Roadside measurement of PM/PN emissions from individual vehicles in Prague

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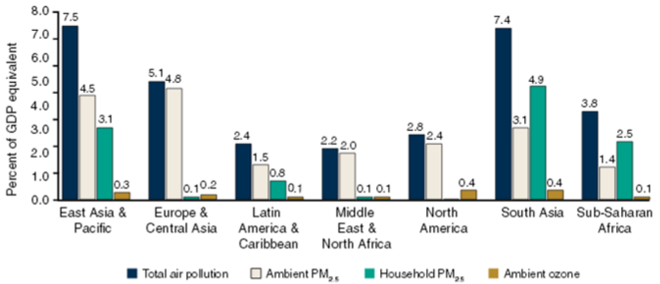
Particulate matter and tropospheric ozone are causing over 400 thousands of premature deaths annually in the EU

(vehicle accidents less than 40 thousands/year)

Economic damages of air pollution in the EU estimated to 5% of GDP (World Bank, 2016)

FIGURE ES.1 Welfare Losses Due to Air Pollution by Region, 2013



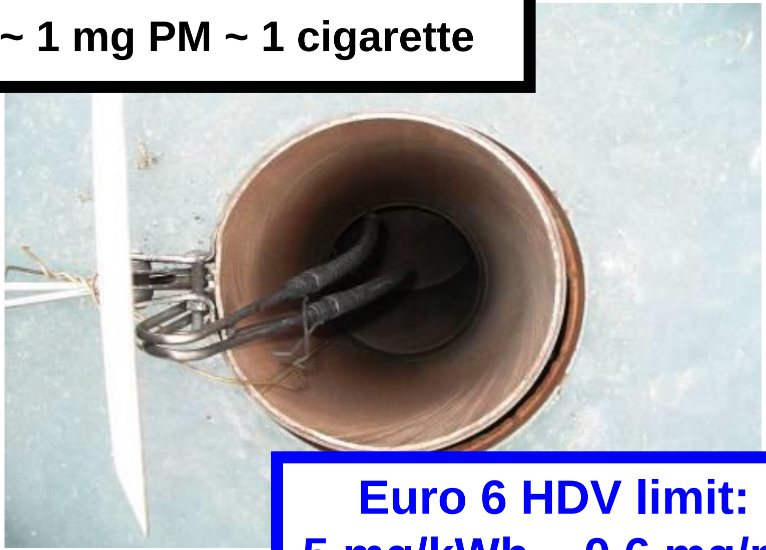
Sources: World Bank and IHME.

Note: Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product.

Emission limits in broader perspective

Internal combustion engines are among cleanest combustion devices.
But they do not have chimneys, and they are not far outside of the cities.
They are among us in the streets where we inhale.

Euro 6 bus - 1 km of travel
~ 1 mg PM ~ 1 cigarette



Euro 6 HDV limit:
5 mg/kWh ~ 0,6 mg/m3

Burning of trash ~ 500 mg/m3
Christian et al., Atmos. Chem. Phys., 10, 565–584, 2010

Czech limit for local heating < 300 kW
(Reg. 201/2012, appendix 10)
125-150 mg/m3 from 1.1.2014
60-75 mg/m3 from 1.1.2018

Sion Primary School (Hradec Králové, CZ) science day: ambient nanoparticle monitoring:

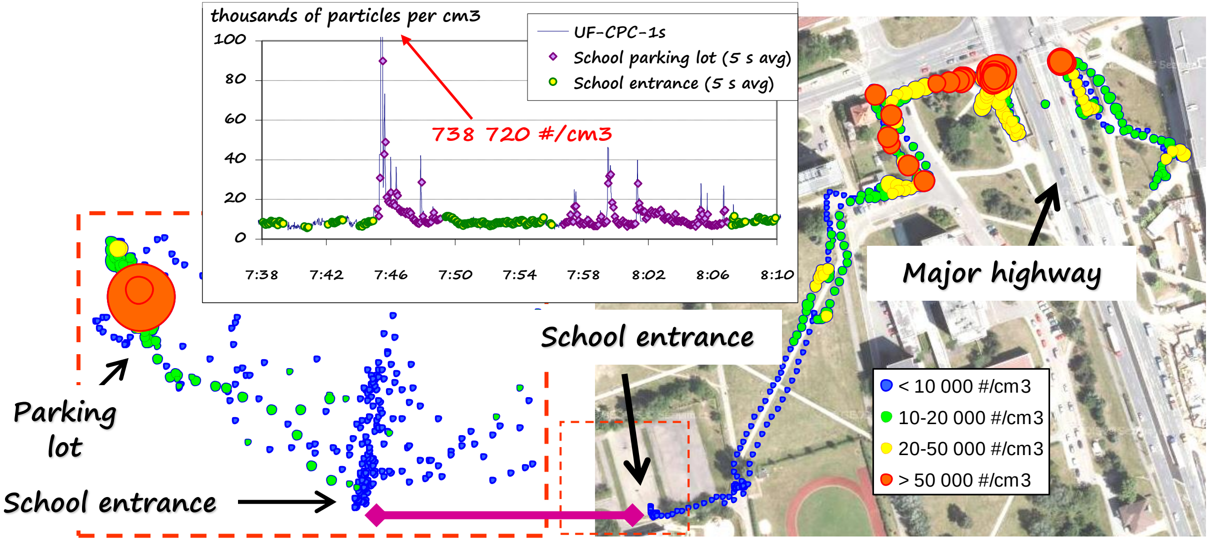
Despite engines being only one of the sources, they are the principal source of nanoparticles in many urban areas…

Highest concentrations: parking lot in front of school

Peaks = individual vehicles

Who won the high emitter prize ???

Can we identify high emitters ???



Problematic pollutants in engine exhaust

- **Particles** - primary and secondary aerosol
- **NO_x** - nitrogen oxides and, as a secondary pollutant, tropospheric ozone
- Diesel total VOC and CO generally not much of a problem, sulphur addressed by fuel standards

- **New and emerging problems with limited regulation:**
- Health related:
- Particle properties - size, structure, composition, bioavailability, toxicity
- NO_2 - formation in oxidation catalysts
- NH_3 - formation in lean NOx reduction catalysts (LNT, SCR)
- - formation in three-way catalysts when run rich
- Aldehydes – oxygenated fuels (i.e., ethanol, biodiesel)
- Greenhouse gases:
- N_2O - formation in NO_x reduction catalysts (SCR, LNT)
- CH_4 - methane powered engines, regeneration of LNT catalyst

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)

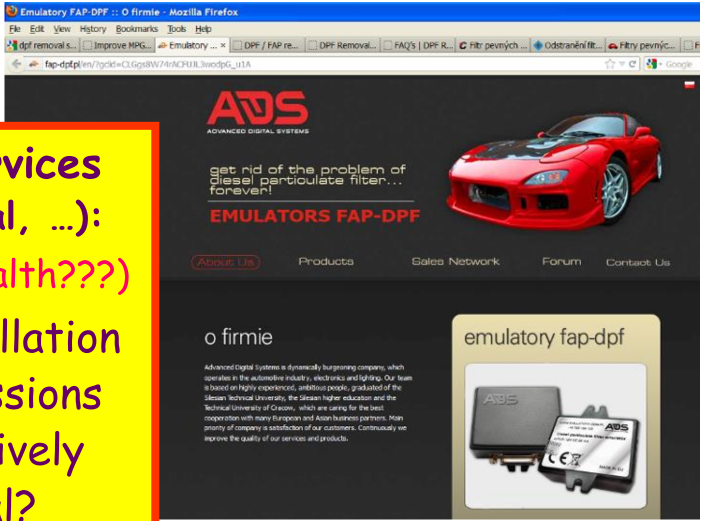
Positive ignition:

