17th ETH Conference on Combustion Generated Nanoparticles
June 23-26, 2013

PM and PAH-Emissions of Non-DPF Trucks under Severe Congestion Conditions

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Introduction

This work investigates the effects of severe congestion, common for transit truck traffic in Prague and elsewhere, on the emissions of particulate matter (PM) and PM-bound polycyclic aromatic hydrocarbons (PAH).

Fine particles emitted by the internal combustion engines are one of the principal sources of adverse health effects attributed to air pollution. The particles emitted by the engines are rather small, on the order of units to hundreds of nanometers (nm) in diameter, with most prevalent particle size in low tens of nm, and with most particles being smaller than 100 nm. Such small particles have a high deposition rate in human lung alveoli, have the capability to penetrate through cell membranes, and have been known to adversely affect respiratory, circulatory and nervous system.

The quality and quantity of the PM emitted by engines depends not only on the construction parameters of the engine, but also on its calibration, wear, technical conditions, and ambient and operating conditions.

This work is concerned with prolonged operation of a diesel engine at low load, and the effects of such operation on exhaust emissions during this time and also during subsequent operation at higher loads.

Extended low load operation of a diesel engine is characterized by very high excess air ratio (often over 10), associated with gradually cooling down combustion chamber surfaces and low exhaust gas temperature (EGT), which often is below the operating temperature of catalytic exhaust aftertreatment devices such as diesel oxidation catalyst (DOC) or a selective reduction catalyst (SCR). At the same time, extended low load operation is common for trucks traversing larger urban areas with severe congestion.

Preliminary on-road tests

Several on-road trucks were loaded to approximately 75% nominal capacity and driven on Prague perimeter road during various times of a day, with the goal to capture passages through congestions.

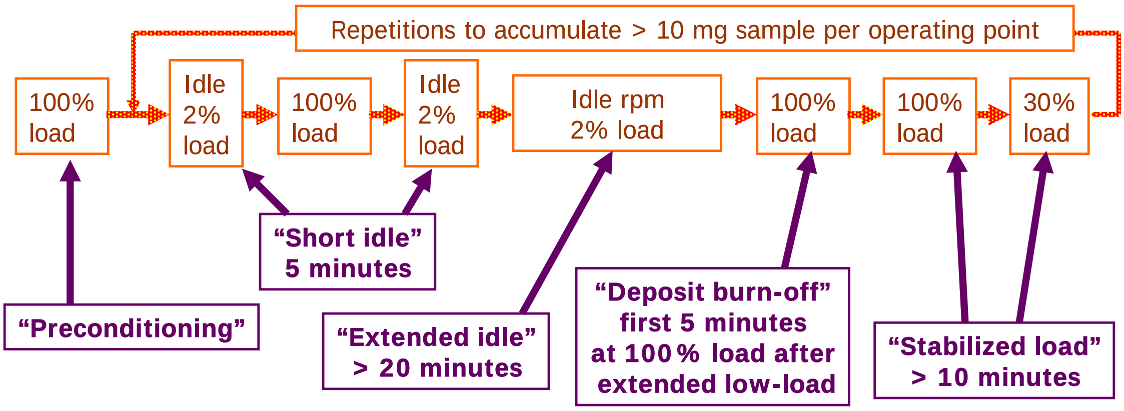
The trucks were equipped with a portable, on-board emissions monitoring system designed by the first author and described at previous ETH conferences. This system samples undiluted raw exhaust at high flow velocities and uses several low-cost, small-size devices to measure concentrations of pollutants of interest. These concentrations are, for each second of measurement, multiplied by the exhaust flow rate inferred from measured engine operating parameters such as engine rpm and intake manifold pressure and temperature. A laser light scattering device is used to qualitatively assess particle mass concentration (subject to assumptions about PM properties). A measuring ionization chamber extracted from a building smoke detector is used to measure total length concentration (sum of diameters of all particles).

The on-board system was complemented by a proportional sampling system constructed by the authors. The sampling system approximated exhaust gas flow from measured intake air flow, and introduced, through a mass flow controller, a metered amount of HEPA-filtered dilution air into a microdilution tunnel (30 mm diameter) located near the end of the tailpipe. The mixture of dilution air and raw exhaust was passed through Teflon-coated glass fiber filters (Pall TX40HI-20WW) at a constant rate regulated by a second mass flow controller.

The yield of PM obtained in this matter was, however, insufficient for advanced chemical analyses and toxicological assays on the sample. For example, approximately 18 mg of PM was collected on over one hundred filters during four days of measurements, while approximately 1 mg is needed for PAH analysis and 1-10 mg for toxicological assays. For this reason, severe congestion was simulated in the laboratory.

Laboratory tests

A Zetor diesel engine (certified to 0.3 g/kWh PM) with a mechanical injection pump coupled to an engine dynamometer was run alternately at intermediate rpm and full load, and at idle rpm and 1-2% of rated power to simulate slow "creep". The engine was operated with no exhaust aftertreatment devices.



Raw exhaust was diluted at nominally 10:1 dilution ratio and sampled by a Hi-Vol sampler (EcoTech 3000) with a $PM_{2.5}$ impactor operating at 67.8 m^3/h rate. A second Hi-Vol sampler was used to provide filtered dilution air. Dilution ratio was verified by CO_2 concentrations measurements. Samples of PM were collected on 20x25 cm fluorocarbon coated and quartz filters, with accumulations of ten to several hundreds of mg of PM per filter. The details of the sampling setup are given at a poster (Vojtisek-Lom et al.) presented at this conference.

The filters were first subjected to gravimetric analysis to determine total PM mass, and then send for organic extraction. A smaller portion (10%) of the organic extract was used for quantification of the US EPA 16 priority PAH by HPLC with fluorescence detection.

The remainder of the extract was used for toxicological analyses which are the subject of the companion paper (Topinka et al.) given at this conference.

Emissions of benzo[a]pyrene, 7 carcinogenic PAH (cPAH) per US EPA (benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenzo[a,h]anthracene, indeno[1,2,3-cd]pyrene), US EPA 16 PAH, and total particulate mass were expressed as mass per kg of fuel consumed, as emissions per kWh are of limited relevance at zero or very low load, and emissions per km are affected by the weight of the truck.

Key results and conclusions

The emissions of a non-DPF diesel engine under severe congestion simulated in a laboratory to accumulate enough PM for toxicological assays.

A pair of high-volume atmospheric samplers was used for dilution and sampling of the exhaust, allowing tens of mg of sample to be collected.

The emissions of PM mass, carcinogenic PAH (cPAH), US EPA 16 priority PAH and benzo(a)pyrene were an order of magnitude higher

1. during extended operation at 2% load, as compared to operation at 2% load immediately after higher load
2. during operation at 100% load immediately after extended low-load operation, as compared to stabilized operation at 100% load

on both diesel fuel and neat biodiesel; the effects for biodiesel, relative to diesel fuel, were higher for PM mass, but lower for cPAH. Biodiesel had lower cPAH except for stabilized full load.

Acknowledgements

Work funded by the EU LIFE+ program, project MEDETOX - Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic (LIFE10 ENV/CZ/651) and by the Czech Science Foundation, project BIOTOX - Mechanisms of toxicity of biofuel particulate emissions (13-01438S).

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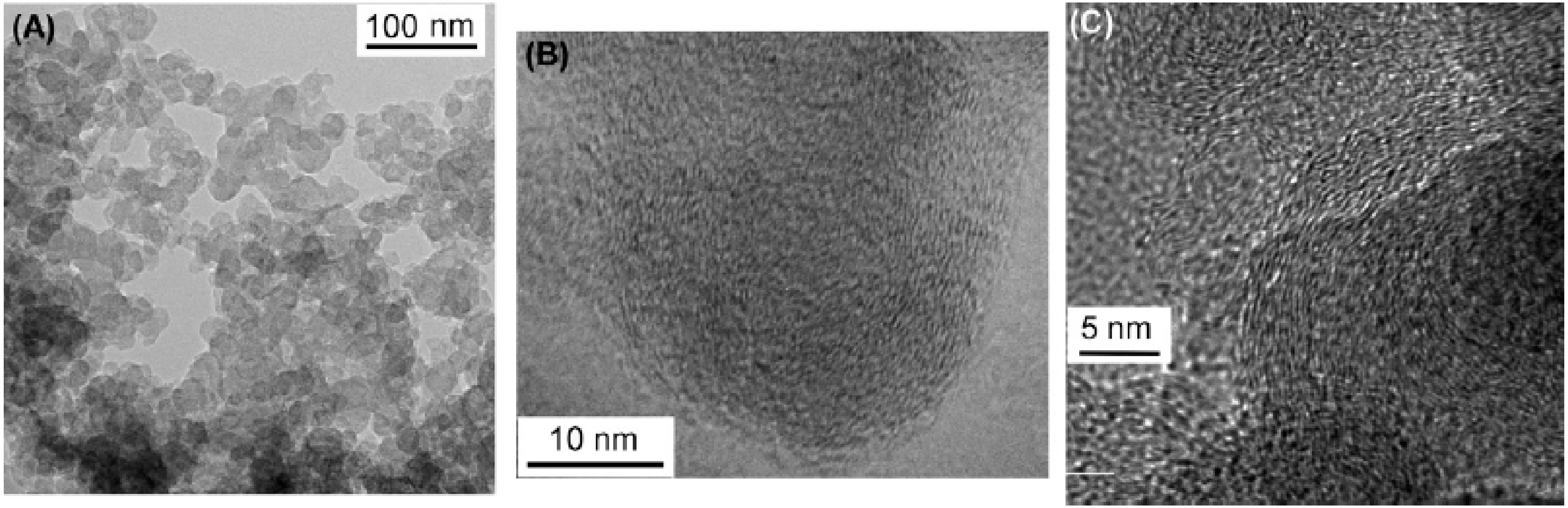
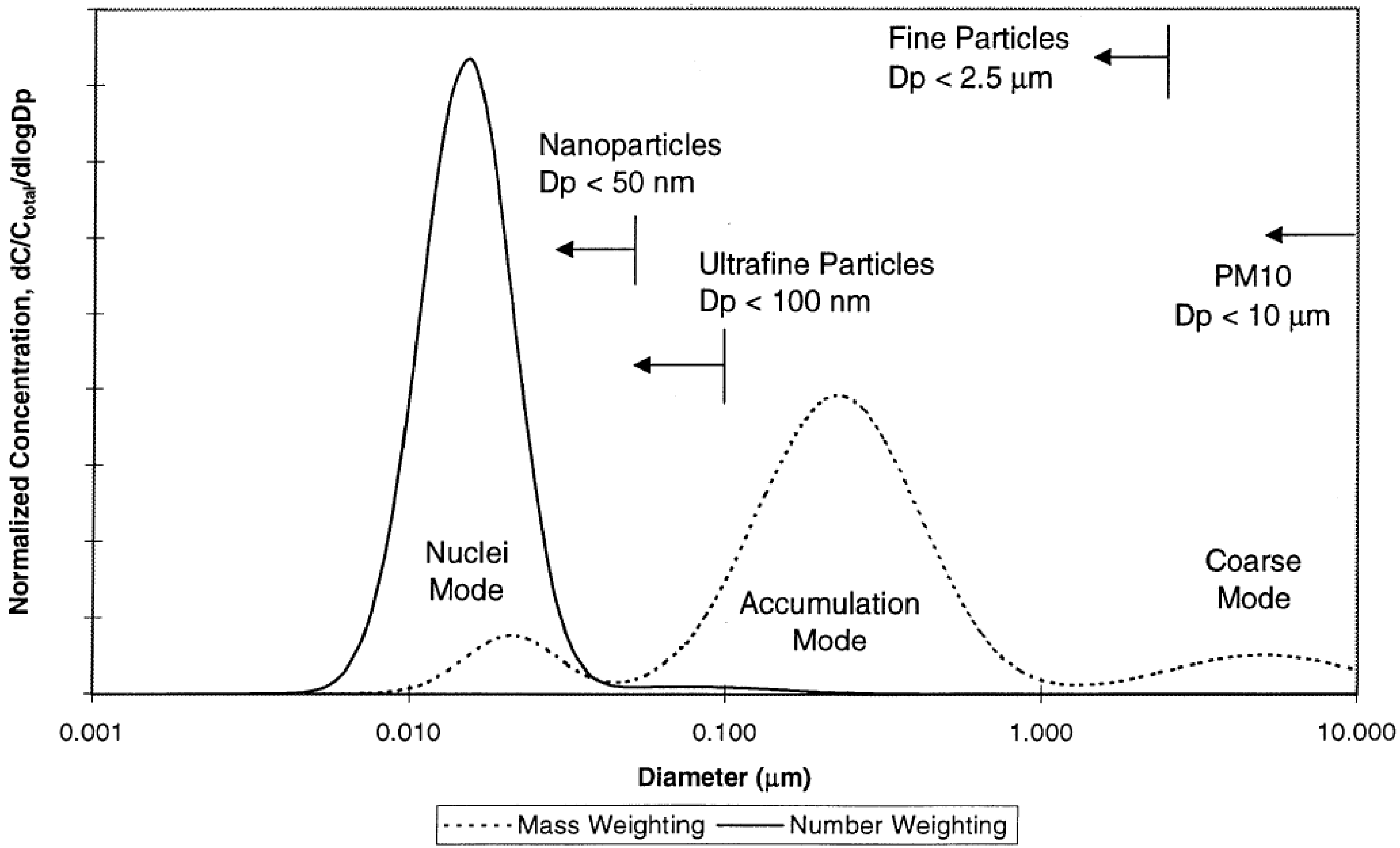
Diesel exhaust particulate matter



