Measurement of late-model diesel automobile real driving emissions of reactive nitrogen compounds with on-board FTIR analyzer

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

Project BIOTOX – Mechanisms of Toxicity of Particles from Biofuels
PM measurement and sampling using high-volume samplers

Gasoline MPI and direct injection, diesel, Traditional and alternative fuels (ethanol, butanol, biodiesel, NExBTL, blends)

Real driving emissions measurement
Portable on-board monitoring systems (PEMS)

Cars, buses, trucks, tractors, loaders, mowers, small airplanes, mopeds, ferries, locomotives, construction machinery

Evaluation of real driving emissions (RDE) with portable on-board emissions monitoring systems (PEMS)

Type-approval grade:
AVL – gaseous pollutants
NanoMet 3 – particle number (PN)

In-house built research-grade:
“Mini-PEMS” (13 kg, 60 W)
On-board portable FTIR
(non-regulated compounds)
On-board particle counters and
particle classifier (EEPS)

Services: PEMS & laboratory testing
Test design and facilitation
Data analysis and interpretation

Staff: Michal Vojtisek designed the
first commercially available PEMS
20 years PEMS & RDE in USA & EU

Real driving emissions (RDE) measurement using Portable Emissions Monitoring Systems (PEMS)

Work by the author

One of the first PEMS
Pittsburgh, USA, 1996-1999

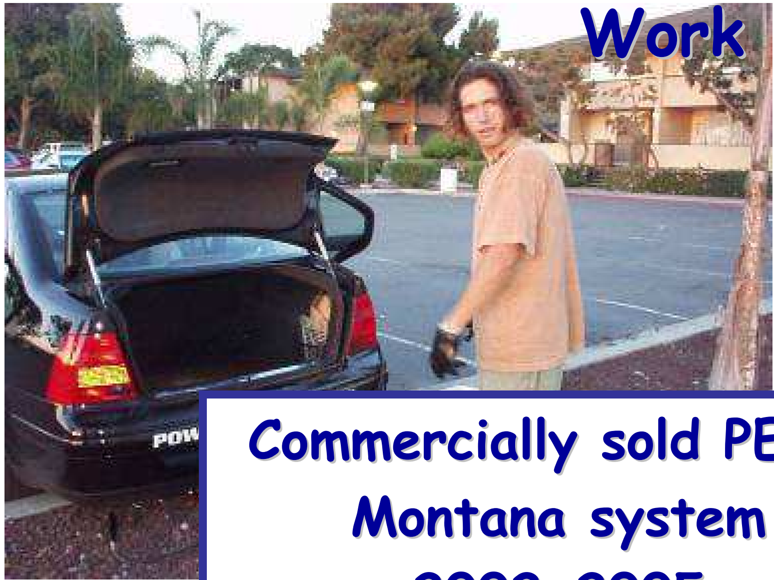
First commercially available PEMS – OEM-2100

Manufactured 1999-2002

Pennsylvania State University
USA, 2001-2003

Real driving emissions (RDE) measurement using Portable Emissions Monitoring Systems (PEMS)

Work by the author



Commercially sold PEMS
Montana system
2002-2005

PEMS FTIR
2004-2006

Portable on-board exhaust emissions monitoring system (current version)

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

heated ionization "fire detector"