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

DPF, SCR cheating services (removal, emulation, rental, …):

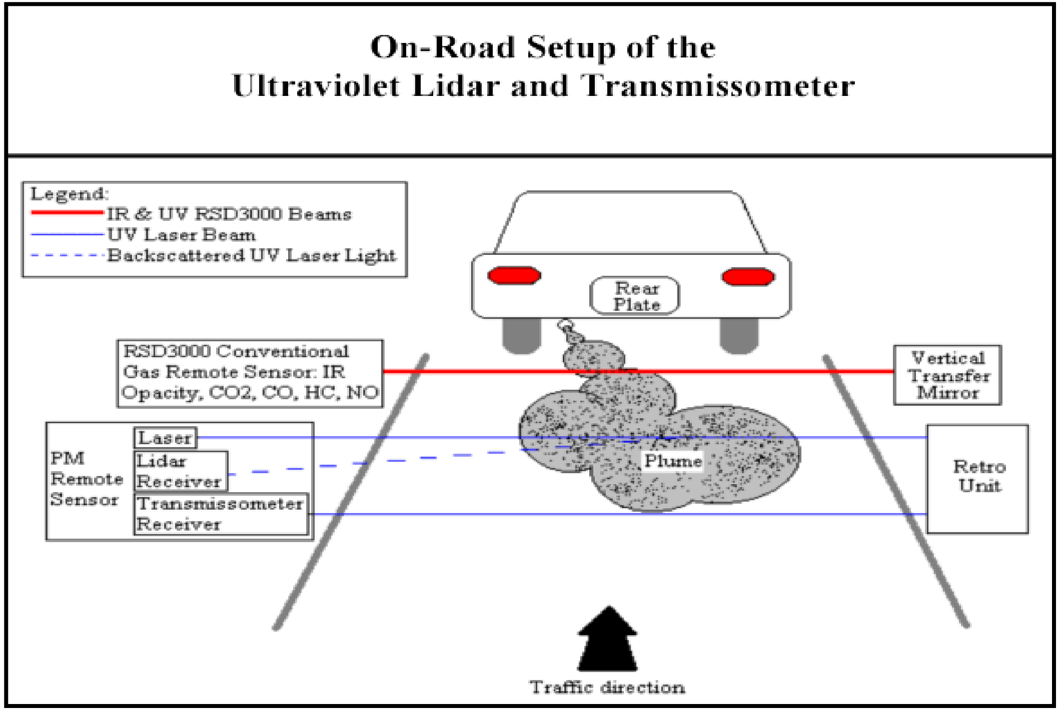
(Organized crime against health???)

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



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)



Desert Research Institute, http://www.dri.edu/Home/Features/text/1003_VehicleEmissions.htm

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

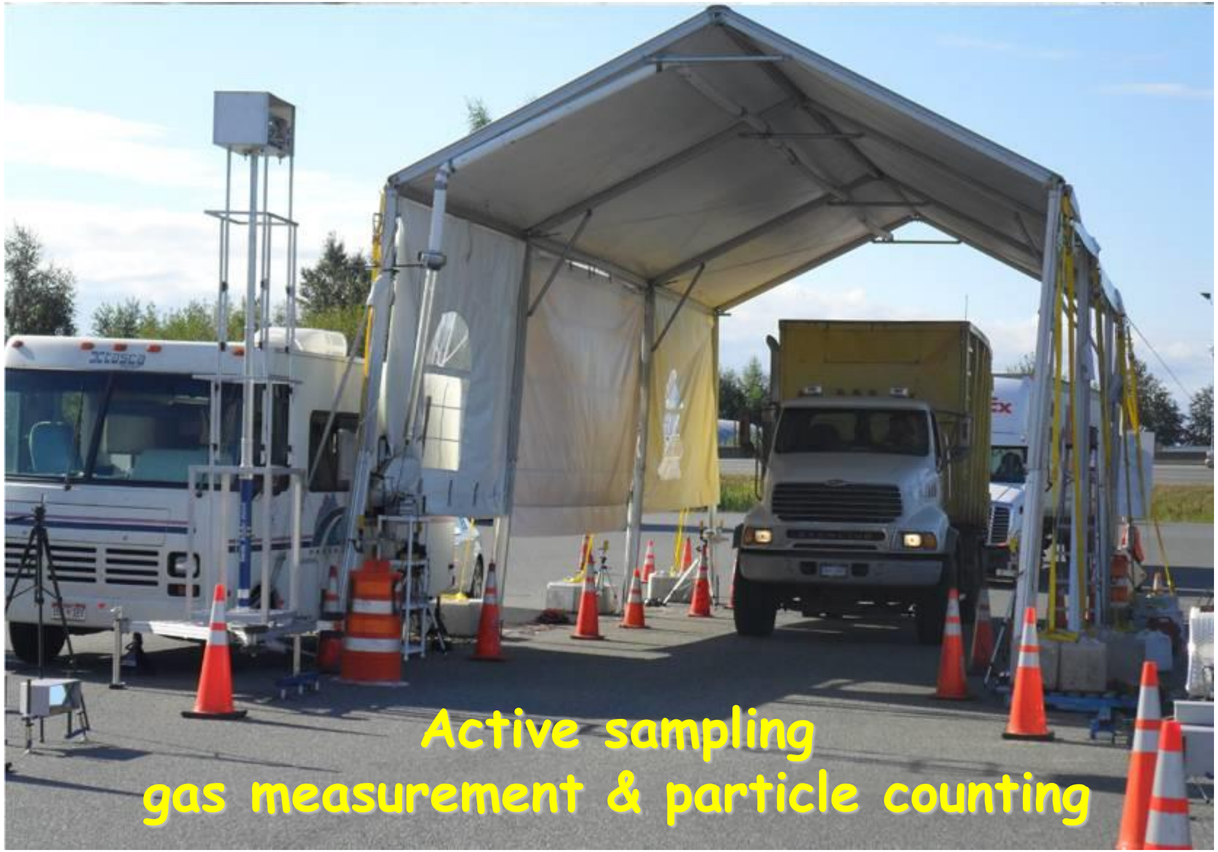
→

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

(And forget about sending nanometer = high-energy radiation across a public roadway.)

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

Riverside measurement of passing vessels

City of Prague Smíchov lock on Vltava (Moldau)

Remote sensing type (sampling) measurement: Neither imissions nor emissions

Sampling near water surface after a passing ship with a stainless "fishing line"

Gases (NO, NO_2, CO, CO_2): FTIR (PEMS, 30 kg, 1 Hz, 5 m optical path, 0.5 cm^{-1} resolution)

Particles: Electric mobility classifier (EEPS), condensation counter (P-trak)

Ratio of particle / CO_2 concentrations -> Emissions factors per kg of fuel

Calculation of emissions factors per kg of fuel

Note:
Ships have multiple engines (propulsion & electric power).
In most cases it was not possible to differentiate among engines (and sometimes among ships).