Liati A., Dimopoulos P.E., Combustion and Flame 157 (2010) 1658–1670.

Typical diesel exhaust PM size distribution



Kittelson, *J. Aerosol Sci.* Vol. 29, No. 5/6, pp. 575-588, 1998

EU vehicle particle emissions: Legislation vs. health effects

Particle metric – legislated: total mass, total count (non-volatiles)

- Health effects depend on size, structure, composition, complex interactions of effects
- Semi-volatile (OC, organic carbon) fraction of PM higher as larger soot particles get reduced through improved combustion
- OC fraction has higher toxicity than elemental carbon?
- New fuels and new technologies can bring new problems

… toxicity of emerging technologies & fuels needs to be considered (ongoing arguments by many)

… choice of operating conditions is important when evaluating toxicity

Known problematic operating conditions:

- Light vehicle gasoline – fast transients, full load
- Light vehicle diesel – fast transients, full load, prolonged idle
- Heavy vehicle diesel – prolonged idle and creep

- most of these are outside of the current driving cycles:
  - NEDC – no extended low-speed driving, no high speed or load
  - Heavy-duty cycles – no extended low-load operation
- most of these are common in congested urban areas

Coindicence of problems in dense / congested urban areas

High concentration of vehicles

-> high ambient concentrations

High population density

-> high number of people exposed

High frequency of problematic operating modes

- **extended idling and creep**
- **dynamic / transient operation**
- **full-power accelerations**

-> higher and/or more hazardous emissions

For toxicity evaluation, focus should be on realistic urban driving conditions.

Focus of this work: Severe congestion

Engine exhaust toxicity project:

MEDETOX

Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic.

EU LIFE+ program (LIFE10 ENV/CZ/651), 2011-2016

Institute of Experimental Medicine, Academy of the Sciences of the Czech Republic – Jan Topinka, coordinator

Faculty of Mechanical Engineering, TU Liberec

Ministry of the Environment of the Czech Republic

Goal:

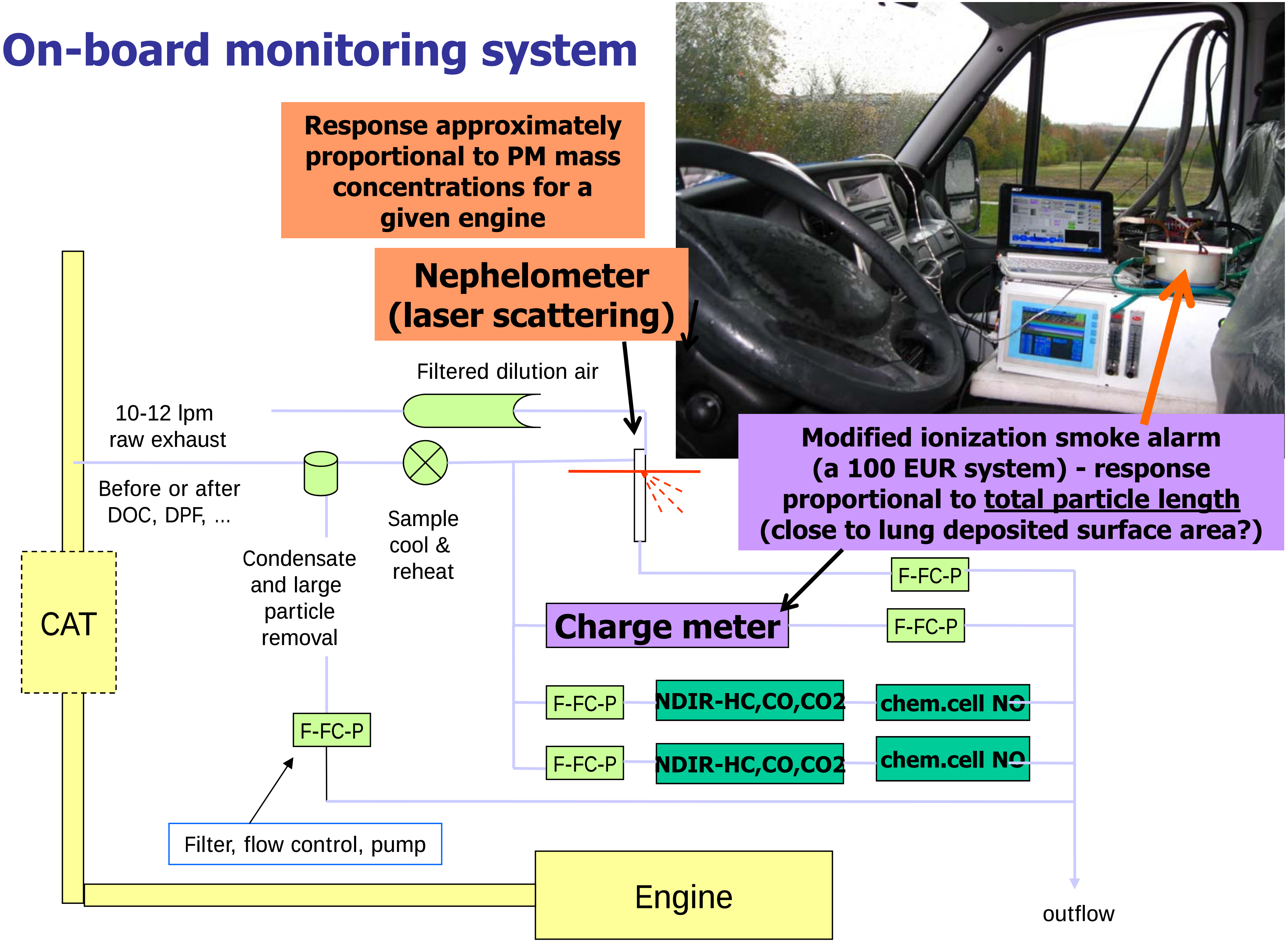
Demonstrating innovative methods of monitoring toxicity
on-board sampling system, focus on urban driving
off-line toxicological assays on collected samples

PEMS – Portable emissions monitoring system

-> PETS – Portable exhaust toxicity assessment system

Measurement of gases and PM with on-board system
Sampling of PM with on-board proportional sampling system

On-board monitoring system



PM length measurement – comparison

0.1 g/kWh PM engine, various fuels and modes, EC 1%-79%
reference: EEPS sampling from dilution tunnel

heated ionization "fire detector"