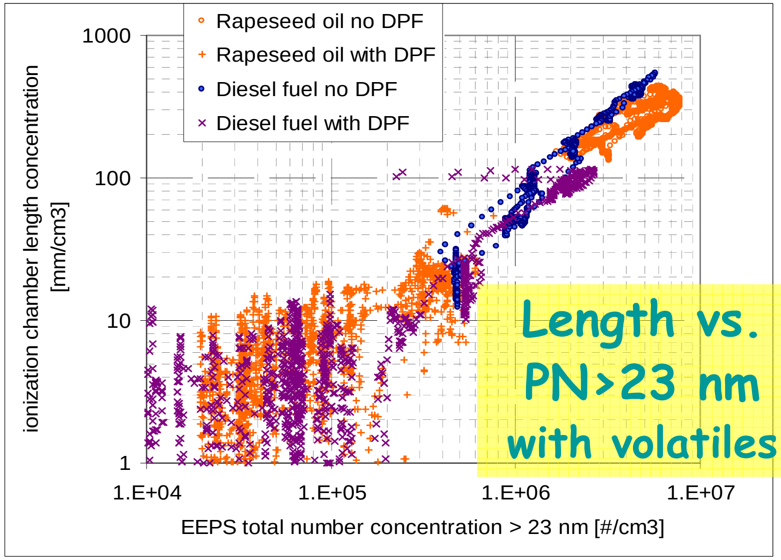
undiluted raw exhaust

(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

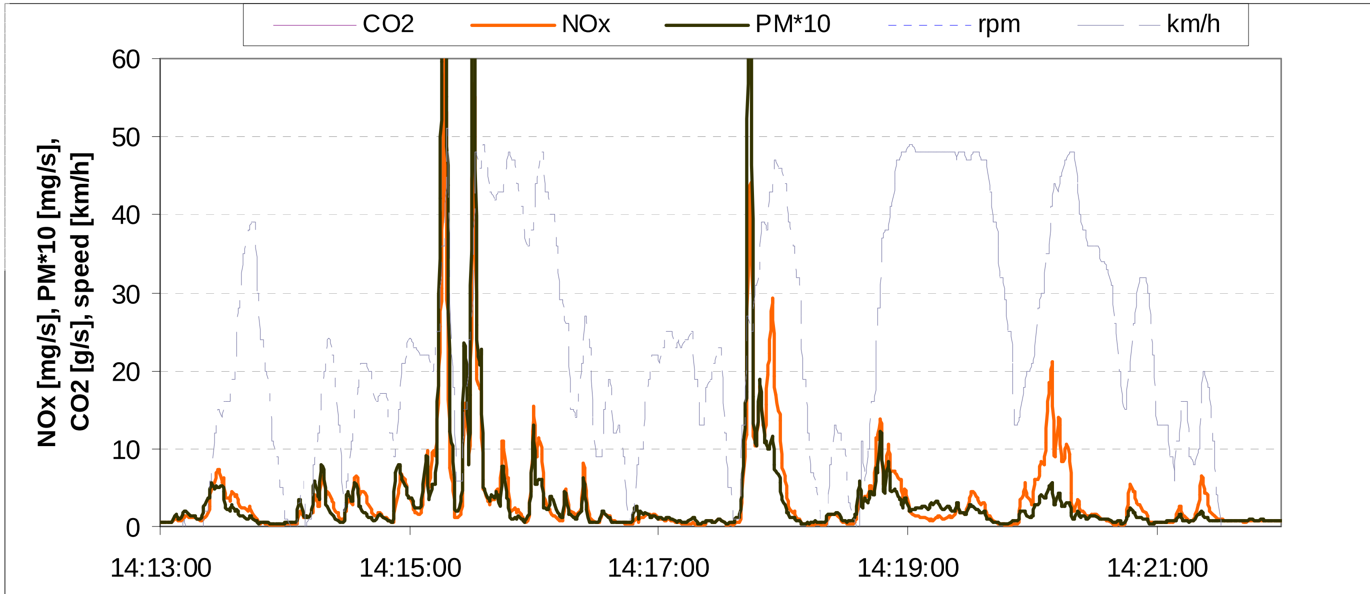
Incl. PM on SI

SAE 2013-24-0102

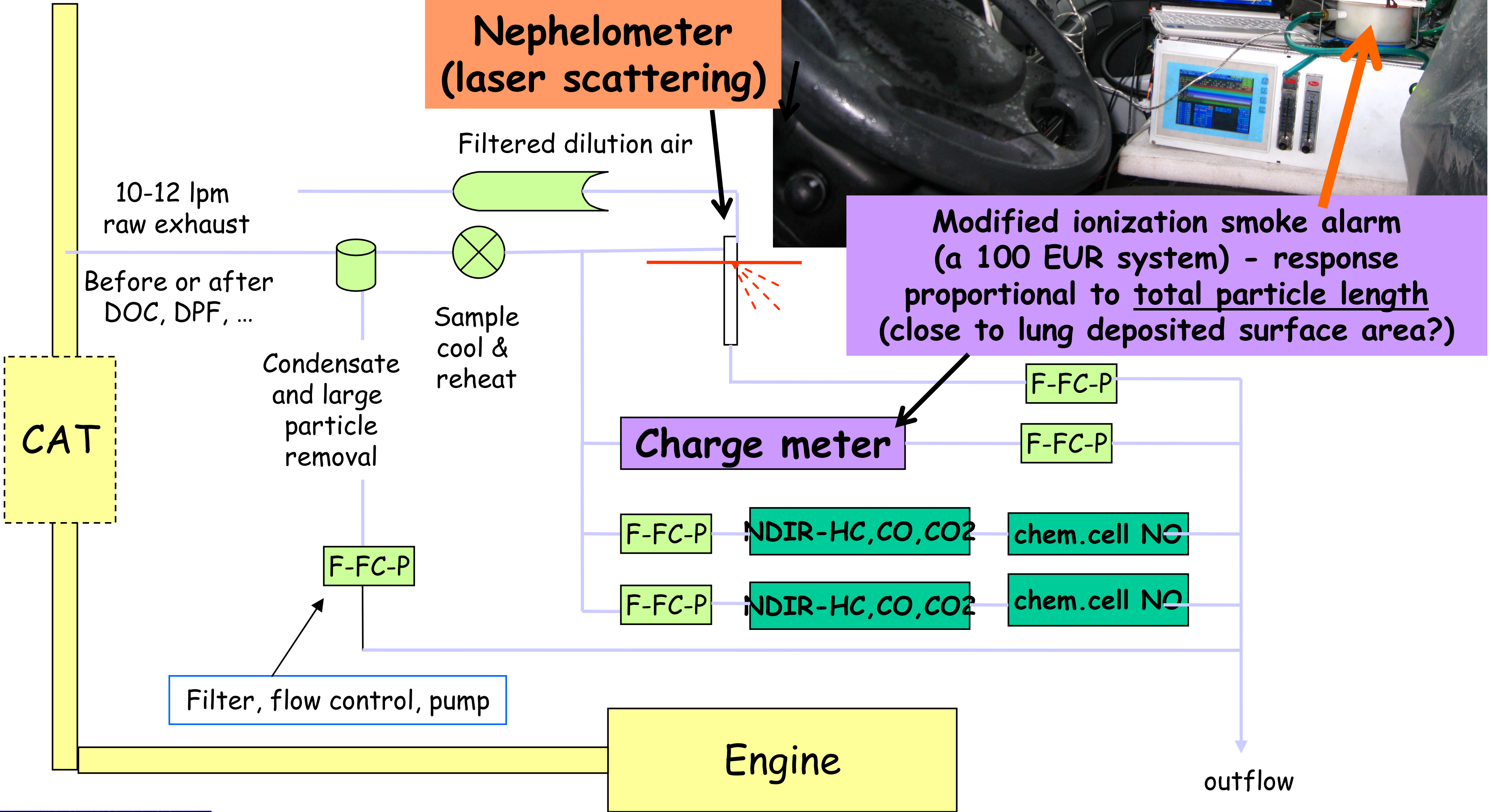
SAE 2013-24-0168

Installs on motorcycles to locomotives

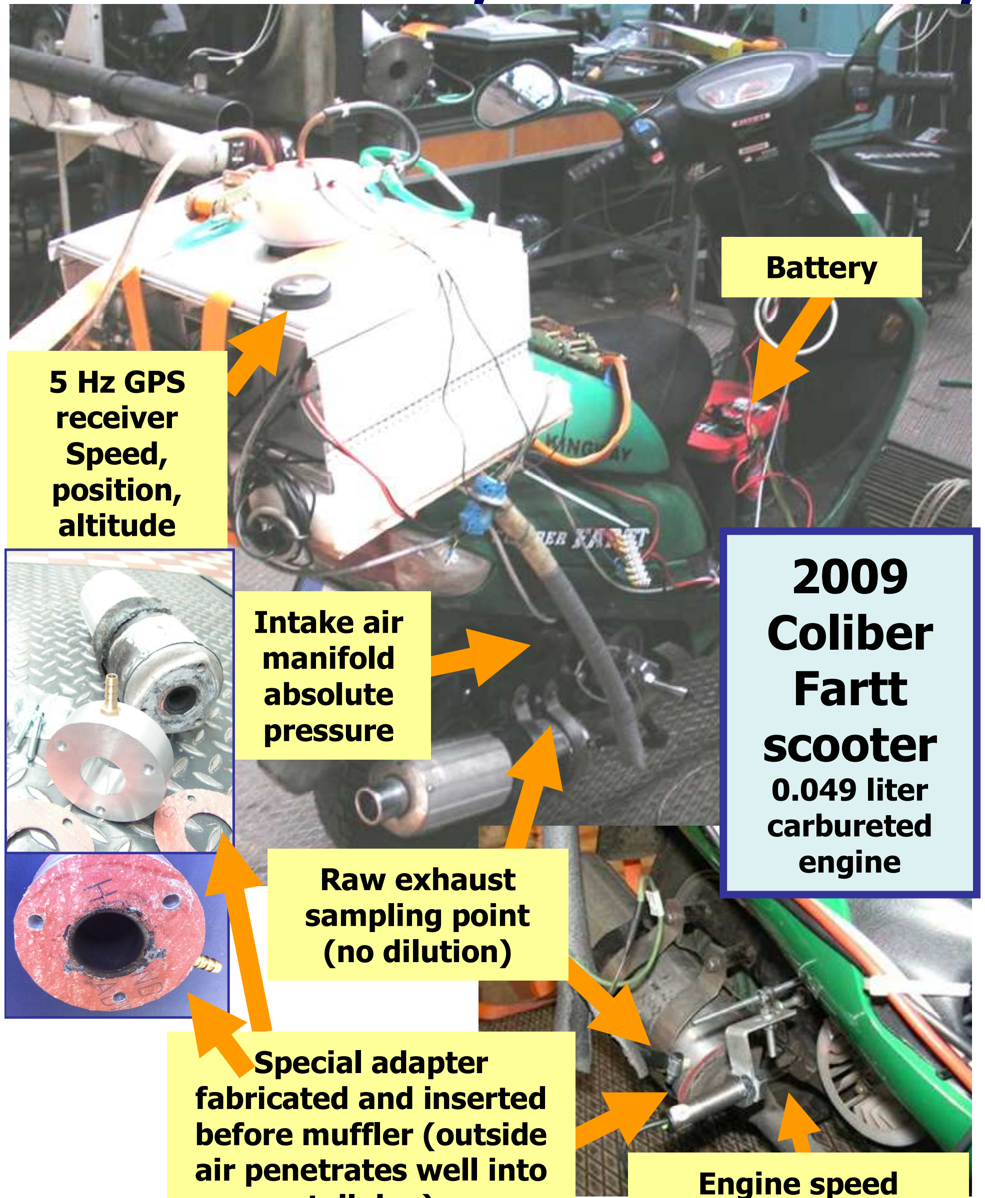
This example → from a Euro 4 diesel car



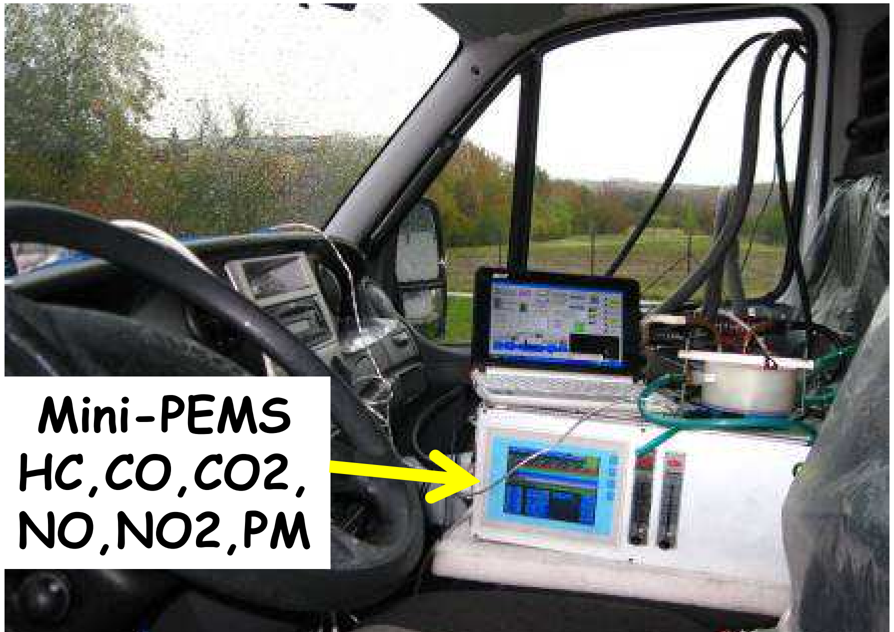
On-board monitoring system



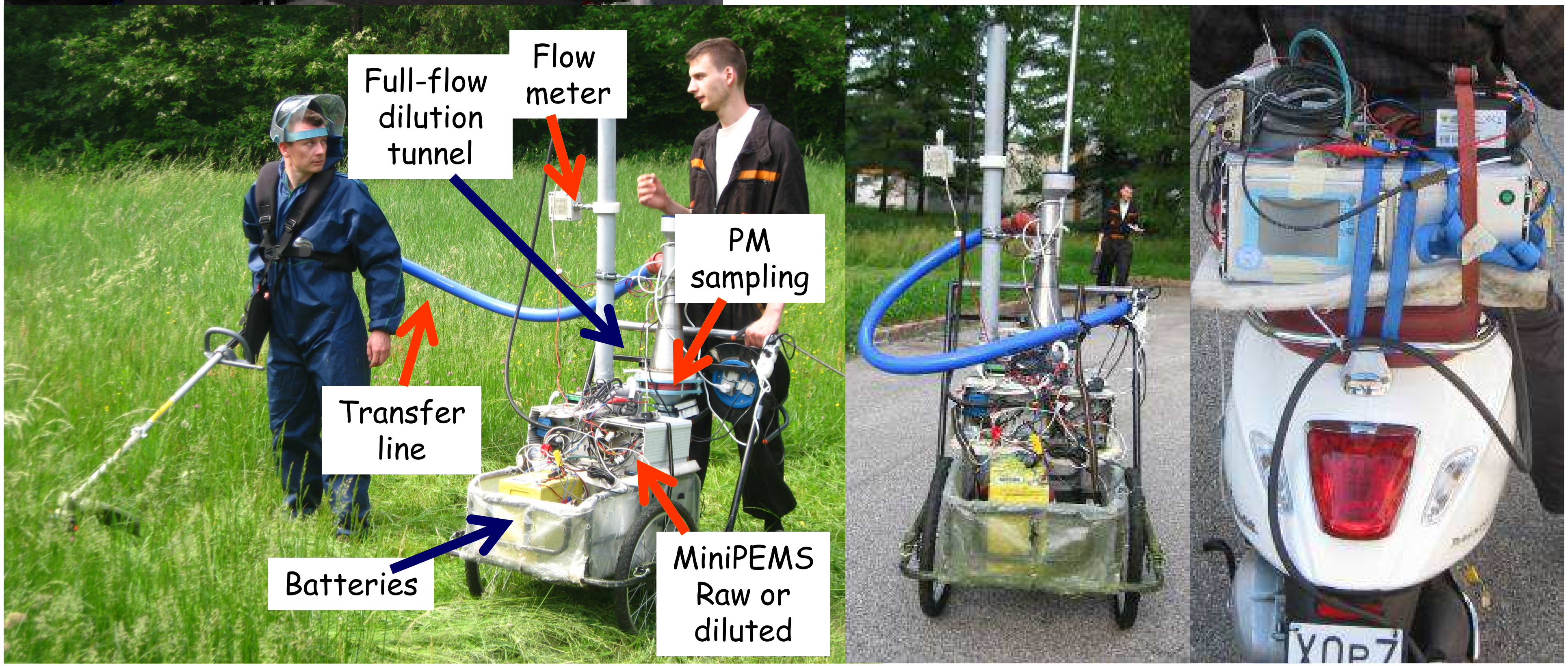
On-board system versatility: Motorcycle to locomotive



Portable on-board exhaust emissions monitoring system
HC, CO, CO_2, NO, NO_2, PM mass, PM length
Calculated exhaust flow
"Motorcycle to locomotive"



Full-flow dilution tunnel with particle sampling for small non-road engines



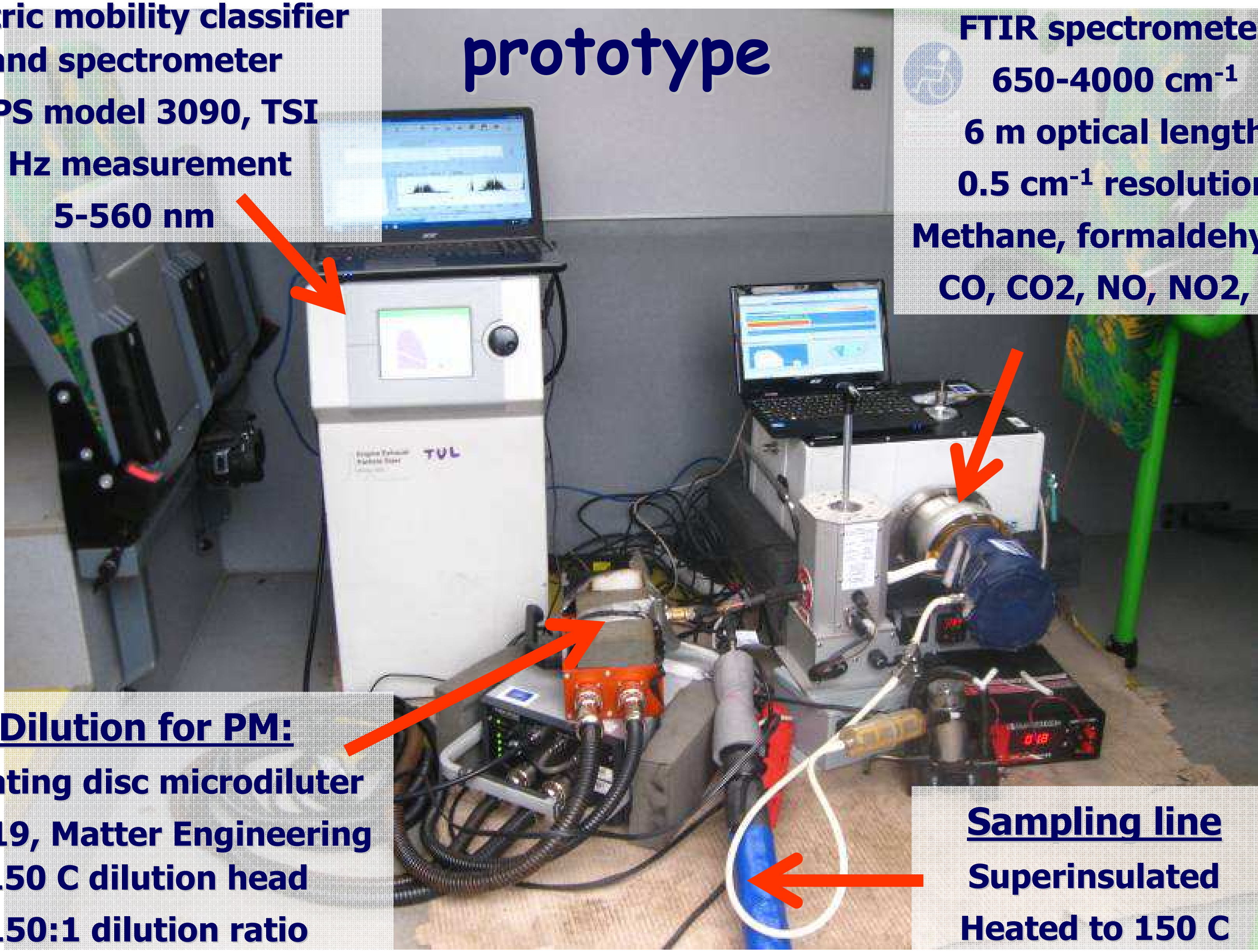
MEDETOX prototype

PM sizes and count:

Electric mobility classifier and spectrometer
EEPS model 3090, TSI
1 Hz measurement
5-560 nm

Gases:

FTIR spectrometer
650-4000 cm^{-1}
6 m optical length
0.5 cm^{-1} resolution
Methane, formaldehyde, CO, CO2, NO, NO2, ...



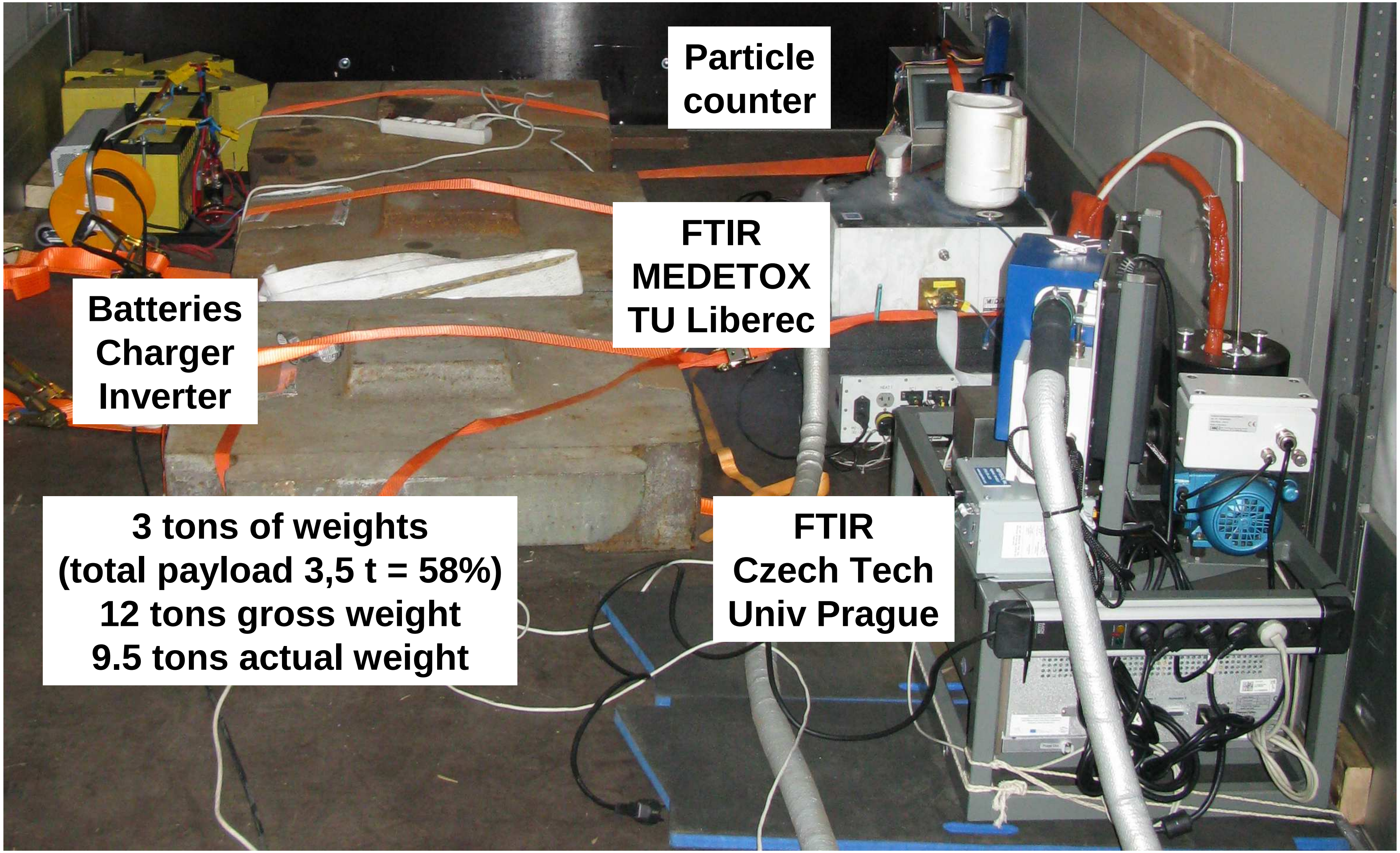
Dilution for PM:

Rotating disc microdiluter
MD-19, Matter Engineering
150 C dilution head
150:1 dilution ratio

Sampling line

Superinsulated
Heated to 150 C

Euro 6 diesel truck (DOC, DPF, SCR)
Two FTIR-PEMS & "ordinary" PEMS & particle counter



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

On-board FTIR

~ 30 kg

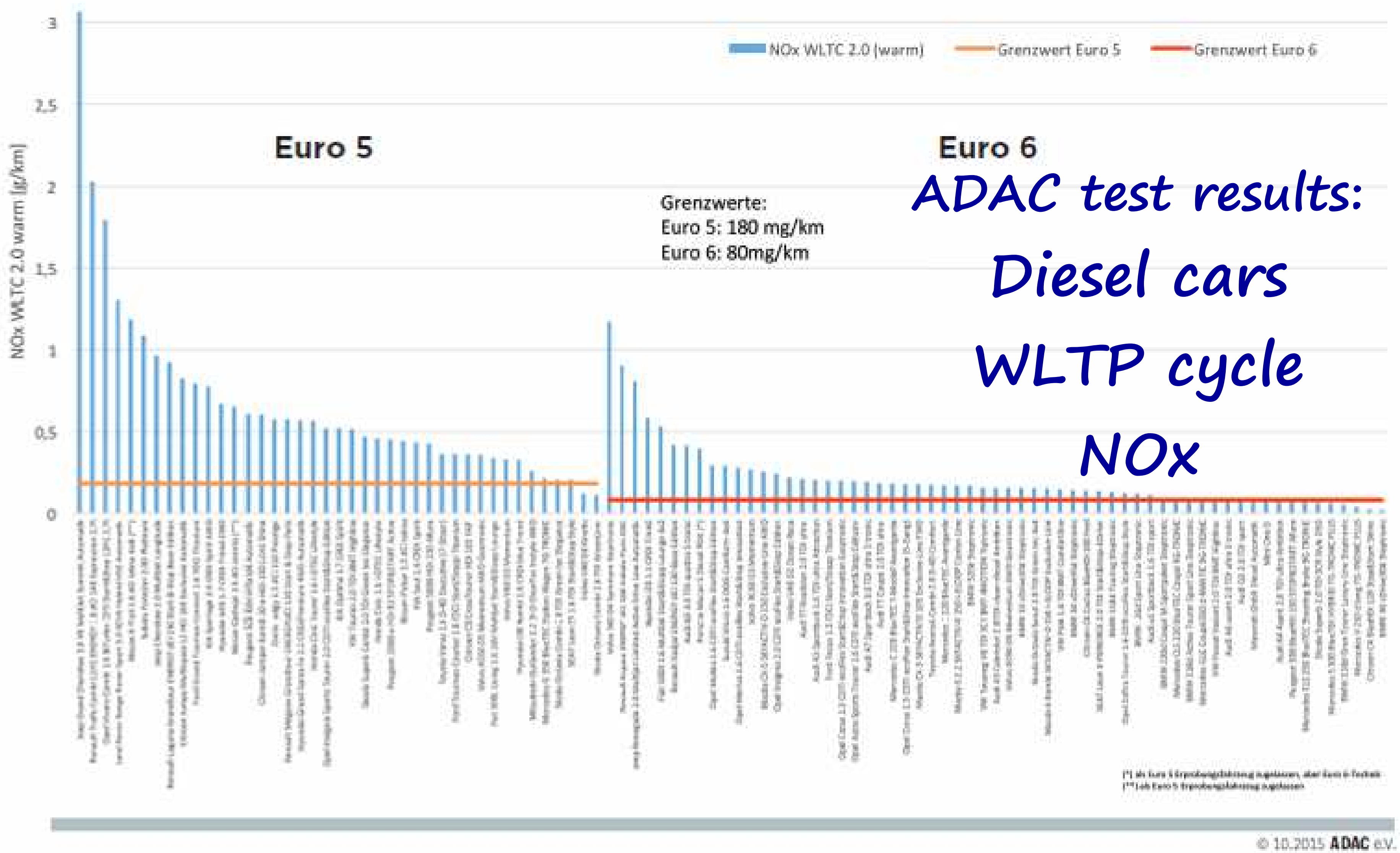
~ 300-400 W

3 hours on

26 kg of batteries

ADAC EcoTest: Stickoxide im WLTC 2.0 (warm)

Euro 5 und Euro 6 Diesel Pkw - getestet ab 2014

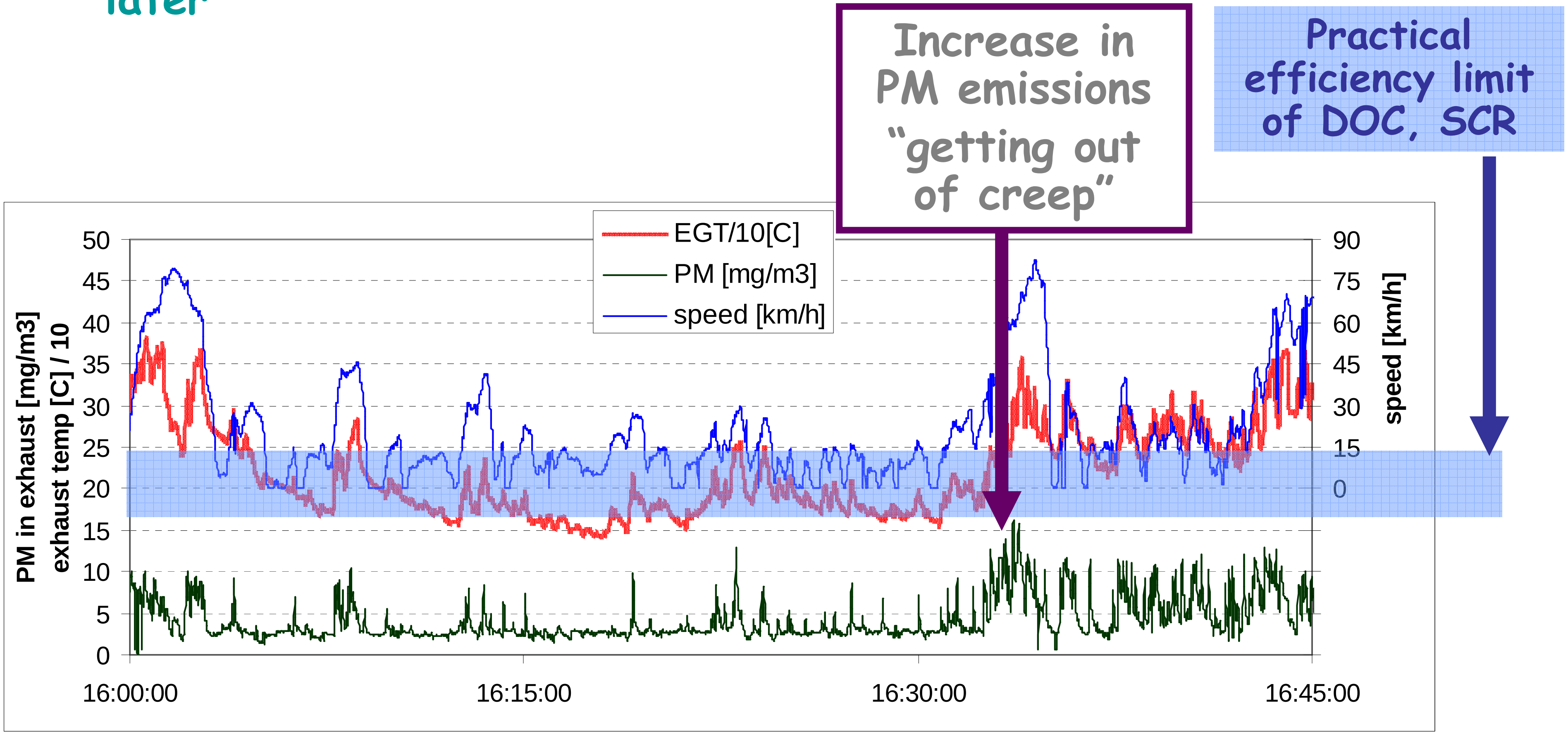


Why are NOx higher during real driving

- **Technology limits**
  - low SCR temperature – cold start, creep
- Optimization for cycle / off-cycle emissions
  - No EGR at full load
  - Catalyst sized for low flow and too small for high loads
- „No one is watching"
  - Switching off EGR, LNT fuel / SCR urea injection
  - „Cycle beating" strategy

Heavy vehicle creep problem

* Deterioration of combustion at idle
* Low exhaust gas temperatures decrease efficiency of catalytic devices (DOC, SCR)
* Particulate matter stored in exhaust system to be released later



Congestion effects: DAF 1505 truck, 2006, Euro 5 Paccar engine, 540 thousands km, with loaded trailer (39 tons total weight)

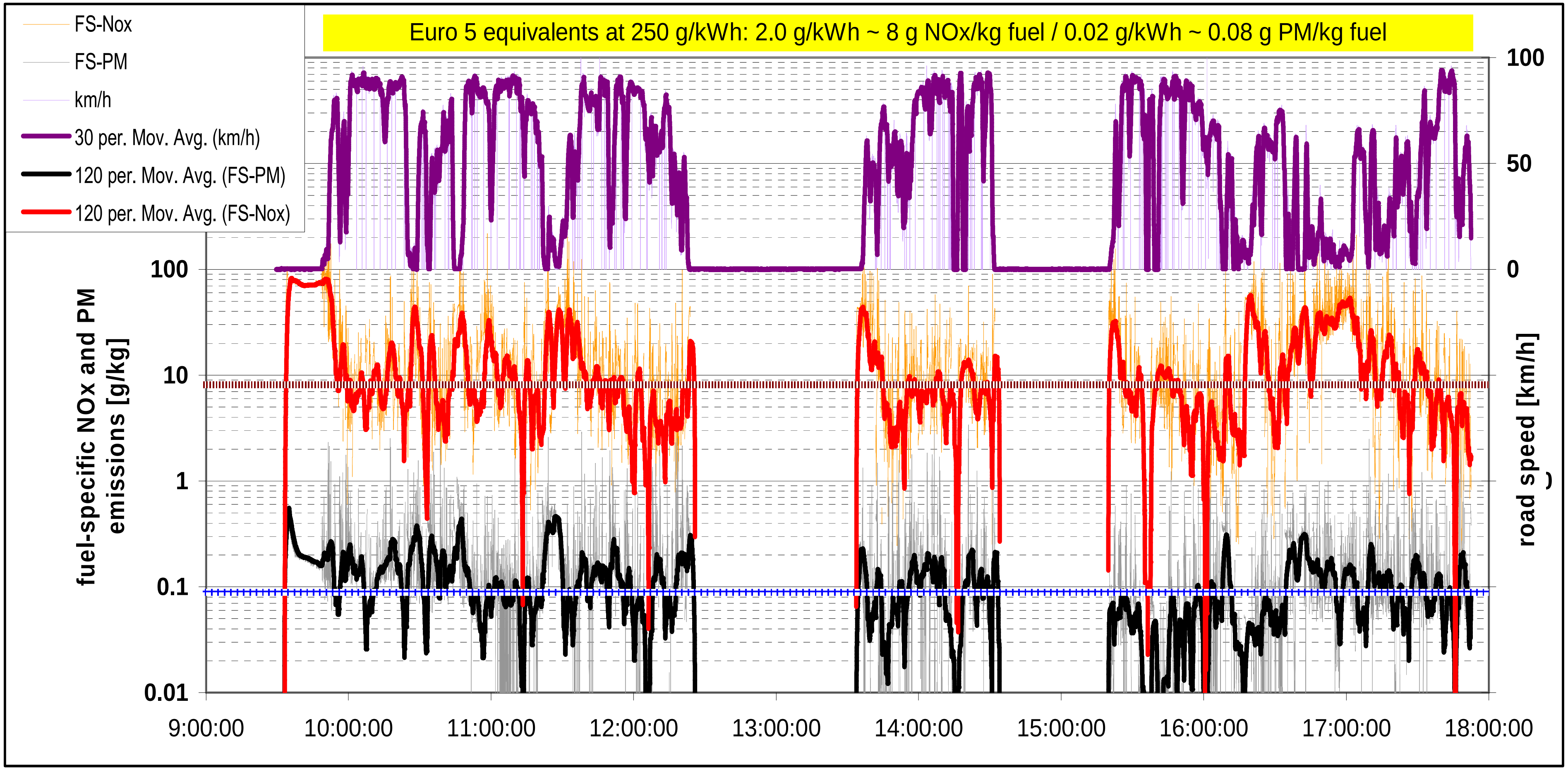
The horror of transit truck traffic

We took a DAF truck with semi-trailer, 39 tons, EURO 5 but no DPF, and circulated the Prague perimeter road waiting for congestion to happen