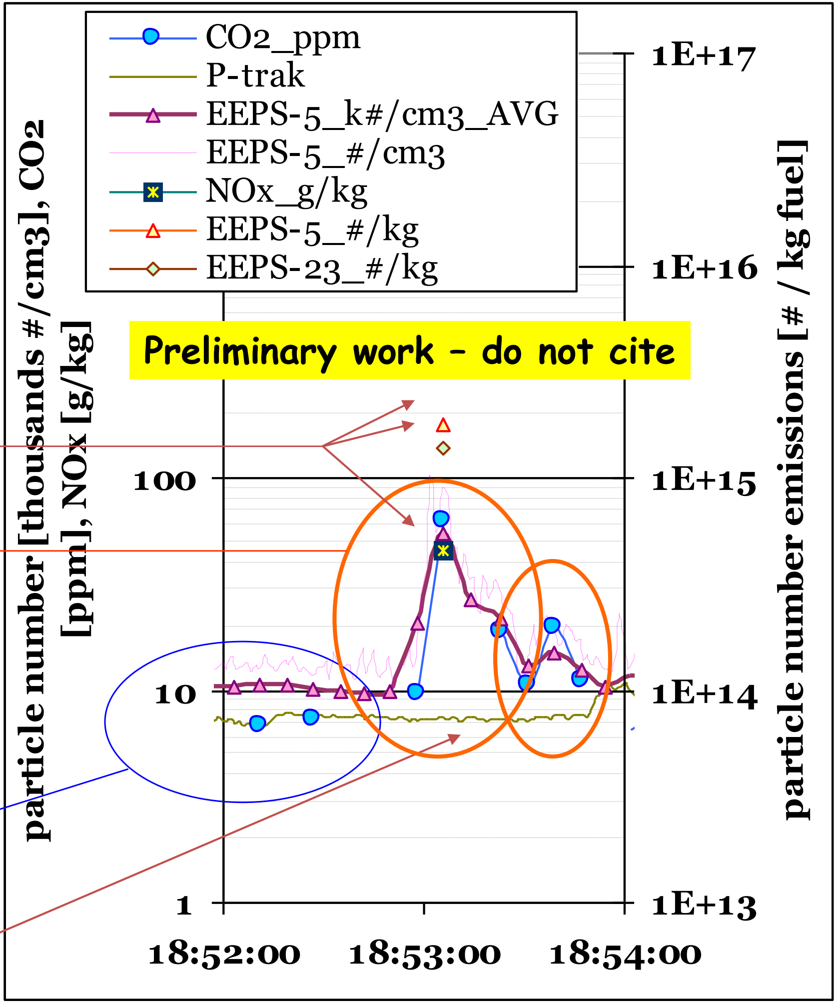
Emission factors per kg fuel

Concentrations measured above water surface after a passing ship

Source discrimination:
Cooking: not much CO2 or NOx.
Far sources (road) show up on background (P-trak).

Background concentrations

Concentrations at the edge of the chamber (P-trak) - „background“



Some open questions:

Calculate with peak heights or peak areas?

What is „background“?

Deconvolution of multiple signals?

Particle transformation?

Particle density (diesel exhaust vs. ambient)

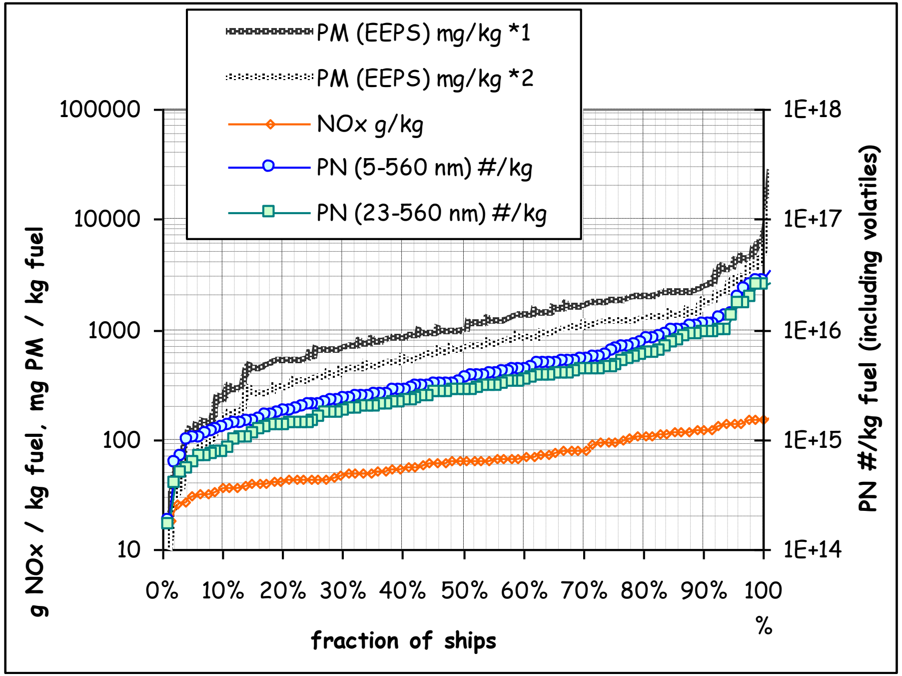
Riverside measurement of passing vessels, Prague, 2017

fleet mean (n=109) per kg fuel: 5.7±6.2 x 10^{15} PN >5nm, 4.5±5.2 x 10^{15} PN >23nm, 1.6±2.7 g (*1) or 1.0±1.5 g (*2) PM mass, 63±42 g NOx

worst 10% vessels ~ 40% PM, 20% NOx, but NOx and PM high overall:

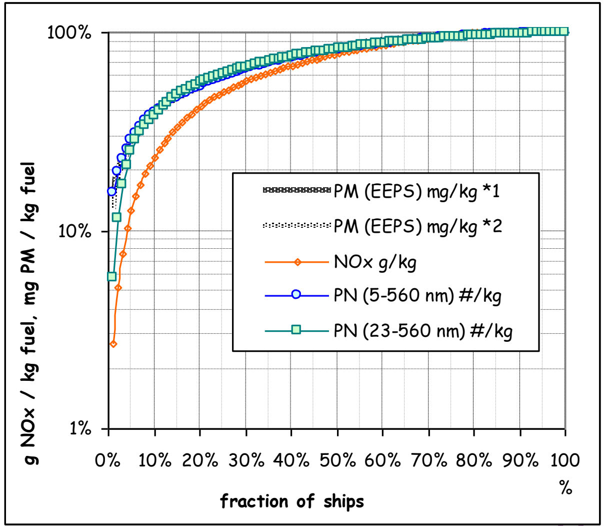
at 250 g/kWh: 80% vessels above 100 mg/kWh PM (Euro III), 8 g/kWh NOx (Euro I)

