.7%)

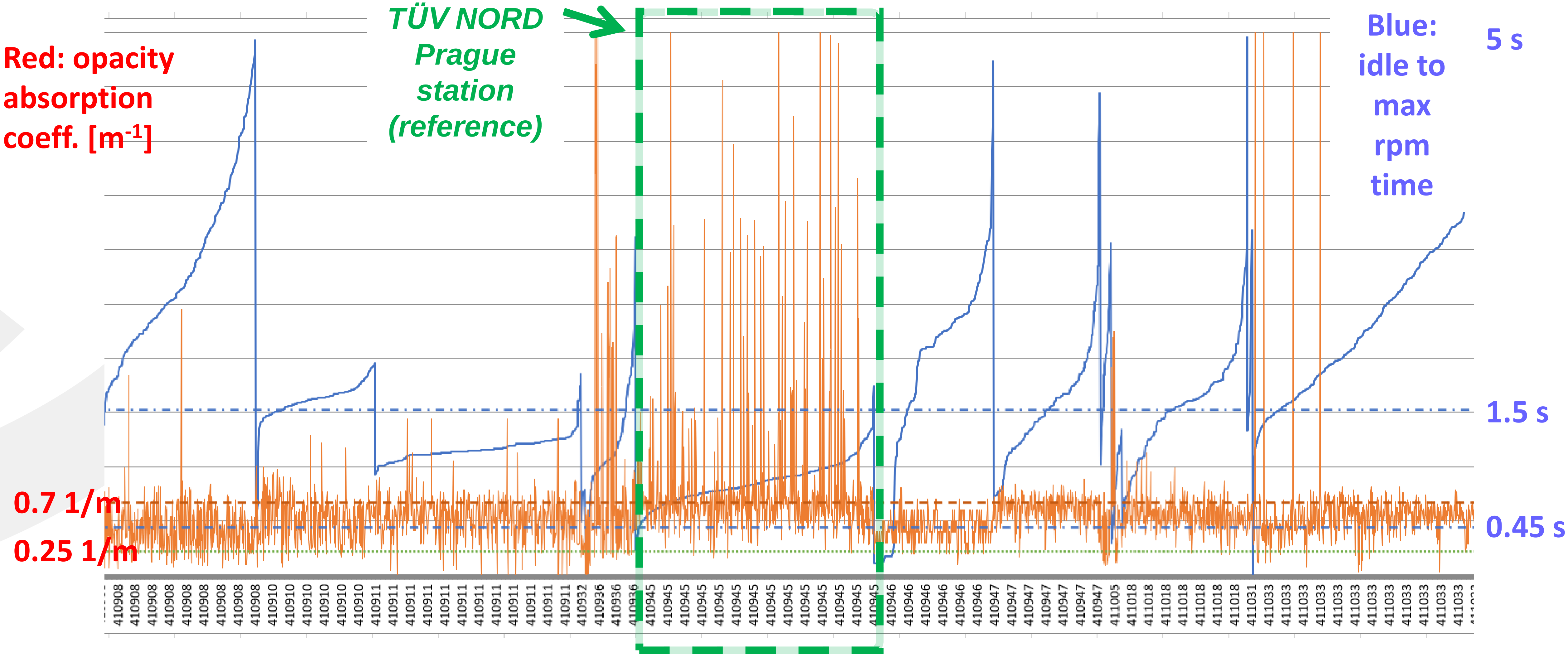
SCR emulator found on a truck during remote sensing campaign and confiscated by the police, Sept 14, 2022

Top 10 inspection stations with lowest fail rates

	City or county where the station is located	Number of vehicles passed	Number of vehicles failed	Mean age [years]	failed (%)
1	Mladá Boleslav	5628	3	14,3	0,05 %
2	Praha	10418	15	11,7	0,14 %
3	Praha	5786	9	14,1	0,16 %
4	Karlovy Vary	11281	24	12,2	0,21 %
5	Praha	8711	21	11,3	0,24 %
6	Praha	11610	29	12,0	0,25 %
7	Kladno	8681	25	12,7	0,29 %
8	Benešov	7578	23	14,2	0,30 %
9	Pardubice	5990	20	15,5	0,33 %
10	Ústí nad Orlicí	5409	21	13,9	0,39 %

Source: Data from Ministry of Transport database analyzed by the Czech Association of Emissions Technicians (ASEM)
http://www.asem.cz/uploads/3/9/3/1/39314181/pr%CC%8Ci%CC%81loha_3_-_statistika_istp_sme.pdf

Czech Republic periodic emissions inspection data example
VW AGR diesel engine data, sorted by technician and accel time

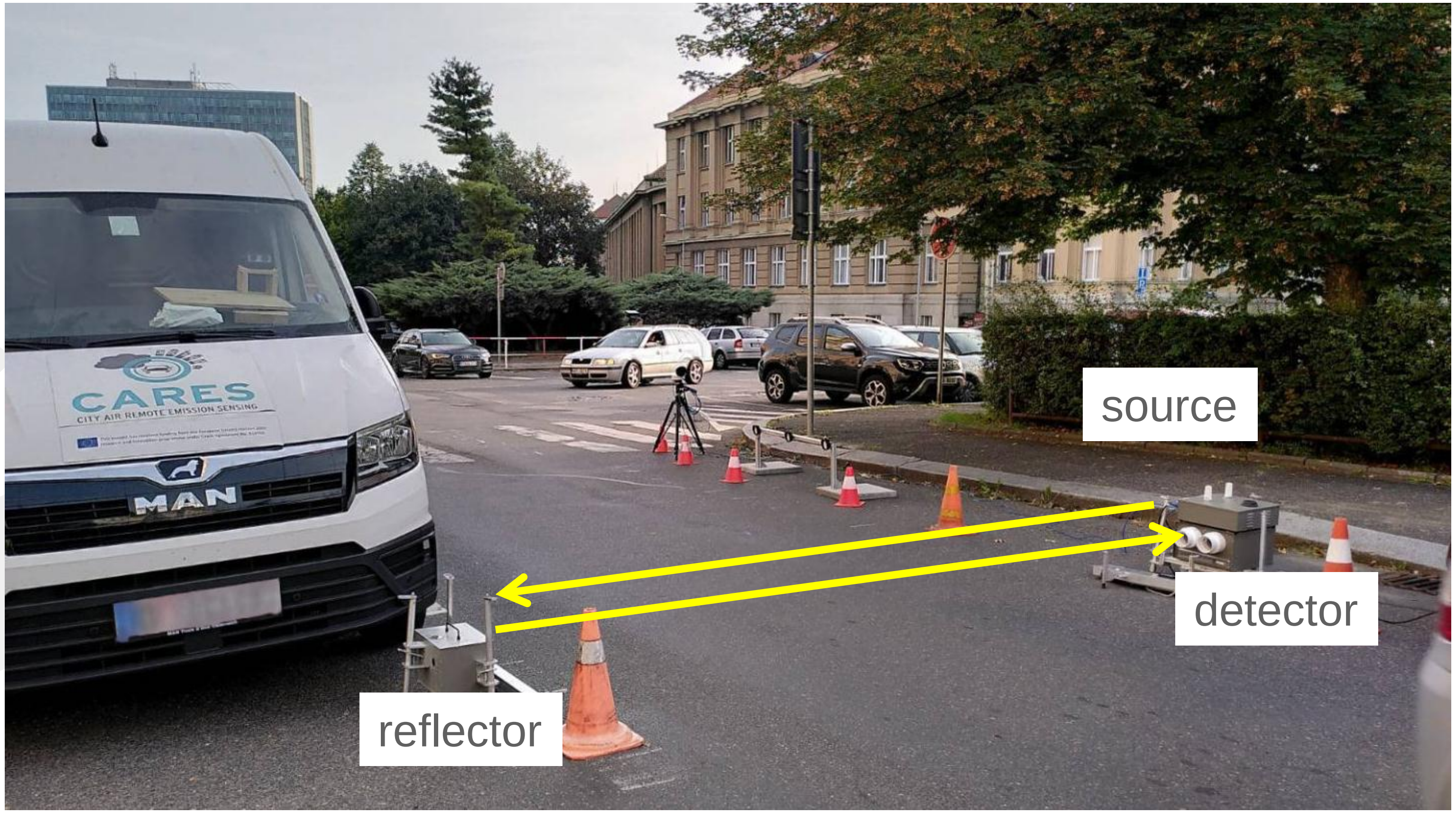


Source: Data from Ministry of Transport database analyzed by the Czech Association of Emissions Technicians (ASEM)
http://www.asem.cz/uploads/3/9/3/1/39314181/pr%CC%8Ci%CC%81loha_3_-_statistika_istp_sme.pdf

Traditional remote sensing of vehicle emissions: open-path transmission / absorption spectroscopy

(NDIR – HC,CO,CO_2; NDUV – NO,NO_2,NH_3; "opacity" – black carbon)

