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Consideration of congested urban traffic in exhaust toxicity assessment

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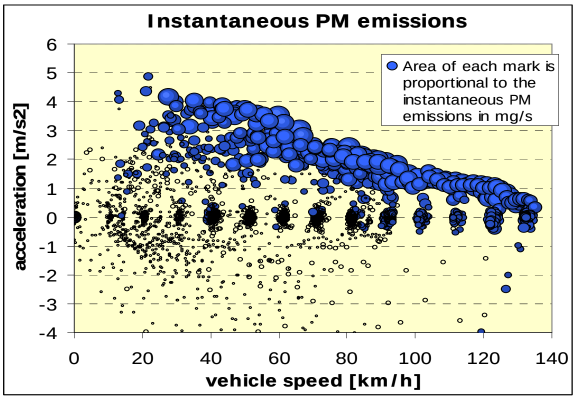
Internal combustion engines, the prime mover of majority of road vehicles and various mobile machinery, are also major source of harmful nanoparticles in urban areas. Due to doubts whether reductions in the limits imposed on total particle mass emissions yielded a corresponding reduction in the damage to public health, and the enormous complexity of the mechanisms causing health damage, a trend has evolved of assessing the health damage potential of engine exhaust through various biological and toxicological assays. Such tests are typically carried on jointly by engine emissions and biological/toxicological laboratories.

This paper presents an argument for focusing on realistic urban operating conditions when evaluating the effects of internal combustion engine exhaust on human health.

This argument is based on the coincidence of three unfavorable factors in congested urban areas: (1) Technical challenges arising from highly variable, low average load engine operating conditions, (2) high density of engines, and (3) high density of population in the immediate vicinity of vehicle travel paths. The first argument is elaborated on in this work.

In the European Union, the emissions of light duty vehicles are measured, for type approval purposes, on NEDC driving cycle. This cycle is composed of constant speed and constant acceleration (or deceleration) segments. With most contemporary vehicles, this cycle extends from idle to moderate engine rpm and from zero to moderate load, with relatively little transients. Realistic operation in urban areas tends to be, however, more transient, and many drivers venture, often intermittently, abruptly, and for short periods, into higher loads and higher engine rpm. With increasing congestion, the fraction of time spent at idle increases and is higher compared to NEDC.



Traditional European automobile spark ignition engines, that is, engines featuring port fuel injection, closed-loop air-fuel ratio control using exhaust gas oxygen sensors, and three-way catalysts, produce, during relatively steady conditions at moderate speeds and loads, and when in good working conditions, very little emissions. When such engines are overfueled (operated with excess fuel relative to stoichiometric conditions), the emissions of particles (and also hydrocarbons and carbon monoxide) increase sharply. Injection of excess fuel is programmed into some engines deliberately to ensure adequate driveability during strong transients and to protect the three-way catalyst by lowering exhaust gas temperatures at high loads and at high engine rpm. As an example, the dependency of instantaneous PM emissions on vehicle speed and acceleration is plotted in Fig. 1 for a typical gasoline car (Skoda Fabia, Euro 3).

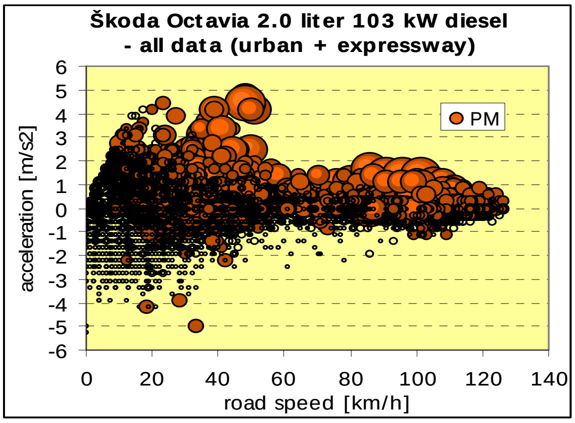


Fig. 1: PM emissions of a typical gasoline car as a function of vehicle speed and acceleration.