*1 PM density of 0.8 g/cm3 (atmospheric), *2 particle size-dependent PM density (fresh fractal diesel soot)



Average ship: 25-40x Euro VI limits

(0.25-0.4 g/kWh PM, 17 g/kWh NOx @ 250 g/kWh, Euro VI steady-state: 0.01 g/kWh PM, 0.4 g/kWh NOx)



Prague tourist boat 2017 gallery of shame (selection)

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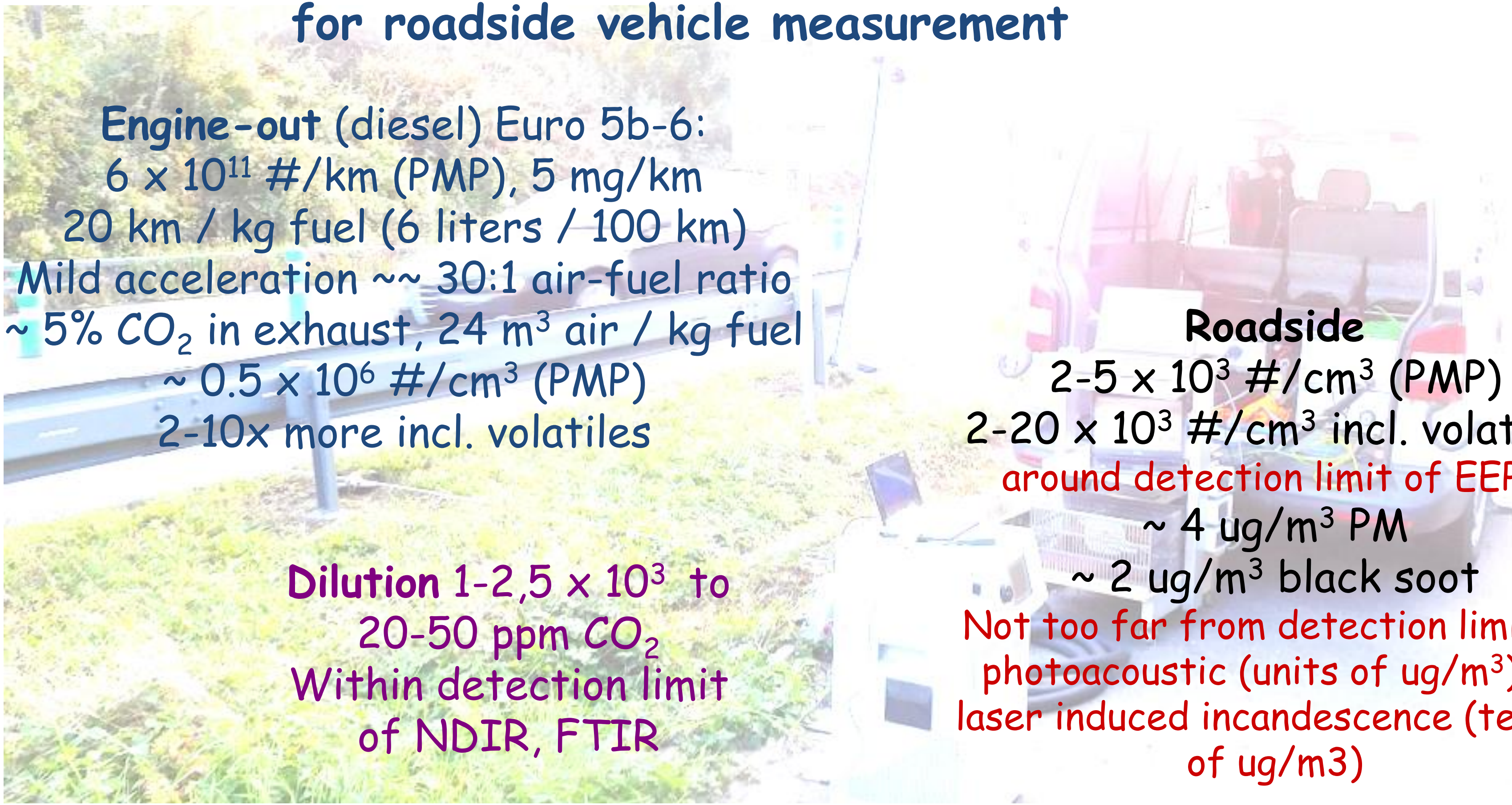
Warning: Do not inhale

High emitters contribute substantially, but emissions of all ships were generally high.
No periodic technical inspection
No emissions-related enforcement
Old engines, lenient emissions limits
This in historic city center, future LEZ (?)

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

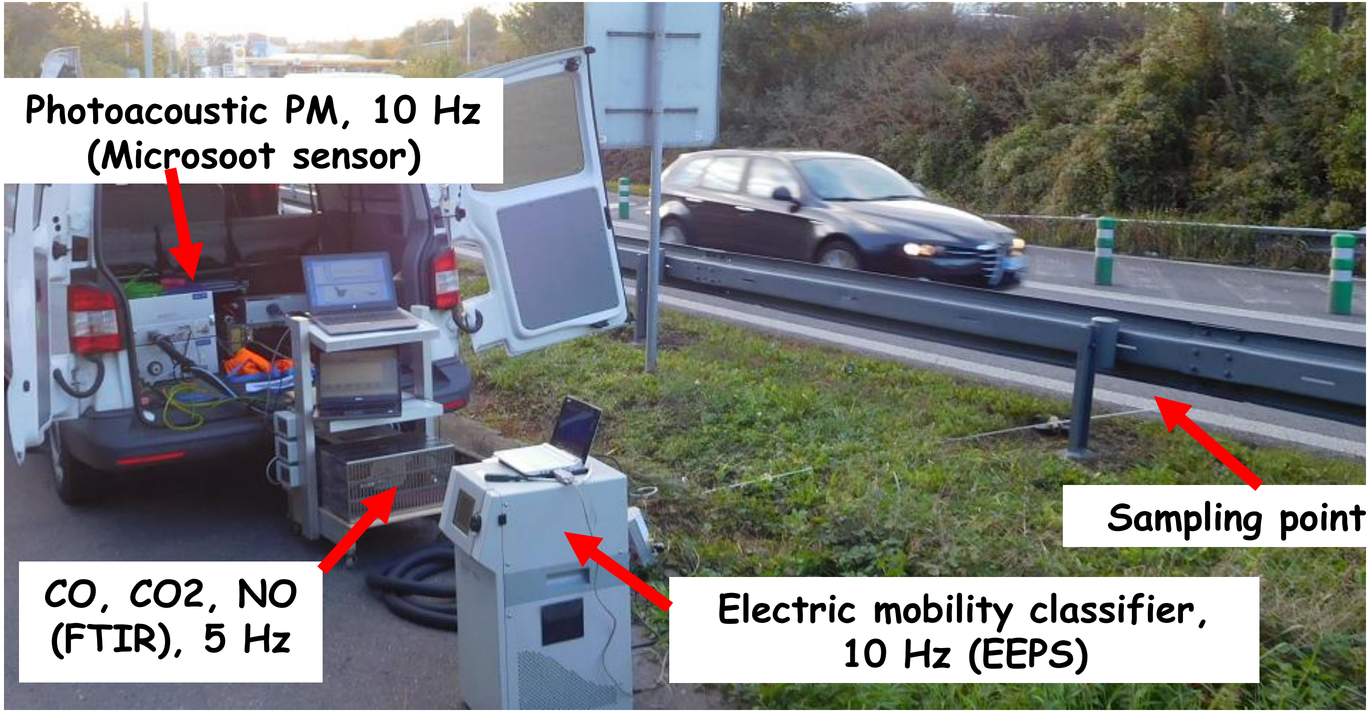
Dilution 1-2,5 x 10^3 to
20-50 ppm CO_2
Within detection limit
of NDIR, FTIR

Roadside
2-5 x 10^3 #/cm^3 (PMP)
2-20 x 10^3 #/cm^3 incl. volatiles
around detection limit of EEPS
~ 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)

Trial runs …

Remote sensing practices adopted: single lane traffic, positive acceleration, vehicle speed and acceleration recorded (radar), vehicle license plate recorded (camera with plate recognition).