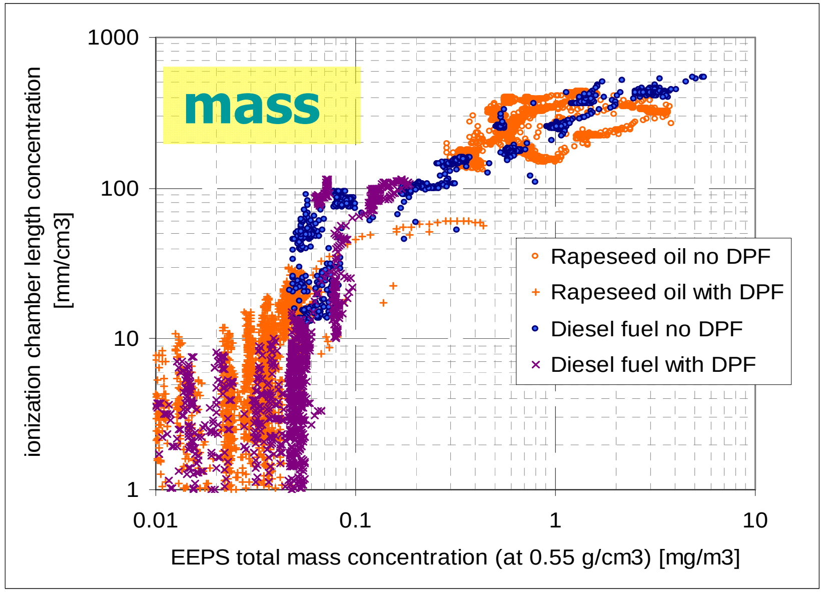
undiluted raw exhaust

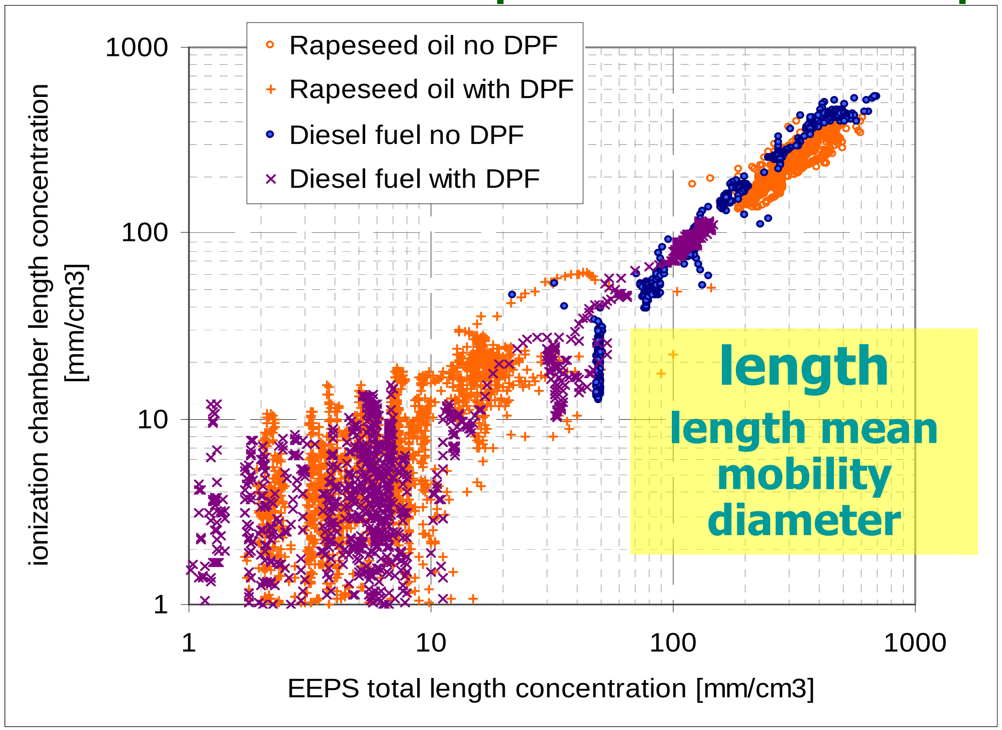
(multiplied by intake air flow for comparison measurements)

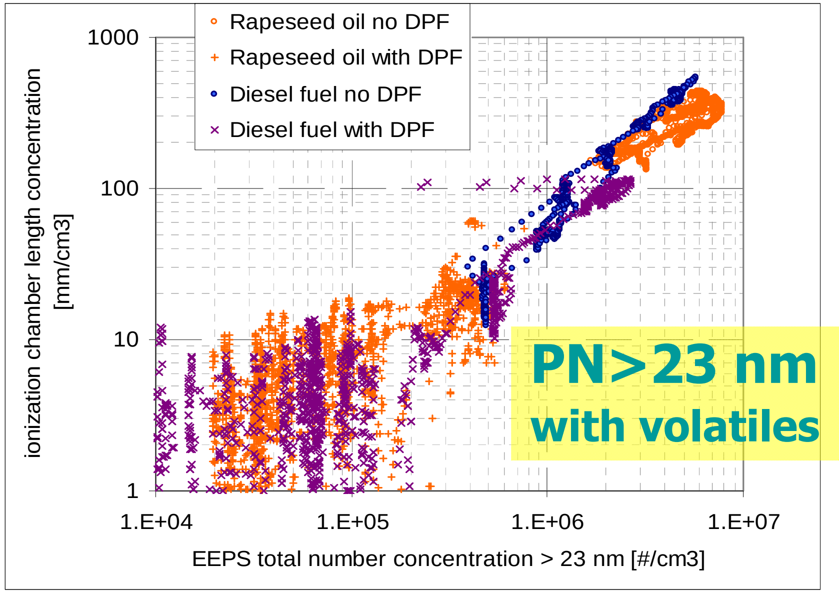
~ 0.1 mg/m3 sensitivity

cheap (100 EUR)

"poor man's PEMS" concept



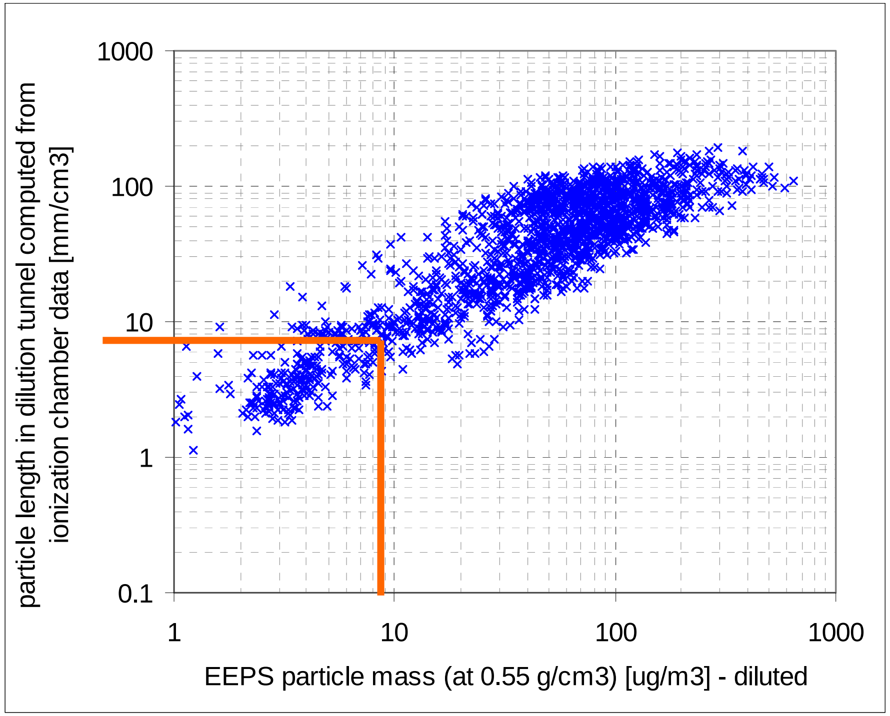


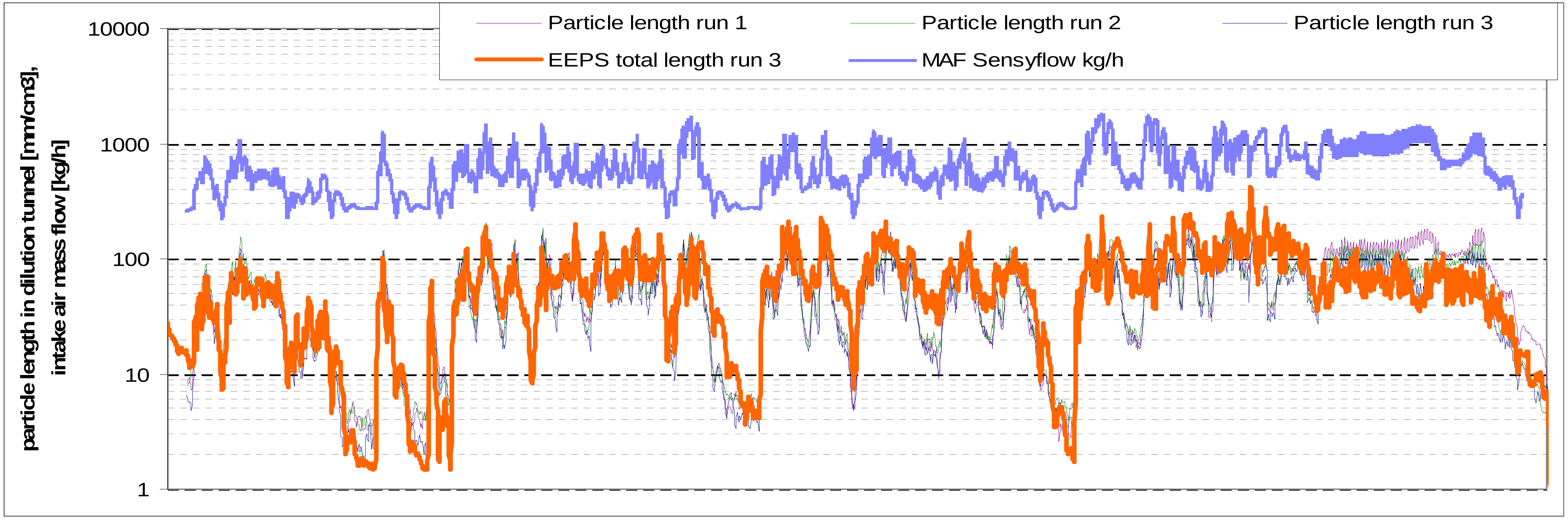


PM length measurement

PM length:
heated ionization chamber
sampling raw exhaust
x exhaust flow (calculated)

Reference:
EEPS sampling from CVS
(diesel, 0.02 g/kWh PM, WHTC cycle)

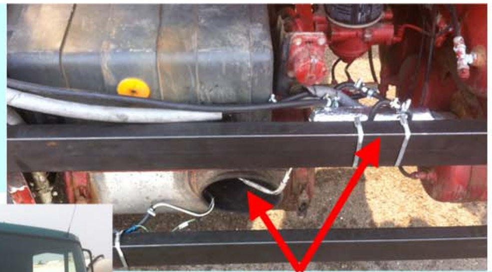




Assessment of congestion and "creep" on the road

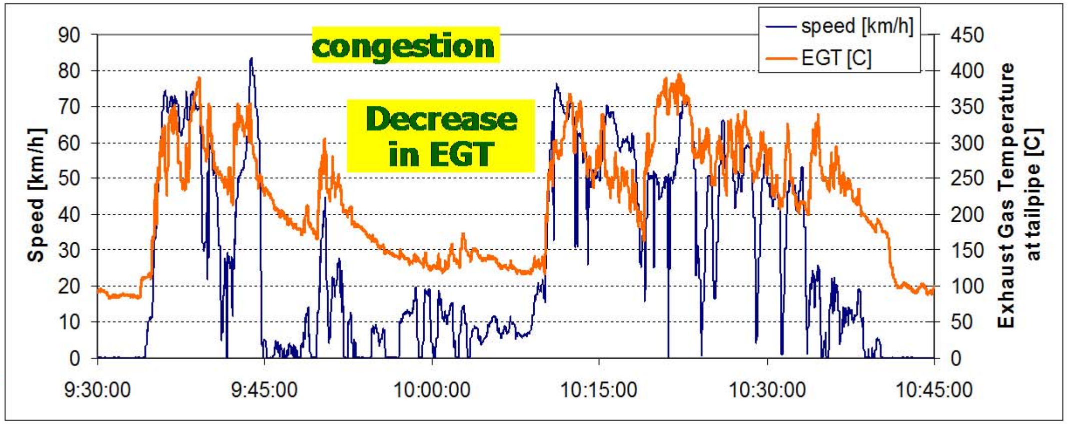
EURO 3 – no aftertreatment
2003 Iveco Trakker