"Urban creep":

combustion worsens, DOC cools down, SCR cools down, EGR not feasible

Result: NOx and PM up to one order of magnitude higher



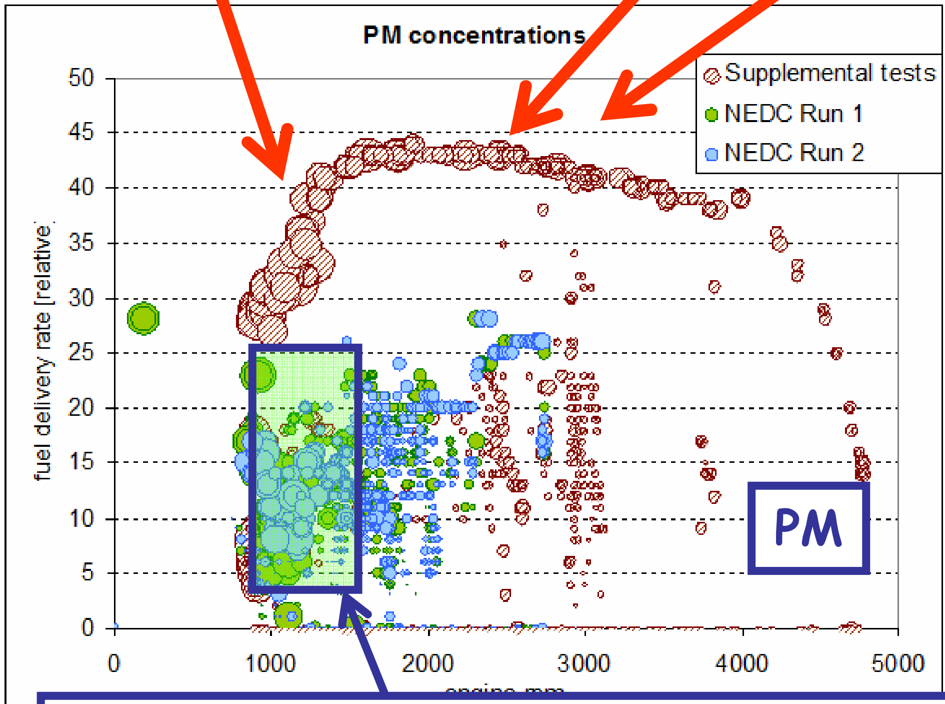
Challenges of EU automobile diesel engines
Euro 4 Skoda Fabia – chassis dynamometer runs
NEDC vs. full-power loaded accelerations

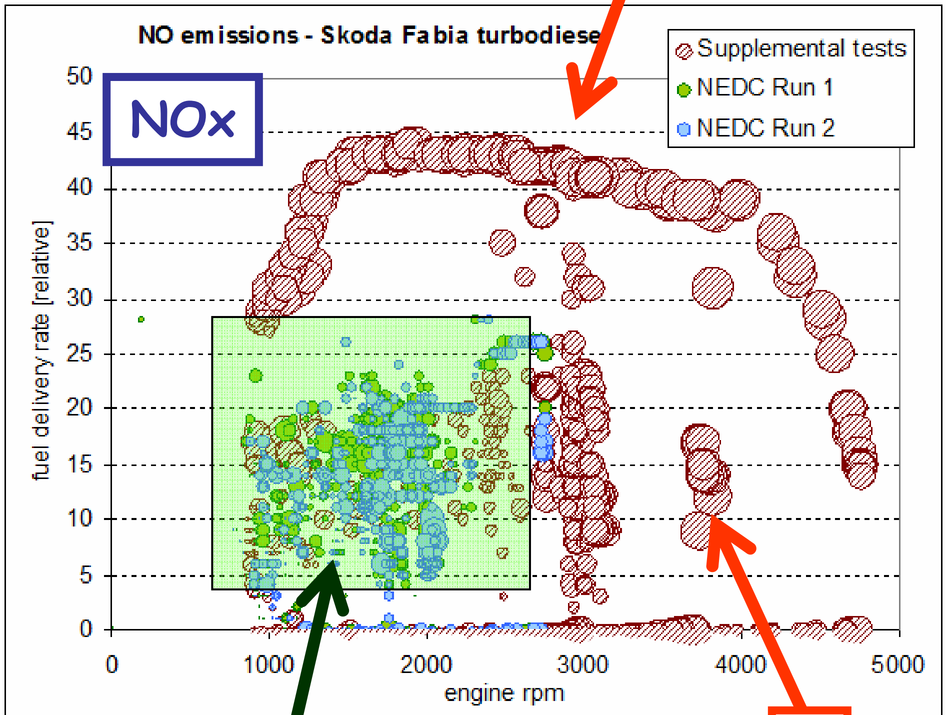
Problem compounded by downsizing & turbocharging: Relatively low torque at idle.

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

?

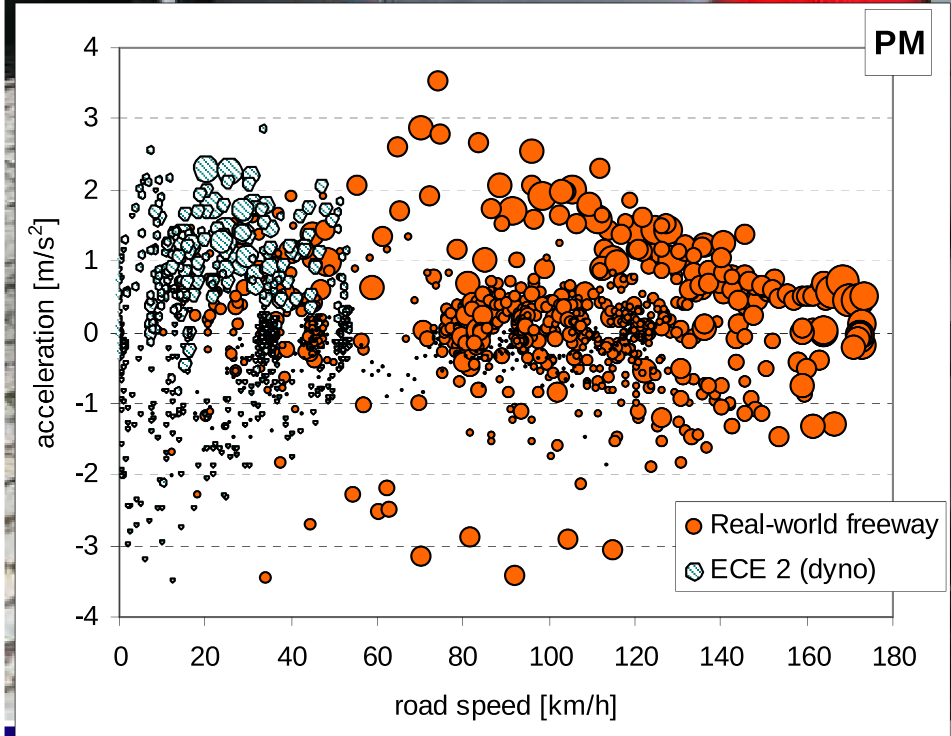
Euro 4 Skoda Octavia – real-world city driving tests

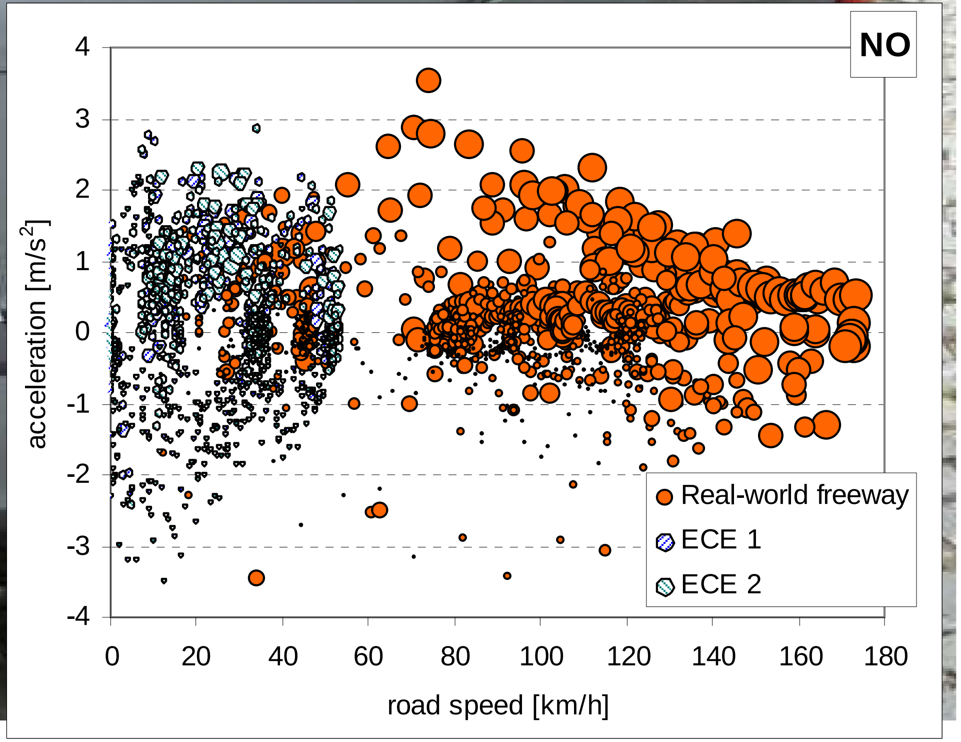
Measurement by the author.

Euro 4 Škoda Octavia – high-speed freeway tests

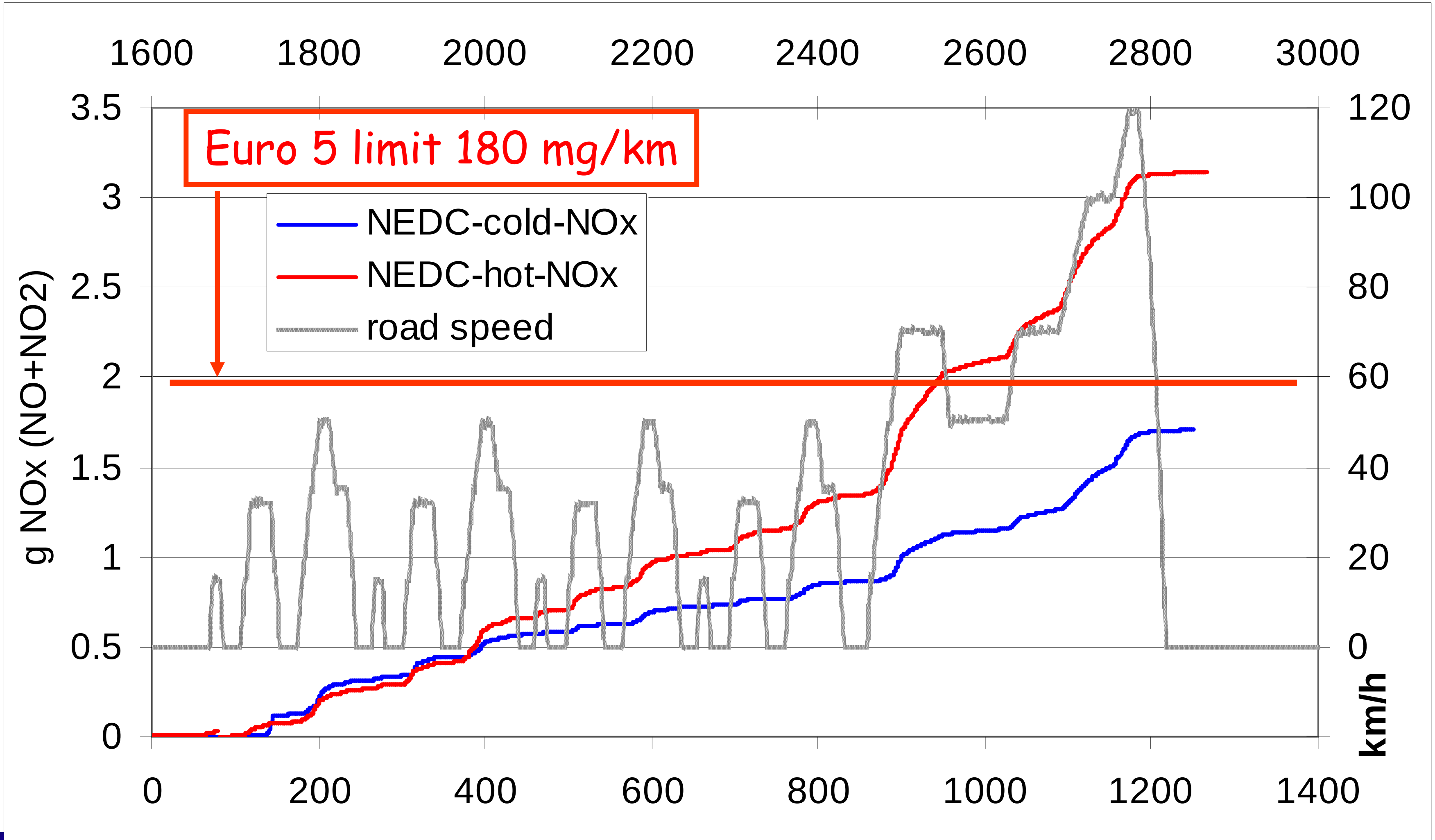
Aggressive, high-speed driving on a freeway, not atypical for Czech roads