No link to the vehicle registry – no info in registry about aftertreatment



Instrumentation used as PEMS and already adapted for on-road use

FTIR:
New method created for low CO_2 concentrations

Power: (4 hours)
2x2 kW inverter
2+4 kWh LiFePo

Roadside Measurement Concept Verification

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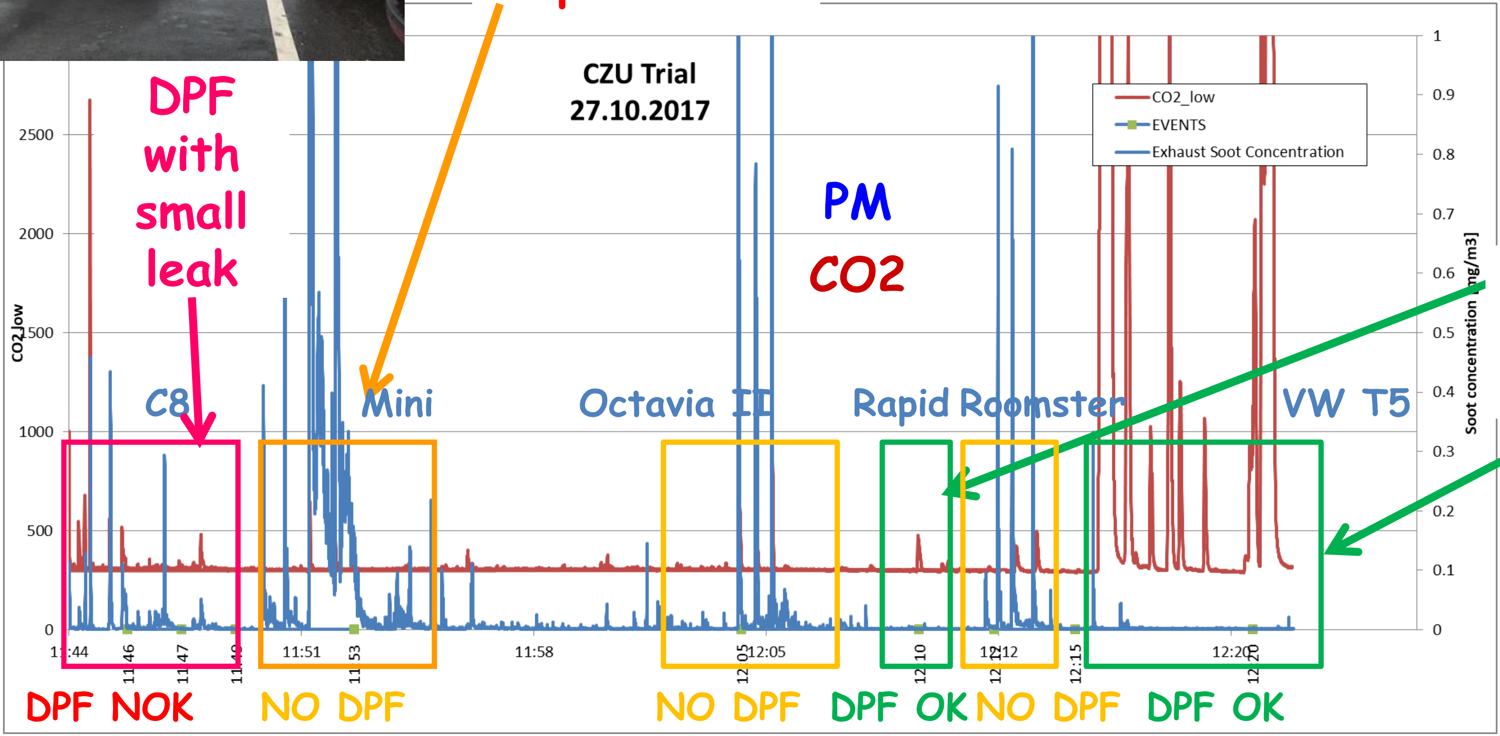
"Rolling coal": no DPF *and* mechanical problem

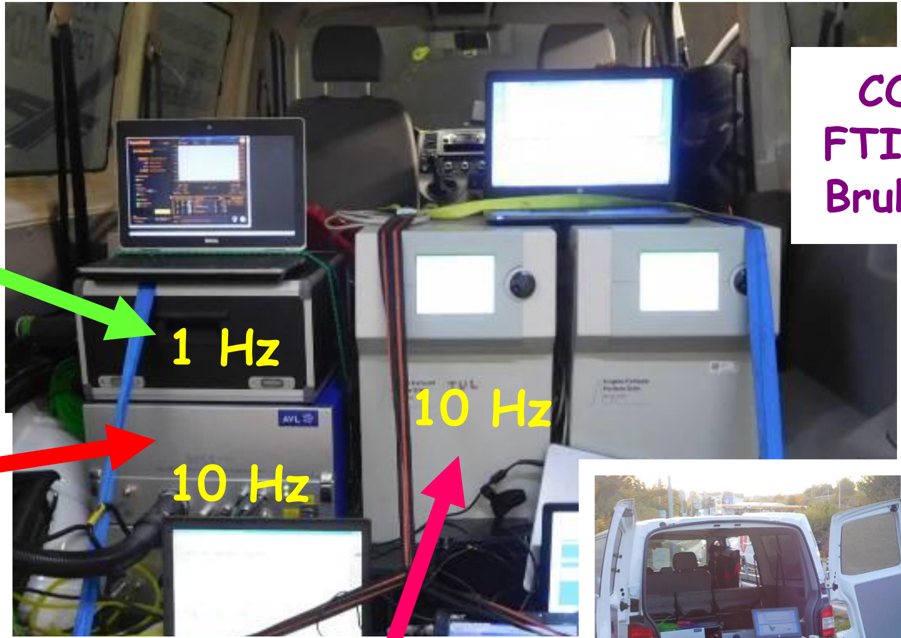


Vehicle DPF OK

Evaluation of vehicle technical condition in Prague
Particulate matter measurement

NanoMet3:
Number of non-volatile particles (PN)
Rotating disc diluter
Evaporation tube
(volatile particle remover)
Diffusion charger
Electrometers