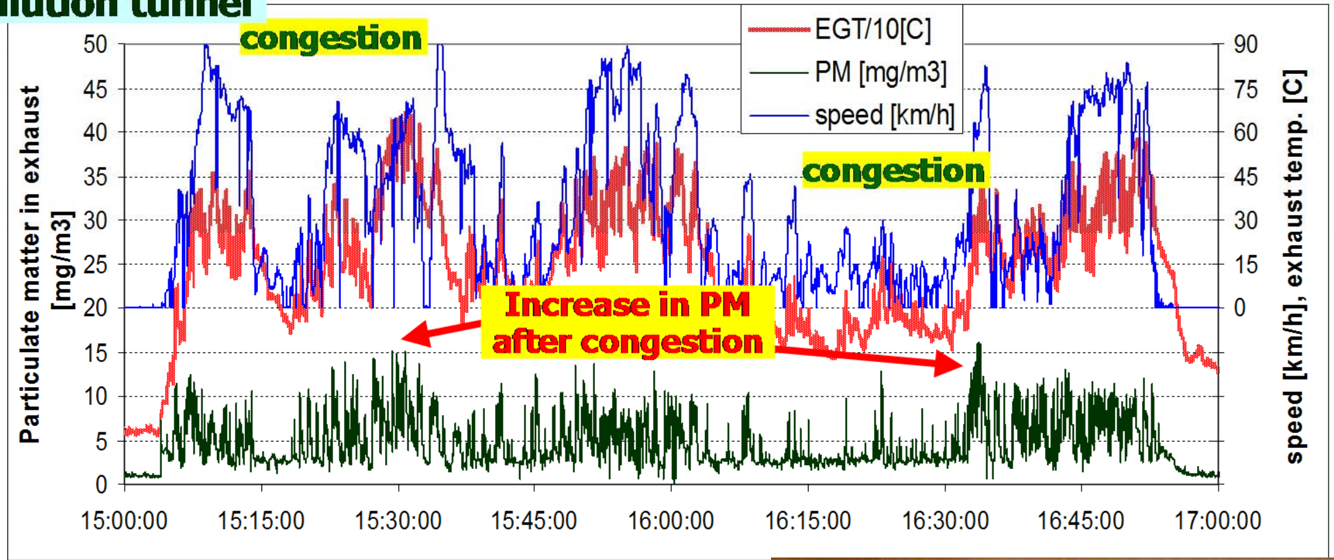
Proportional exhaust particle sampling



Miniature partial-flow dilution tunnel

On-board measurement & sampling system

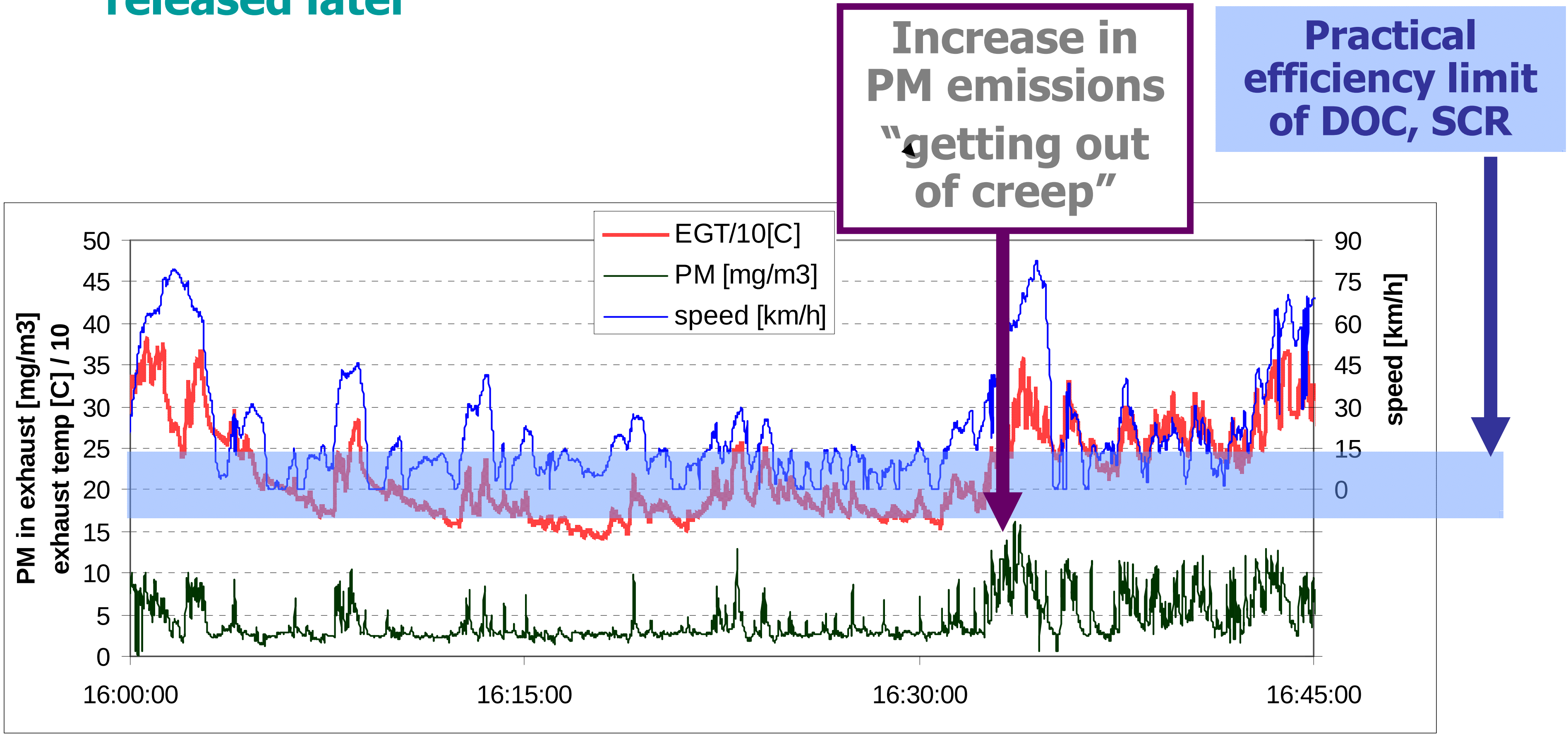




17 mg of PM collected on ~110 filters during a week of field measurement not sufficient for toxicology

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



Heavy vehicle creep problem

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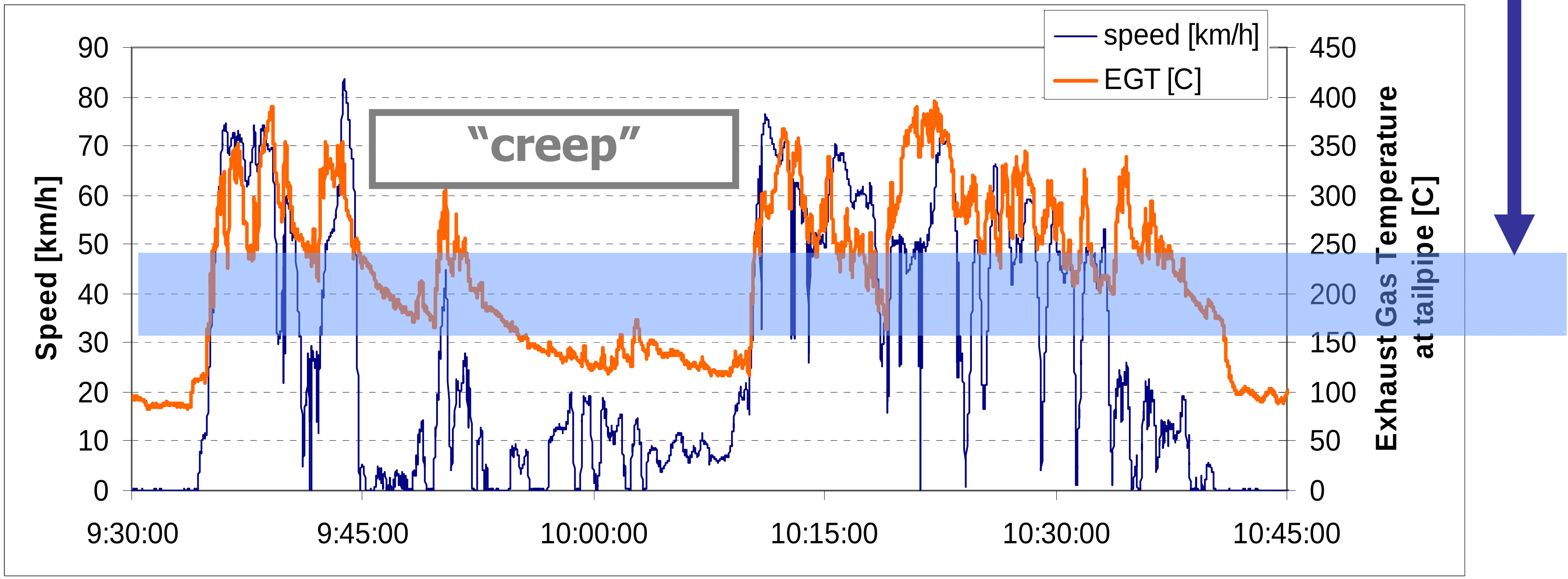
Practical efficiency limit of DOC, SCR



Laboratory simulation of creep

Reason: 17 mg of PM collected on ~110 filters (47 mm) during a week of field measurement not sufficient for toxicological assays