… nowadays tunable diode laser and other spectroscopic techniques



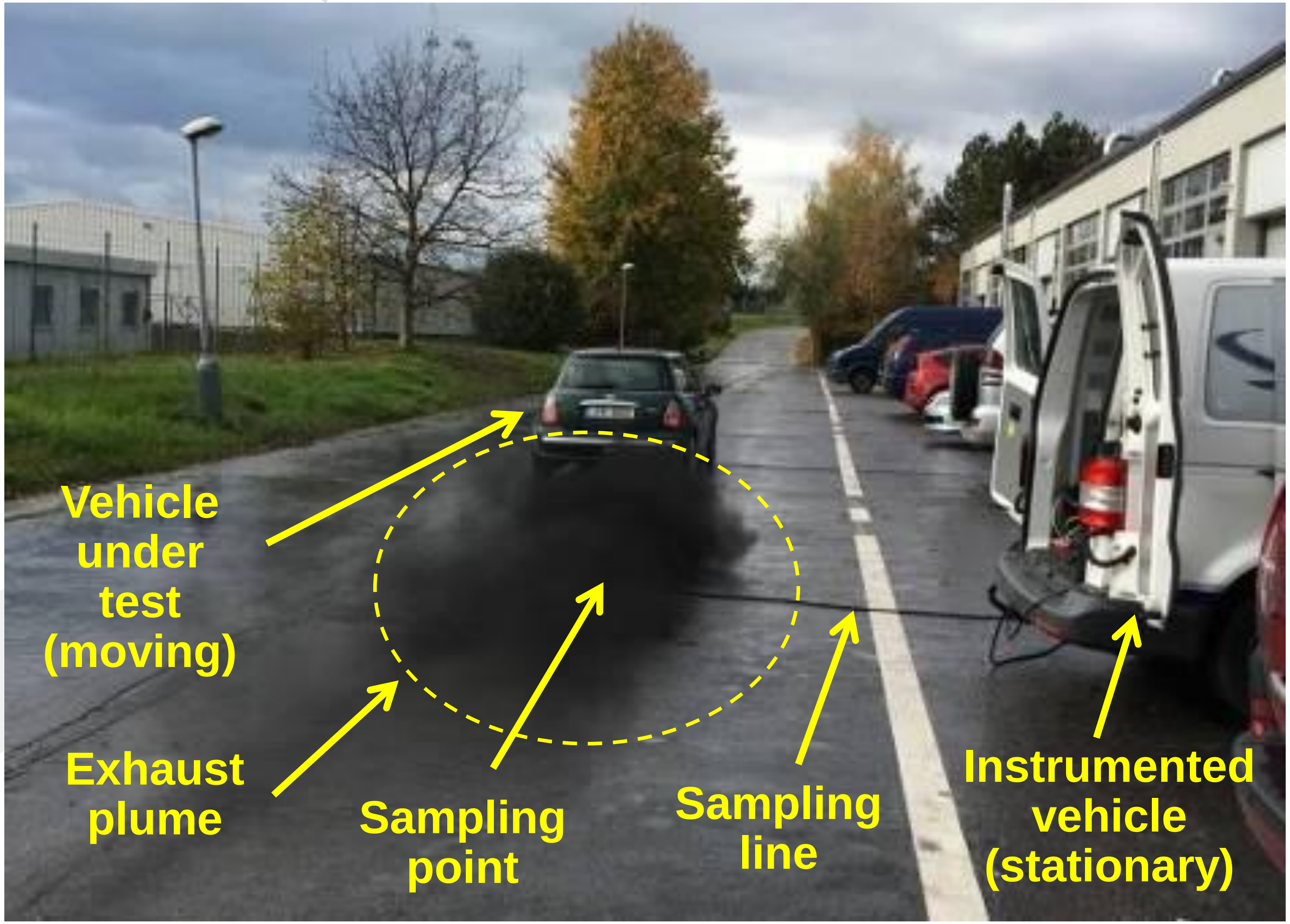
Interaction of particles with light becomes extremely small for particles << wavelength

→

light absorption, light scattering, photoluminescence, etc. do not work for nanoparticles.

… and forget about sending nanometer (= high-energy) radiation across a public roadway…

Point sampling overview



Emission factor calculation

$$EF = \frac{[pollutant]}{[CO_2]} \times const.$$

Concentrations net of background

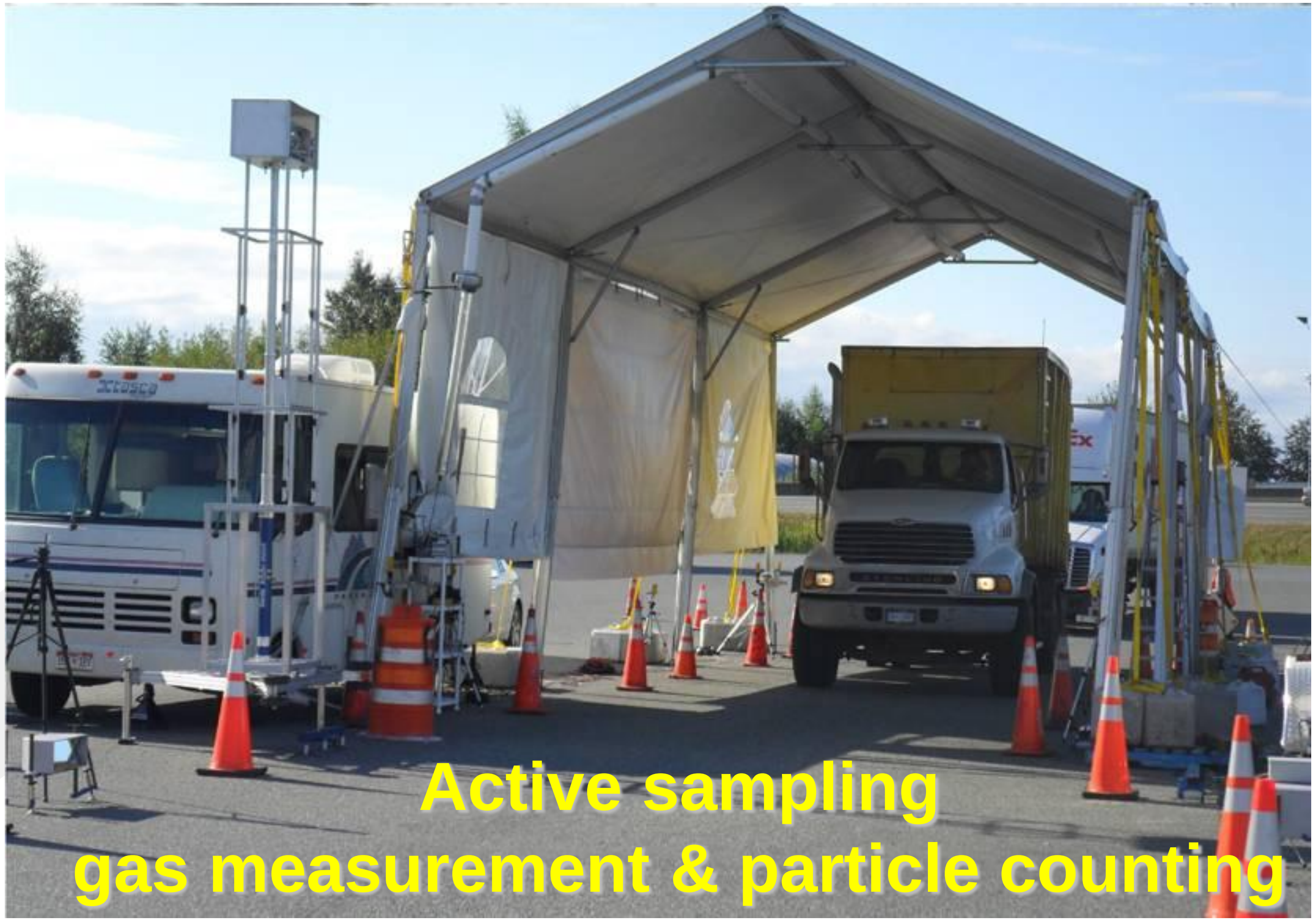
Most often, EF in

[g pollutant / kg fuel]

[# of particles / kg fuel]

Sampling approaches: "Measurement tent" etc.

(Bishop et al., Environ. Sci. Technol. 2015, 49, 1639−1645)



Measurement of individual vehicles by sampling approach – many other groups:

Tunnel studies
(Univ. California)

Ship plumes
(several groups)

Bus plumes
(Hallquist, Sweden)

Bus chasing
(Aerodyne, New York; Finland; …)

Particle concentration to CO_2 concentration ratio -> emissions factor particles per kg fuel

Deriving emission factor

$$EF = \frac{[pollutant]}{[CO_2]} \times const.$$

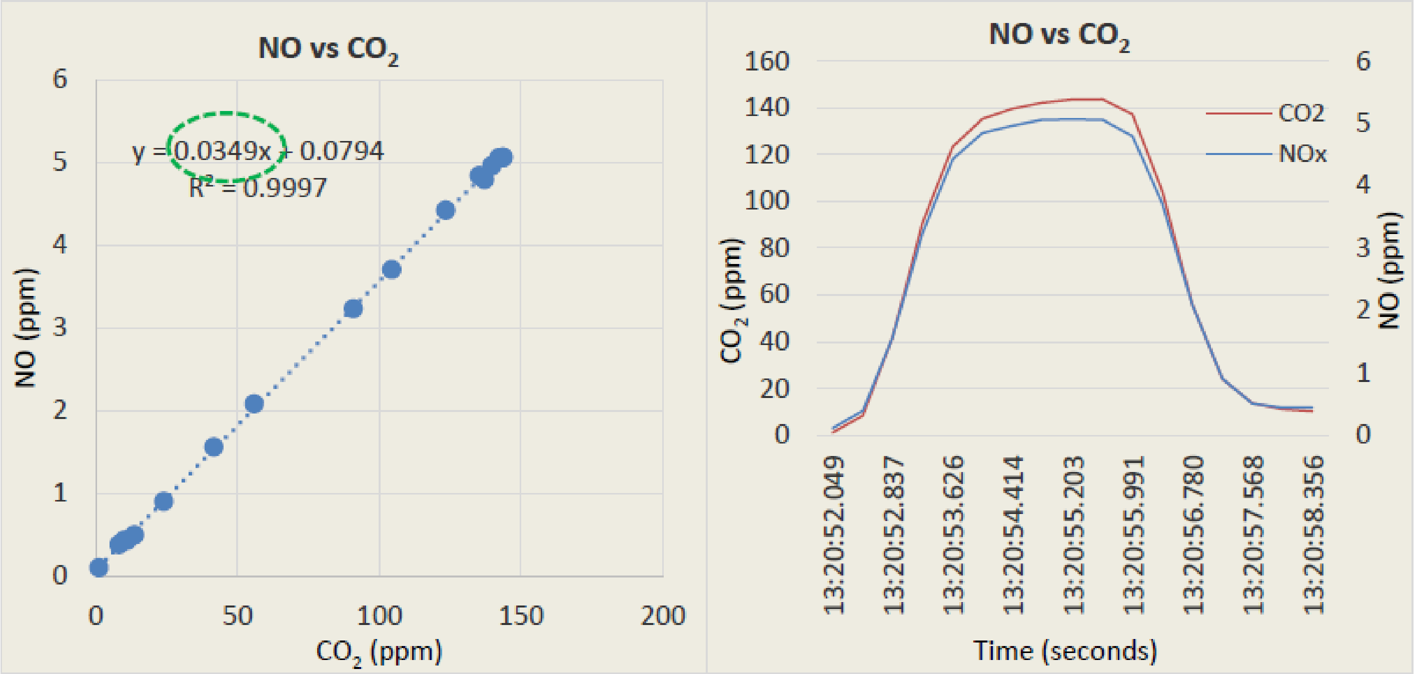
Peak maximum

$$EF = \frac{[pollutant]_{maximum} - [pollutant]_{background}}{[CO_2]_{maximum} - [CO_2]_{background}} \times const.$$

