20th ETH Conference on Combustion Generated Nanoparticles
Zurich, Switzerland, June 13-16, 2016

FTIR-PEMS, Mini-PEMS & Micro-PEMS: Extending portable on-board emissions monitoring systems to non-regulated pollutants and small engines

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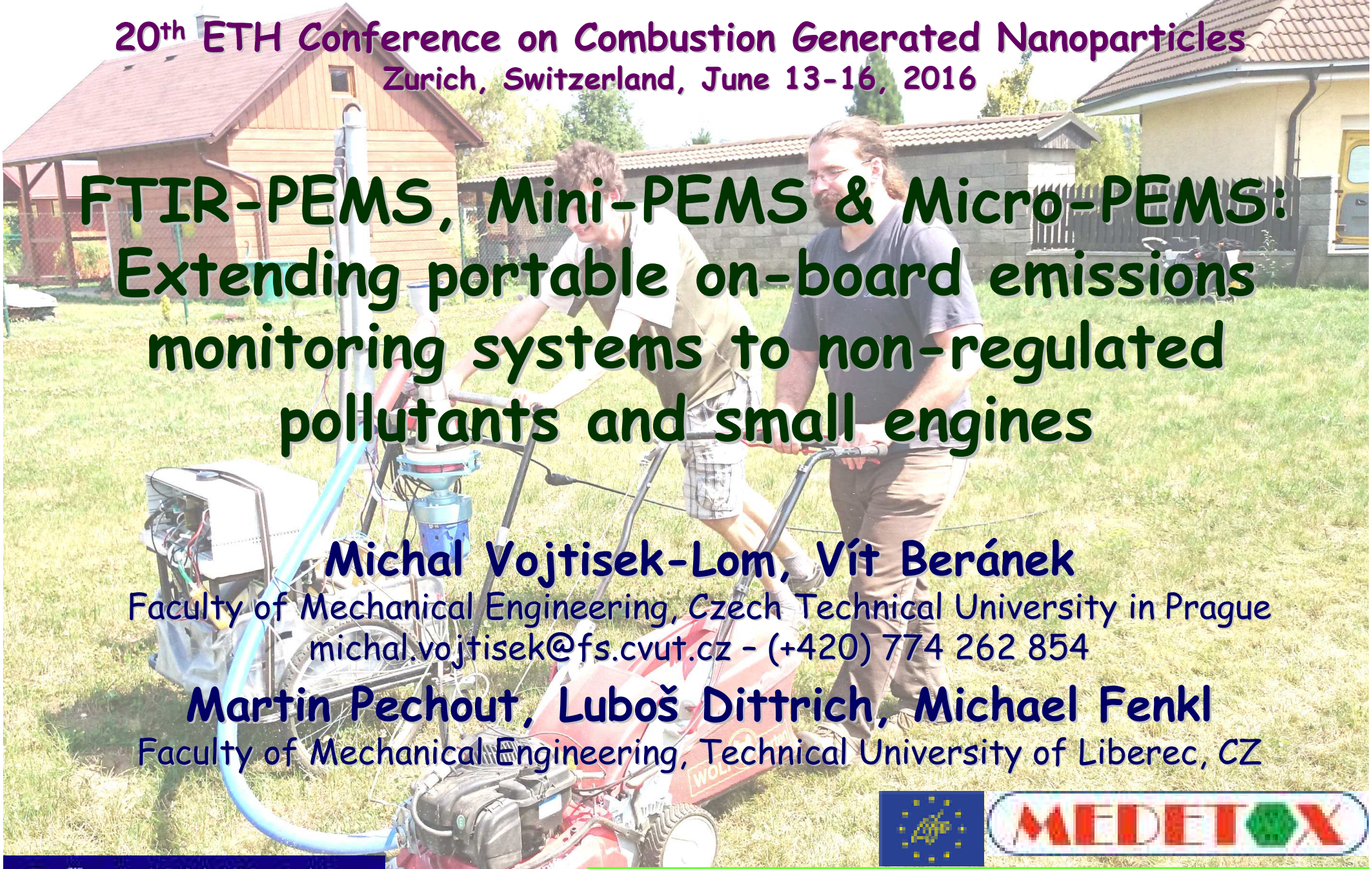


Czech Technical University in Prague
Faculty of Mechanical Engineering

TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechanical Engineering

EU LIFE+ program, project MEDETOX - Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic (LIFE10 ENV/CZ/651)
www.medetox.cz

Particulate matter and ground-level ozone are responsible for over 400 thousands premature deaths in the EU

(traffic accidents for „only“ 39 thousands)

Problematic pollutants in engine exhaust

- **Particles** + secondary aerosol
- **NO_x** + tropospheric ozone
- CO, benzene, lead – no longer a problem

New and emerging problems:

- NO_2 - formation in oxidation catalysts
- NH_3 - formation in reduction catalysts
- - formation in three-way catalysts when run rich
- Aldehydes – oxygenated fuels (ethanol)

Greenhouse gases

- N_2O - NO_x reduction catalysts (SCR, LNT)
- CH_4 - natural gas engines, LNT catalyst

Real-world emissions could be higher than during „standardized tests" (i.e., type approval)

- Optimization for type-approval conditions
  - No EGR at full load
  - Catalyst sized for low flow and too small for high loads
- **Technology limits**
  - low SCR temperature – cold start, creep
- Malfunction & deterioration
- „No one is watching"
  - Switching off EGR, LNT fuel / SCR urea injection
  - „Cycle beating" strategy
  - DPF removal, SCR deactivation, etc.

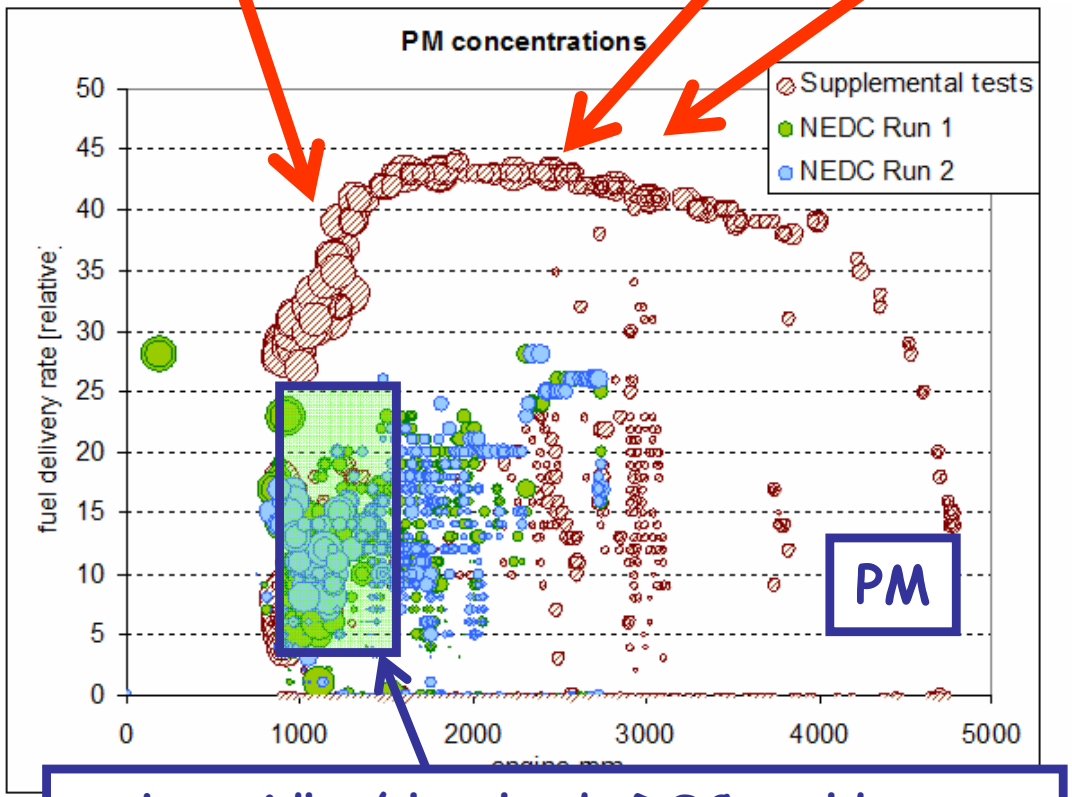
Challenges of EU automobile diesel engines
Euro 4 Skoda Fabia – chassis dynamometer runs
NEDC vs. full-power loaded accelerations

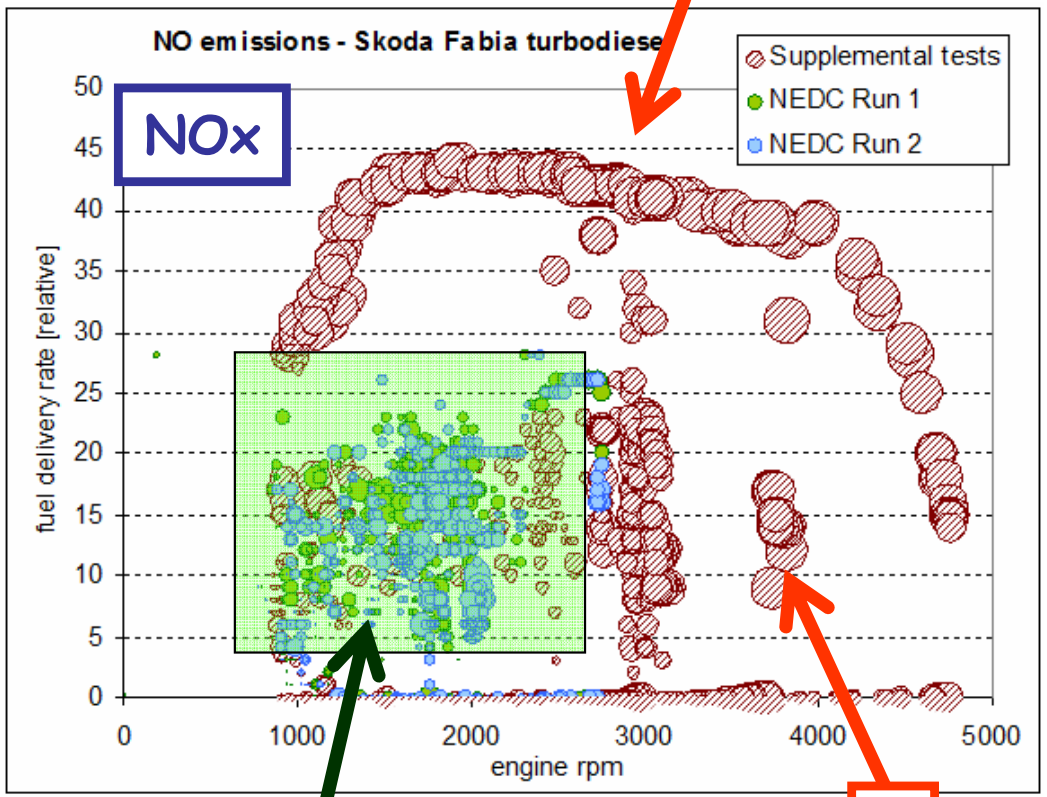
Problem compounded by downsizing & turbocharging: Relatively low torque at idle.

Problem compounded by cold DOC during accelerations after long idle

Maintaining adequate excess air competes with desire for additional torque

NOx: Use of EGR competes with the desire for additional torque





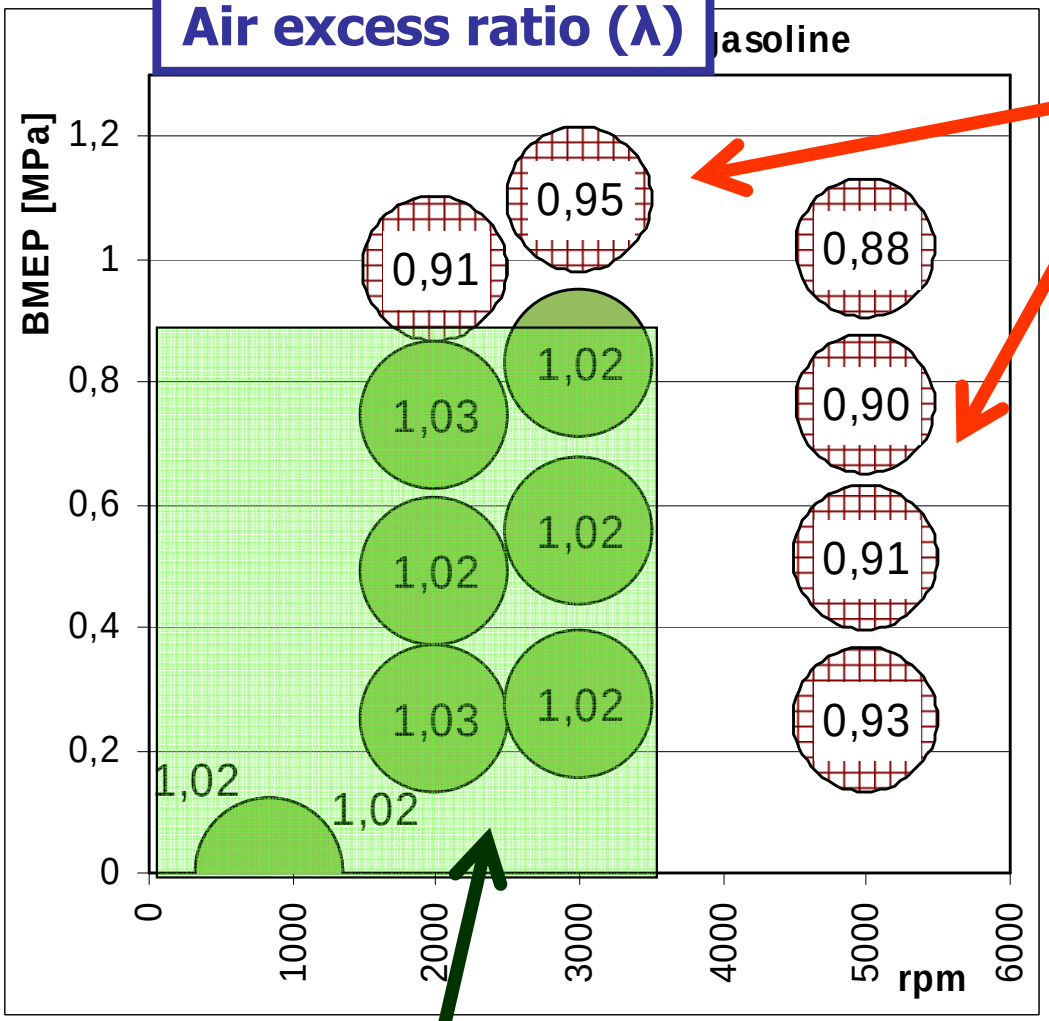
Long idle / low load: DOC cooldown, combustion deterioration, high fraction of OC in PM

NOx reduced by EGR

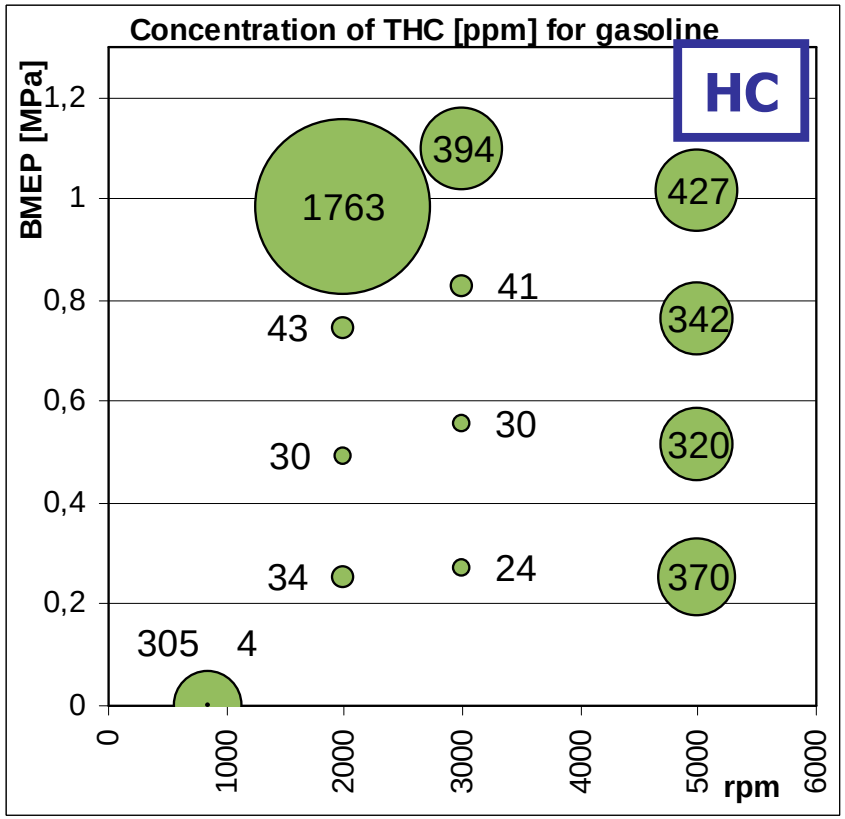
?