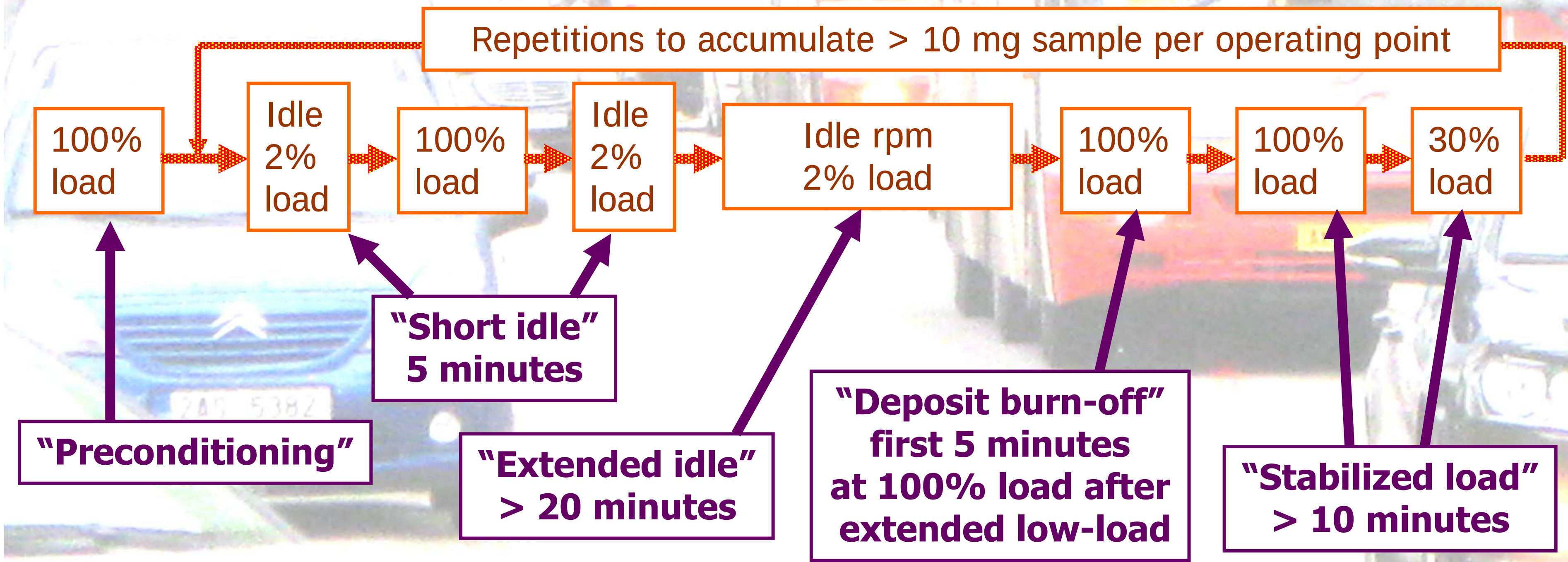
Steady-state operating points:

idle and max. torque ("intermediate") rpm

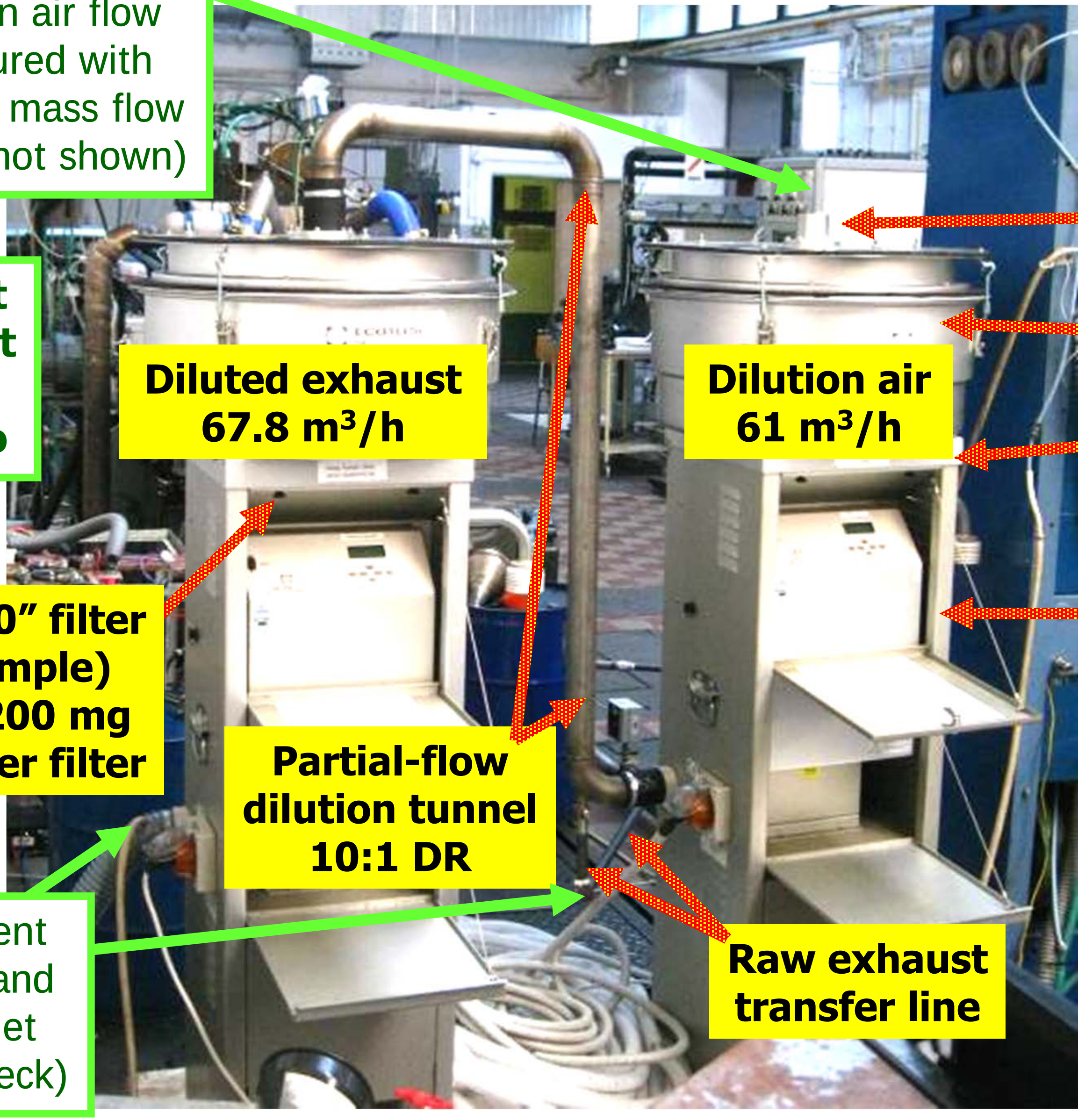
30% load – corresponds to "highway cruise" **(EGT 265°C)**

100% load – corresponds to hill / acceleration **(EGT 460°C)**

2% load at elevated idle – corresponds to "creep" **(EGT 100°C)**

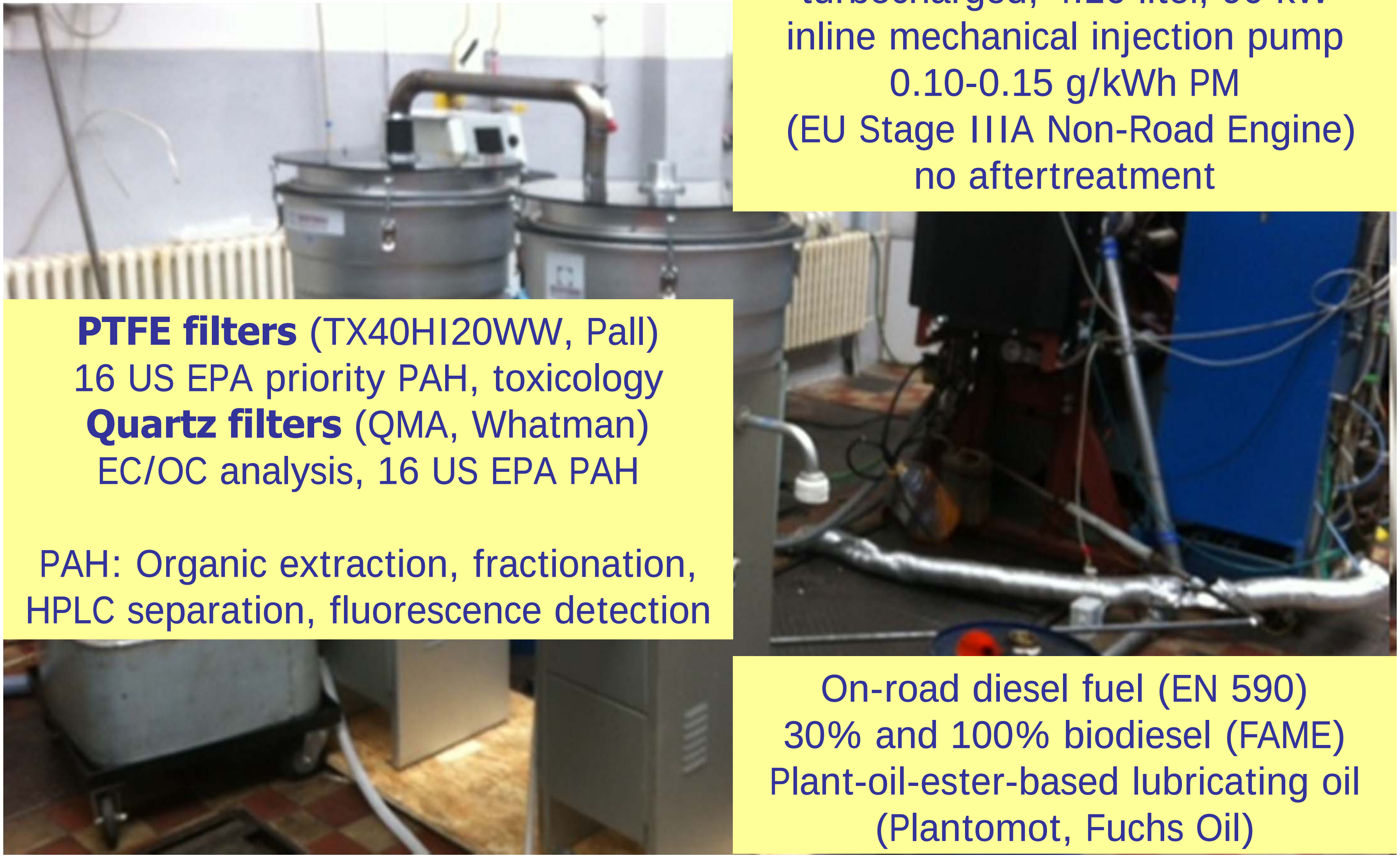


Exhaust sampling with tandem atmospheric hi-vol samplers



Laboratory simulation of creep

Engine:
"Traditional" diesel Zetor 1505
turbocharged, 4.16 liter, 90 kW
inline mechanical injection pump
0.10-0.15 g/kWh PM
(EU Stage IIIA Non-Road Engine)
no aftertreatment