Peak area

$$EF = \frac{sum\{[pollutant] - [pollutant]_{background}\}}{sum\{[CO_2]_{maximum} - [CO_2]_{background}\}} \times const.$$

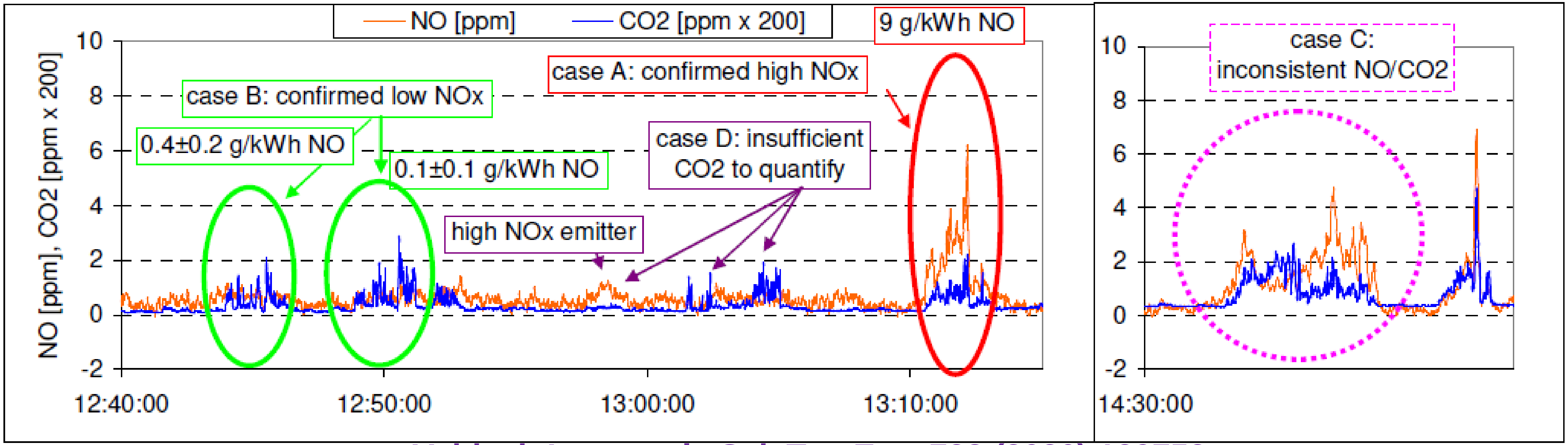
Linear regression, robust regression



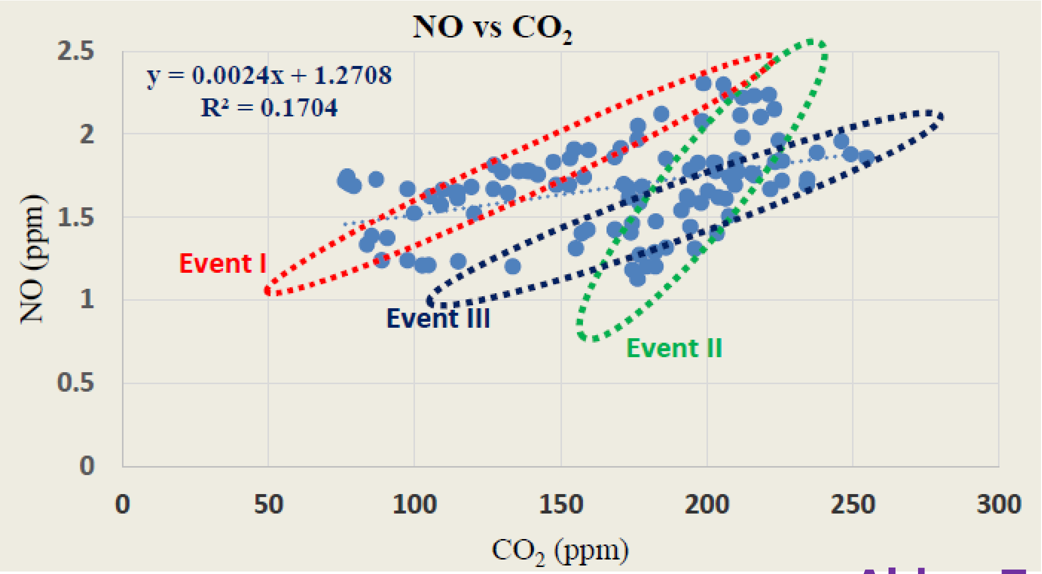
Alden Fred Arul Raj, diploma thesis, Czech Tech University, 2020

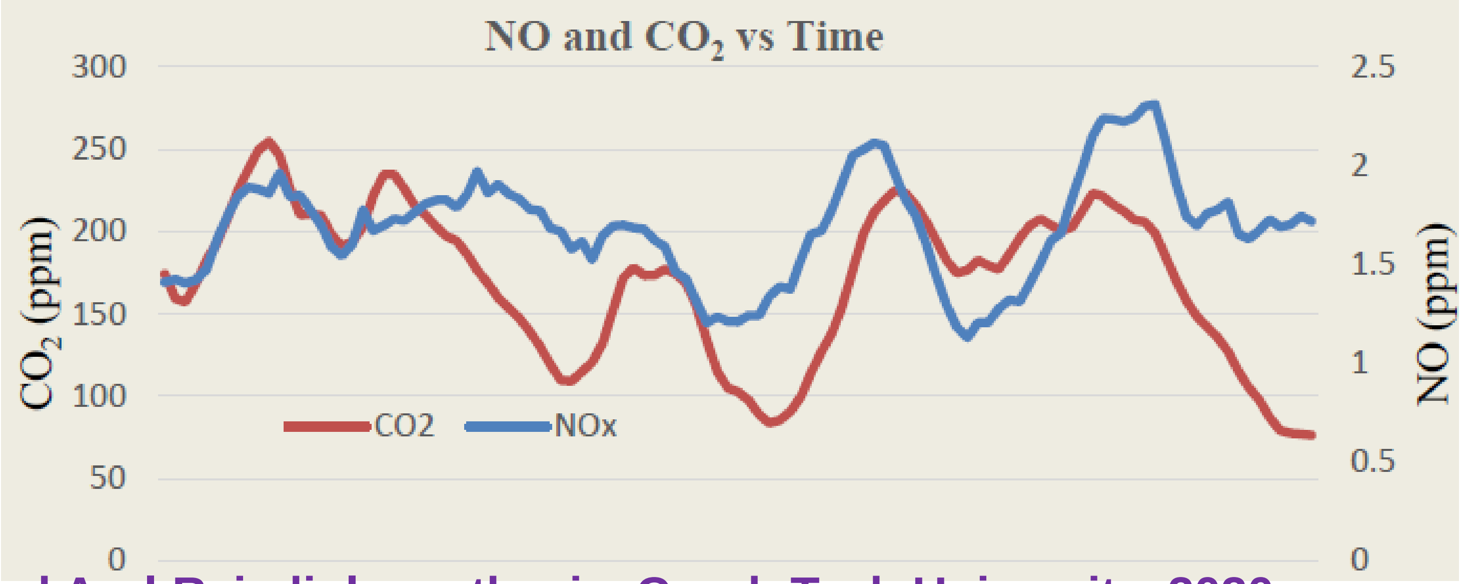
LENS L-vehicles Emissions and Noise mitigation Solutions

Deriving emission factor (shown on NOx)



Vojtisek-Lom et al., Sci. Tot. Env. 738 (2020) 139753





Alden Fred Arul Raj, diploma thesis, Czech Tech University, 2020

Evaluation of vehicle technical condition in Prague
Particulate matter measurement

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NanoMet3:
Number of non-volatile particles (PN)

Rotating disc diluter
Evaporation tube
(volatile particle remover)
Diffusion charger
Electrometers

CO_2 & other gases:
FTIR (5 Hz, 0.5 cm^{-1})
Bruker Optik, 5 m cell

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MicroSoot Sensor:
Photoacoustic detector of soot mass concentration

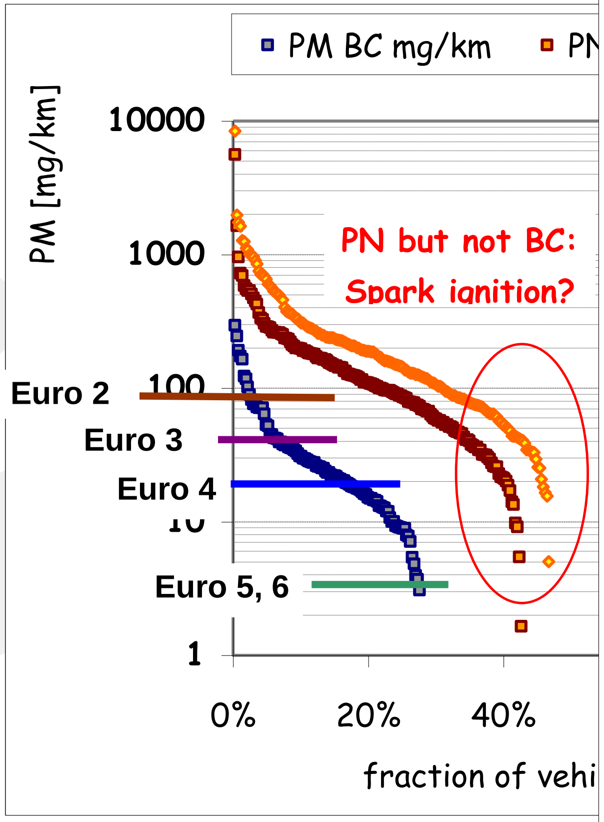
Engine Exhaust Particle Sizer:
Mobility diameter resolved number concentrations