Results contrasted with ECE cycle test on a chassis dynamometer





Cumulative NOx emissions over cold vs. hot start NEDC
Euro 5, VW Passat



This work: Škoda Octavia Euro 5 diesel, LNT

Goal: Examination of RDE emissions of nitrogen species: NO, NO2, NH3, N2O

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

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

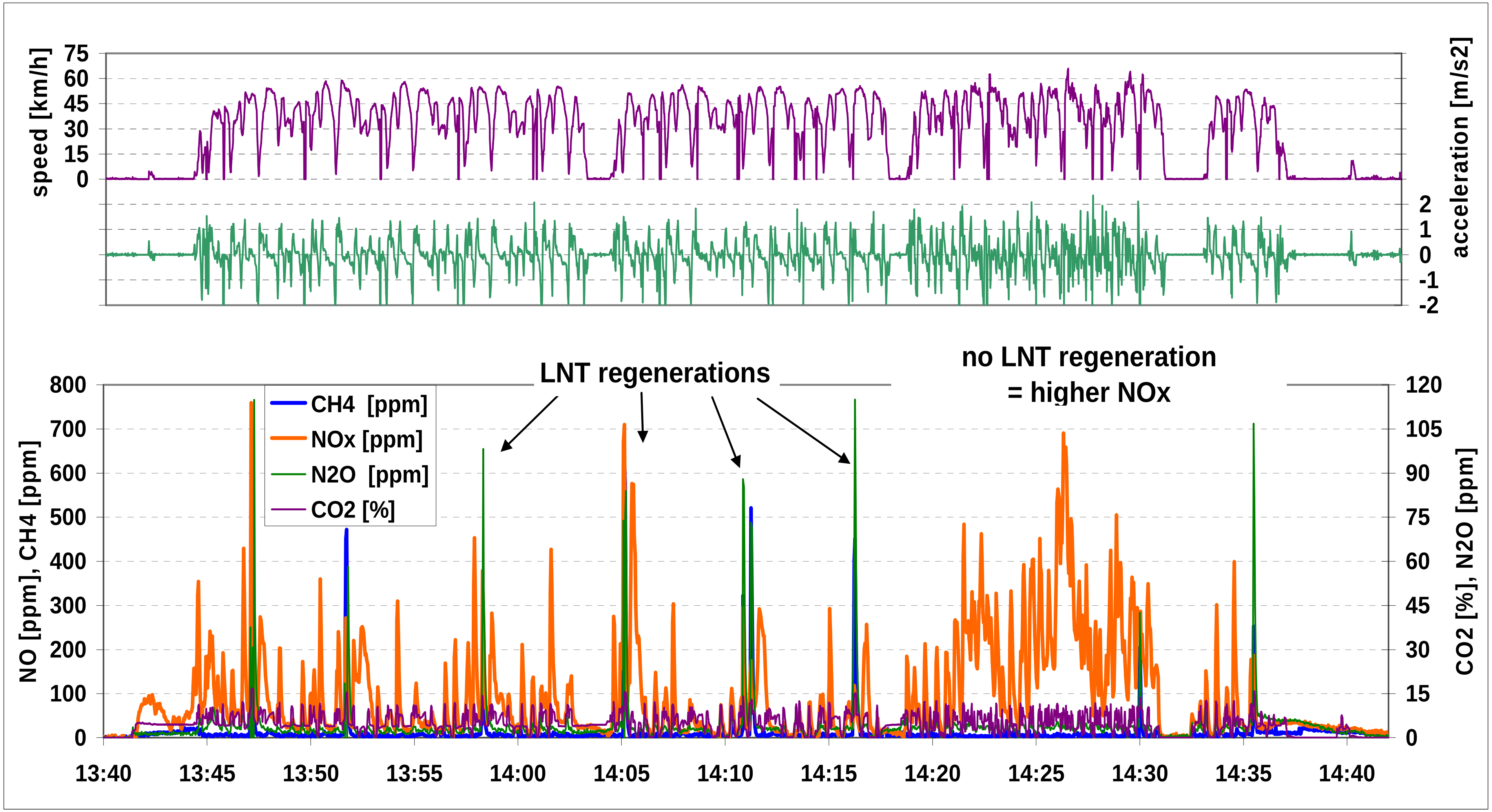
(limited by battery and liquid nitrogen capacity)

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

Germany:
431.75 km, 4:52
6.4 mg/km N2O
687 mg/km NOx
158 g/km CO2

Switzerland:
84.66 km, 1:53
217 mg/km NOx
140 g/km CO2

Euro 5 diesel car, LNT

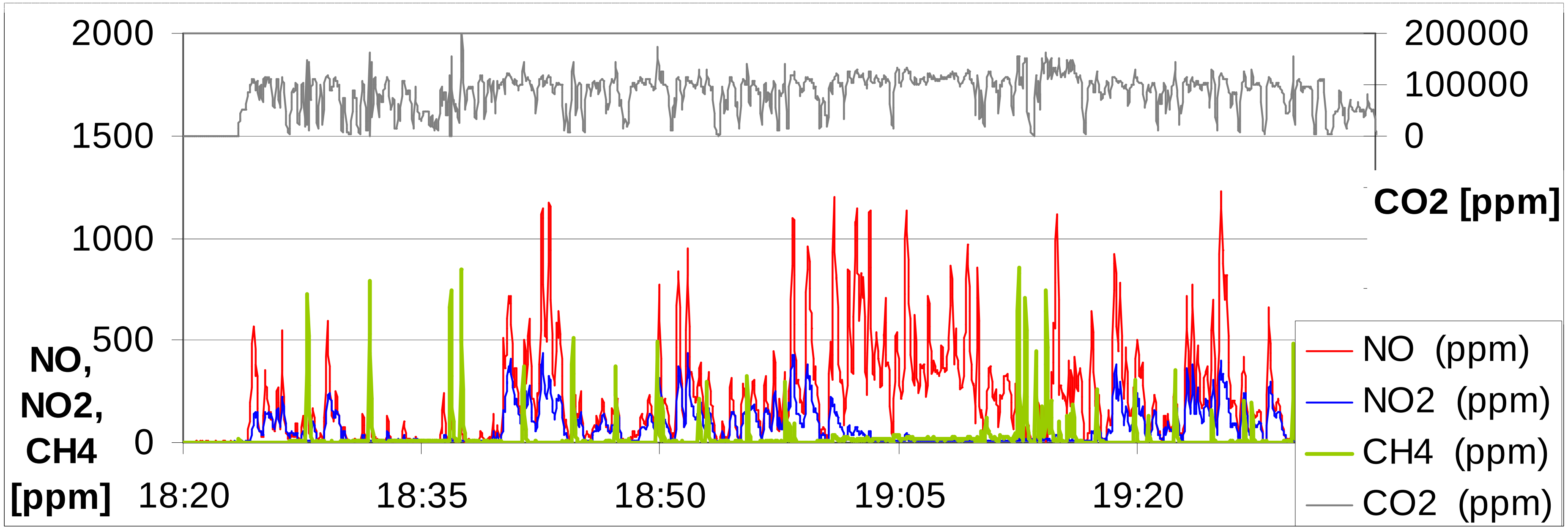


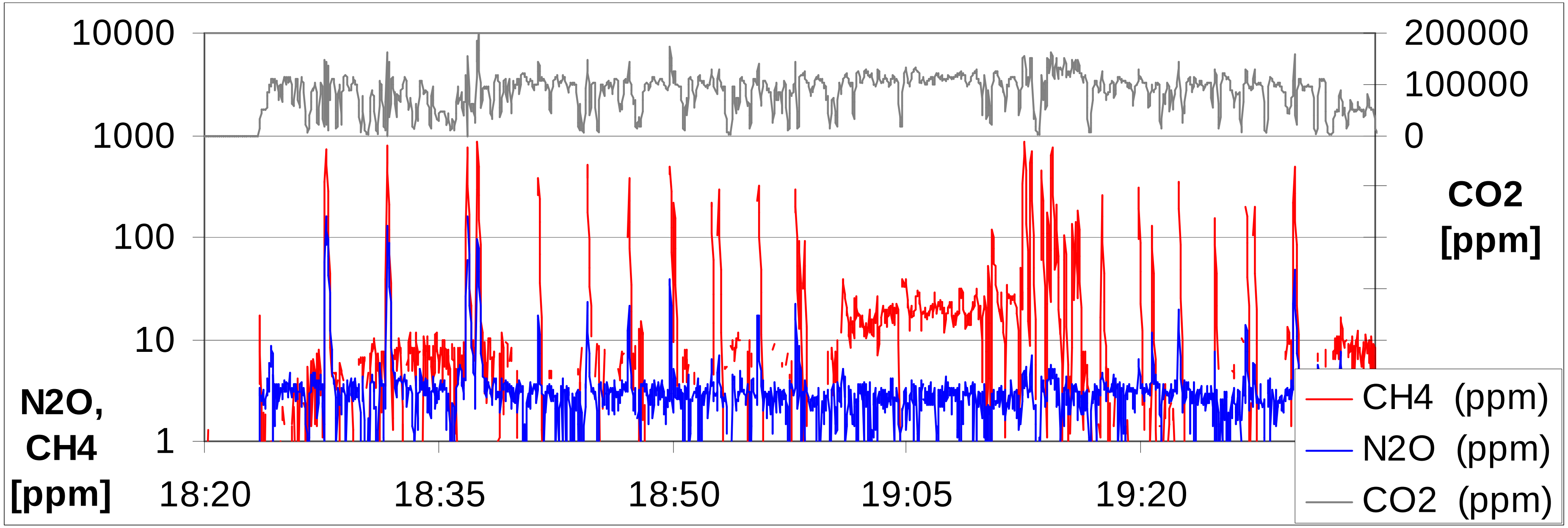
LNT regeneration: spikes in CO_2 (> 14%) and CO

Spikes in CH_4, N_2O (otherwise negligible)