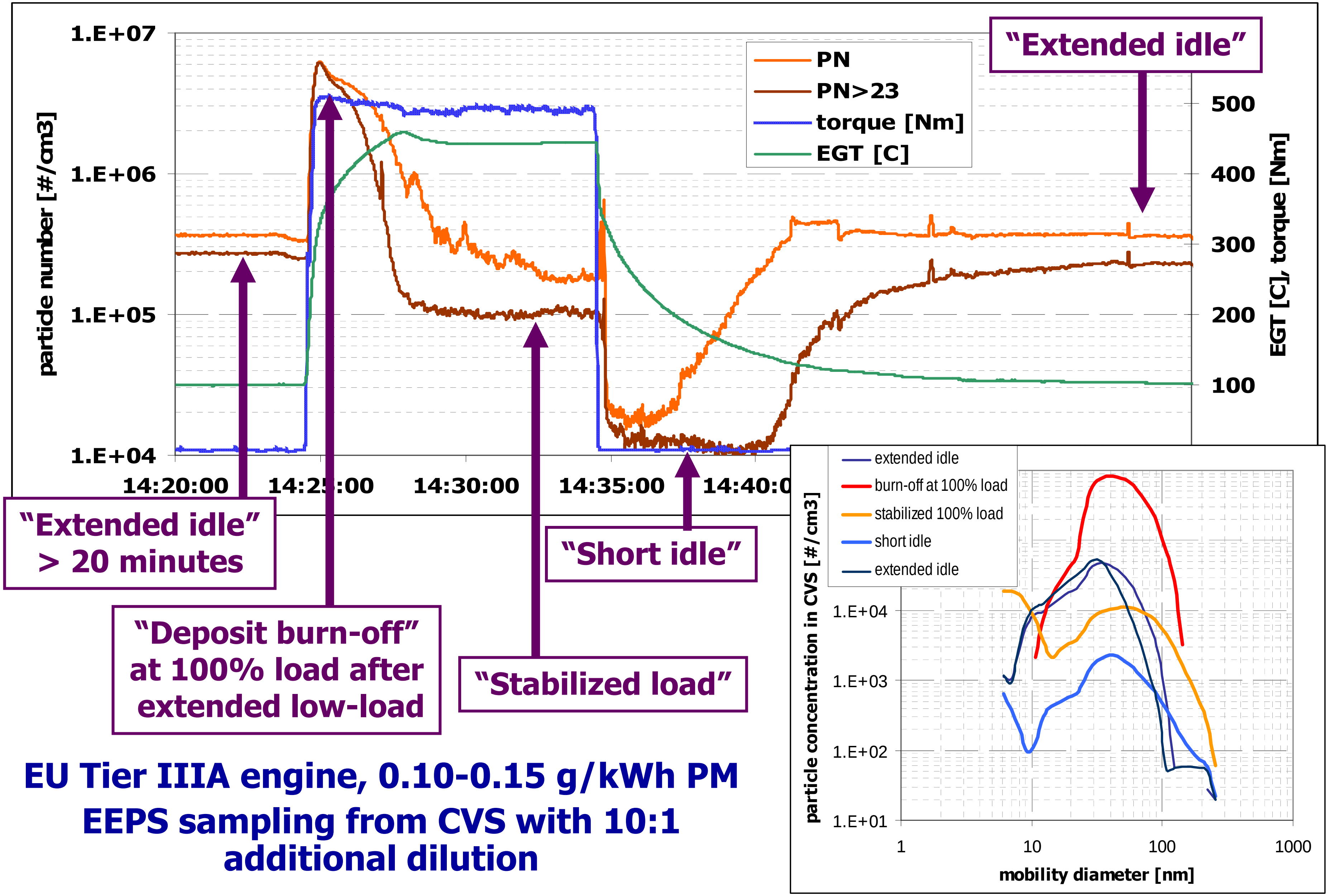


PTFE filters (TX40HI20WW, Pall)
16 US EPA priority PAH, toxicology
Quartz filters (QMA, Whatman)
EC/OC analysis, 16 US EPA PAH

PAH: Organic extraction, fractionation,
HPLC separation, fluorescence detection

On-road diesel fuel (EN 590)
30% and 100% biodiesel (FAME)
Plant-oil-ester-based lubricating oil
(Plantomot, Fuchs Oil)

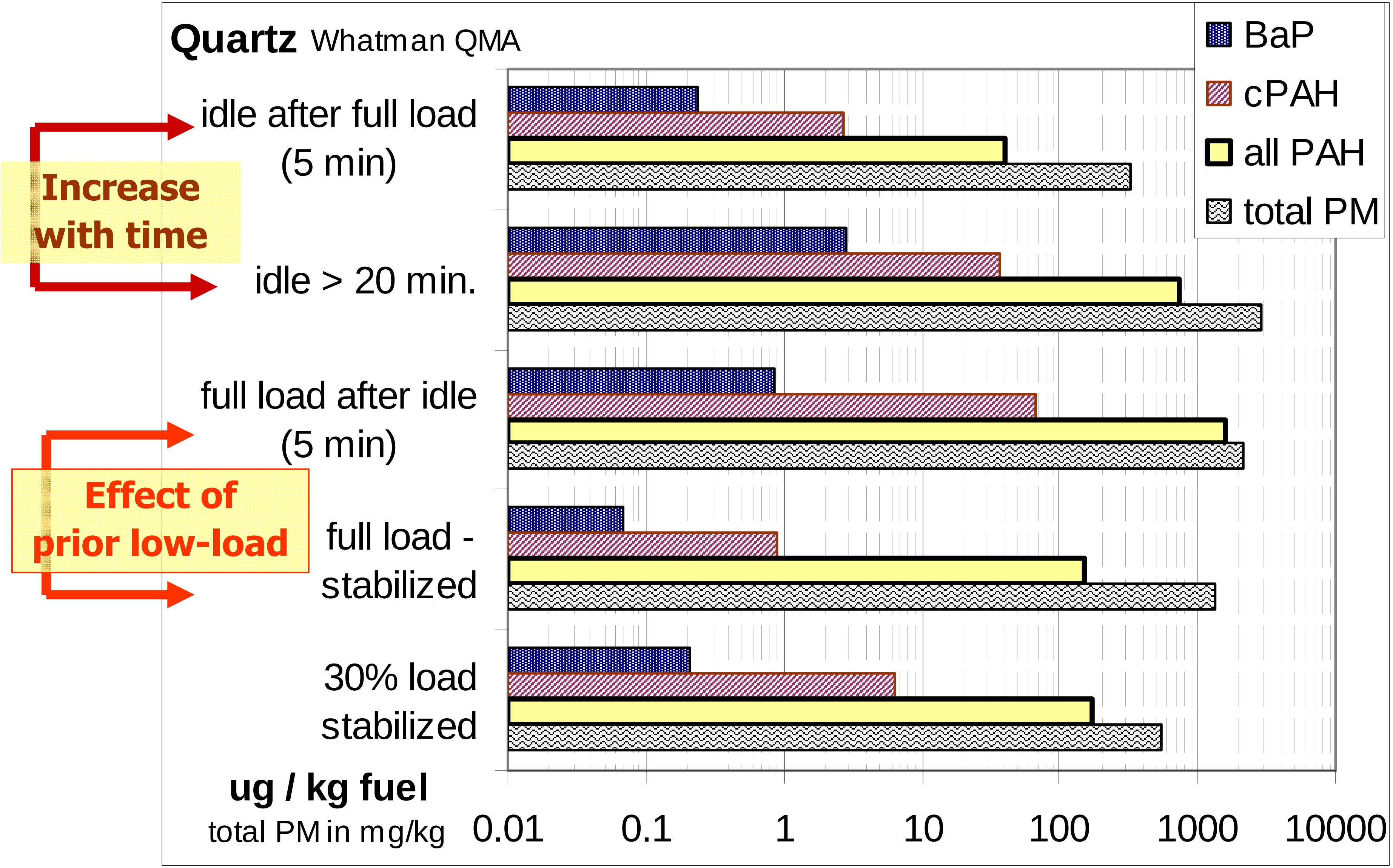
Laboratory simulation of creep



EU Tier IIIA engine, 0.10-0.15 g/kWh PM
EEPS sampling from CVS with 10:1 additional dilution

Results – diesel fuel – logarithmic scale

An order of magnitude increase during + after extended low-load of emissions of BaP, carcinogenic PAH, all PAH, PM mass



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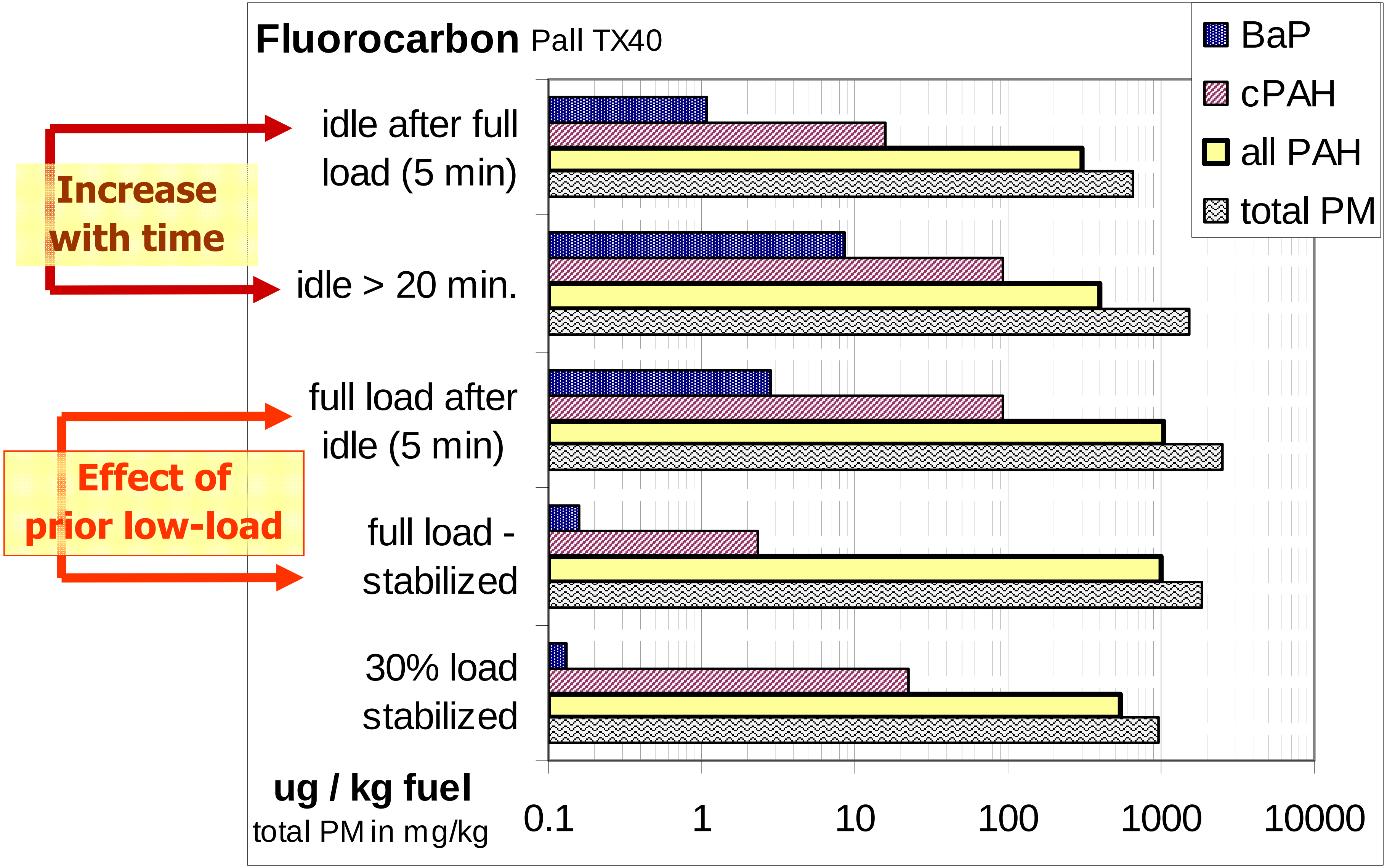