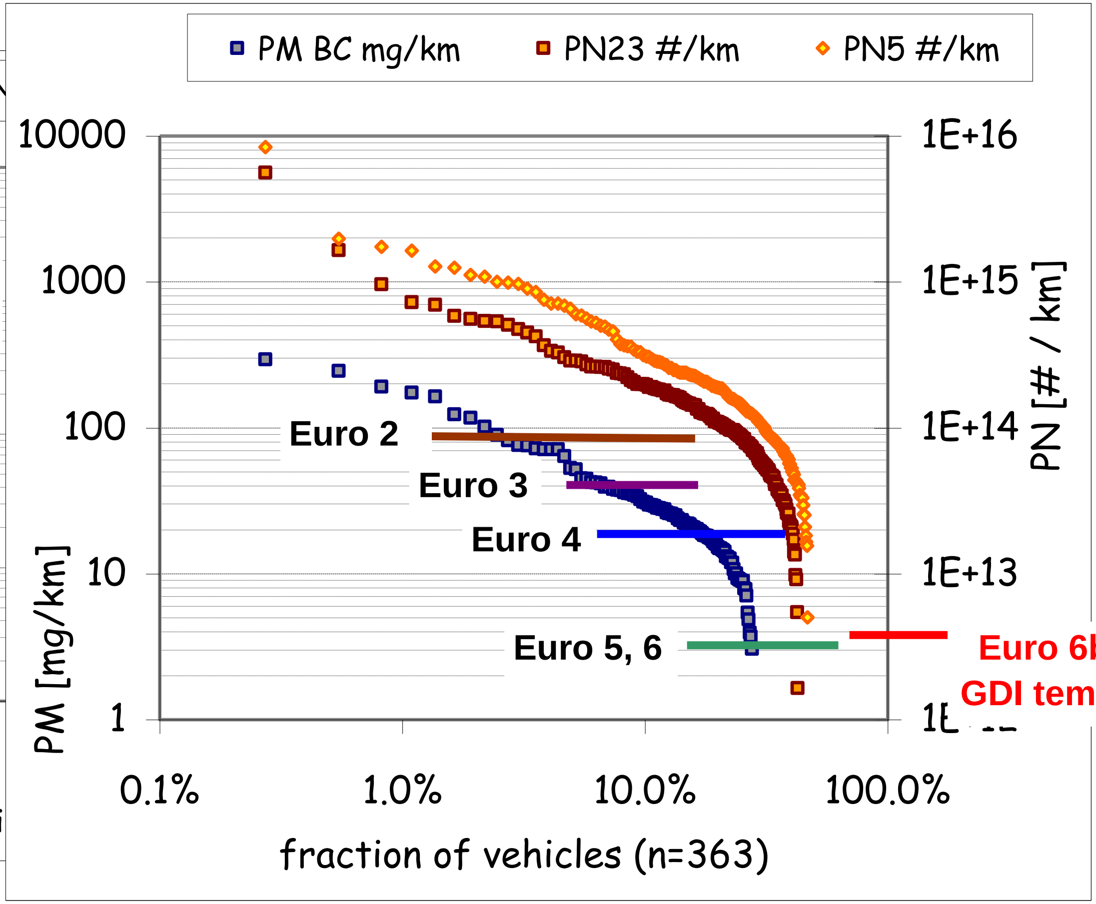
Diffusion charging, Classification based on electric mobility diameter,
Detection of charged particles by electrometers

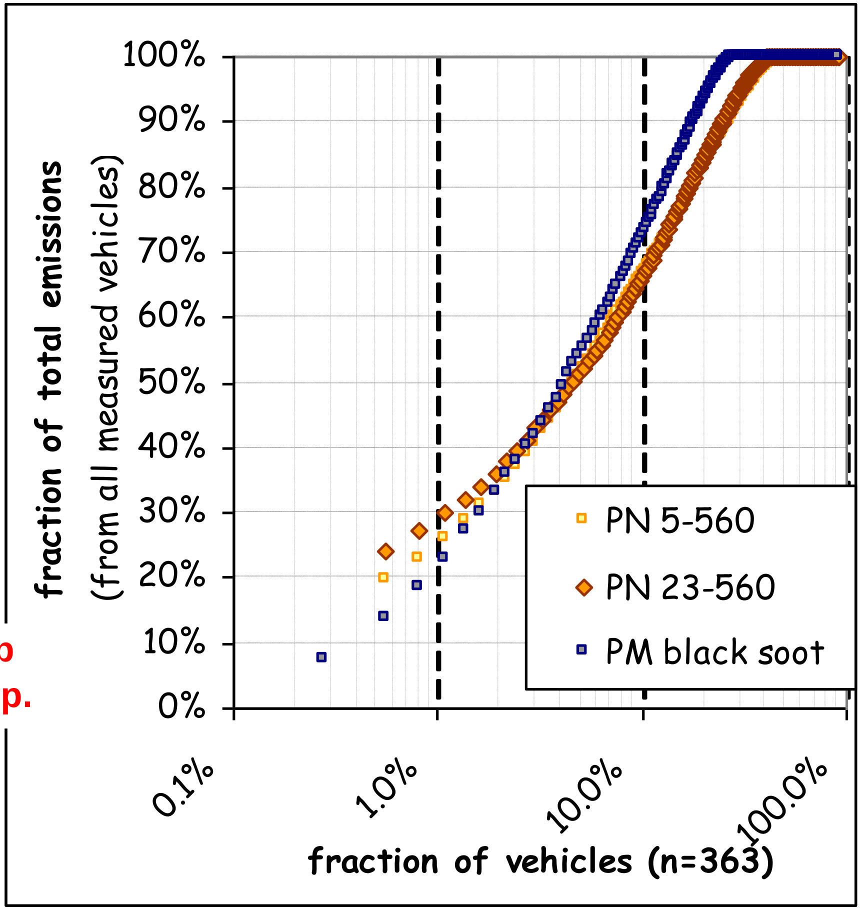
Roadside measurement, Trutnov, CZ, May 28, 2018

~ 3 hours, ~ 700 vehicles, ~ 360 CO_2 signals, ~ 150 measurable PM

1% of vehicles ~ 20-30% of particulates (BC, PN)
10% of vehicles ~ 65-75% of particulates (BC, PN)







28 worst emitters were stopped and inspected by police – Skácel et al., NPC 2018, Vojtíšek et al., NPC 2018

Target detection limits and measurement sensitivity for roadside vehicle measurement

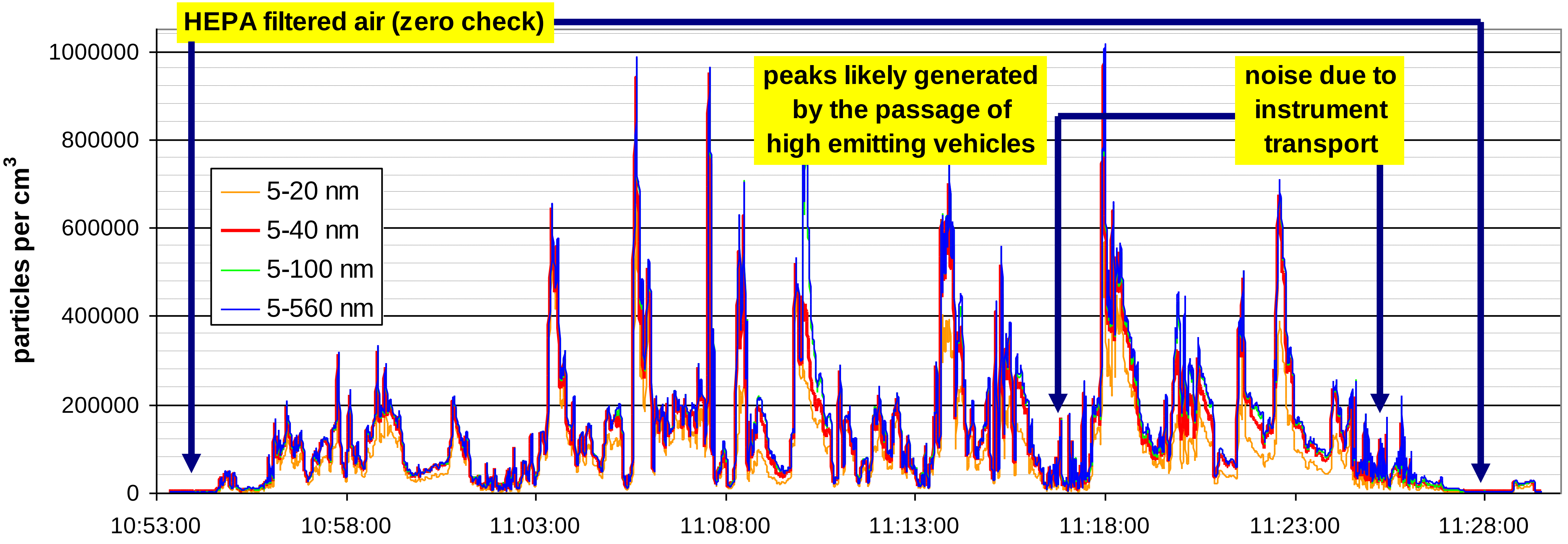
Engine-out (diesel) Euro 5b-6:
6 x 10^{11} #/km (PMP), 5 mg/km
20 km / kg fuel (6 liters / 100 km)
Mild acceleration ~~ 30:1 air-fuel ratio
~ 5% CO_2 in exhaust, 24 m^3 air / kg fuel
~ 0.5 x 10^6 #/cm^3 (PMP)
2-10x more incl. volatiles

Dilution 1-2,5 x 10^3 to 20-50 ppm CO_2
well within detection limit of NDIR, FTIR

Roadside
200-500 #/cm^3 (PMP)
~ 10^3 #/cm^3 incl. volatiles
around detection limit of DC-based devices
~ 4 ug/m^3 PM
~ 2 ug/m^3 black soot
Not too far from detection limit of photoacoustic (units of ug/m^3) or laser induced incandescence (tenths of ug/m3)

In reality, the limit of quantification of particle concentrations may be given by fluctuating background