MicroSoot Sensor:
Photoacoustic detector of soot mass concentration

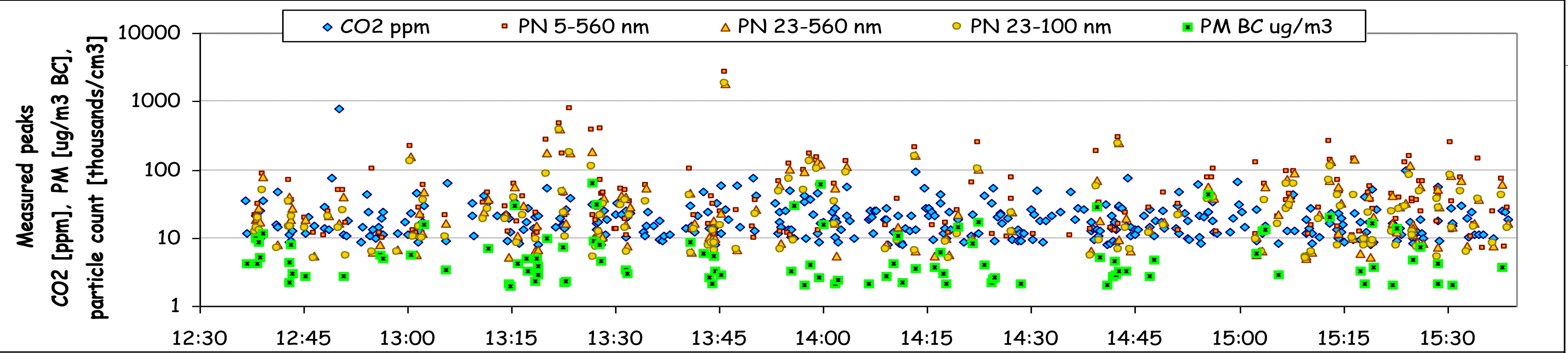


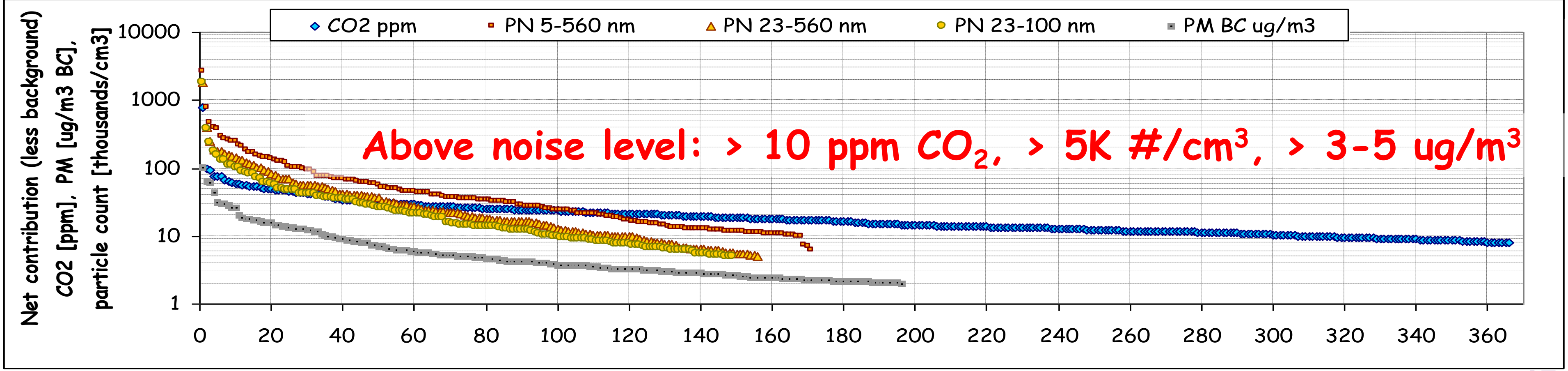
CO_2 & other gases:
FTIR (5 Hz, 0.5 cm^{-1})
Bruker Optik, 5 m cell

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





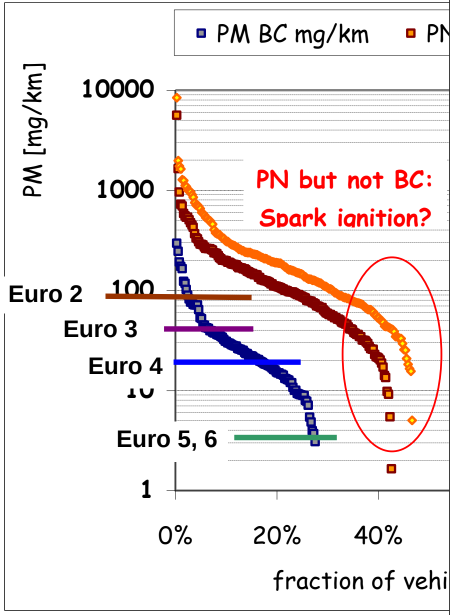
Vojtisek-Lom et al.: Roadside measurement of PM/PN emissions from individual vehicles in Prague. ETH Nanoparticle Conference, June 19, 2018

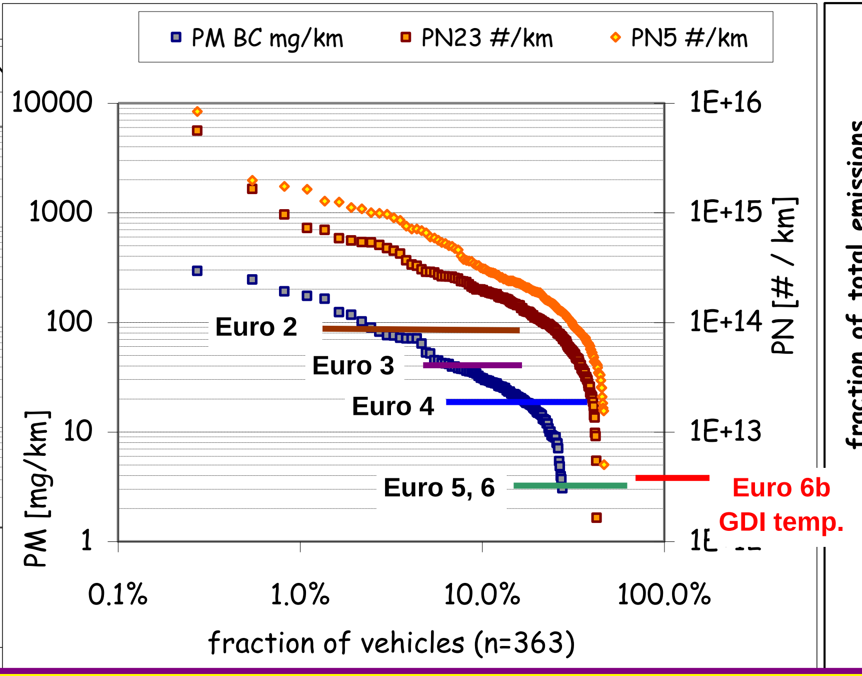
Roadside measurement, Trutnov, CZ, May 28, 2018