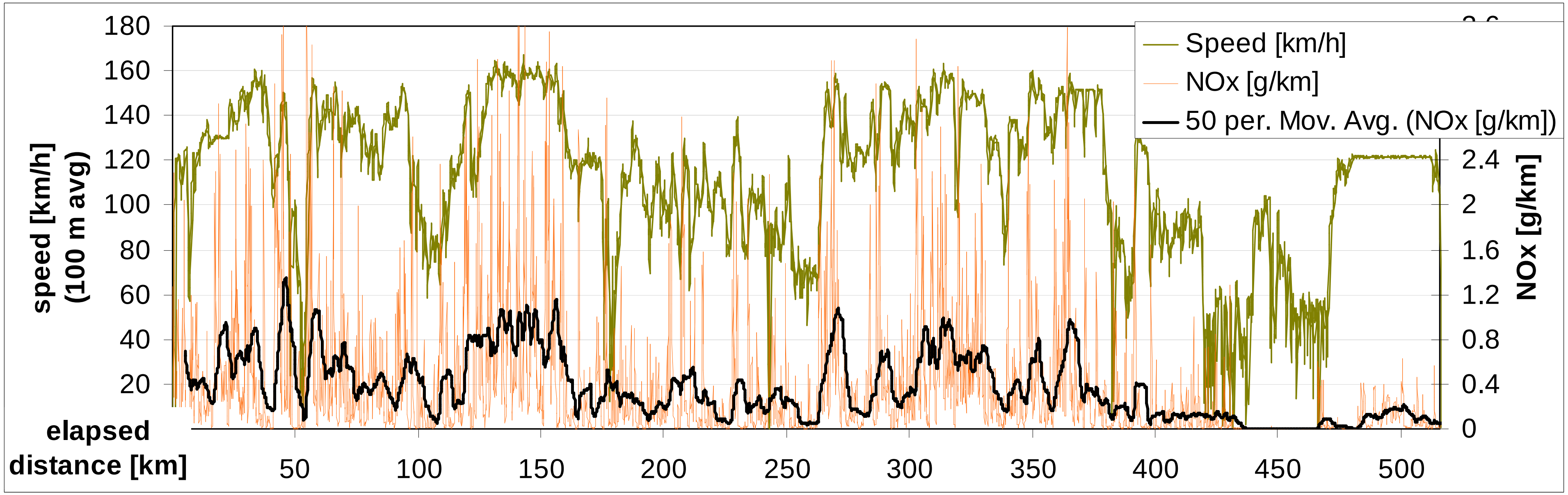
No regeneration = saved fuel, high NOx

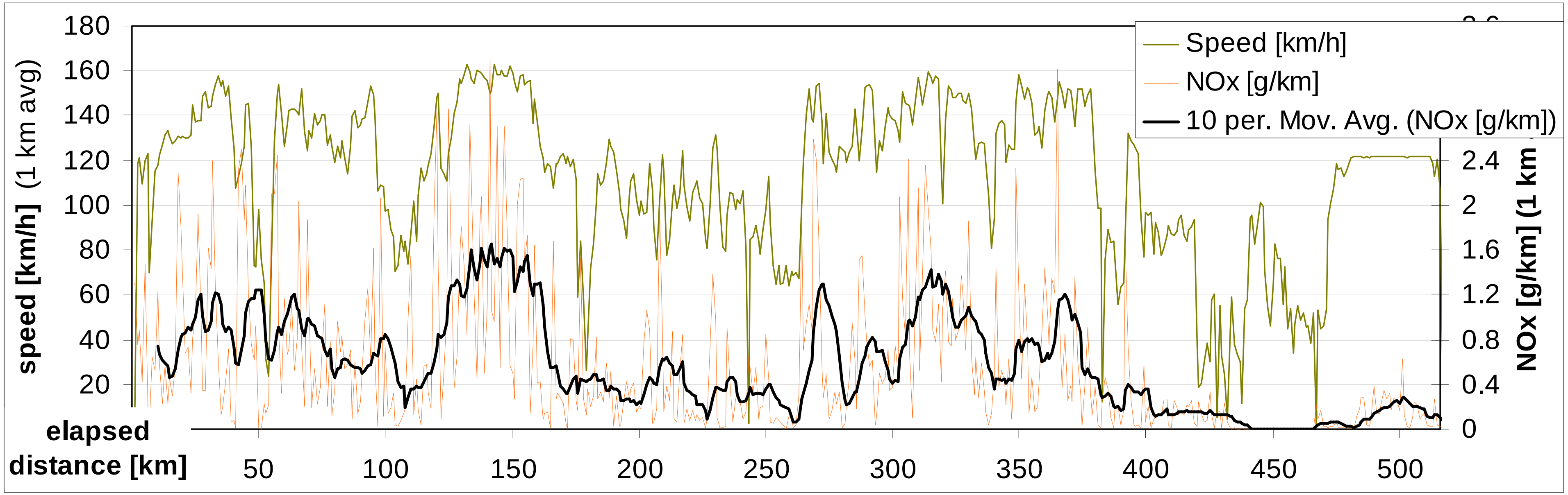
Škoda Octavia Euro 5 diesel, LNT





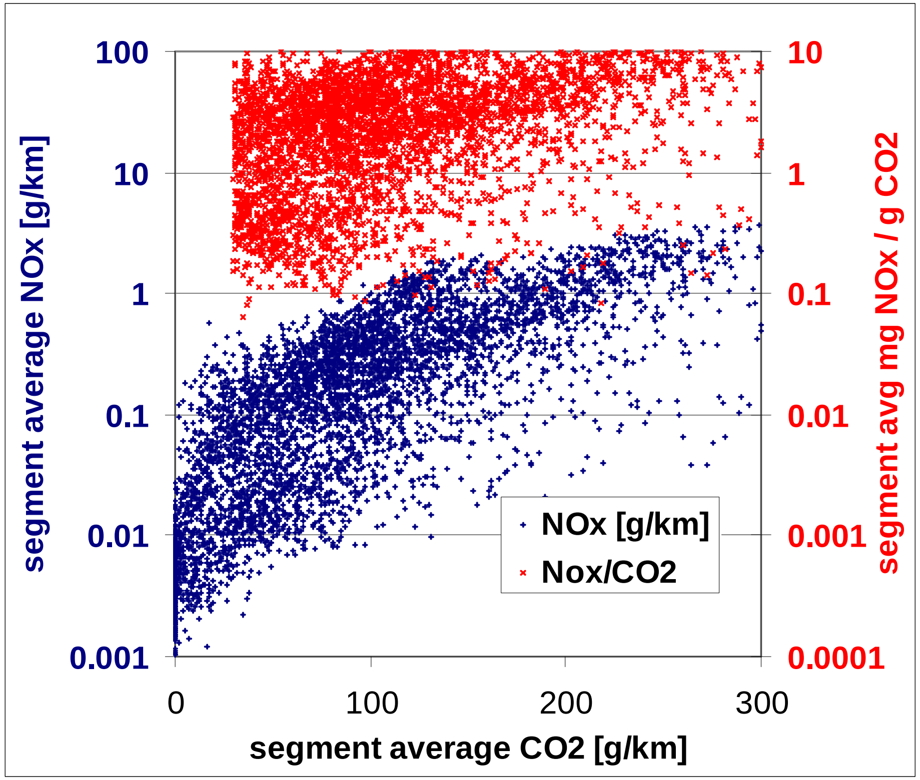
Škoda Octavia Euro 5 diesel, LNT



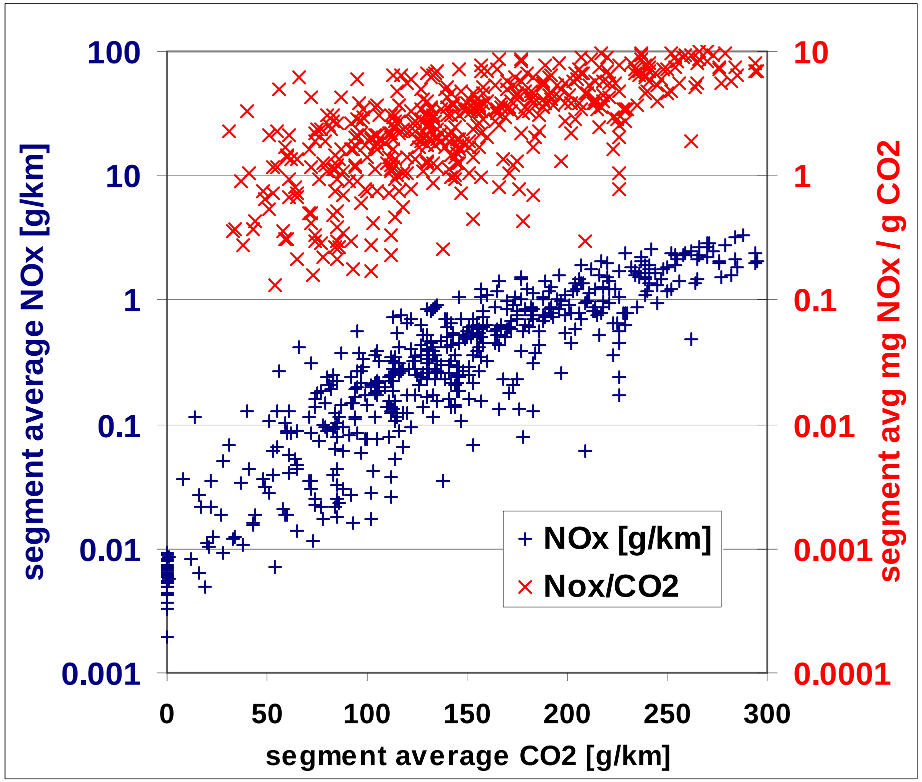


Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution



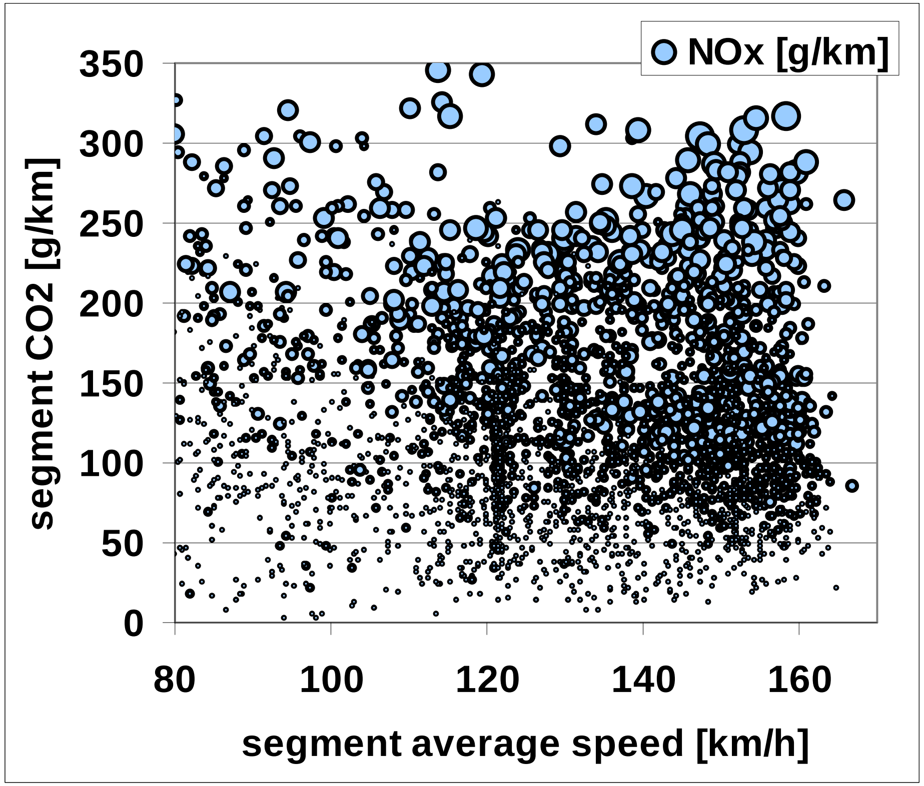
1 km resolution



NOx – both absolute and per CO_2 (per kg fuel) – Exponentially increase with fuel consumption (g/km CO_2)

Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution



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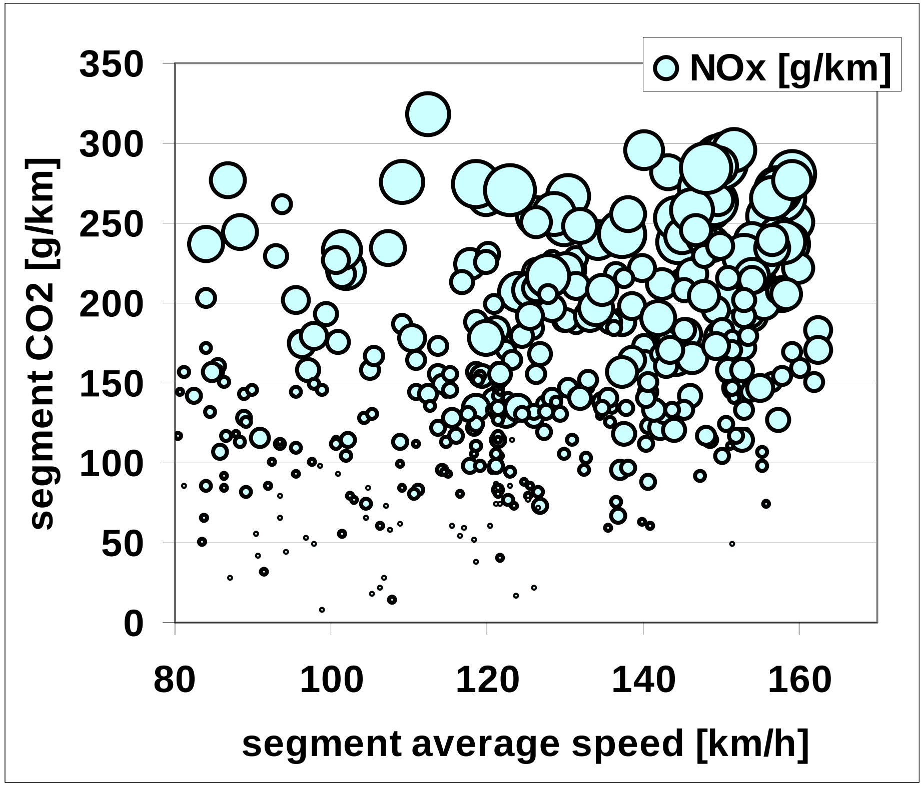
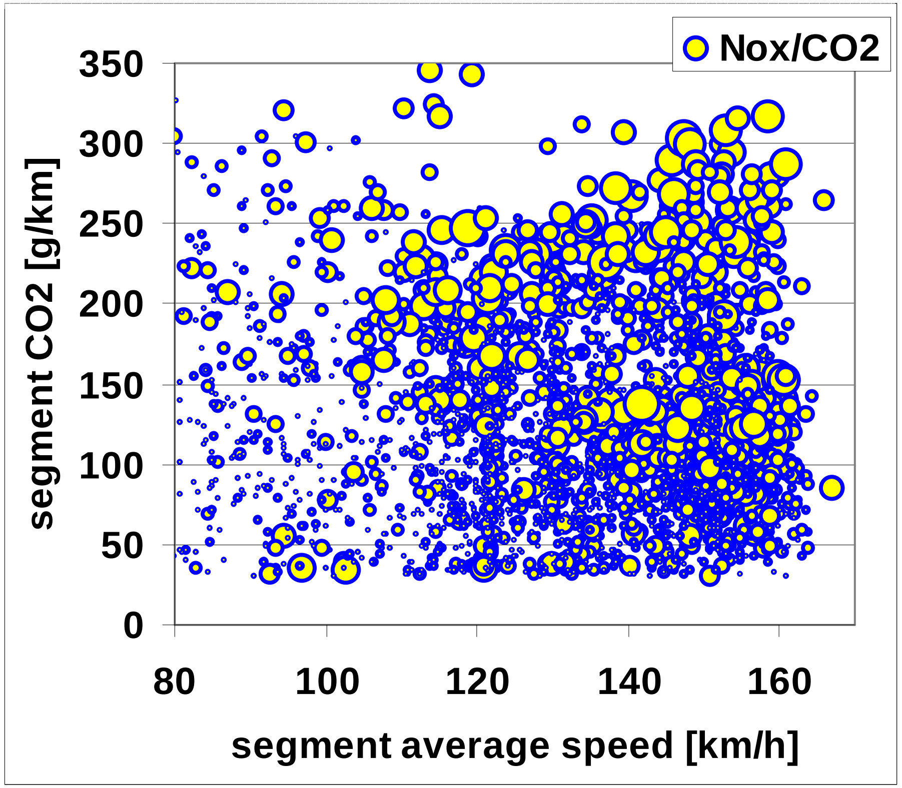