Roadside concentrations, PN 5-560 nm, incl. volatiles, motorway in Prague

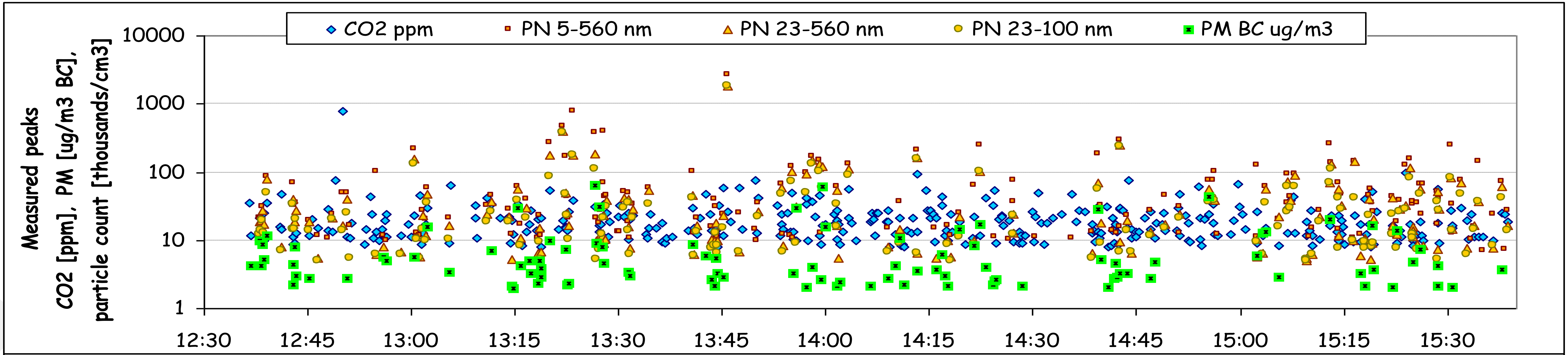


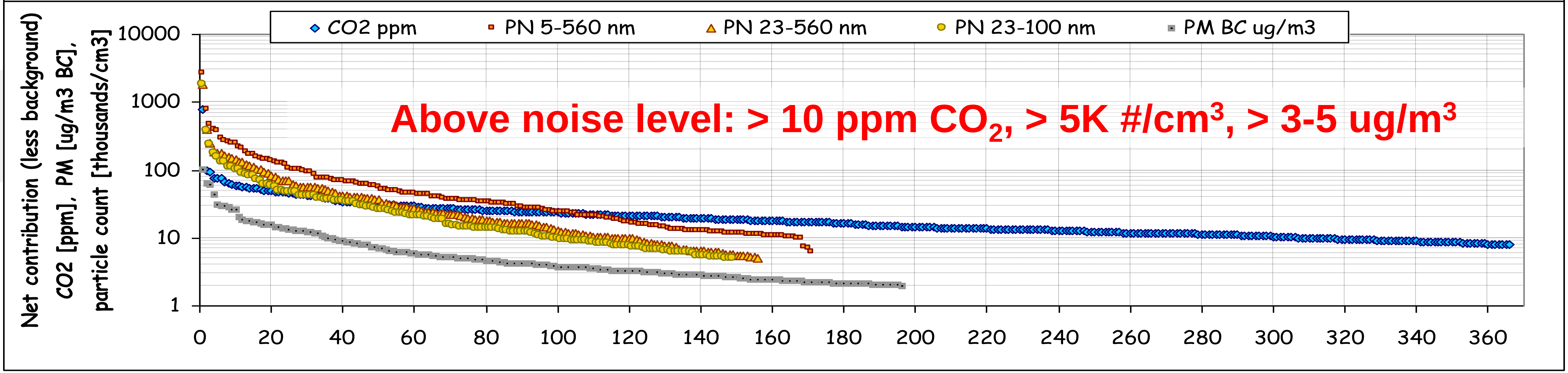
In reality, the limit of quantification of particle concentrations may be given by fluctuating background

Urban background 7-8000 #/cm^3, higher near roadways

Roadside measurement, Trutnov, CZ, May 28, 2018

~ 3 hours, ~ 700 vehicles, ~ 360 CO_2 signals, ~ 150 measurable PM





Maximum CO_2 concentration over background in a peak: minimum required values and observed range - given by sensitivity of PN/PM measurement, CO_2 can be measured within a few ppm (NDIR)

Hak et al., Atmos. Environ. 43 (2009) 2481–2488: tens of ppm CO_2 range

Bishop et al., Environ. Sci. Technol. 2015, 49, 1639−1645: CO_2 > 75 ppm

Preble et al., ES&T, 49, 8864−8871, 2015 & Preble et al., CARB report 12-315, 2019

https://ww3.arb.ca.gov/research/apr/past/12-315.pdf

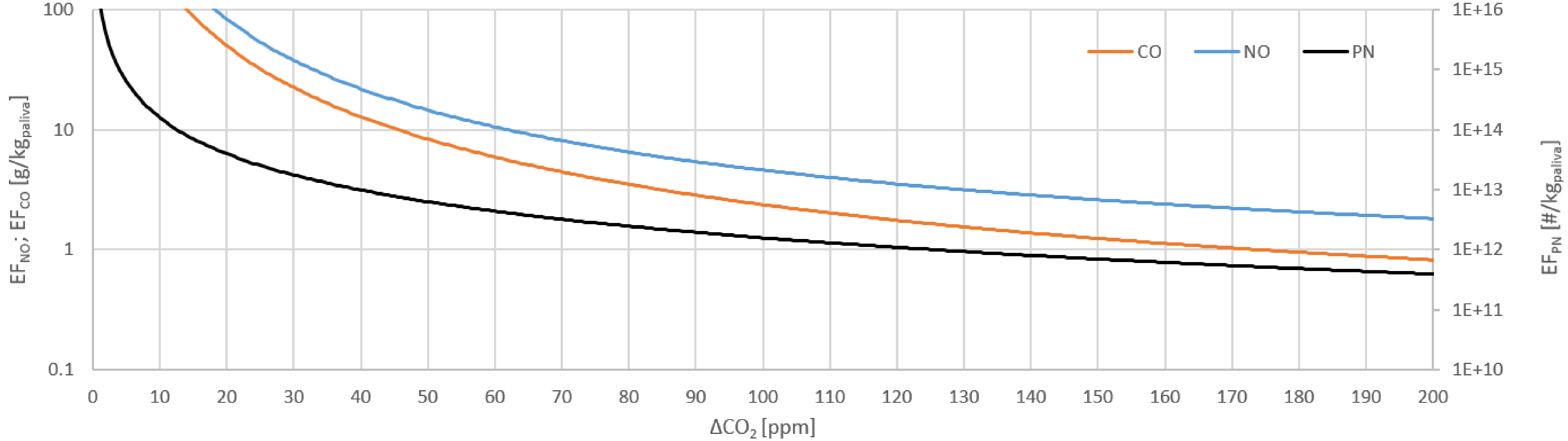
tens to low hundreds of ppm CO_2

Vojtisek-Lom et al., ETH NPC 2018: > 10 ppm CO_2, 10-100 ppm range

Farren et al., Sci Tot Env, 2023, preprint: > 10 ppm CO_2, 10-100 ppm range

Shen et al., Science of the Total Environment 816 (2022) 151609: > 10 ppm CO_2

CARES project - Lelystad test campaign data – point sampling by CTU & CZU
Limit of quantification for NO, CO and PN as a function of maximum CO2 in the plume over background
Ondřej Vyštein, diploma thesis, Czech Technical University in Prague, 2022



@ 20 ppm CO_2 peak: PN noise 1000 #/cm^3 ~ 2.5x10^{12} #/kg fuel ~ 5x10^{11} #/km

@ 200 ppm CO_2 peak: PN noise 1000 #/cm^3 ~ 2.5x10^{11} #/kg fuel ~ 5x10^{10} #/km

- same PN instrument but better detection limit – OR -

@ 200 ppm CO_2 peak: PN noise 10 000 #/cm^3 ~ 2.5x10^{12} #/kg fuel ~ 5x10^{11} #/km

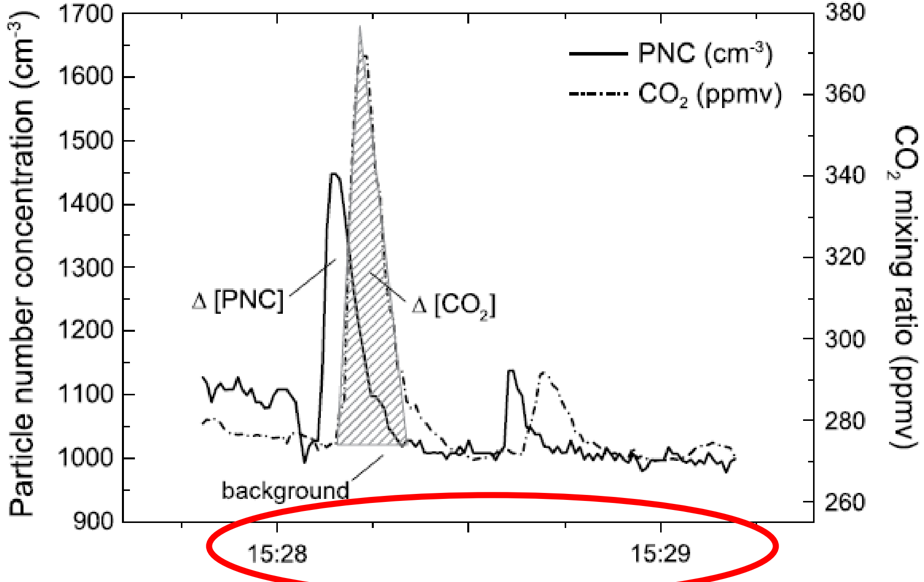
- same detection limit but higher noise / higher detection limit instrument can be used

Time spacing between vehicles

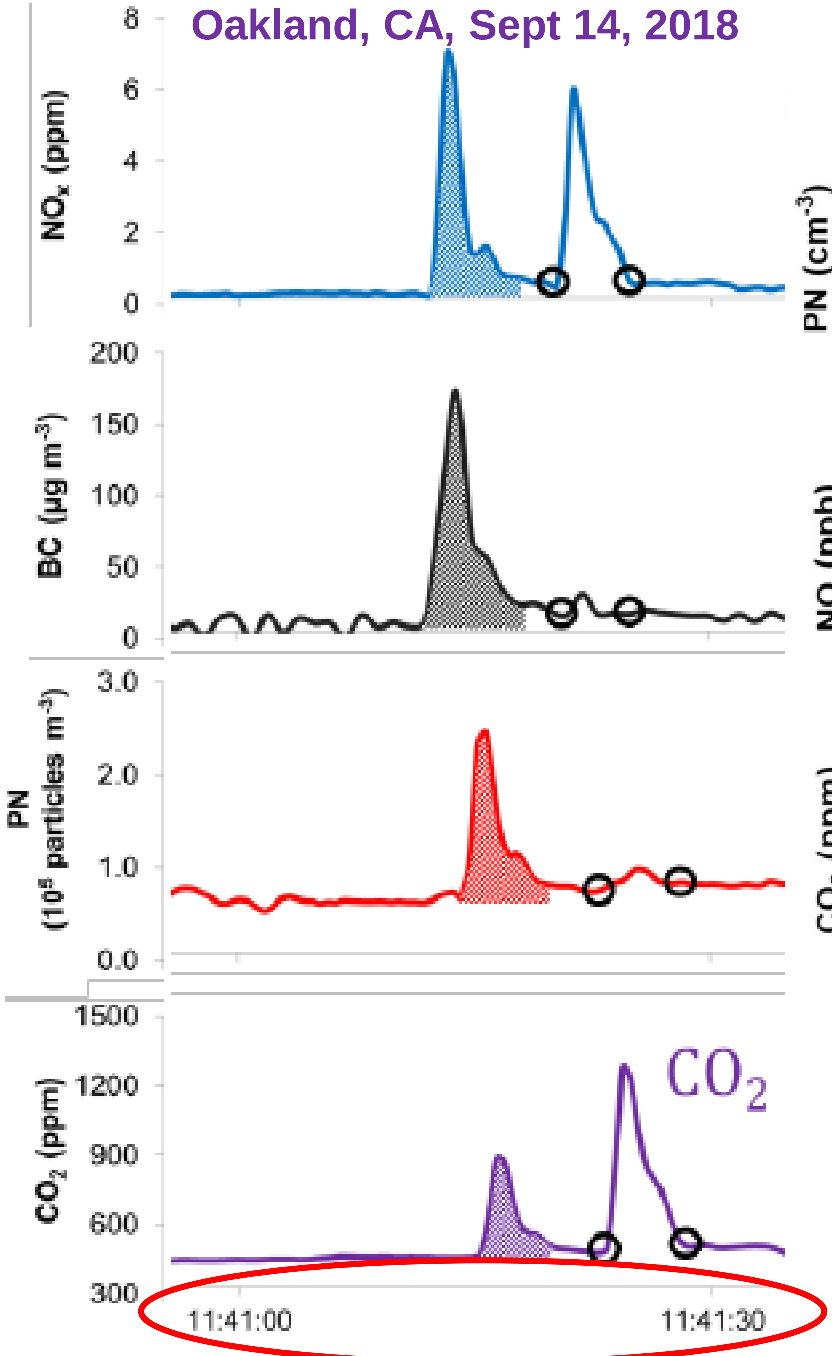
No one says it clearly, but from all studies, it seems like ~ 10 seconds plume duration ….