Challenges of EU automobile gasoline engines
Euro 4 Skoda Fabia – engine dynamometer runs

Air excess ratio (λ)



Reducing exhaust gas temperatures (catalyst protection) by fuel-rich operation at high rpm and at high loads



Stoichiometric operation

Role of on-board, real-world emissions measurement

ON-BOARD INSTRUMENTATION
OR CHASE VEHICLE

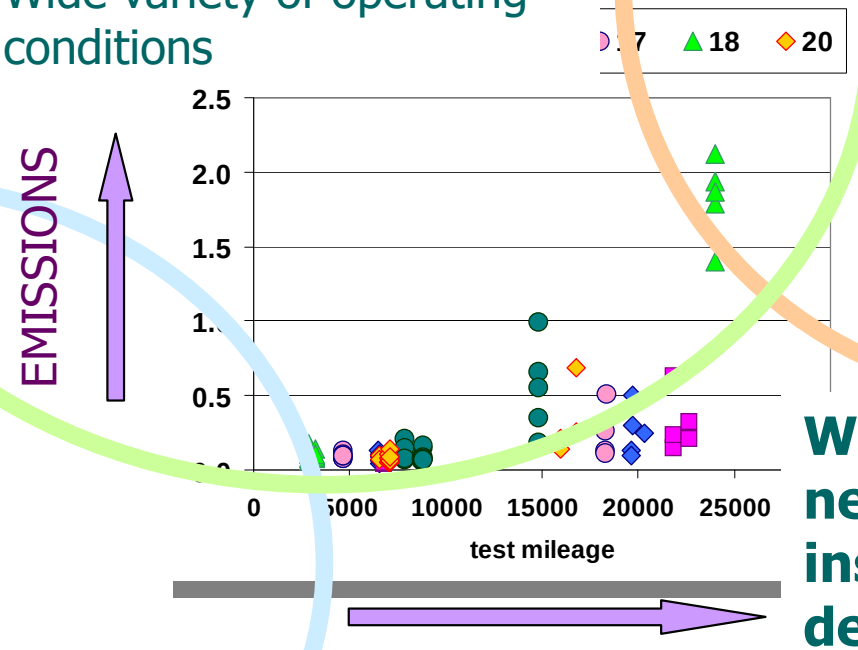
Measurement of individual vehicles during real-world oepration
Low to intermediate number of vehicles
Wide variety of operating conditions

REMOTE SENSING
I/M PROGRAMS

Inspection & maintenance
Screening
High number of vehicles
Low cost
Low precision

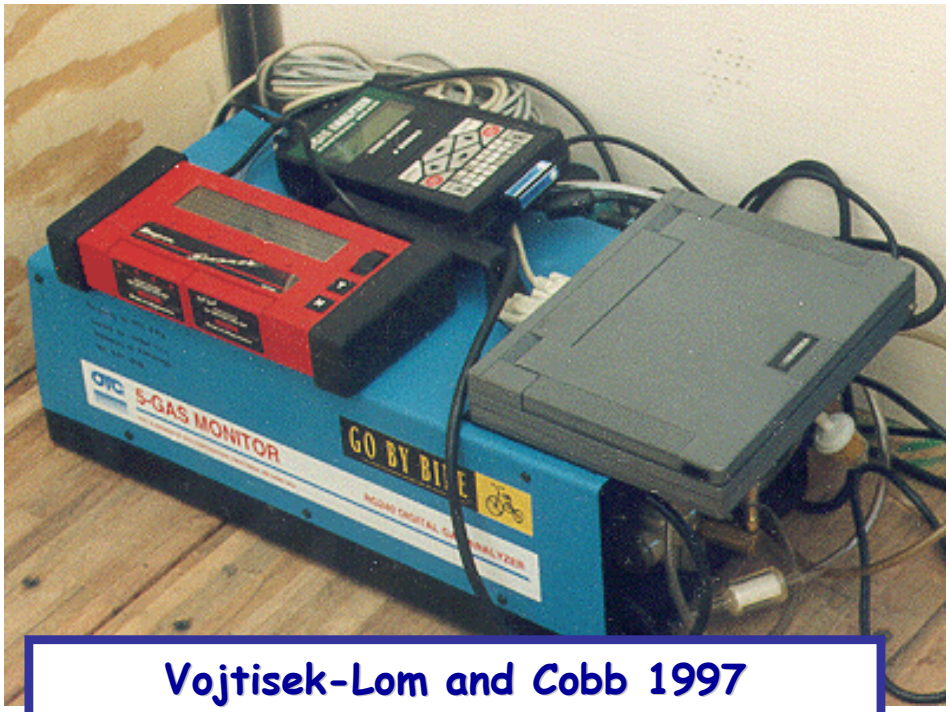
LABORATORY

Research
Engineering
Type Approval
High quality, high cost,
Small number of vehicles

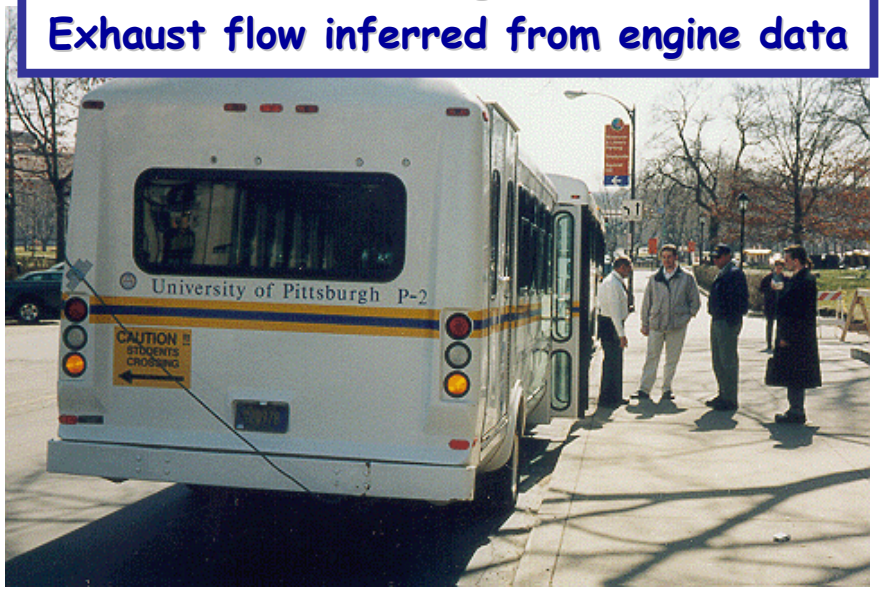


With PEMS, it is always necessary to match the instrumentation and test designs to what we want to find out.
(Low-cost high-throughput vs. detailed high-accuracy measurement)

Early portable on-board emissions monitoring systems



Vojtisek-Lom and Cobb 1997
Univ. of Pittsburgh, 1996-1999
Exhaust flow inferred from engine data



Leo Breton, US EPA, mid 90's
(US patent 6,148,656 filed 1999)
Measured exhaust flow

Vojtisek-Lom 1999
First commercially sold PEMS

"PEMS" acronym started to be used around 1998

by Matt Spears (US EPA), Chris Frey (NC State University), and others, as a generic term for on-board monitoring system that is portable or at least transportable and can be easily fitted on a vehicle

What is or should be "PEMS" now?

Those on-board monitoring system that are portable?

Only PEMS meeting type-approval legislation requirements, or also PEMS used for research, engineering and other purposes?

On-board monitoring & sampling system (transportable)

Dr. Jesse Tu, California Air Resources Board, PEMS workshop, UC Riverside, 2011

On-board monitoring & sampling system (not road-legal)

Southwest Research Institute, Reno, NV, USA
Foto by author, Pennsylvania Transportation Institute, 2003

On-board emissions monitoring system (high precision, low detection limit, more "transportable" than "portable")

System VOEM – Flemisch Technology Institute (VITO), Belgium

Lenaers G., Pelkmans L. and Debal P. (2003): The Realisation of an On-board Emission Measuring System Serving as a R&D Tool for Ultra Low Emitting Vehicles. Int. J. Veh. Design, Vol.31, No. 3, pp 253-268.

http://www.lne.be/themas/milieu-en-mobiliteit/downloads/studie-en-onderzoek/report_on_first_measurement_campaign_on_euro_2_bus_before_retrofitting_with_clean_air_power_system.pdf

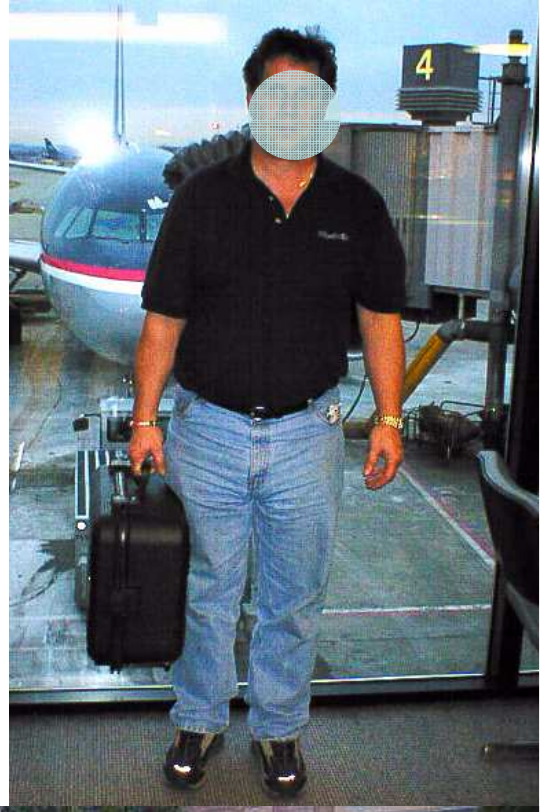
"Downsizing" PEMS:

Transport as carry-on luggage on airplane

(Vojtisek-Lom and Allsop, SAE 2001-01-3641)

Compact design used for non-road engine tests

(Lanni and Vojtisek-Lom, ETH 2007)



Miniature portable on-board emissions monitoring system (MiniPEMS)

HC, CO, NO, NO_2, PM mass, PM length

heated ionization "fire detector"

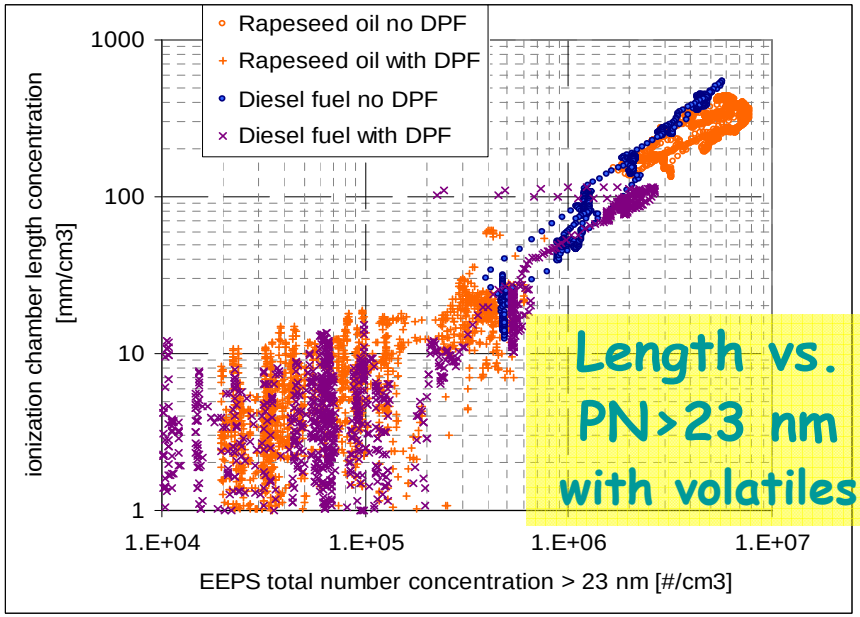
undiluted raw exhaust

(multiplied by intake air flow for comparison measurements)

~ 0.1 mg/m3 sensitivity

cheap (100 EUR)