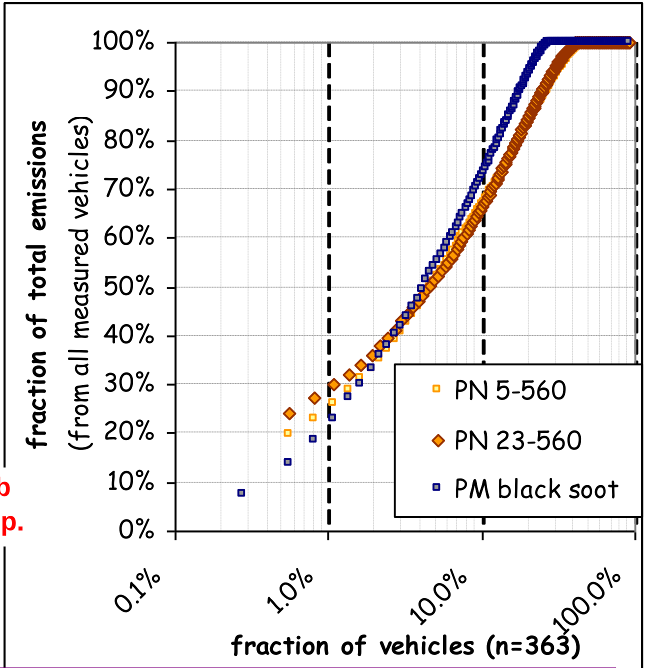
~ 3 hours, ~ 700 vehicles, ~ 360 CO_2 signals, ~ 150 measurable PM

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

CENTRUM VOZIDEL UDRŽITELNÉ MOBILITY

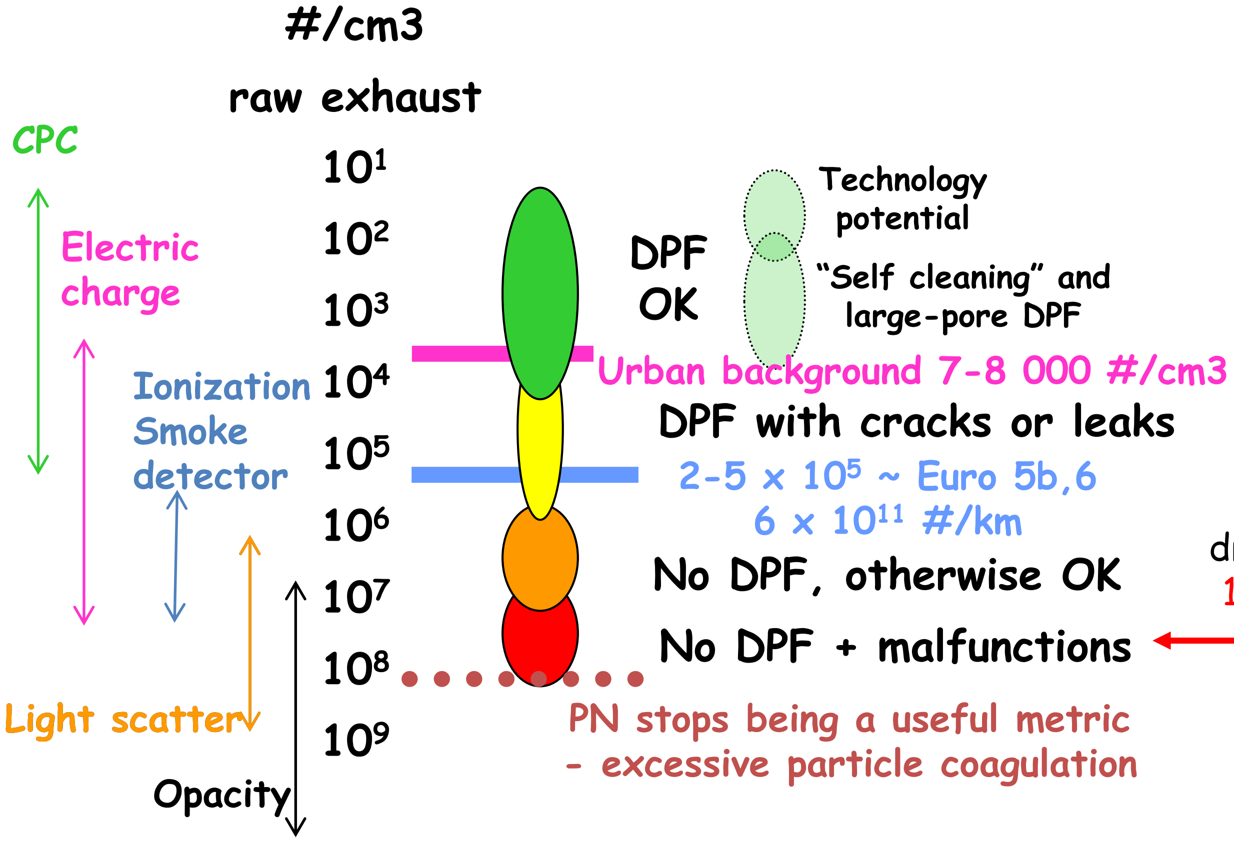






28 worst emitters were stopped and inspected by police – see poster Skácel et al.

What are we really after, and what PN detection limit do we need for roadside & periodic inspection?



"Native" DPF failures:
around 1% (target value)
TNO study: ~ 5% DPF non-working

"Intentional" DPF failures:
* occurrence unknown but non-zero, varies by region
* are often associated with engine malfunction (DPF gets removed or drilled due to excessive engine-out PM)

1 malfunctioning vehicle with removed DPF could correspond to tens to hundreds of „partially damaged" DPF

Roadside DPF check using inexpensive instrument

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Light scattering detectors and ionization chamber detectors are sold at tens of USD/EUR as household smoke detectors.