~ 2 s is considered safe driving & is typical in road capacity models

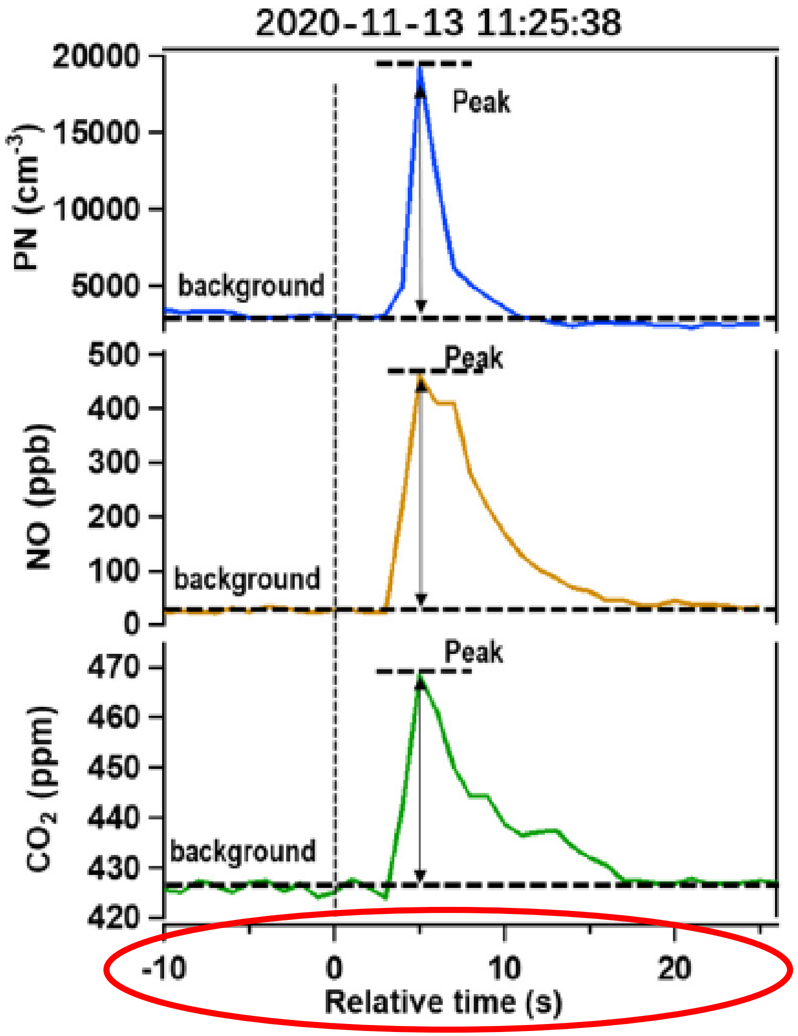
Hak et al., Atmos. Environ. 43 (2009) 2481–2488



Preble et al., ASIC, Oakland, CA, Sept 14, 2018



Shen et al., Science of the Total Environment 816 (2022) 151609



L-vehicles Emissions and Noise mitigation Solutions

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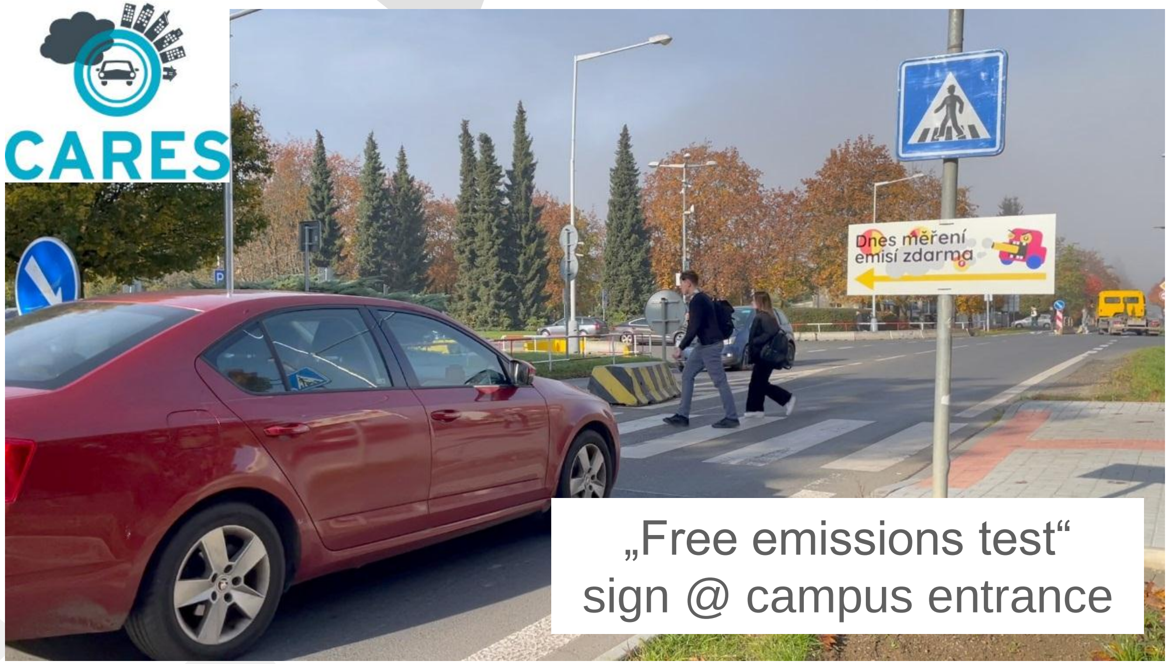
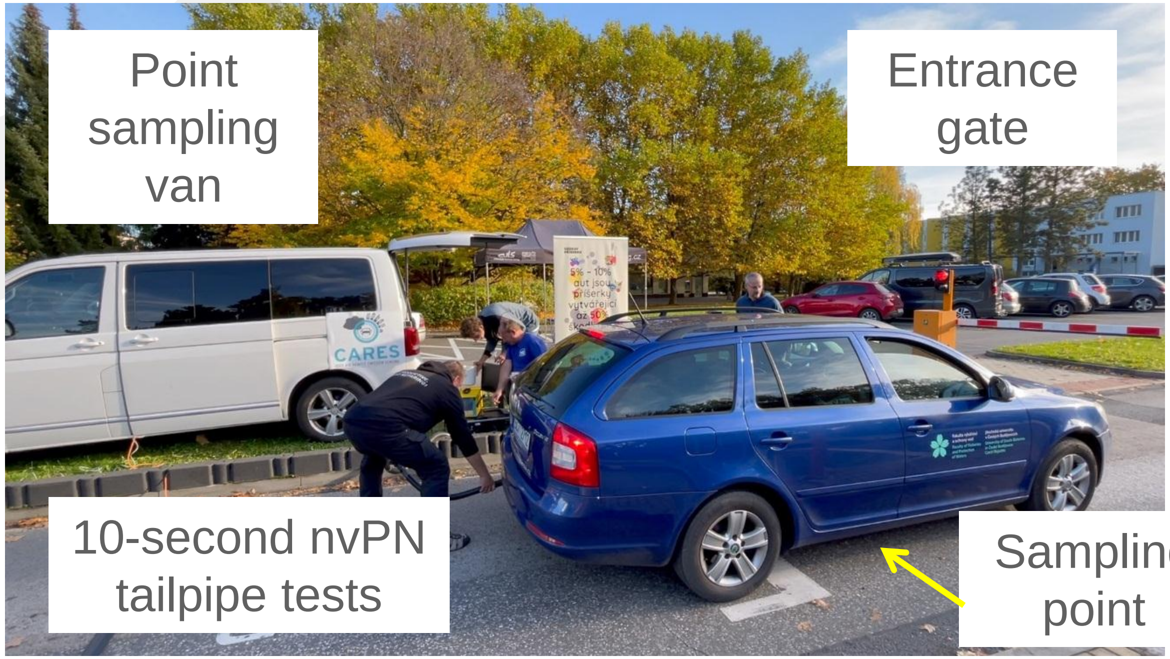
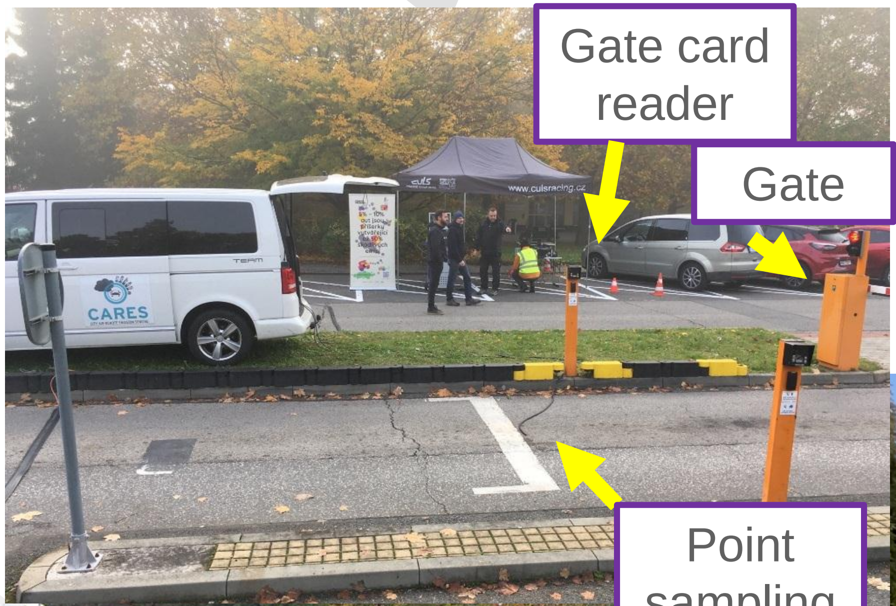
Point sampling during “free emissions test day” @ CZU entrance