"poor man's PEMS" concept



Length vs. PN>23 nm with volatiles

Online real-world measurements

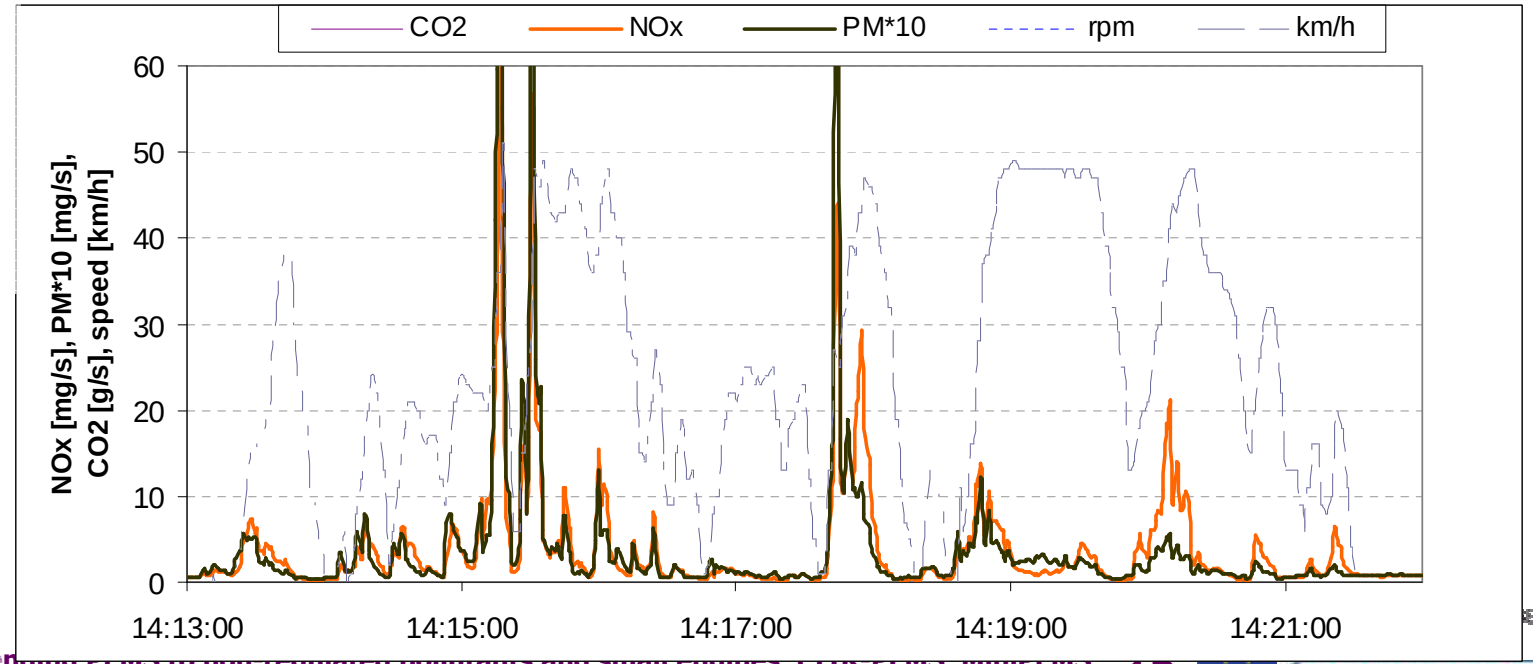
qualitative PM on SI

SAE 2013-24-0102

SAE 2013-24-0168

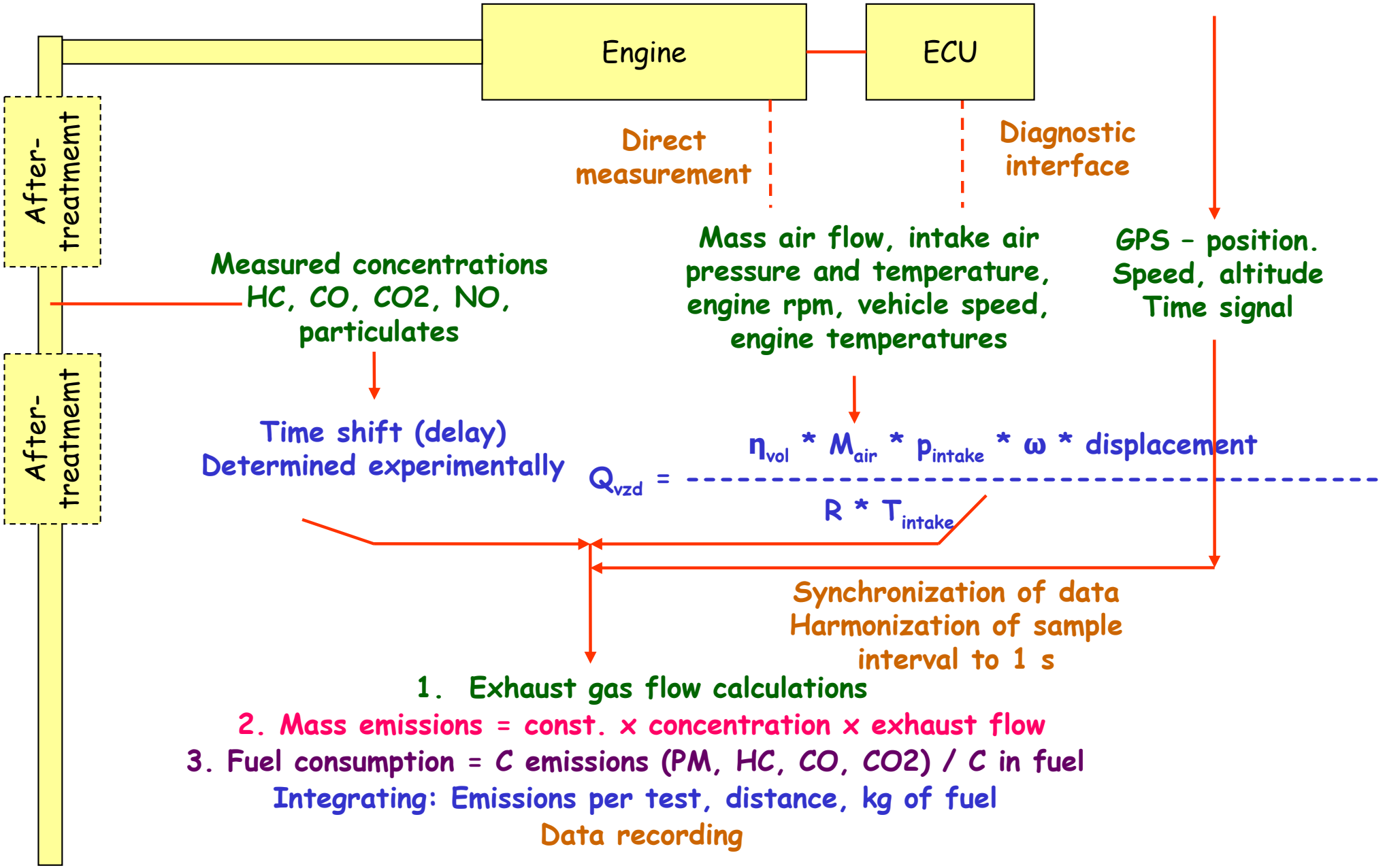
Installs on motorcycles to locomotives

This example → from a Euro 4 diesel car

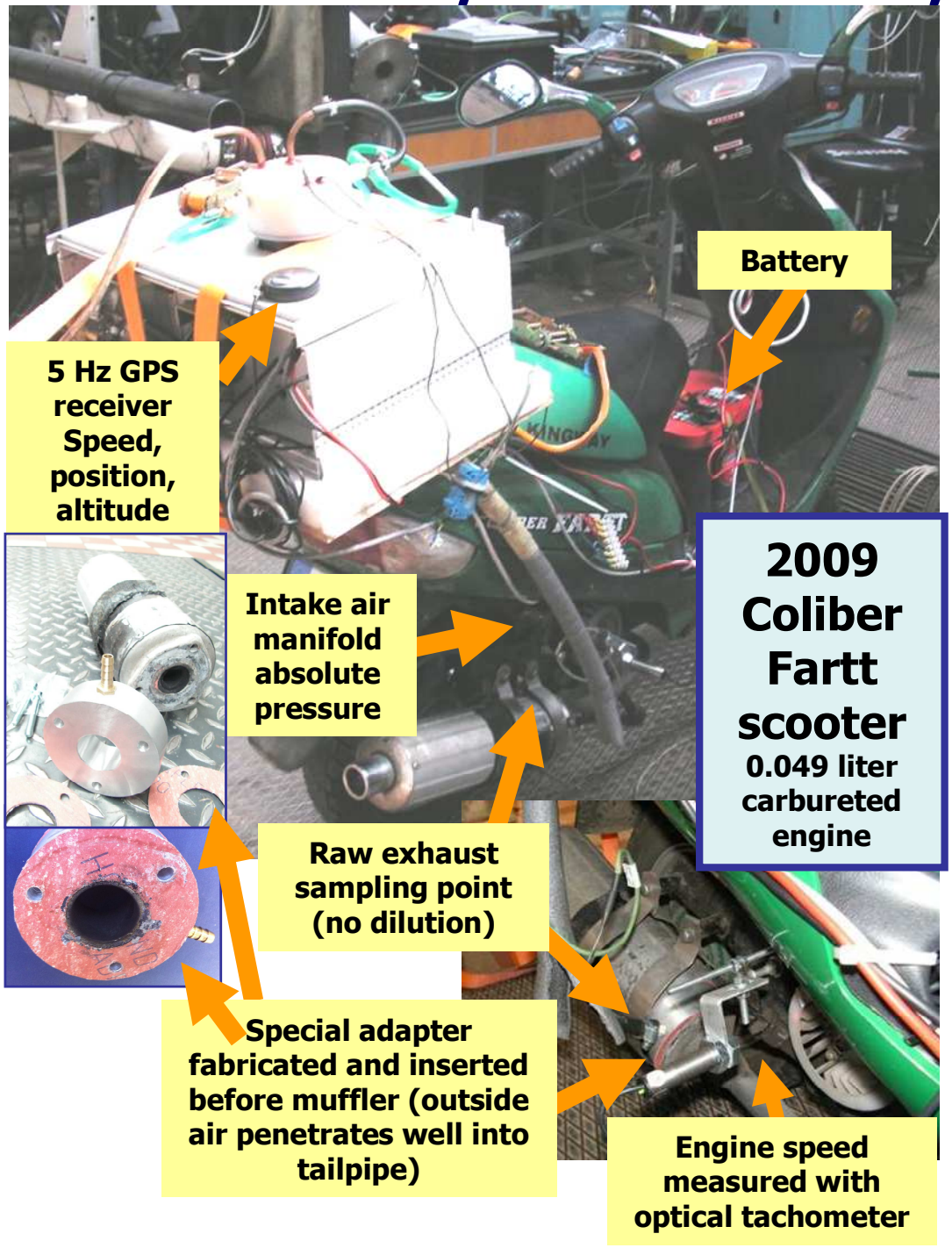


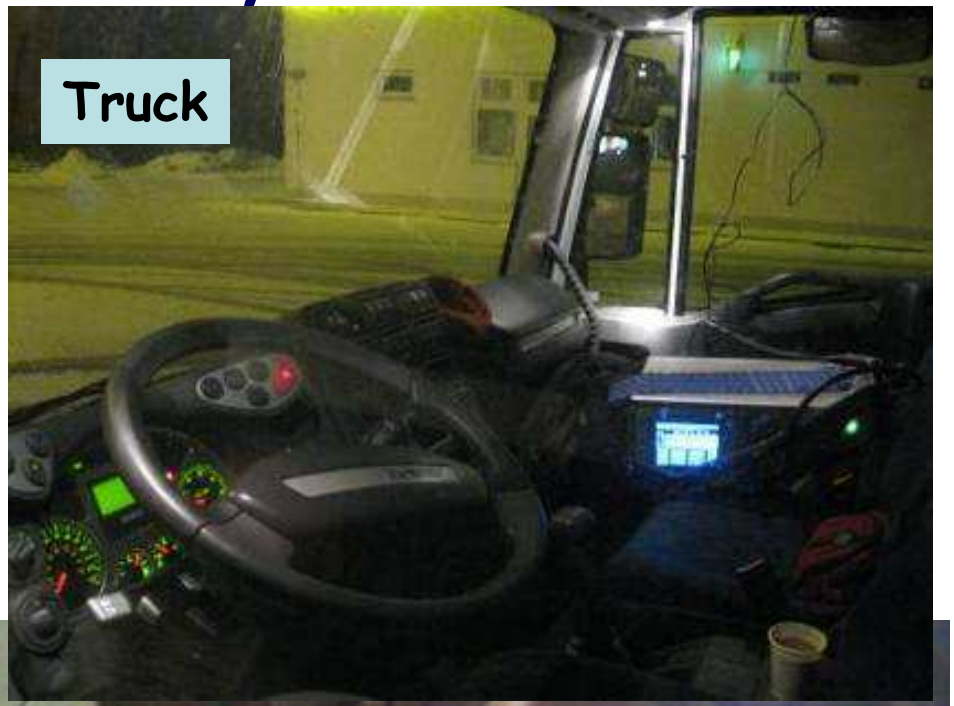
Low-cost on-board system overview

(Vojtisek-Lom and Cobb, CRC On-road vehicle emissions workshop, 1998)



On-board system versatility: Motorcycle to locomotive



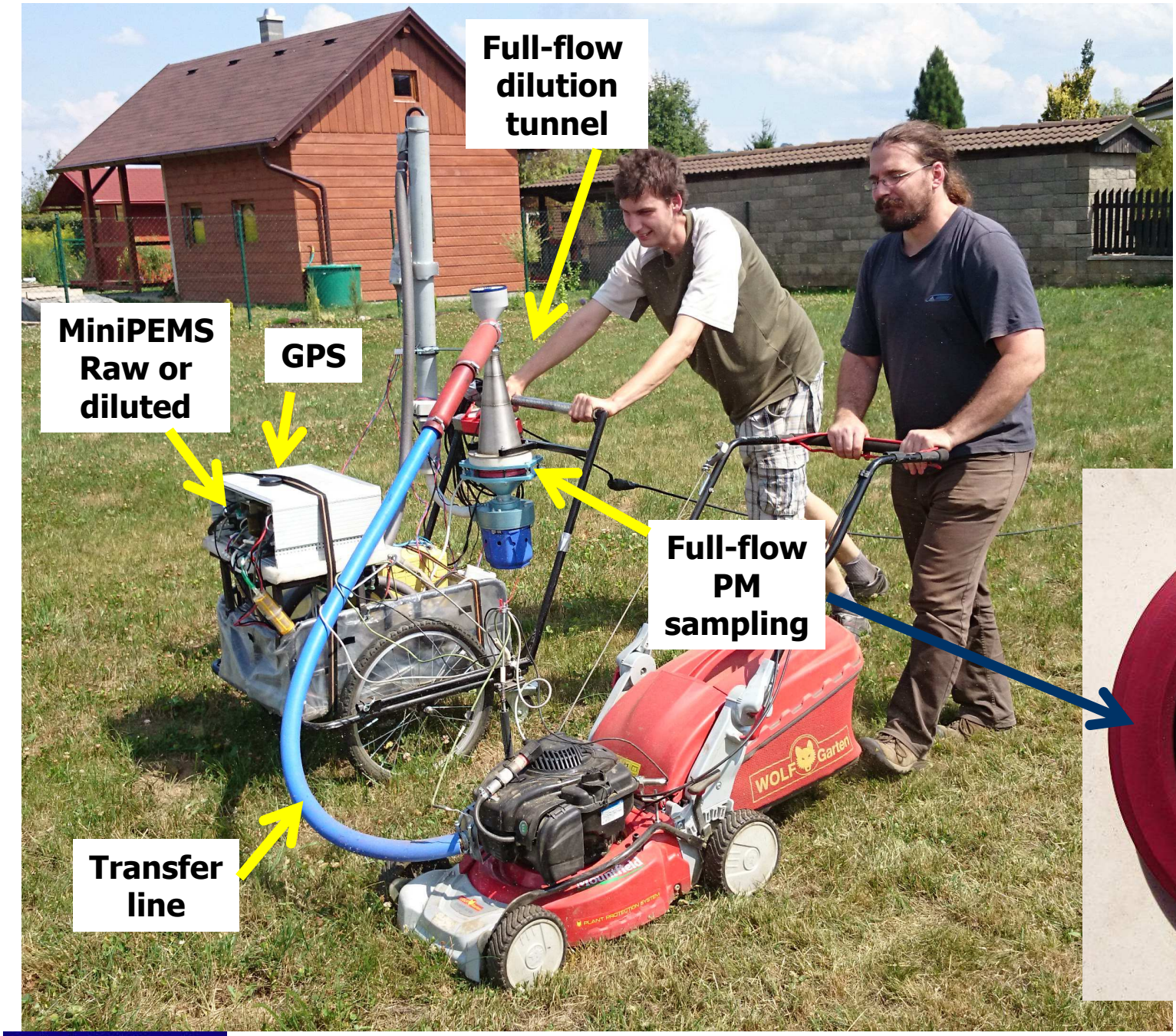


Motorcycle (scooter) – test summary per km

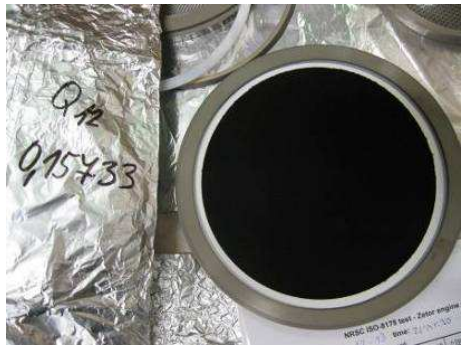
Emissions per km	HC [g]	CO [g]	NO_x [g]	PM laser [mg]	PM ion1 [km]	PM ion2 [km]	CO_2 [g]
Urban	2.72	11.2	0.50	3.3	406	386	53
Rural	1.30	8.4	0.41	2.7	320	255	39