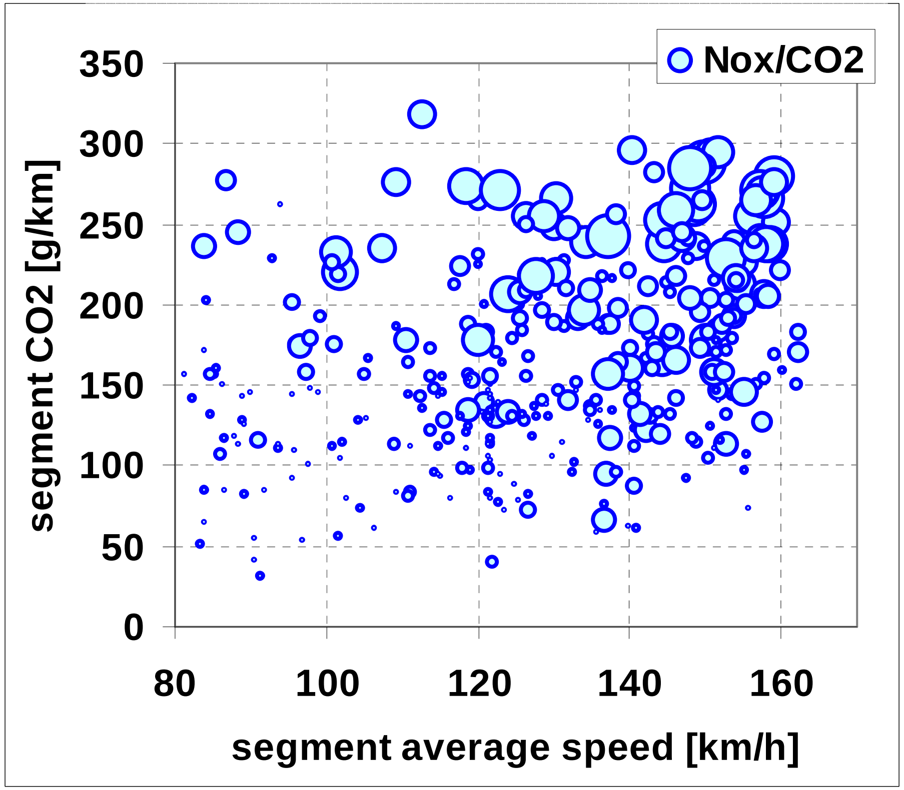
NOx exponentially increase with road speed

Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution



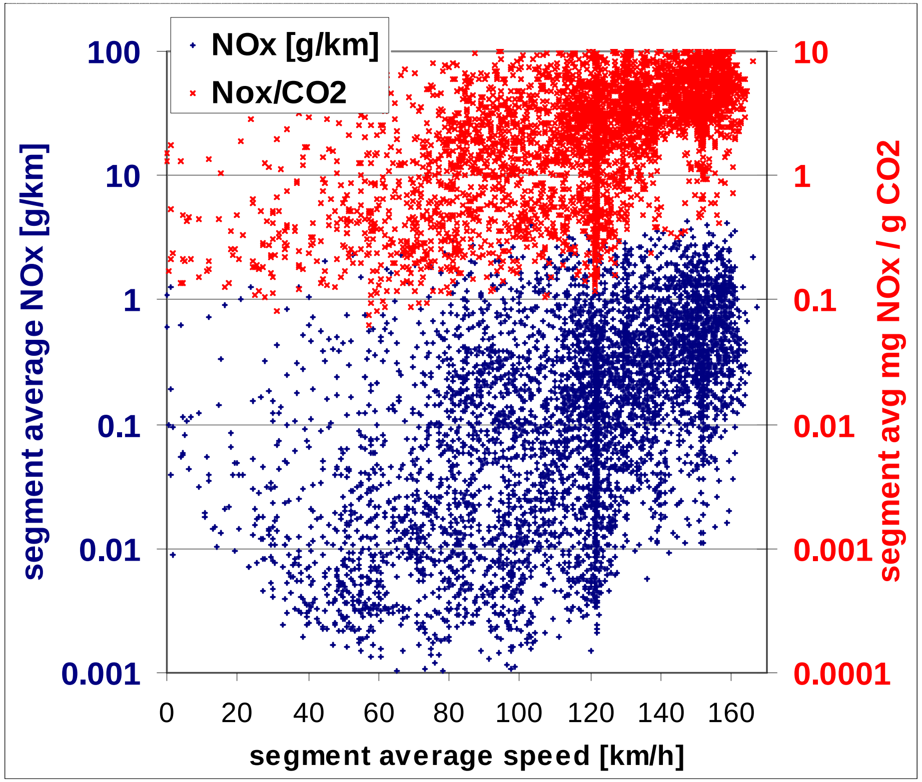
1 km resolution



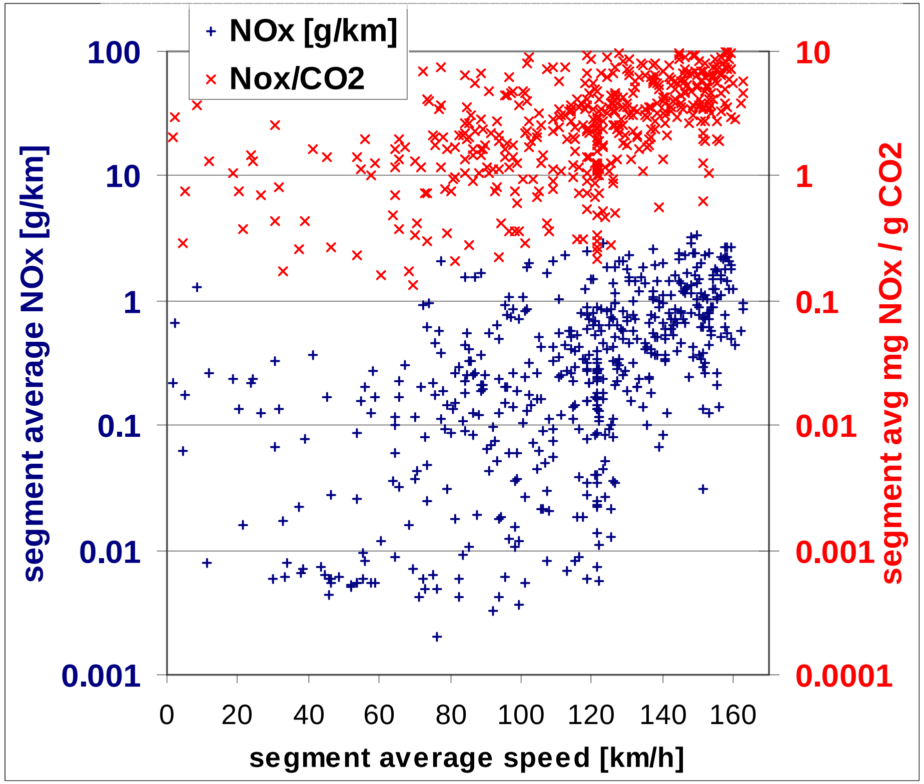
NOx per kg CO2 (per kg of fuel) exponentially increase with road speed

Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution



1 km resolution



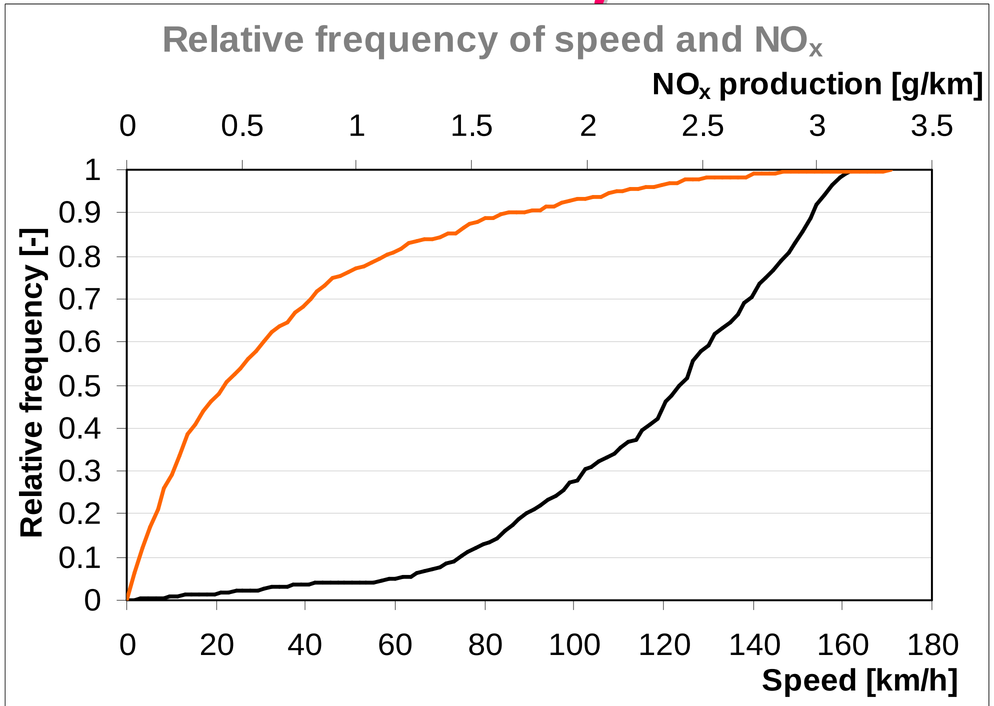
NOx – both per km and per kg CO2 (or kg of fuel) exponentially increase with road speed

Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

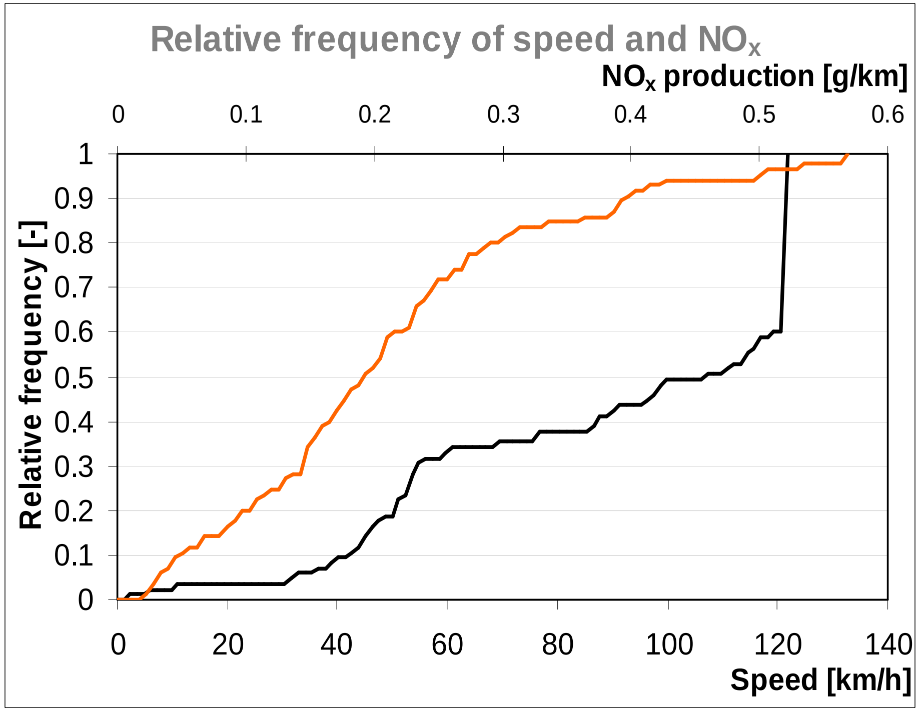
NOx appear to be well comparable with Euro 5 standards throughout Switzerland (max. 120 km/h, avg. 0.217 g/km).

On the autobahn in Germany, NOx were generally higher (>0.18 g/km >70% of the distance, avg. 0.69 g/km).