Point sampling @ CZU entrance

Sign: 5-10% of cars are beast that produce half of exhaust PM



Gate card reader

Gate

Point sampling

Point sampling
FTIR (CO, NO, CO_2)
EEPS (5-560 nm)
NanoMet3 (nvPN)

Gate

Tailpipe @ idle, 10 s
NDIR (CO, CO_2)
NanoMet3 (nvPN)

LENS L-vehicles Emissions and Noise mitigation Solutions

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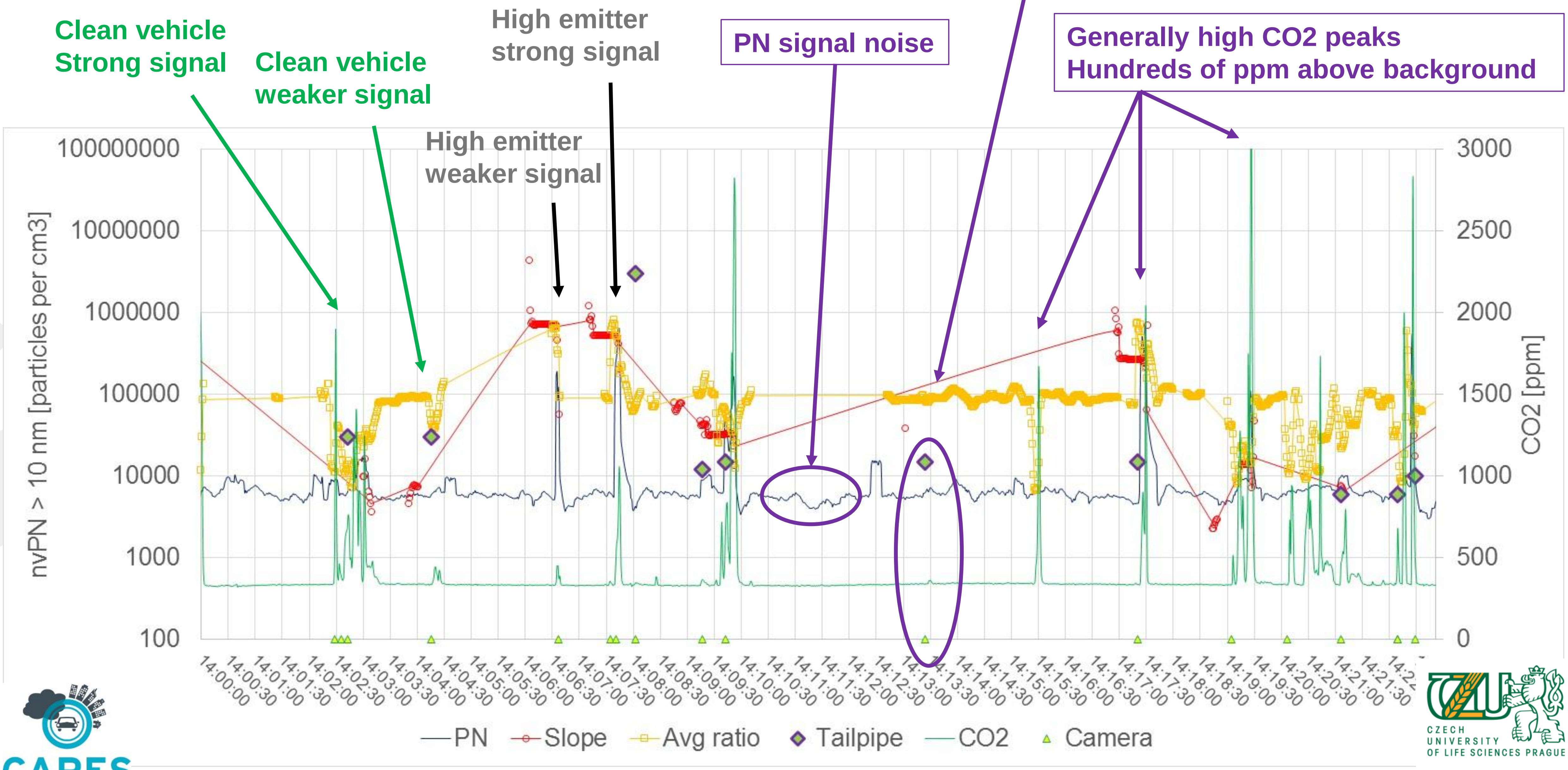
Point sampling during “free emissions test day”

Czech University of Life Sciences campus (Kamýcká street, Prague)
Free emissions test day – Oct 19-20, 2022



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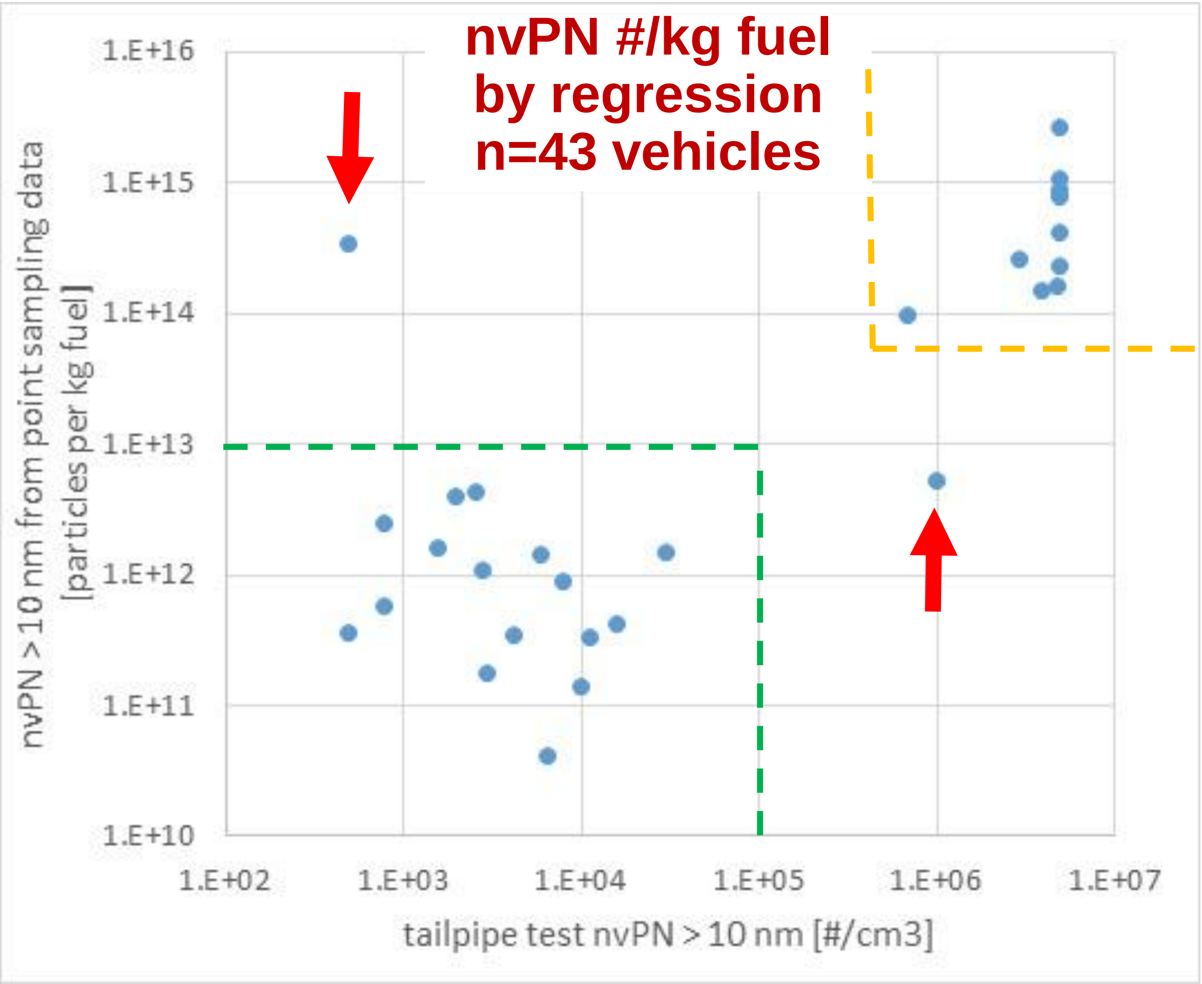
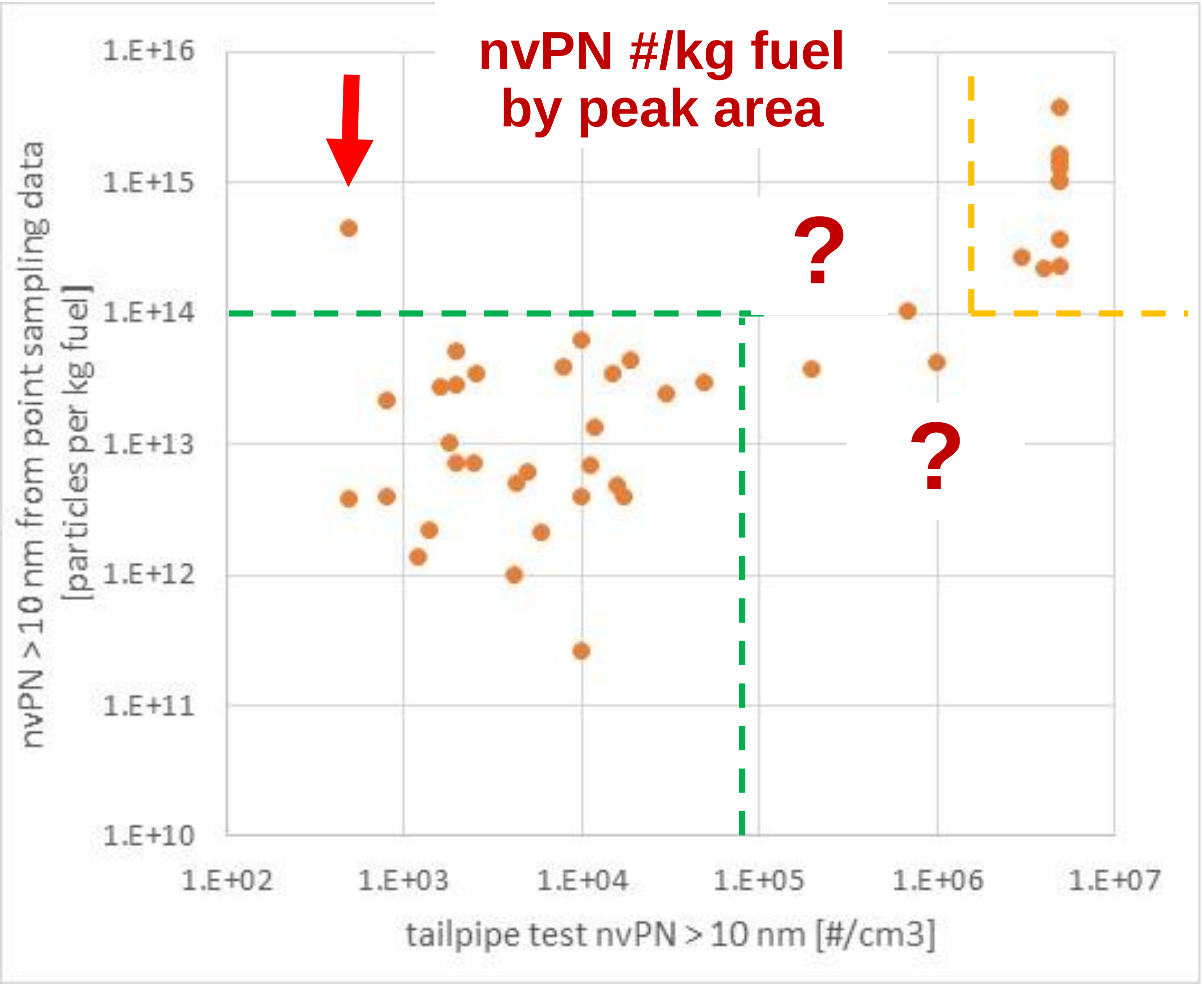
Point sampling during “free emissions test day“ @ CZU entrance