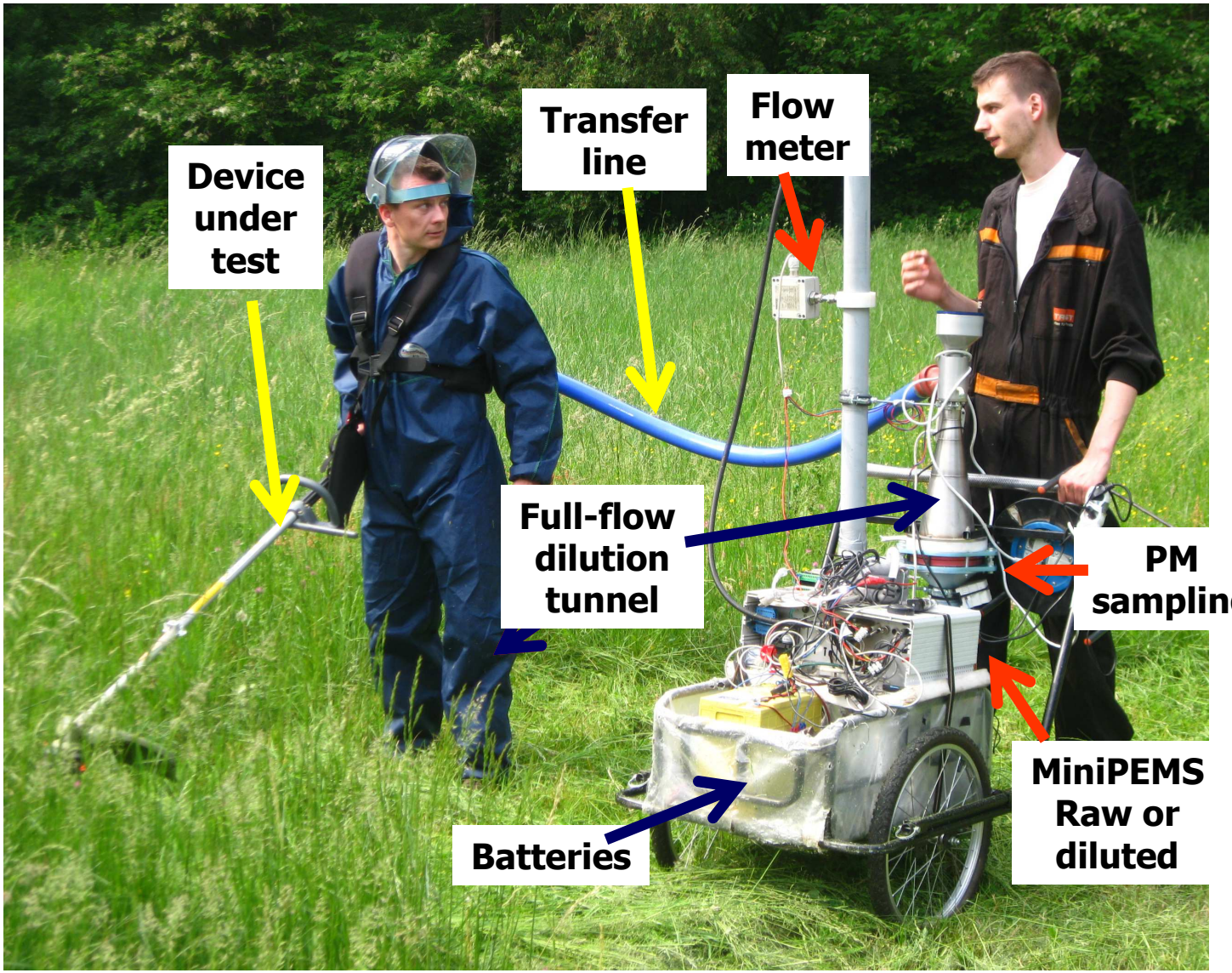
- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m

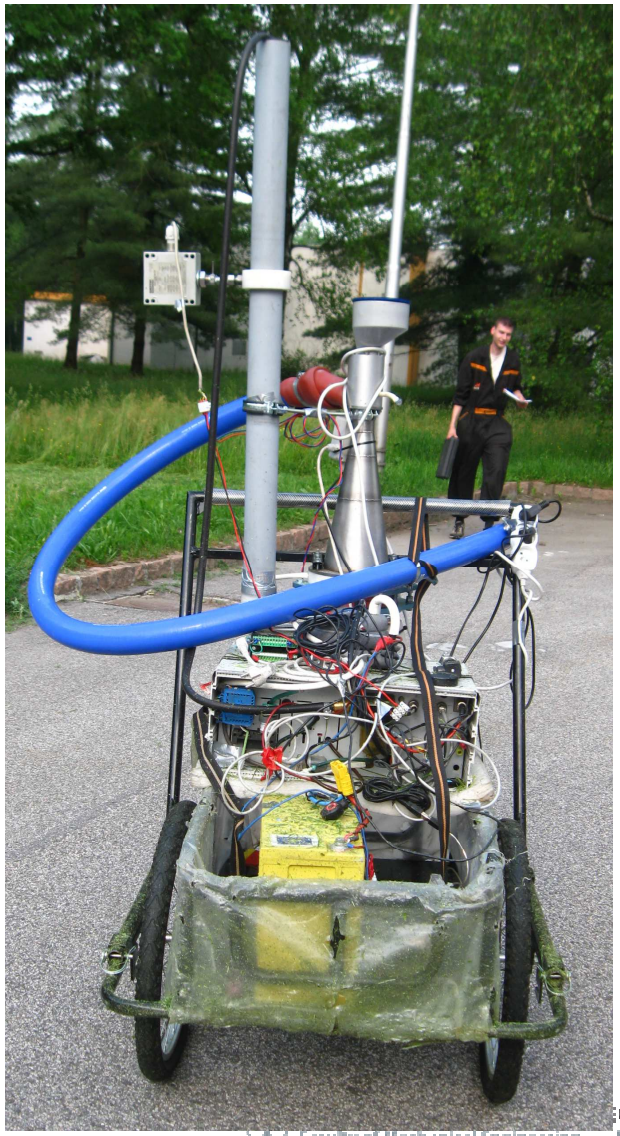
These ~20 mg of particles are not from a diesel engine, but from garden machinery!



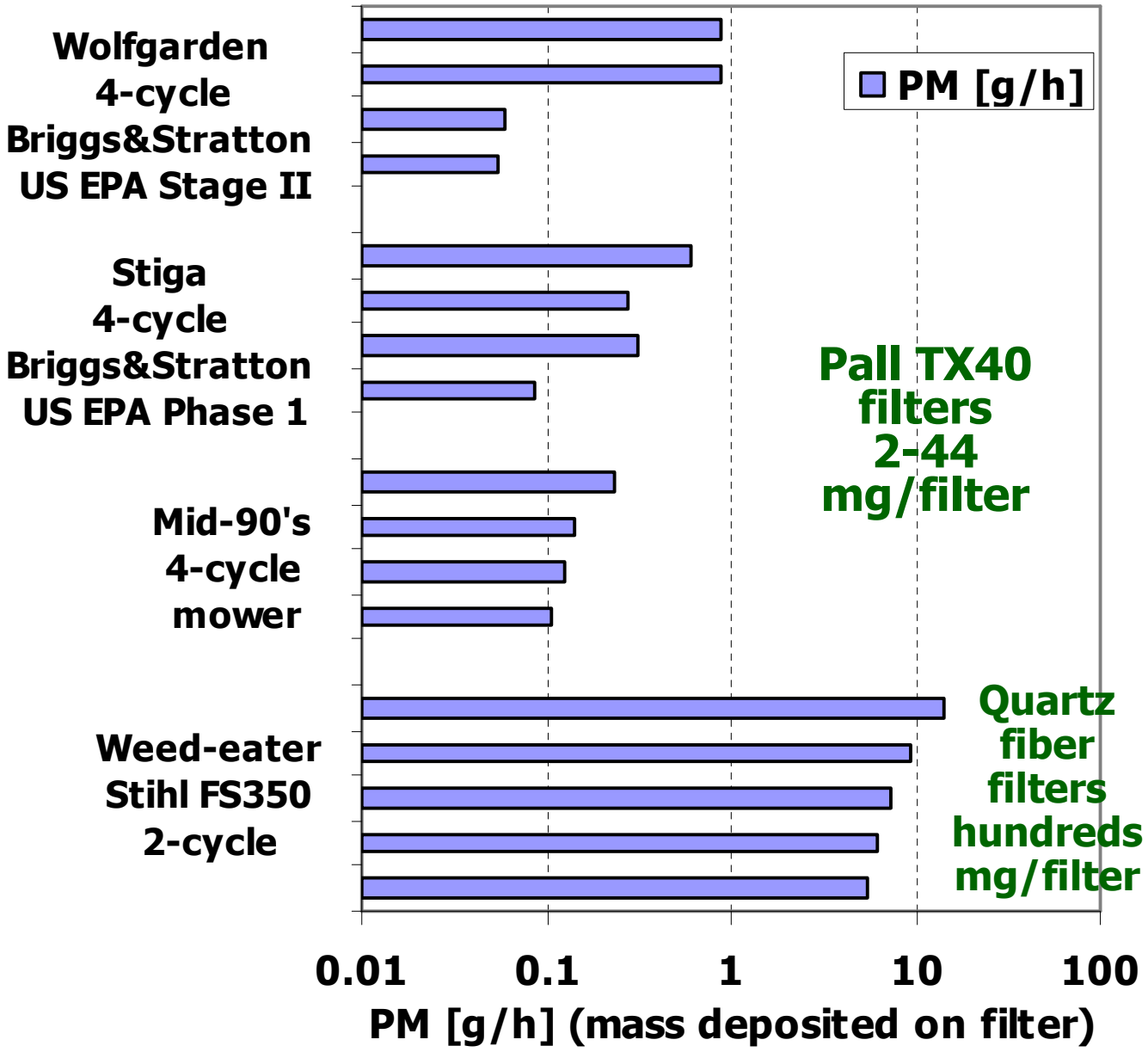
Extending PEMS to small non-road engines: Off-board emissions monitoring system Full-flow dilution tunnel with particle sampling







Lawnmower and weed-eater – test summary



FTIR (Fourier Transform Infra Red) Spectrometer

- measures large portion of infrared spectra
- quantification of compounds absorbing in IR through deconvolution of spectra

- greenhouse gases CO2, CH4, N2O
- reactive nitrogen compounds NO, NO2, NH3, HCN, HCNO
- various heterogeneous molecules present in concentrations that can be detected and discerned from other compounds

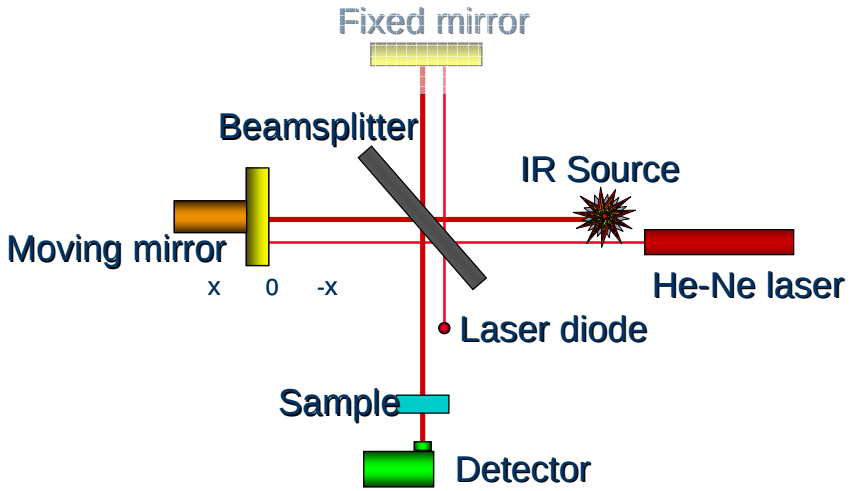
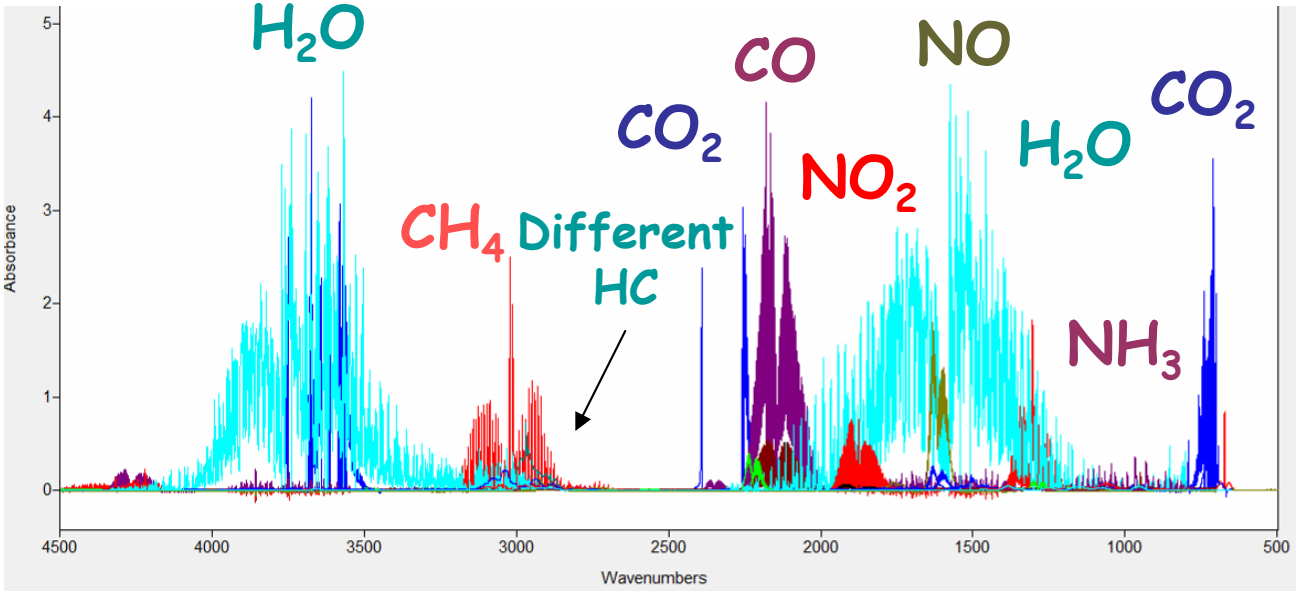
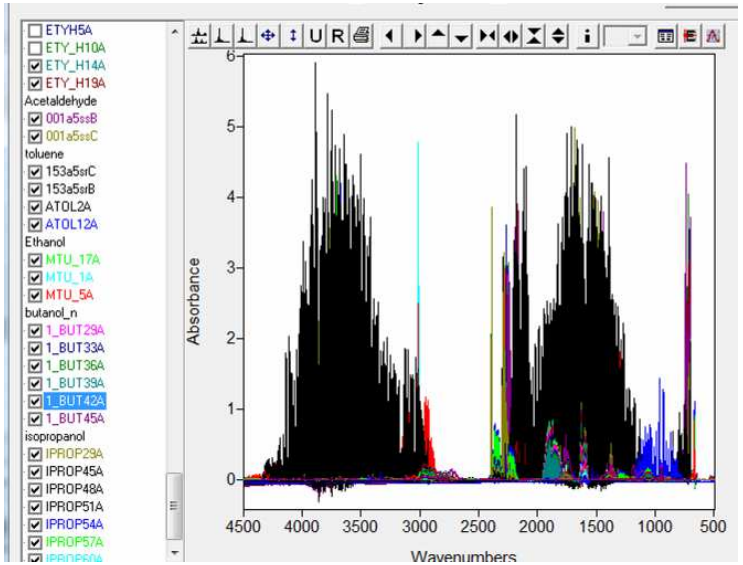