Germany

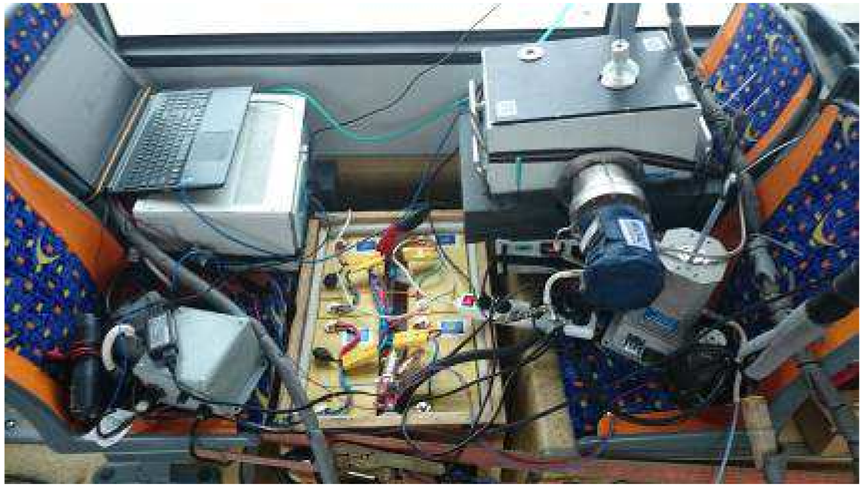


Switzerland



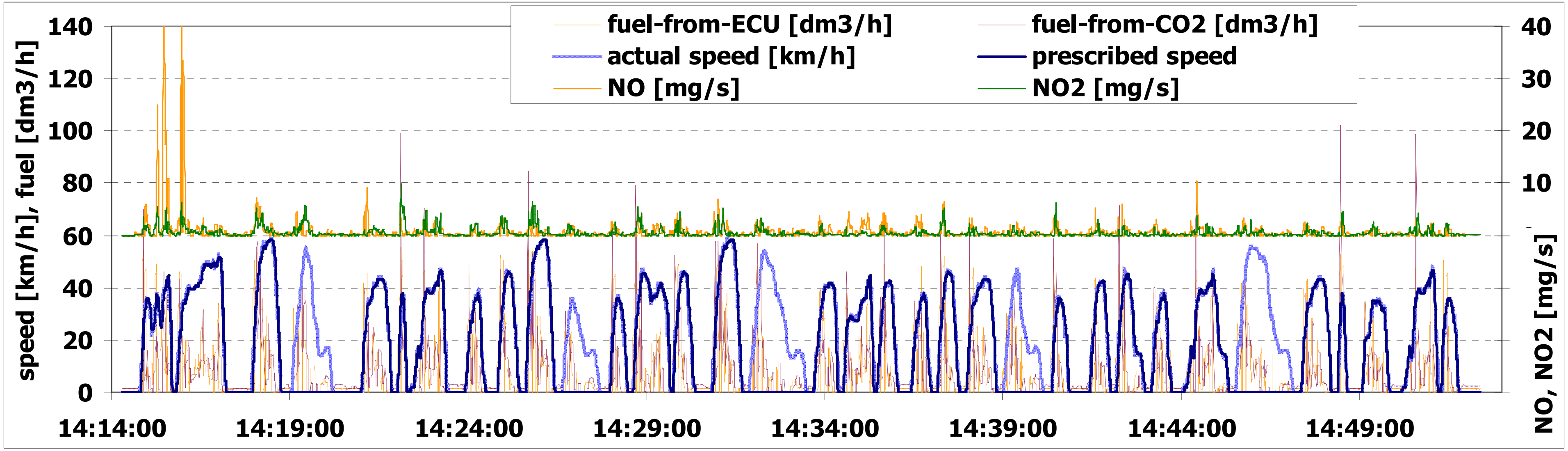
SOR CN12 Euro 6 diesel bus
Hradčany military airport
Braunschweig driving cycle

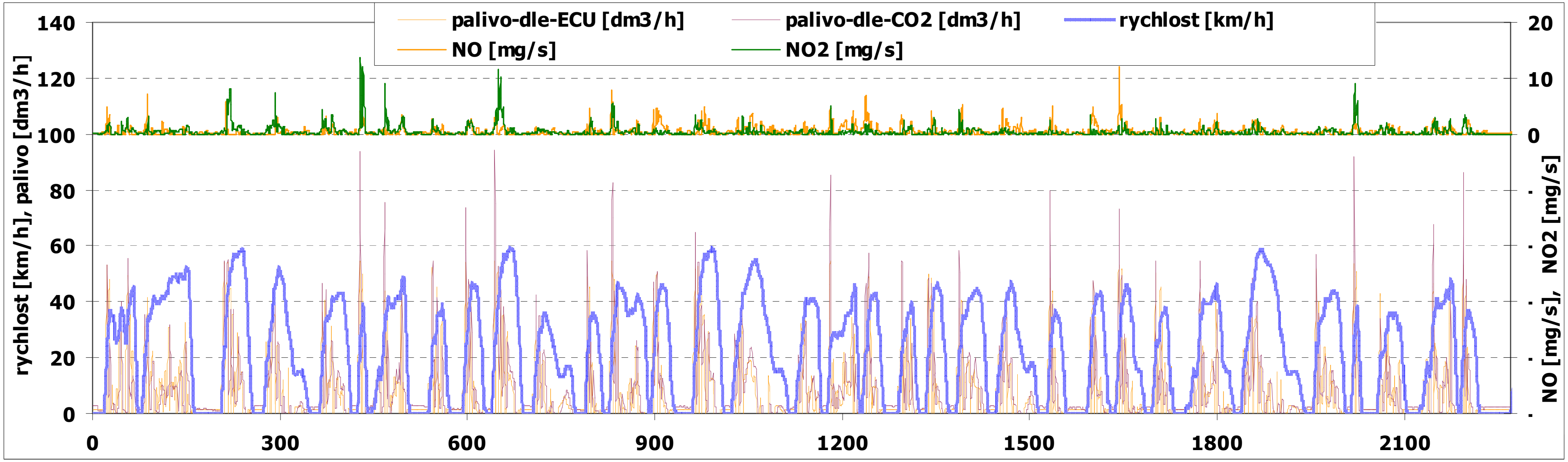
Goal: Evaluation of production of N2O, NH3, NO2 by diesel and CNG buses



SOR CN12 Euro 6 diesel bus – Hradčany military airport

NO, NO2, N2O, NH3, …., CO, CO2, PM





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)

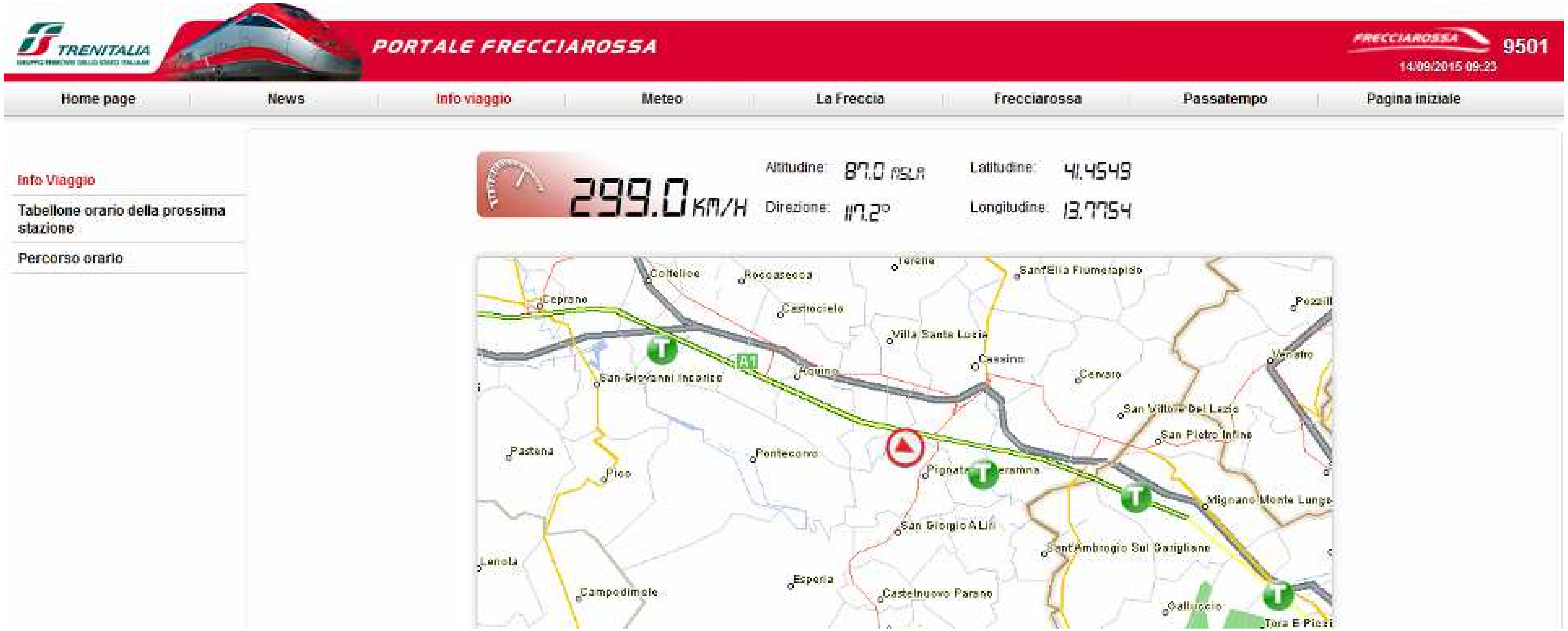
Diesel car NOx limit: 180 mg/km Euro 5, 80 mg/km Euro 6

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.

Do we limit the diesel engine to heavy-duty vehicles, just like in the United States?

Is car really the best way for high-speed intercity travel?



Conclusions & Implications

Real driving emissions of NO, NO2, NH3, N2O (+ more) measured with portable FTIR

> 500 km, 6 ¾ hours on batteries and liquid nitrogen

Measurement is possible

Interpretation of spectra for additional compounds is also possible later after the measurement

Difficult to generalize based on one or several vehicles

Results suggest NOx elevated at higher (off-cycle) speeds, and „compliant" results throughout Switzerland (<= 120 km/h)

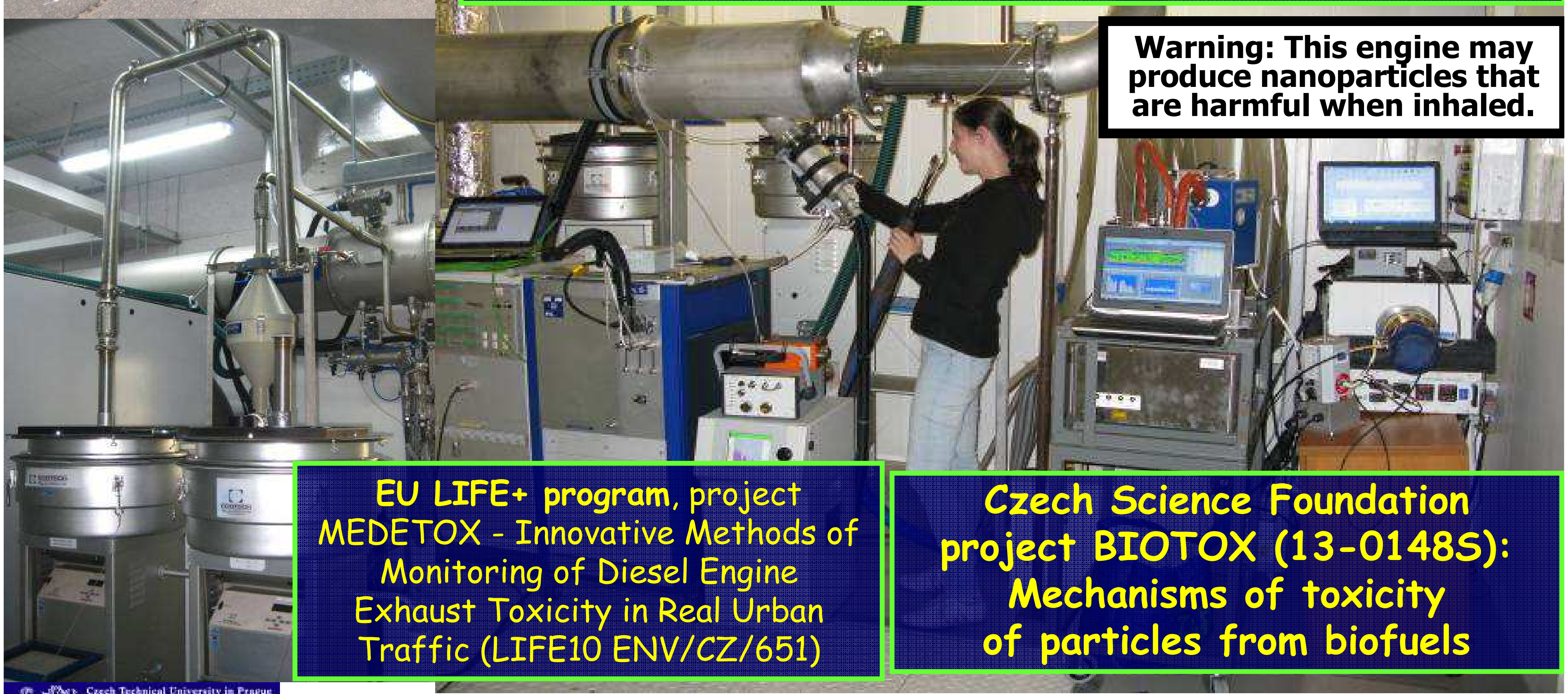
Germany: 431.75 km, 4:52
6.4 mg/km N2O, very low NH3
687 mg/km NOx, 158 g/km CO2

Switzerland: 84.66 km, 1:53
217 mg/km NOx, 140 g/km CO2

Thank you !

European Social Fund, CZ.1.07/2.3.00/30.0034
Support of Research Teams at Czech Technical University in Prague.

Warning: This engine may produce nanoparticles that are harmful when inhaled.



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

Czech Science Foundation project BIOTOX (13-01485): Mechanisms of toxicity of particles from biofuels