#/cm3

raw exhaust

CPC

Electric charge

Ionization Smoke detector

Light scatter

Opacity

10^1

10^2

10^3

10^4

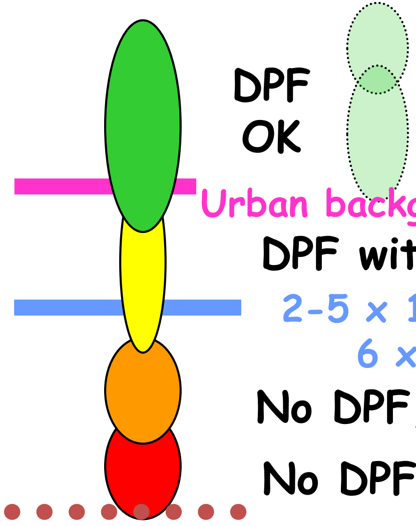
10^5

10^6

10^7

10^8

10^9



DPF OK

Technology potential

"Self cleaning" and large-pore DPF

Urban background 7-8 000 #/cm3

DPF with cracks or leaks

$2\text{-}5 \times 10^5$ ~ Euro 5b,6

6×10^{11} #/km

No DPF, otherwise OK

No DPF + malfunctions

PN stops being a useful metric - excessive particle coagulation

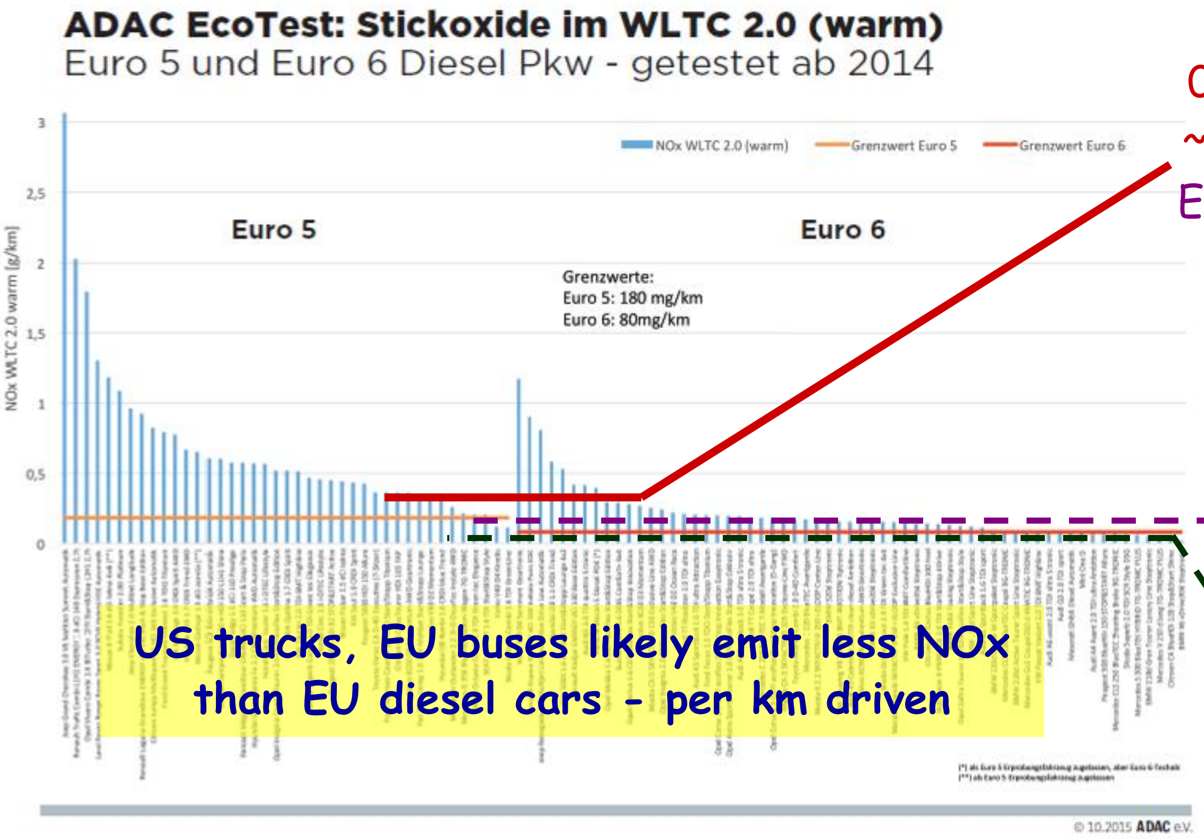
European Metrology Research Program, ENV02 Emissions, WP2: Evaluation of measuring methods for particle emission from modern diesel vehicles in periodic emission control:

<u>The ionization chamber</u> (...) was able to measure diesel particles in the whole studied for particle size range <u>from 30 nm to 150 nm</u>. The sensitivity was limited by noise of the instrument and reliable results were achieved for <u>particle concentrations above 10^5 cm^{-3}</u>.

Roadside inspection for NO_x

Useless until DieselGate resolved and high NO_x vehicles repaired?

Who is to distinguish between "factory" and "user" tampering and malfunction?



0.2 g-bhp/h US EPA 2010 limit
~ 300 mg/km NOx (@ ~ 1 kWh/km)

Euro 6 diesel bus, Braunschweig cycle, < 200 mg/km NOx

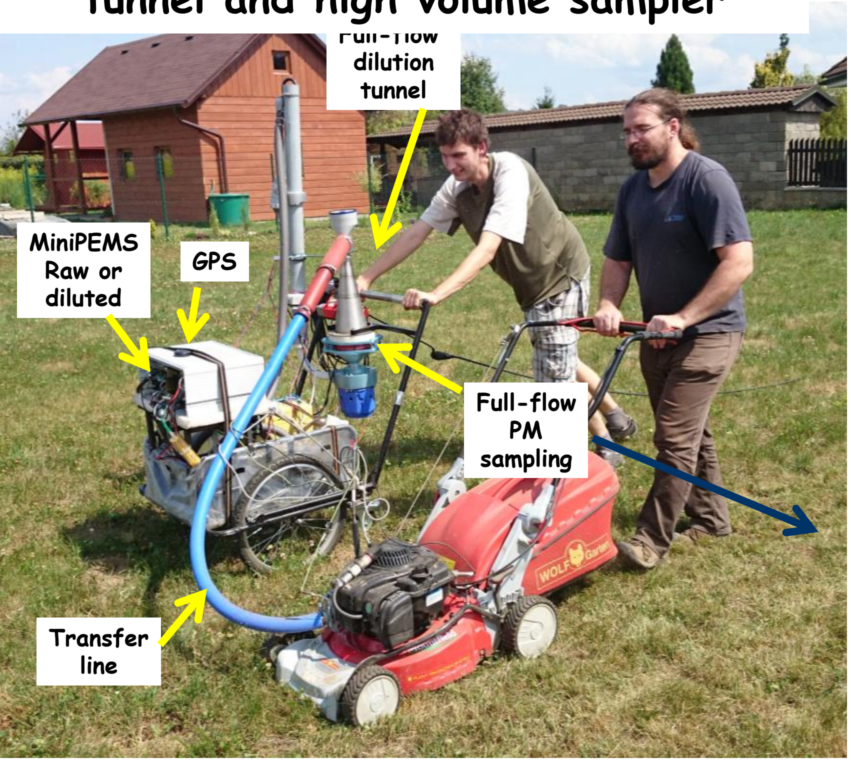
US trucks, EU buses likely emit less NOx than EU diesel cars - per km driven

Proposed (US – California):
0.02 g-bhp/h
~ 30 mg/km NOx

Before going after high emitters, systematic (factory) issues to be found by PEMS or other means, and resolved

Mini-PEMS & Poor man's PEMS

Off-board system with full-flow tunnel and high volume sampler



Focus on making the test possible & practical.

Variances within and among vehicles are often greater than the uncertainty of simpler instruments

???
real real driving vs. EU-defined real driving
???

NO, NO2
CO, CO2
Indicative PM
Indicative HC
Calculated flow
9 kg
3 hr runtime

On-board FTIR – all principal gases

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

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

Conclusions

Fast-response instrumentation (5-10 Hz, adapted research grade PEMS) used to sample & analyze air at roadside / riverside.

Particle emissions from individual vehicles & vessels were assessed from plumes of diluted exhaust and expressed per kg of fuel.

Preliminary results confirm that high emitters contribute greatly to the total particle emissions, and removing even only the worst ones would be helpful.

Main challenge: Matching plumes & analysis results to individual vehicles.

The work is at a concept stage, with open questions.

Acknowledgements:

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