Diagram: Nicolet

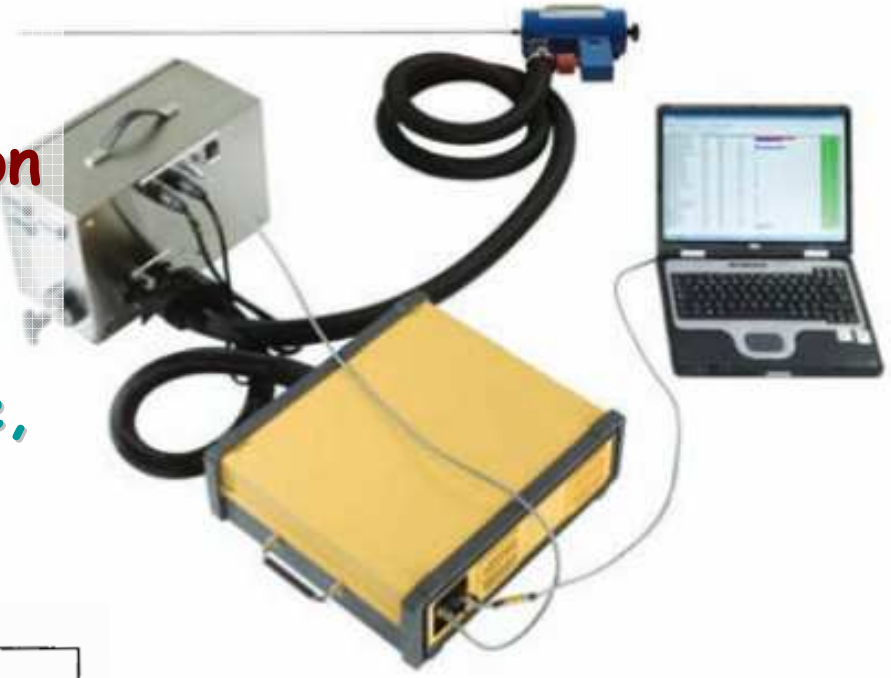




There is a range of FTIR:

Smaller and lighter but less resolution

(i.e. Daham 2005 – Univ. Leeds – Gasmet)



and higher resolution, more sensitive, but less portable

(i.e., Jetter 2000, Nicolet / Honda)…

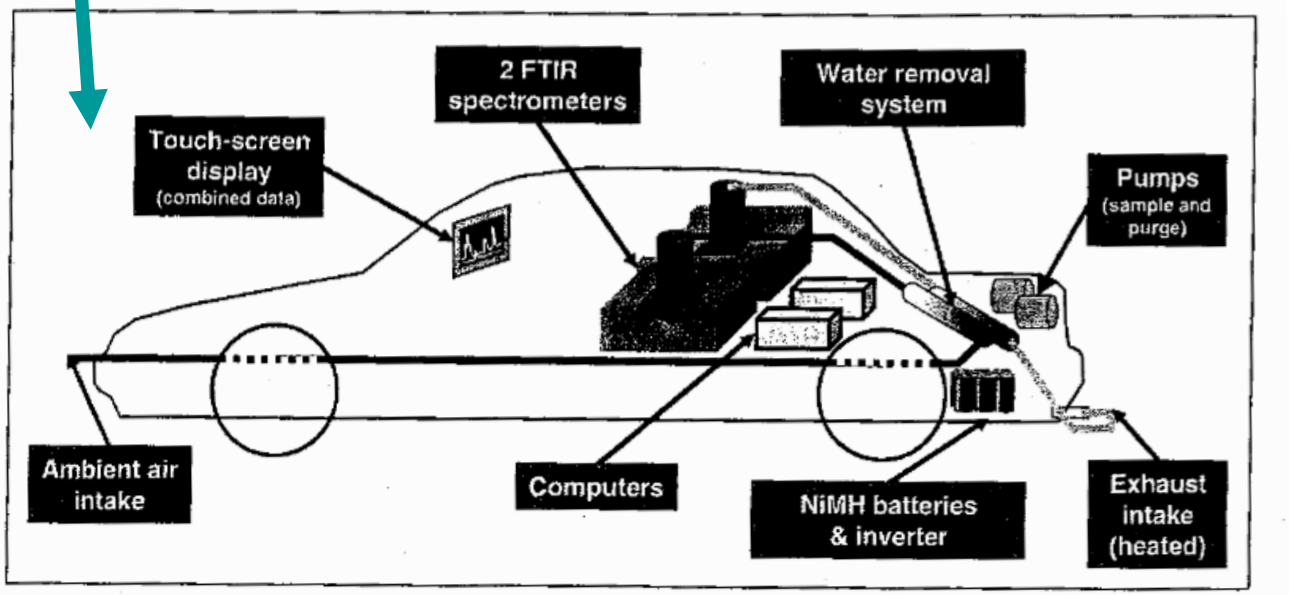


Figure 1. Overview of on-board sampling/analysis system

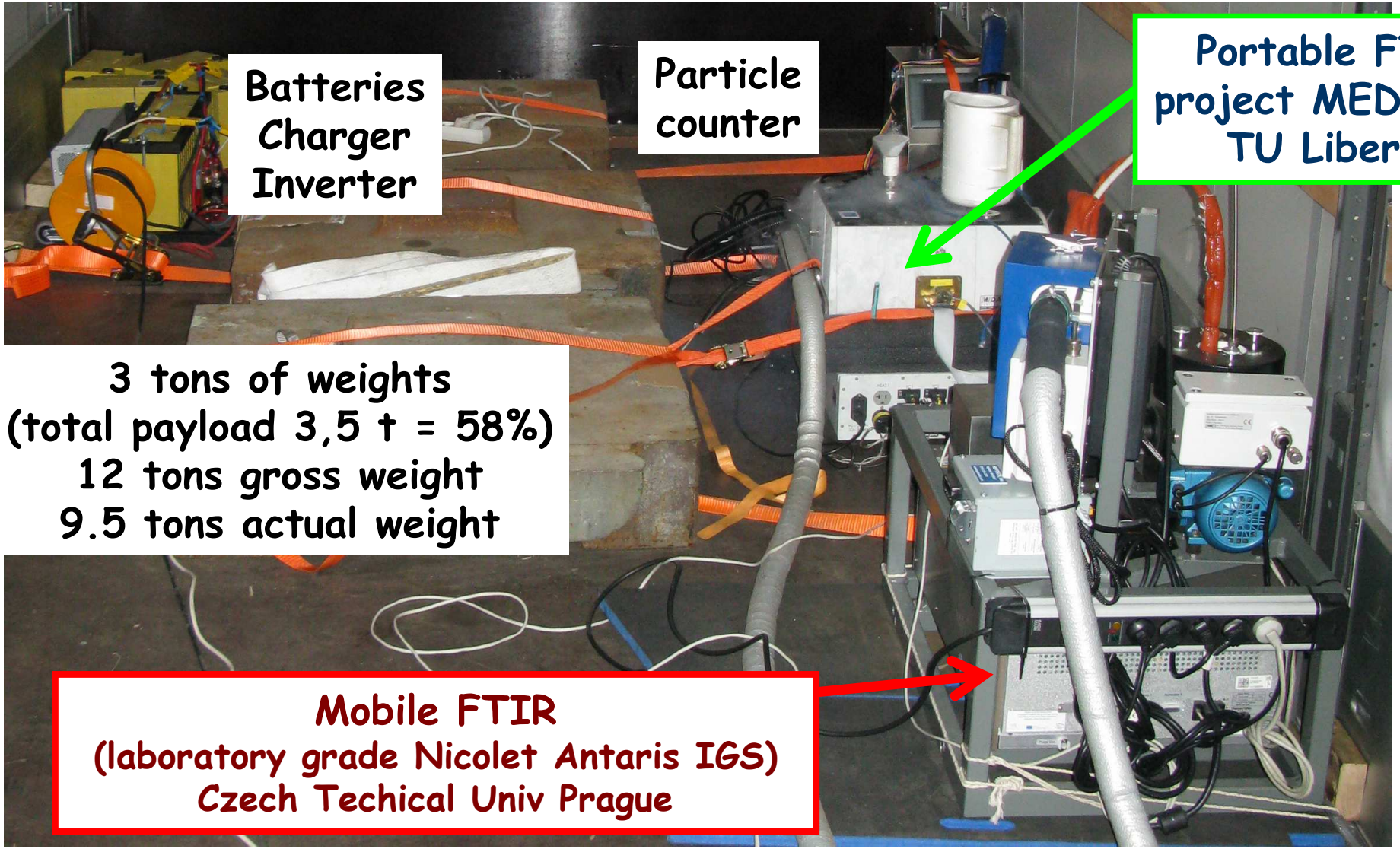
Daham B., Andrews G.E., Li H., Bellesteros R., Bell M., Tate J. and Ropkins K.; Application of a Portable FTIR for Measuring on road Emissions.
SAE technical paper 2005-01-0676.

Jetter, J., Maeshiro, S., Hatcho, S., and Klebba, R., "Development of an On-Board Analyzer for Use on Advanced Low Emission Vehicles," SAE Technical Paper 2000-01-1140, 2000, doi:10.4271/2000-01-1140.

On-board FTIR tests, Euro 6 truck, 12 tons gross weight

"Portable" FTIR: ~35 kg, ~300 W, 0.5 cm^{-1}, 5 m cell, 130 C, t_{10-90} ~3s

"mobile" FTIR: ~90 kg, ~600 W, 0.5 cm^{-1}, 6 m cell, 130 C, t_{10-90} ~3s



Student projects: Unregulated emissions - E85, n-butanol, isobutanol in unmodified gasoline engines in Škoda cars

Nitrogen compounds speciation

NO, NO_2, NH_3

Greenhouse gases

N_2O, CH_4, CO_2

Formaldehyde, acetaldehyde,

other compounds or functional groups

SAE 2015-24-2513

SAE 2015-24-2488

SAE 2013-24-0102

On-board FTIR

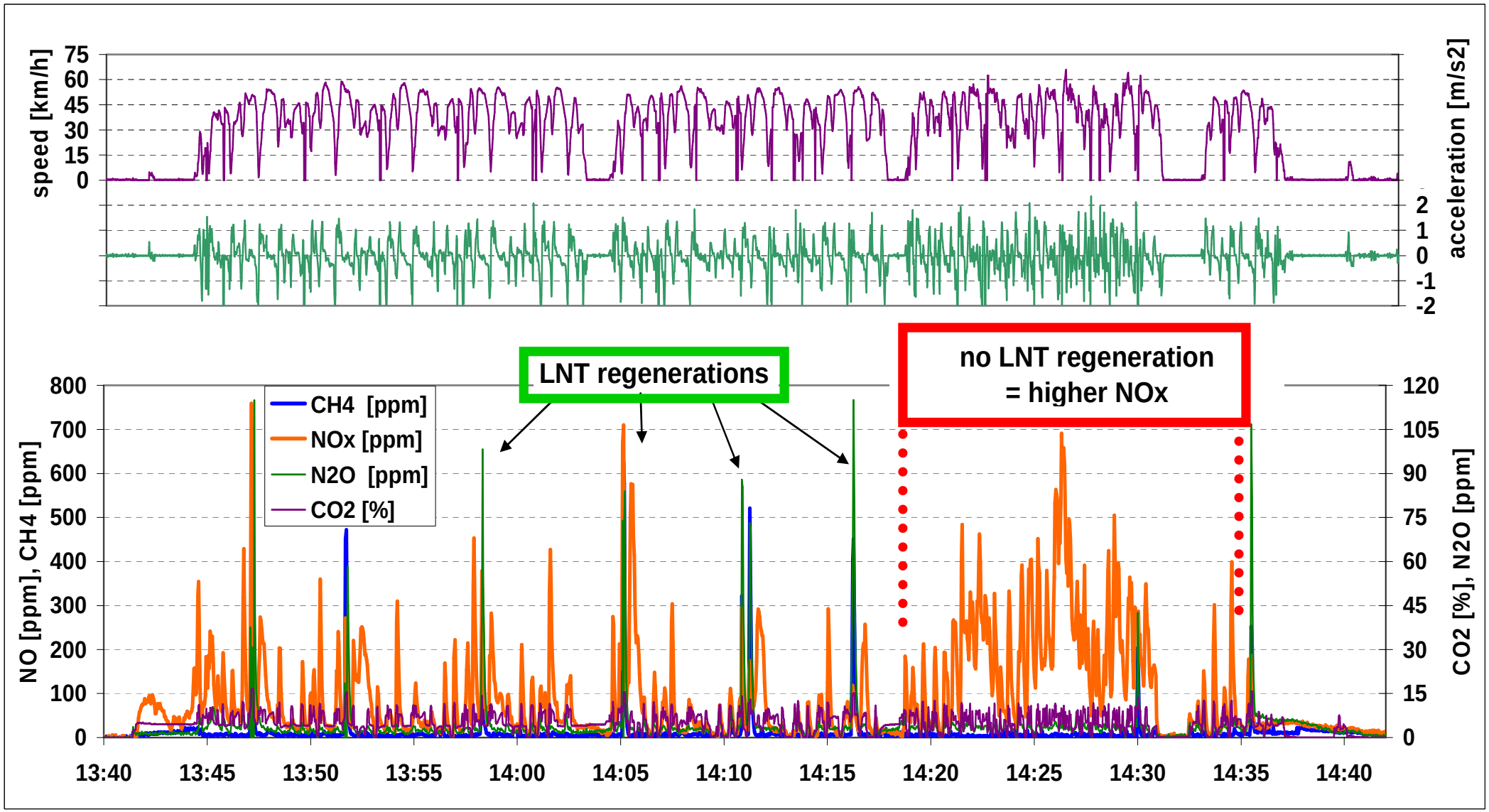
6 m cell

0.5 cm-1 optical resolution

~ 30 kg, ~ 300-400 W

7-8 hours on ~60 kg of batteries

Euro 5 diesel car, LNT



LNT regeneration: spikes in CO_2 (> 14%) and CO

Spikes in CH_4, N_2O (otherwise negligible)

No regeneration = saved fuel, high NO_x

Škoda Octavia Euro 5 diesel, LNT

FTIR-PEMS examination of RDE emissions of nitrogen species: NO, NO_2, NH_3, N_2O

TU Liberec to EC Joint Research Center (Ispra, Italy)

About 8 hours of instrument run time (6:45 sampling time)

(limited by battery and liquid nitrogen capacity)

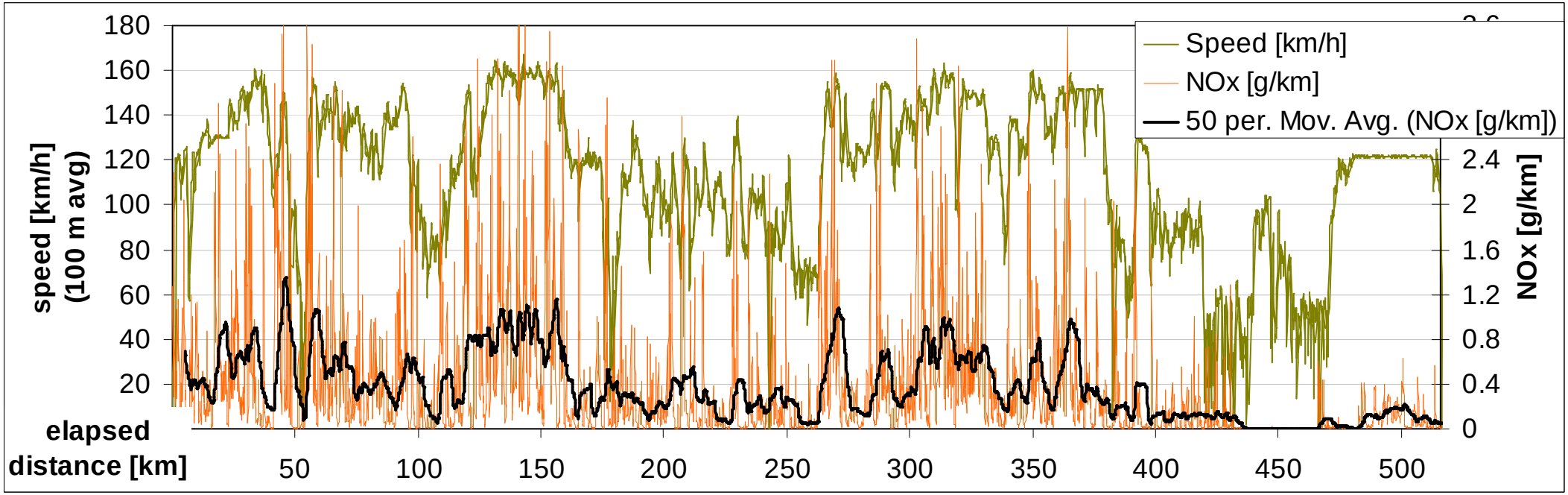
Germany (high speed) & Switzerland (hills and high altitude)