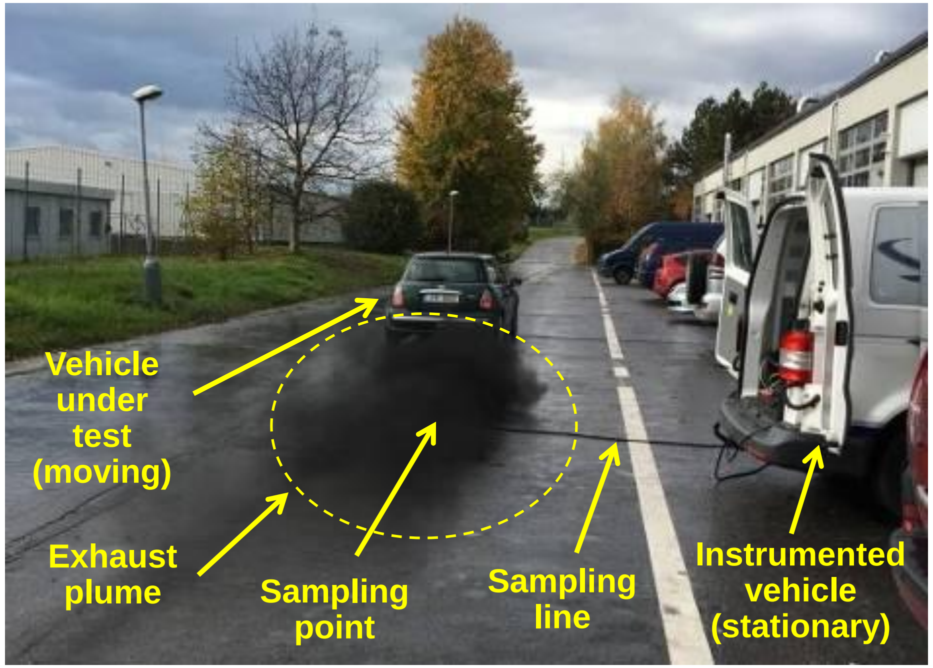
Czech University of Life Sciences campus (Kamýcká street, Prague)
Free emissions test day – Oct 19-20, 2022

- > 500 vehicles measured with point sampling
- Short (10 s) tailpipe nvPN tests (NanoMet3) on 50 vehicles
- 43 vehicles with valid point sampling and tailpipe data





Practical limits of point sampling



Vehicle spacing

- ideally >= 8-10 s, possibly >= 4-6 s
- unlikely below approx. 3 s

Signal strength

- peak [CO_2] above background
- at least tens, better hundreds of ppm

Instrument detection limit

- for PN around 1 K #/cm^3, but not believed to be limiting

Signal discrimination

- between/among successive vehicles and nearby sources
- from background (which is fluctuating)

Difference between “OK” and “not OK” emission factors

- > 1 order of magnitude for gases for TWC, SCR, …
- >> 1 order of magnitude for PN, BC for DPF

Point sampling at a campus entrance: Discussion and Conclusions

Possibly a good example of point sampling technique at its best:

Strong signal of hundreds ppm CO_2

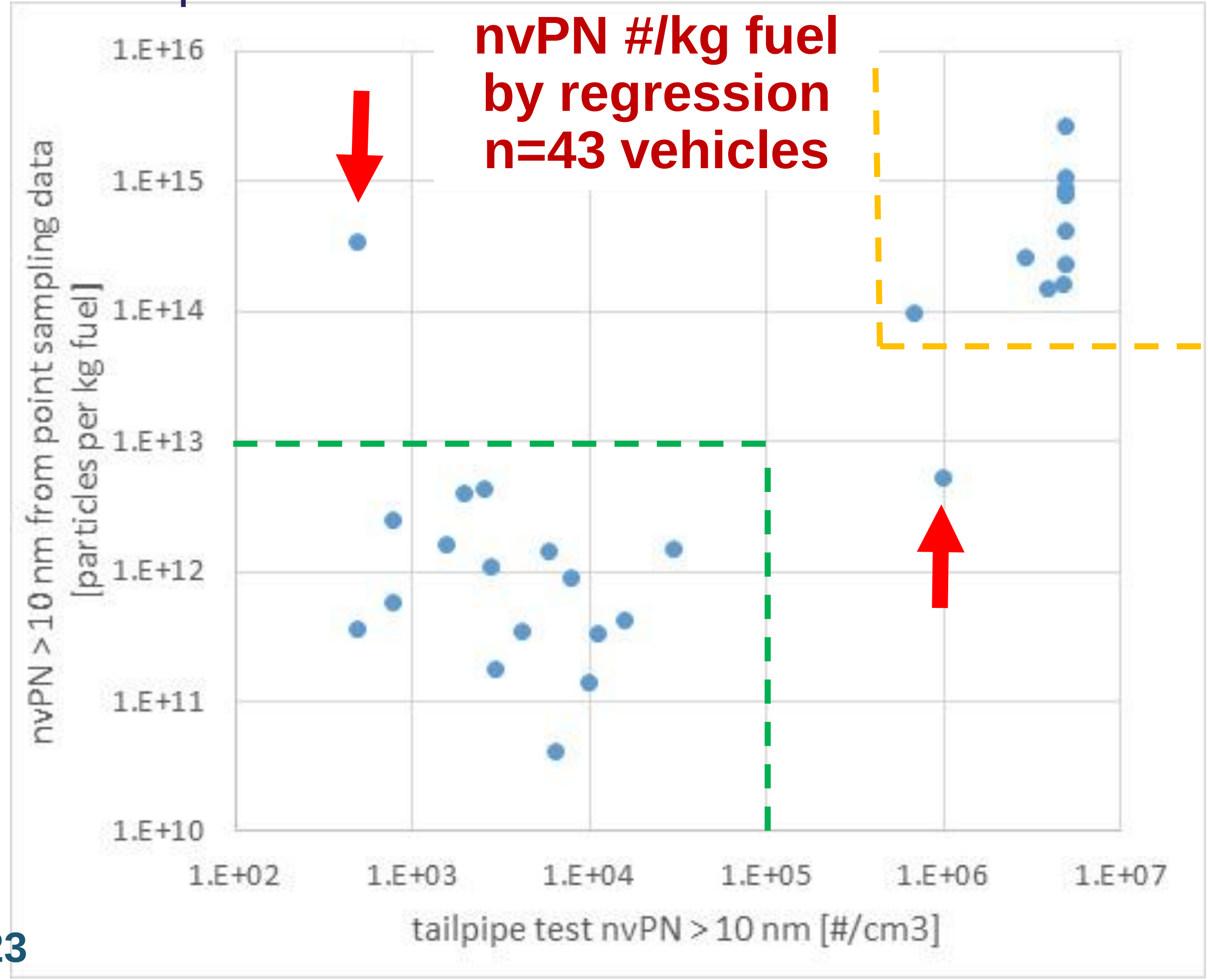
- -> chance for 10 K #/cm^3 level of detection/quantification periodic technical inspection instruments
- -> chance for small vehicles (mopeds) with standard (1 K #/cm^3) DC-based sensors
- -> clear margin between presence/absence of functional particle filter
- -> high (possibly > 90 %) success rate

Need to produce a card or register a license plate

- -> vehicle is identified
- -> spacing of 5-10 seconds possible

Allows for measurement without cooperation from state government (low emissions = a condition to enter a sensitive enclosed area)

Directly addressing high emitters and leaving others (only vehicles entering area and repeatedly identified as excess emitters are "prosecuted")



Funding: Horizon 2020 - www.cares-project.eu,
Horizon Europe - www.lens-horizoneurope.eu

LENS L-vehicles Emissions and Noise mitigation Solutions

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