Results – biodiesel (B100, FAME) – logarithmic scale

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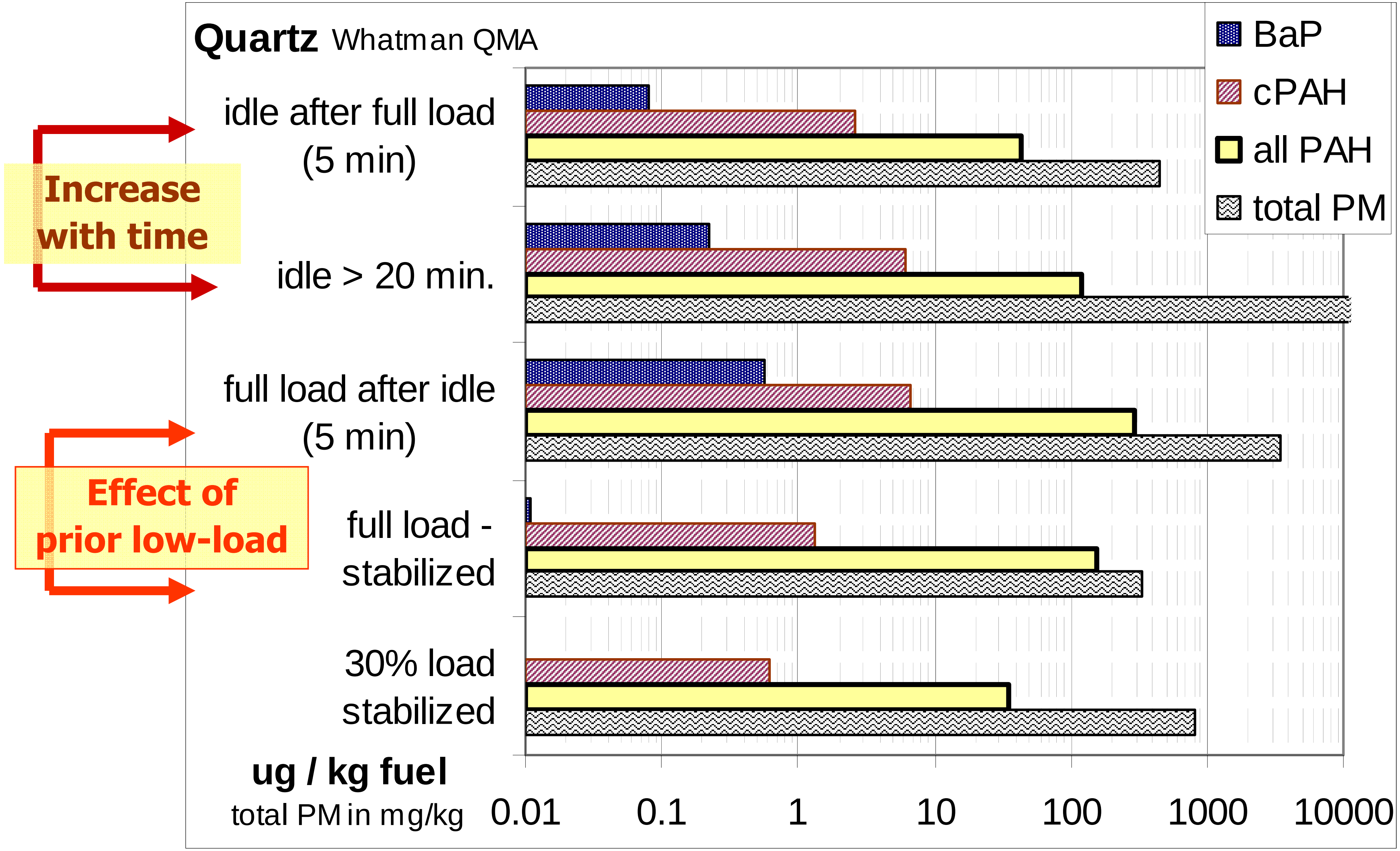

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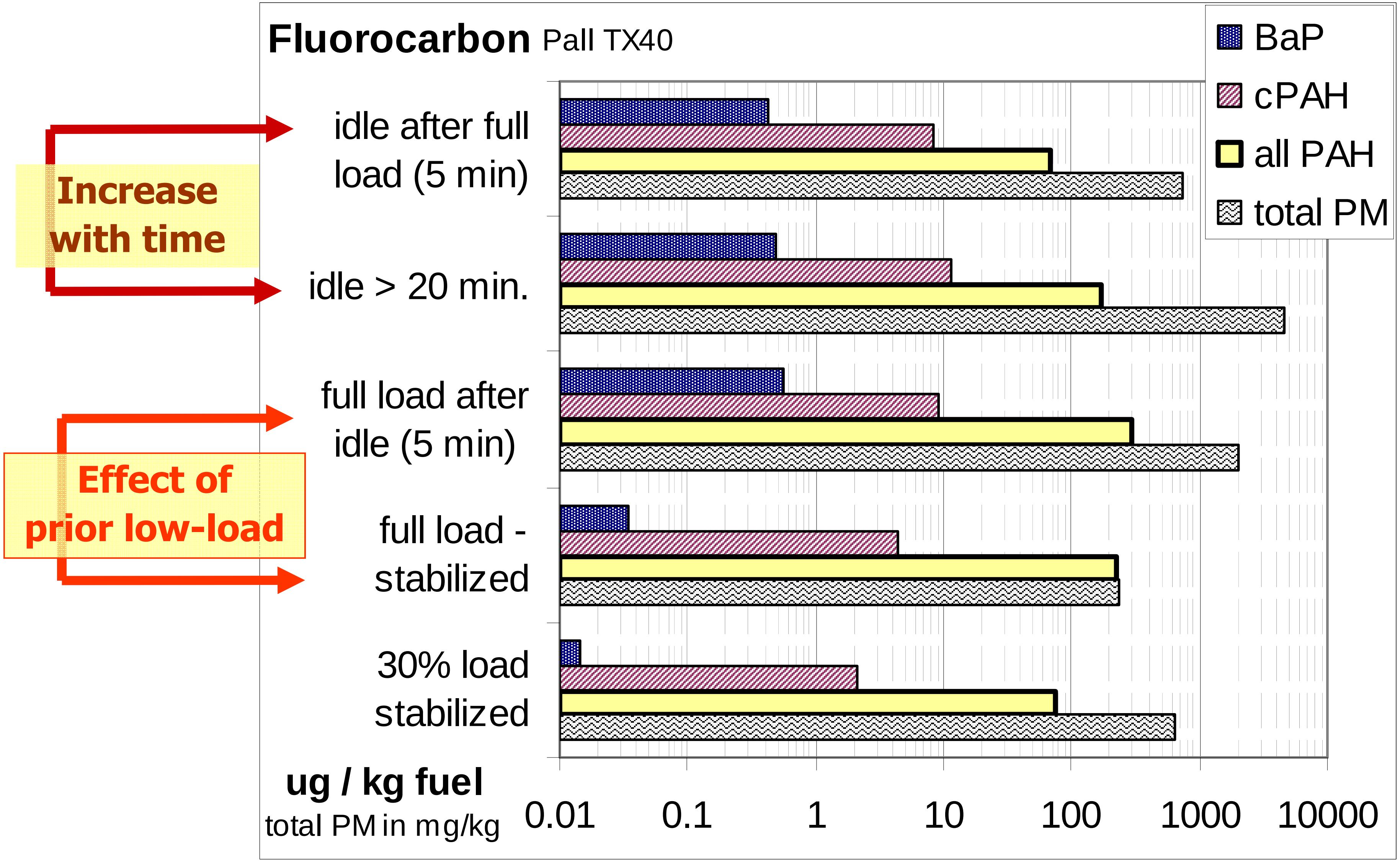


Biodiesel vs. diesel fuel (PTFE filters)

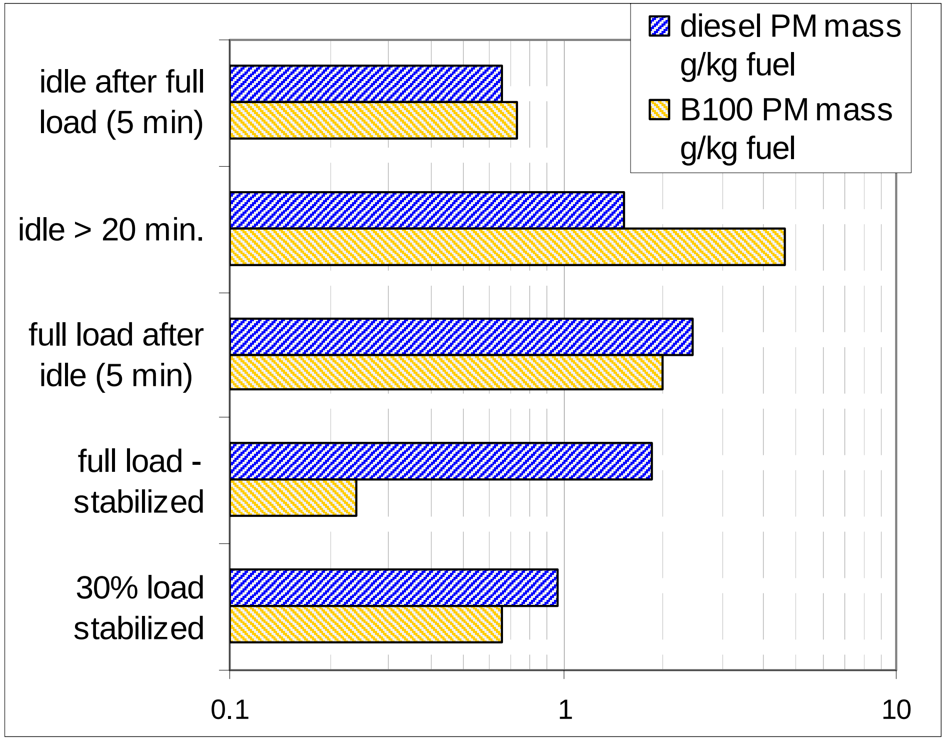
PM mass higher at idle, lower at 30% and 100% load