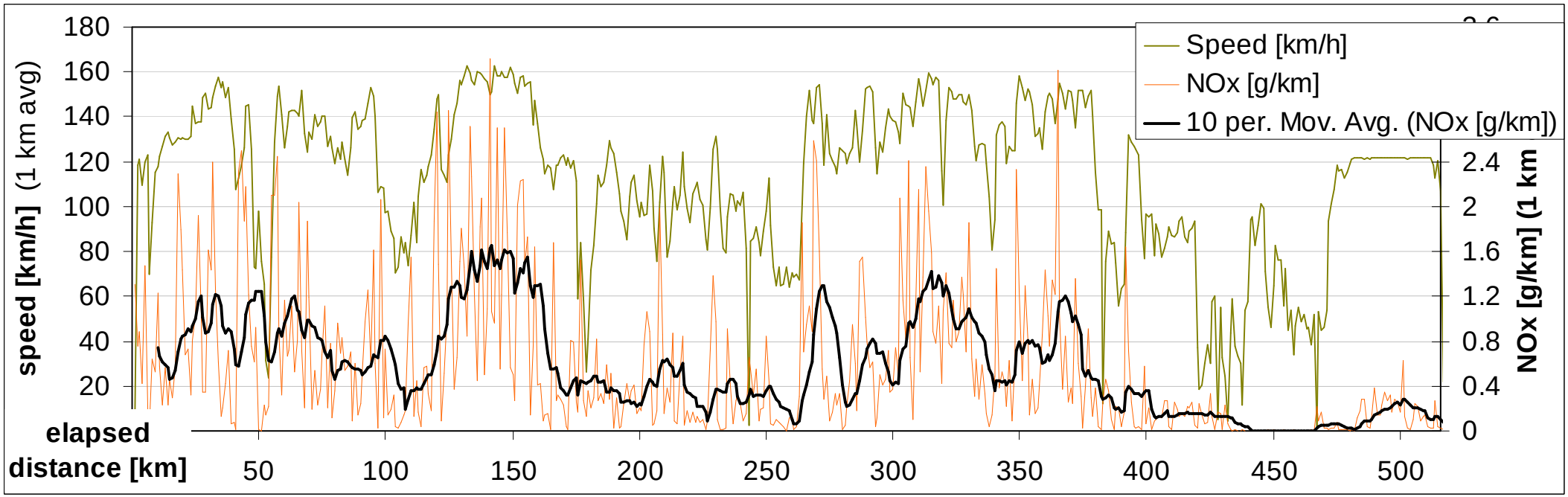
Germany:
431.75 km, 4:52
6.4 mg/km N_2O
687 mg/km NO_x
158 g/km CO_2

Switzerland:
84.66 km, 1:53
217 mg/km NO_x
140 g/km CO_2

Why is the car "NO_x-compliant" in Switzerland but not in Germany???

Škoda Octavia Euro 5 diesel, LNT

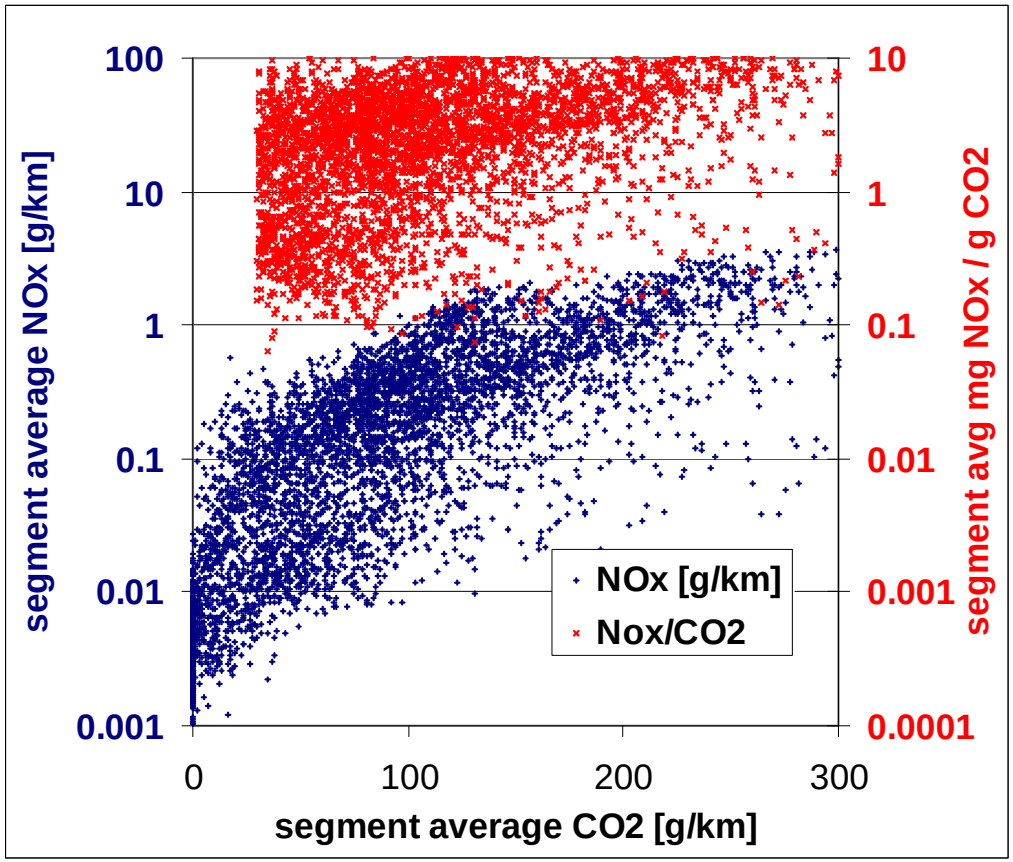




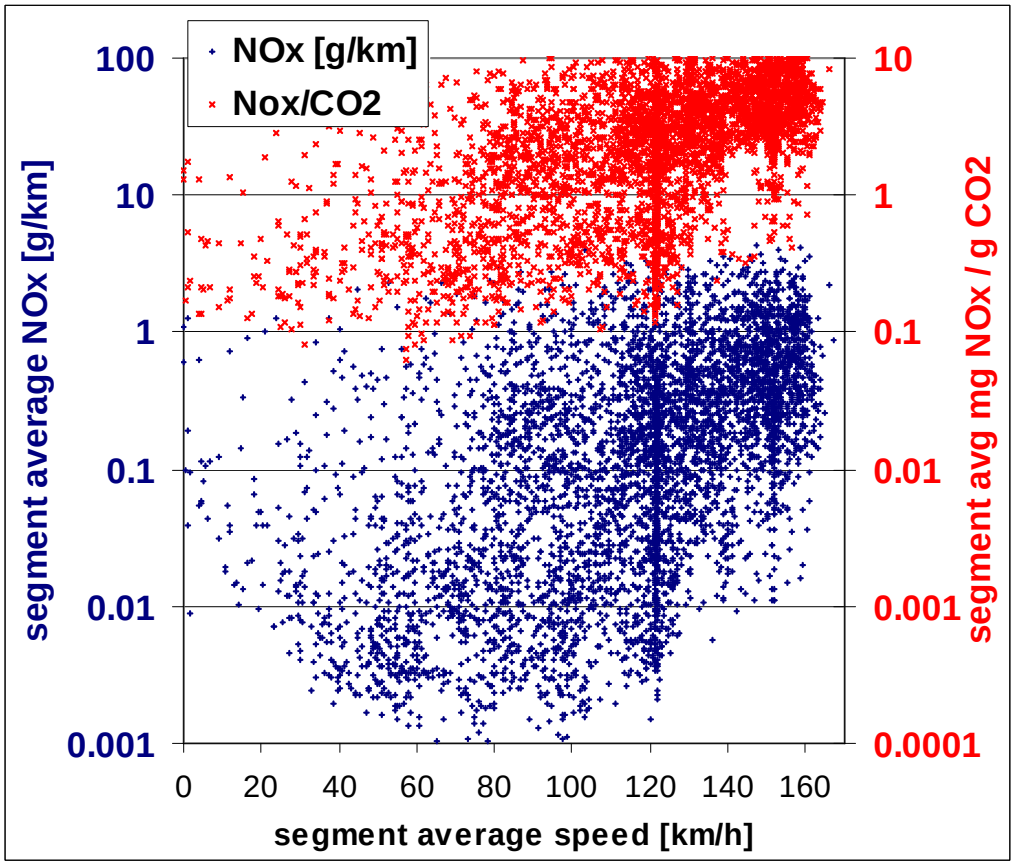
Škoda Octavia Euro 5 diesel, LNT

> 500 km of data, 1 point = 100 m average

NO_x vs. CO_2

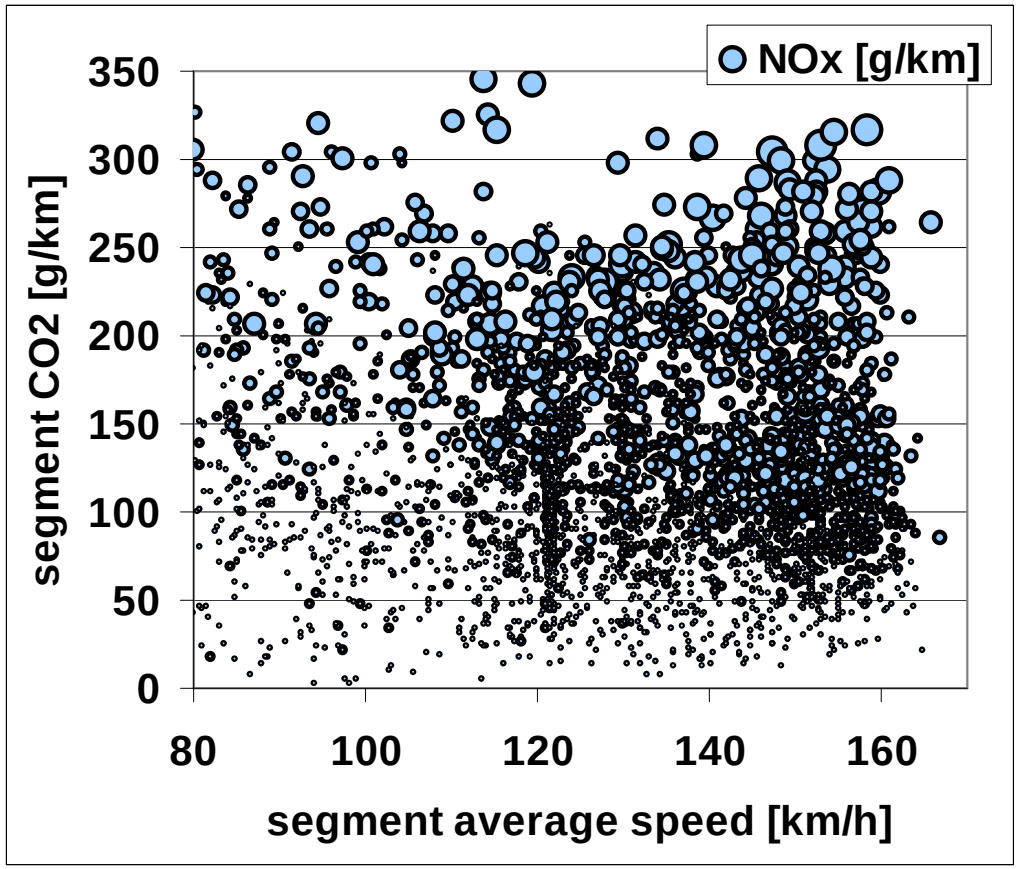


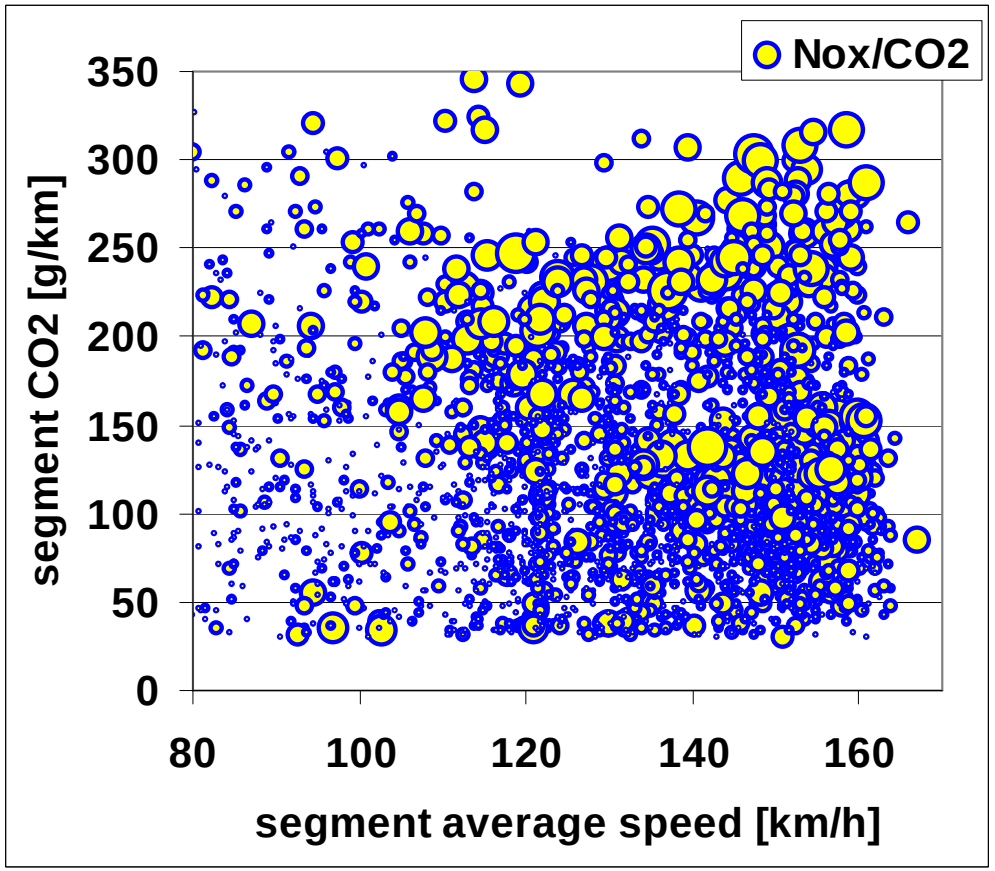
NO_x vs. speed



NOx – both absolute and per CO2 (per kg fuel) – Exponentially increase with speed and with fuel consumption (g/km CO2)

Škoda Octavia Euro 5 diesel, LNT
> 500 km of data, 1 point = 100 m average





NOx – both absolute and per CO2 (per kg fuel) –
Exponentially increase with speed and with fuel consumption (g/km CO2)

SOR CN12 Euro 6 diesel bus – Hradčany military airport

Average emissions - Braunschweig cycle: 195 mg/km NO_x.