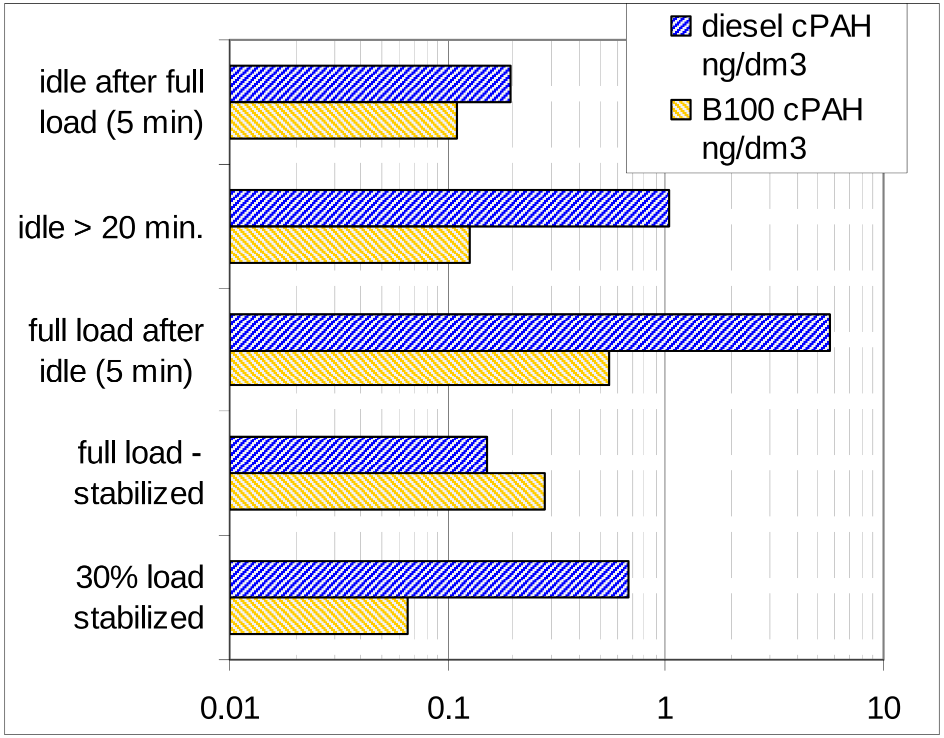
Carcinogenic PAH (sum of US EPA 7-PAH) higher at stabilized full load, otherwise always lower

Effect of extended low load:

PM mass: higher effect of biodiesel than on diesel fuel

cPAH: lower effect on biodiesel than on diesel fuel





Conclusions

The emissions of a non-DPF diesel engine under severe congestion simulated in a laboratory to accumulate enough PM for toxicological assays.

A pair of high-volume atmospheric samplers was used for dilution and sampling of the exhaust, allowing tens of mg of sample to be collected.

The emissions of PM mass, carcinogenic PAH (cPAH), US EPA 16 priority PAH and benzo(a)pyrene were an order of magnitude higher

a) during extended operation at 2% load, as compared to operation at 2% load immediately after higher load

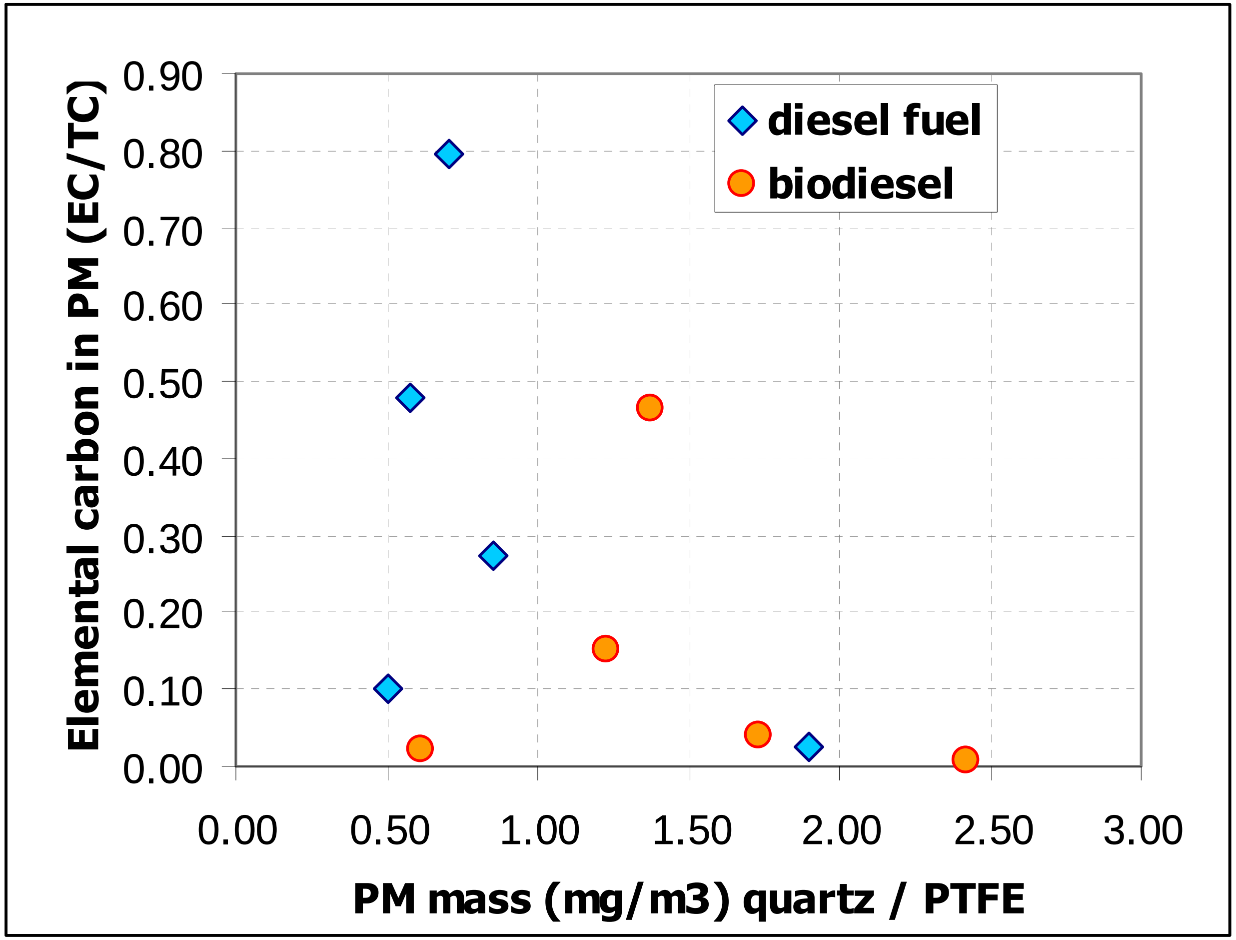
b) during operation at 100% load immediately after extended low-load operation, as compared to stabilized operation at 100% load

on both diesel fuel and neat biodiesel; the effects for biodiesel, relative to diesel fuel, were higher for PM mass, but lower for cPAH. Biodiesel had lower cPAH except for stabilized full load.

Quartz vs. PTFE filters

Quartz filters

- **higher propensity for retention of gaseous OC**
- **lower sampling efficiency until sufficient „particle cake“ accumulated**



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MEDETOX

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EU LIFE+ program (LIFE10 ENV/CZ/651), 2011-2016

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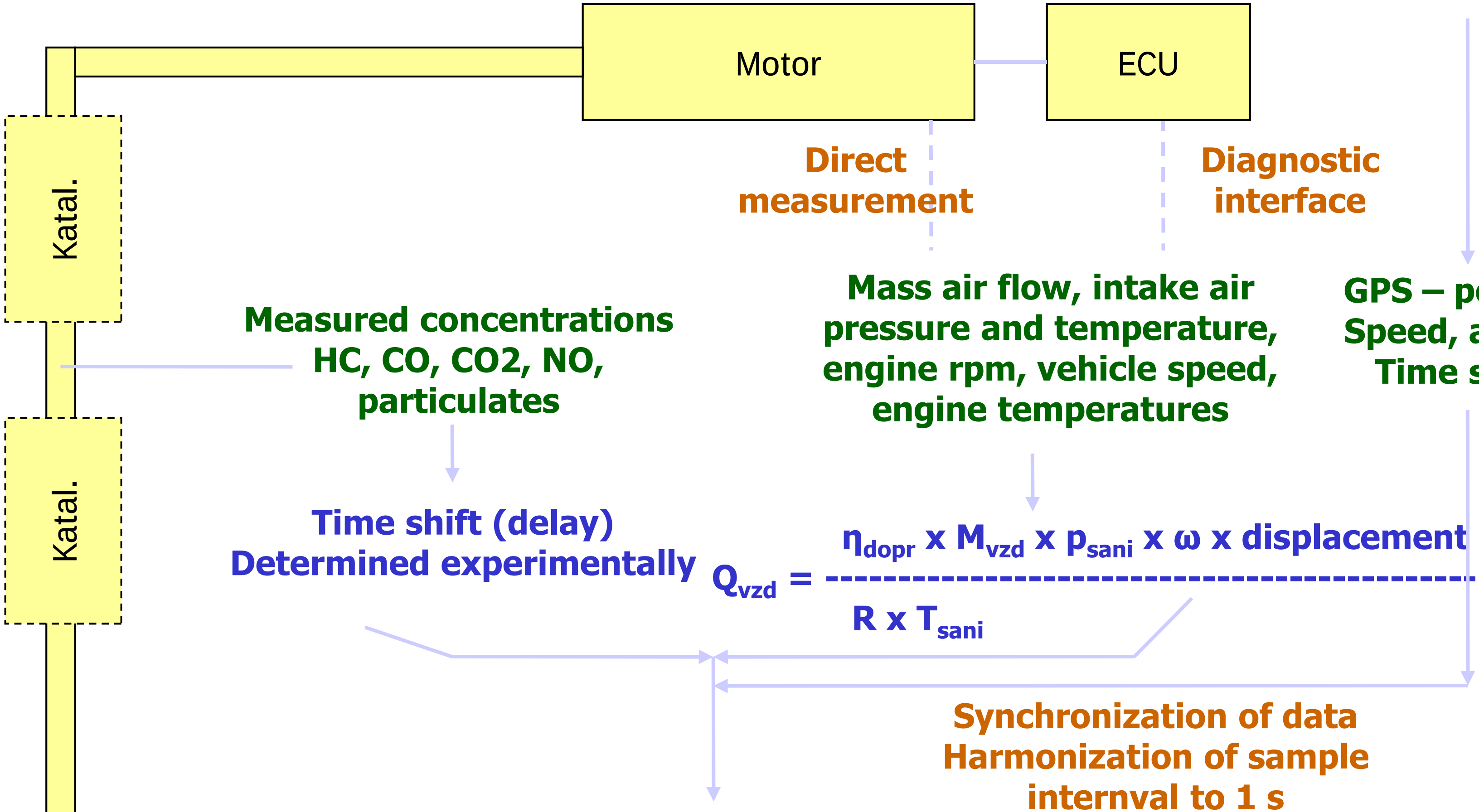
PEMS – Portable emissions monitoring system
-> PETS – Portable exhaust toxicity assessment system

Czech Science Foundation – BIOTOX project (13-01438S)
Mechanisms of toxicity of biofuel particulate emissions

Monitoring system functional diagram



1. Exhaust gas flow calculations
2. Mass emissions = const. x concentration x exhaust flow
3. Fuel consumption = C emissions (PM, HC, CO, CO2) / C in fuel

Integrating: Emissions per test, distance, kg of fuel

Data recording

Assessment of congestion and “creep” on the road

EURO 5 – DOC, DPF (particle filter), no SCR
2012 Iveco Daily, 3.0-liter Iveco engine

Emissions of particulate matter very low even during 1-hour idle and generally well below 1 mg/m3