At 37 liters / 100 km, 220 g/kWh: 162 mg/kWh (Euro 6: 460 mg/kWh)

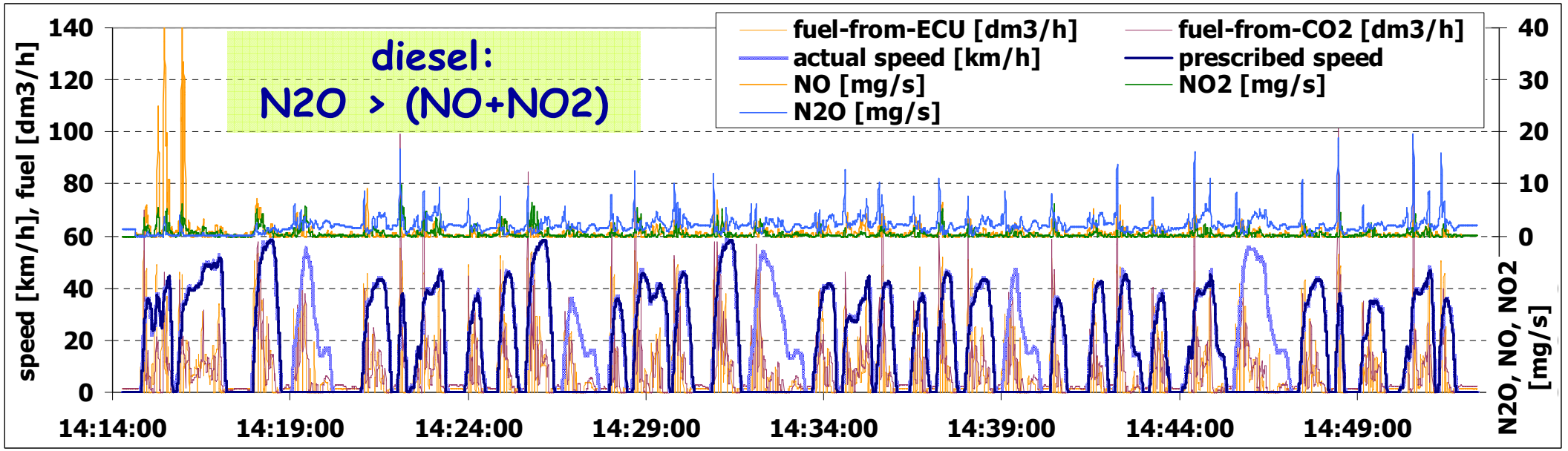
Diesel car NOx limit: 180 mg/km Euro 5, 80 mg/km Euro 6

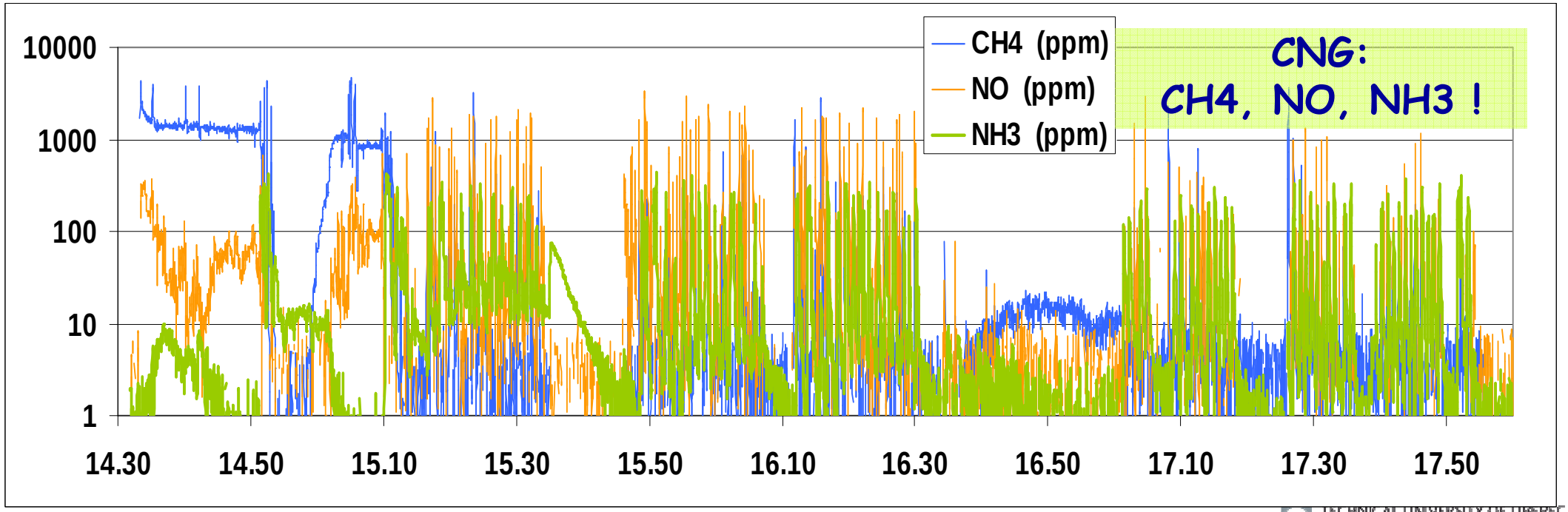
Diesel car real driving NOx: Euro 3-5: 1000 mg/km

One Euro 5 car = 1000 mg/km = 5 buses !!!
But 5 buses can transport 100x more people.

SOR CN12 Euro 6 diesel bus – Hradčany military airport

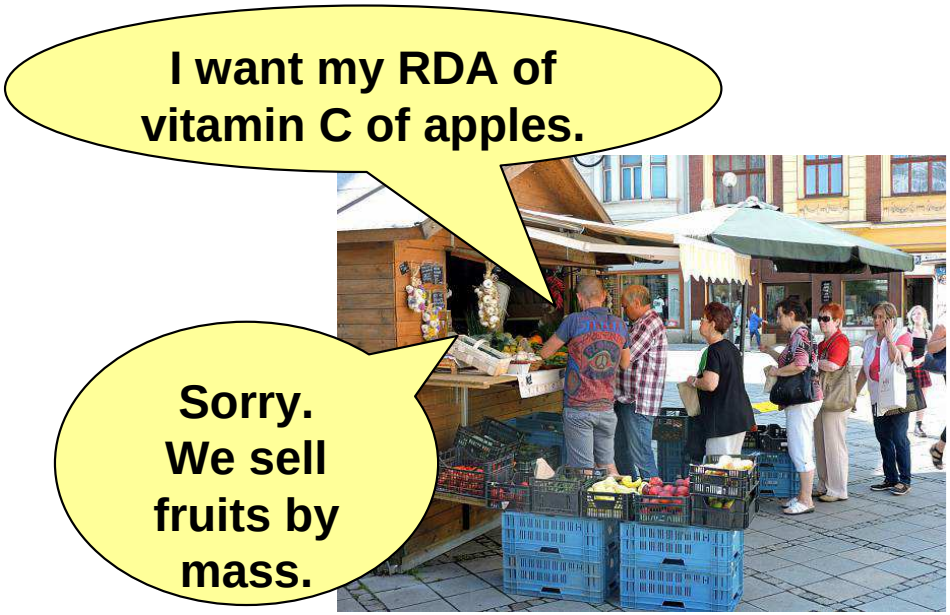
NO, NO2, N2O, NH3, ..., CO, CO2, PM





Moving towards biological metrics for PM: PETS (Portable exhaust toxicity samplers)

We measure particles and sell fruits by count and mass.
But the prices of fruits are not unified, neither per piece, neither per kg.
Both volatiles and < 23 nm particles, excluded from EU PMP, can represent a significant share of toxicity…



Choices:

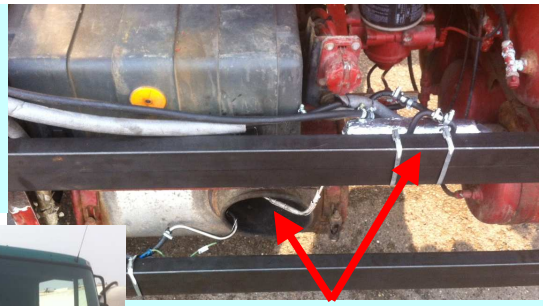
Sample -> extract -> expose to cells
- proportional sampling done for gravimetric PM analysis

Expose cells directly (exposure chamber)
- no information about this done in a moving vehicle but technically feasible

Assessment of congestion and "creep" on the road

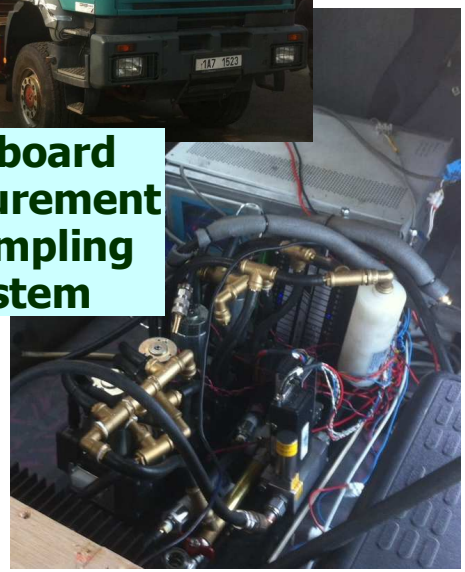
EURO 3 – no aftertreatment
2003 Iveco Trakker

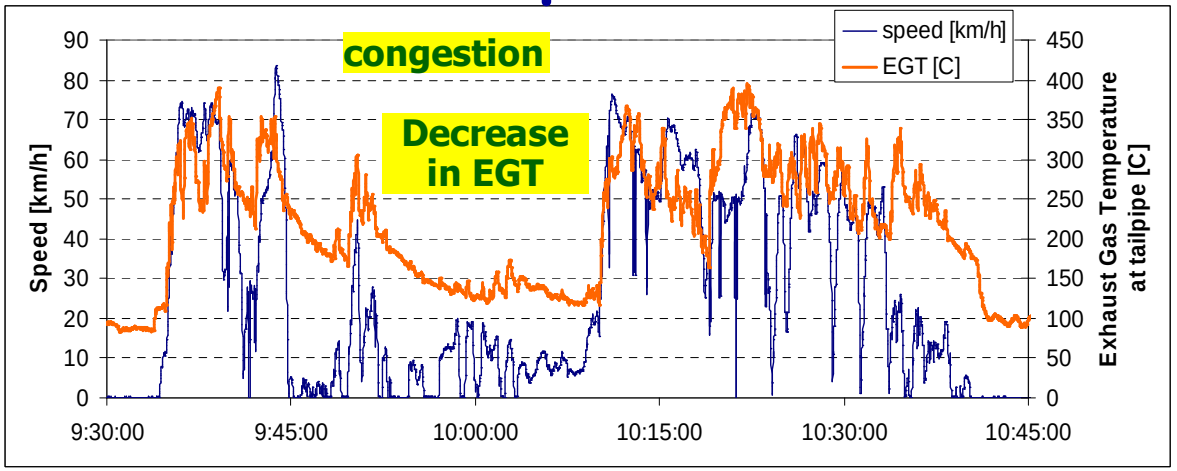
Proportional exhaust particle sampling

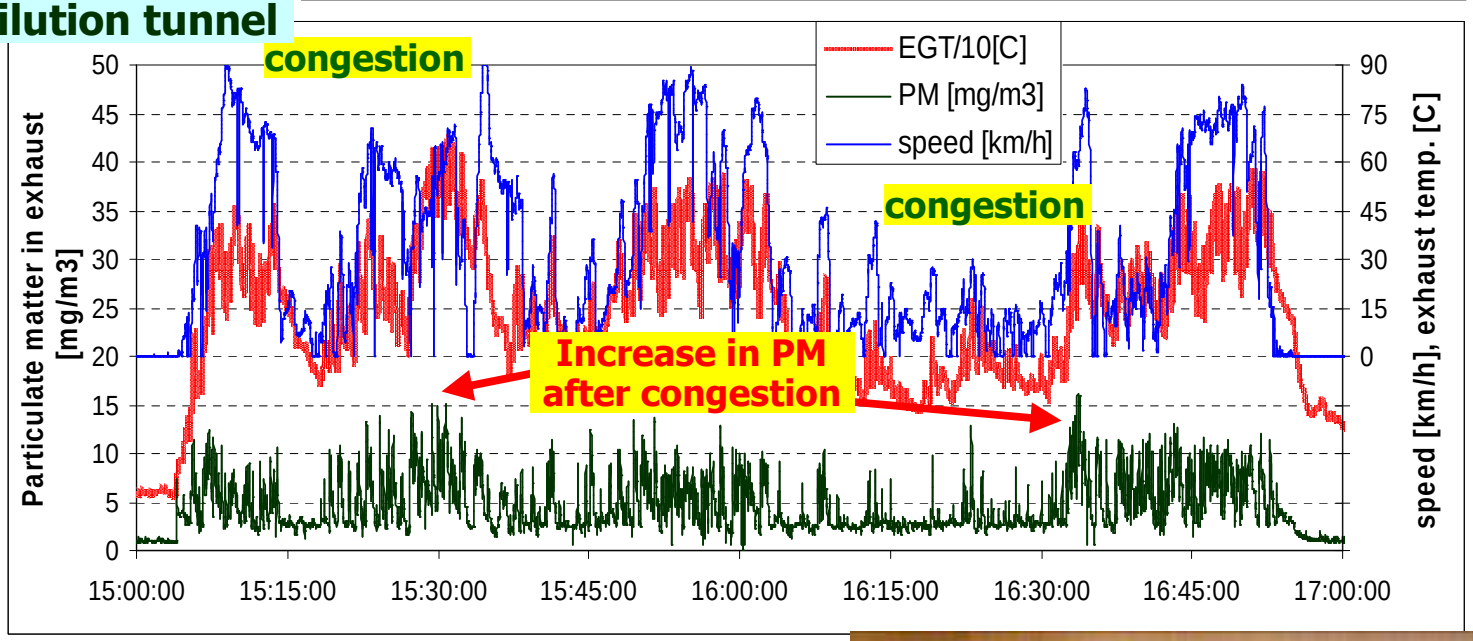


Miniature partial-flow dilution tunnel

On-board measurement & sampling system

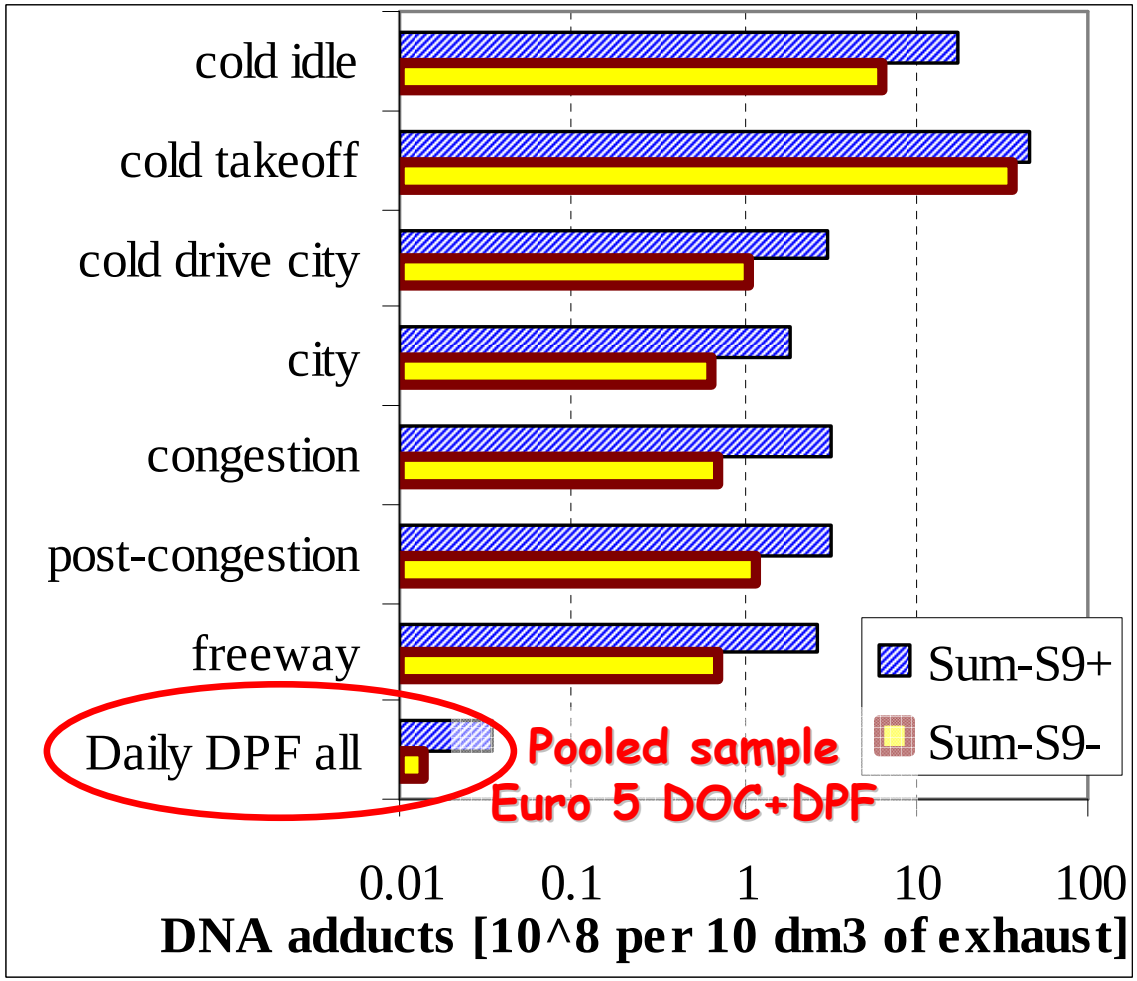




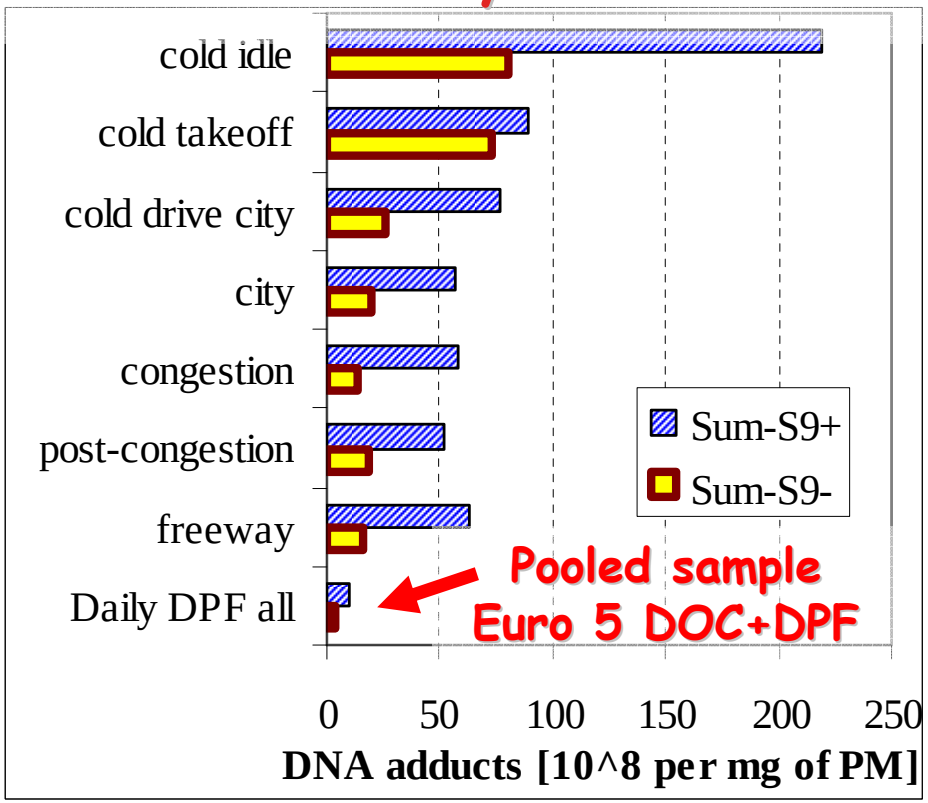


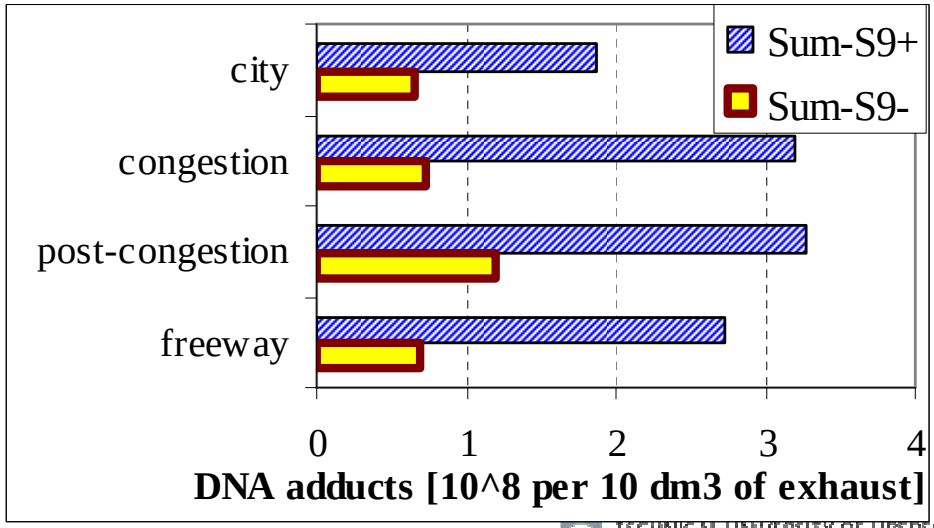
17 mg of PM collected on ~110 filters during a week of field measurement

Particle toxicity evaluation
DNA adducts test
(genotoxicity – damage to DNA)
Simple test, around 1 mg of particles needed (comparable to PAH analysis)



Effects of creep and congestion Euro 3 and 5 heavy diesel trucks





Micro-PEMS concept

„Inline" module fitted at tailpipe

NOx and particle concentrations, air-fuel ratio:
Sensors used in heavy-duty diesel engines
(engine management, OBD - on-board diagnostics,...)

Other gaseous pollutants:
Inline optical methods (tunable diode laser, NDIR, NDUV, NDvis)

Exhaust flow:
Pitot tube, ultrasonic, vortex sensors, or calculated from OBD data

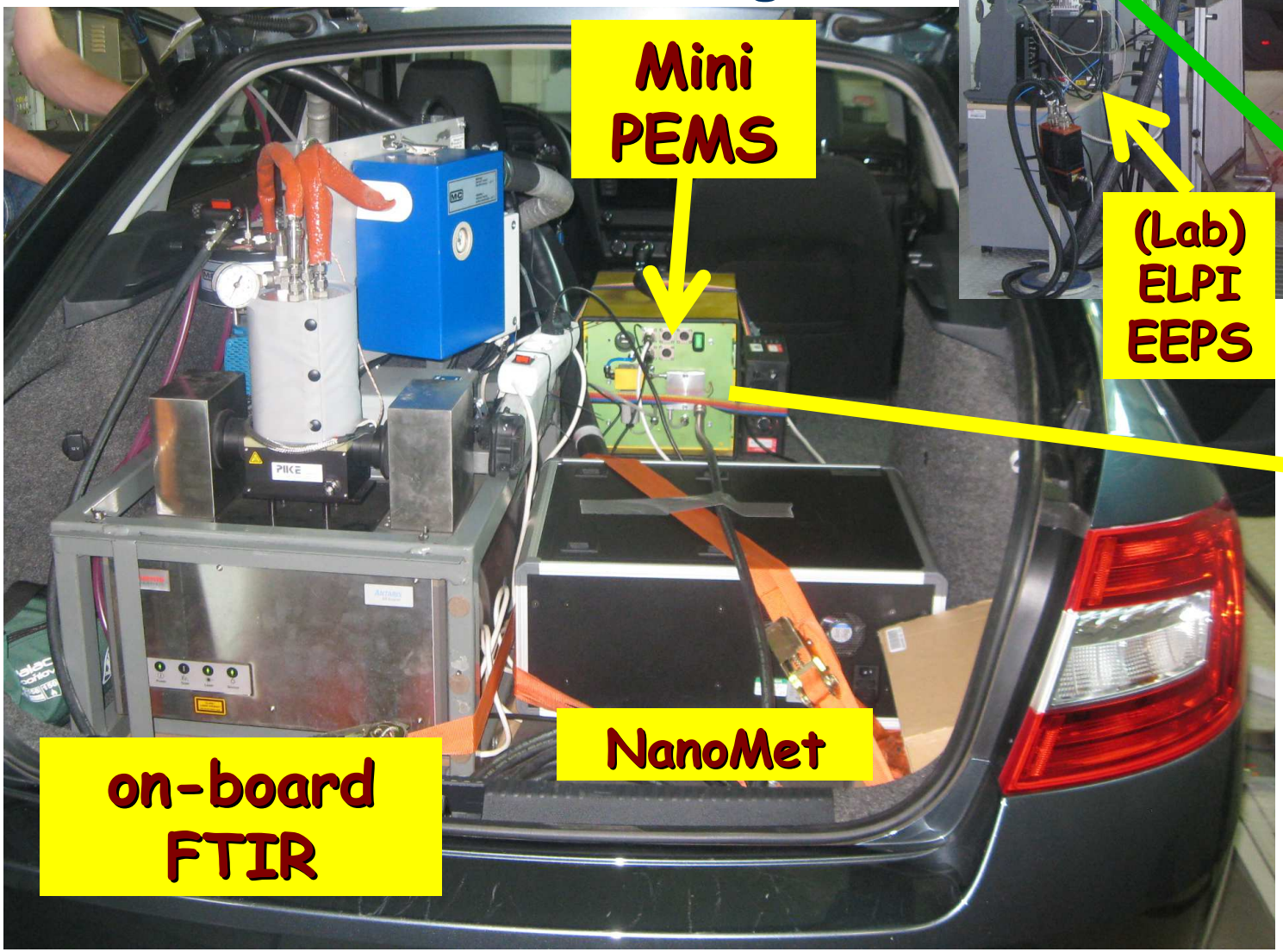
GPS, GSM or Wifi antenna: vehicle side or roof

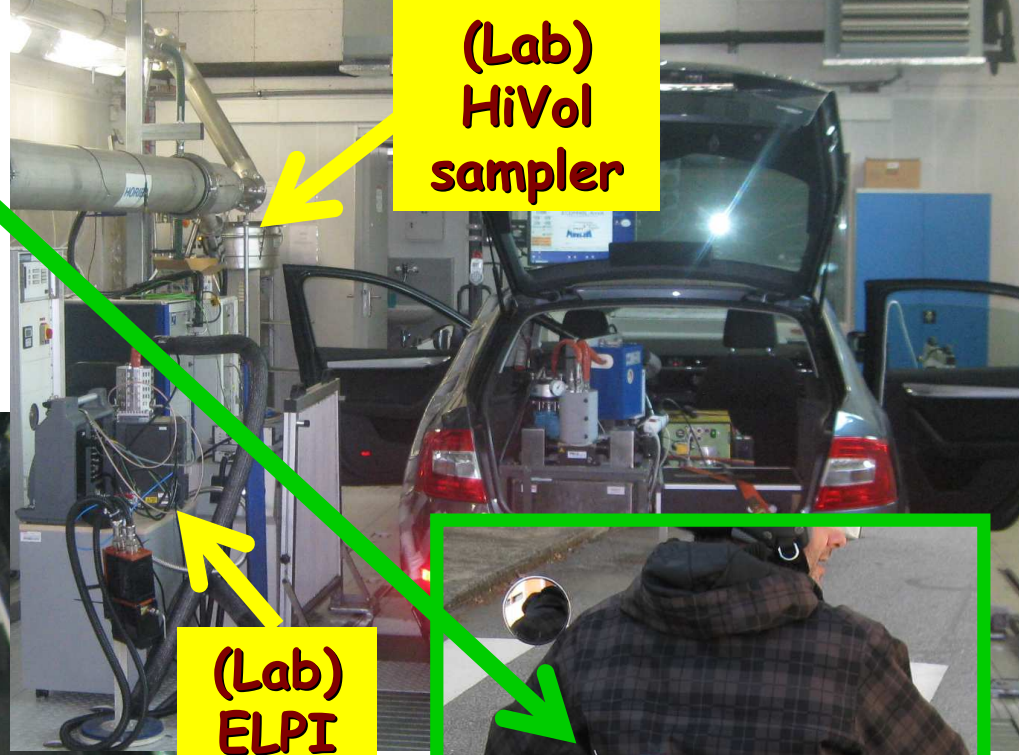
Power:
Thermoelectric cells using exhaust heat, photovoltaics on roof

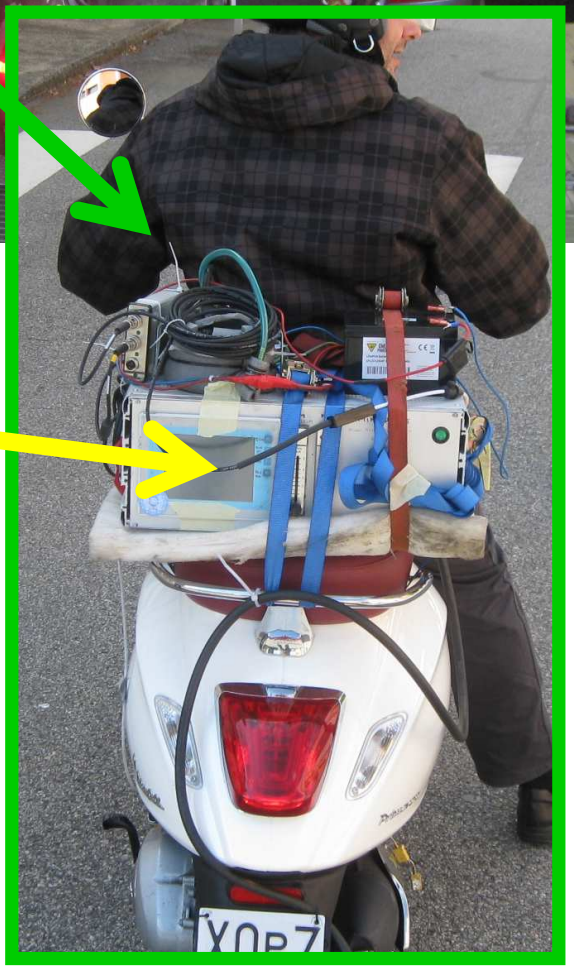
cost: hundreds of EUR/CHF/USD

some elements (NOx, flow) already in use – TNO, Southwest research institute

Current work: MiniPEMS for small motorcycles (photo from PEMS validation & fuel effects testing)







Conclusions

On-board emission measurement systems measure in/on a moving vehicle. Portable measurement systems (PEMS) can be readily transported and installed on a vehicle or mobile machinery.

PEMS is a concept that can be extended to other metrics, measurement methods, and applications.

On-board FTIR

might allow for measurement of greenhouse gases (CO_2, CH_4, N_2O), reactive nitrogen (NO, NO_2, NH_3), and other heterogeneous molecules present in concentrations that can be detected and discerned.

MiniPEMS

might allow real-world testing of small motorcycles & non-road engines

Portable sampling and exposure systems

for toxicity assays might allow for more direct assessment of effects of new fuels and technologies on human health.

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Czech Technical University in Prague
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MEDETOX

EU LIFE+ program, project MEDETOX - Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic (LIFE10 ENV/CZ/651)
www.medetox.cz