Traditional European automobile compression ignition (diesel) engines use advanced features (such as combustion chamber geometry or high pressure multi-stage fuel injection), exhaust gas recirculation (EGR), and oxidation catalyst to maintain relatively low emission levels at moderate rpm and loads. At high loads, EGR is typically disabled to increase air flow into the engine, and the demand for additional torque is satisfied by increasing the fueling rate, until the quantity of particles, which beyond some point rises sharply, reaches some acceptable limit. On vehicles with closed-wall particle filters, the particles are retained by the filter, and the acceptable limit is given by technical concerns about the ability of the filter to regenerate. On vehicles without closed particle filters, given that full load operation is nearly always well outside of the NEDC, the “acceptable limit” is a subject to relatively open interpretation, which varies widely among manufacturers (and individuals who perform aftermarket recalibrations of engine control units to increase maximum engine torque).

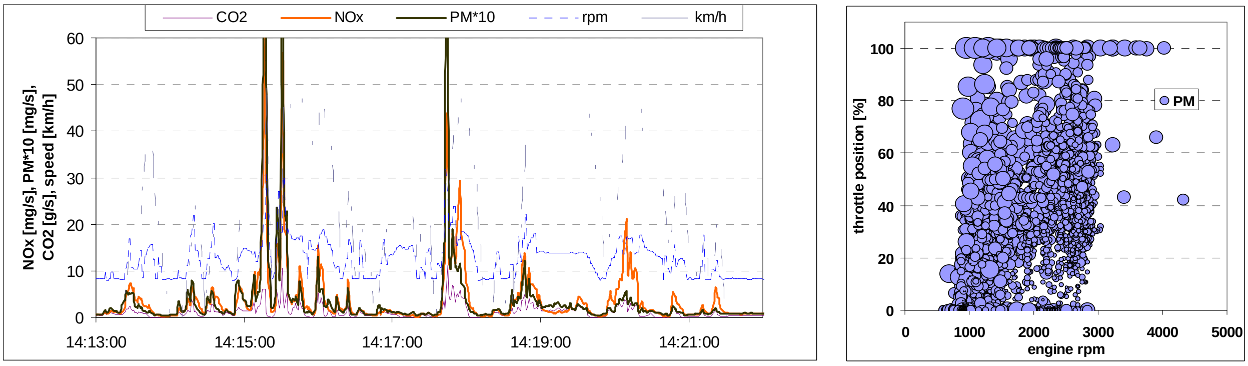


Figure 3: PM emissions from a Škoda Octavia diesel car were dominated by short spikes primarily during accelerations from low speed. Example of time traces is on the left, with "steady" driving at 50 km/h around 14:19. On the right, PM concentrations in the exhaust are plotted as a function of engine speed and throttle position (surrogate for engine load).

Utilization of turbochargers in automobile engines has increased the maximum torque at moderate and high engine speeds, resulting in smaller displacement and/or higher performance. We have observed that many accelerations out of intersections commence, however, at close to idle rpm. Given the relative scarcity of torque at low rpm, the acceleration typically occurs at high relative load. A conservatively calibrated engine limits the fueling rate, at the expense of slower takeoff. An engine calibrated for performance (“pleasure to drive“) offers an immediate response, at the expense of higher PM emissions. PM emissions from a typical Czech diesel car (Skoda Octavia) during urban driving are shown in Fig. 3 (left), where the peaks during accelerations from low speeds are visible. The concentrations of PM as a function of engine speed and throttle position (surrogate for torque) from another diesel Skoda Octavia car are given in Fig. 3 on the right.

Prolonged operation at idle or very low loads poses an emissions challenge for both automobile and heavy-duty diesel engines. The engines operate very lean, at high excess air ratios, and therefore low exhaust gas temperatures. The internal surfaces of the combustion chamber and exhaust system, including aftertreatment devices, cool down, resulting in, relative to moderate or higher loads, less complete combustion, decreased efficiency of catalytic aftertreatment devices, increased formation of secondary particulate matter within the exhaust system, and deposition of “organic carbon” (semi-volatile materials) in the exhaust system. As an example, fuel-specific NO_x and PM emissions from a Euro 5 over-the-road truck (DAF 1505 with a semi-trailer, 39 tons, Euro 5 engine with DOC and SCR) during operation on Prague perimeter road, (a freeway) are shown in Fig. 4. When travel speed (upper lline, right axis) decreases due to congestion, NO_x (middle line, red) and PM (bottom line, black) increase.

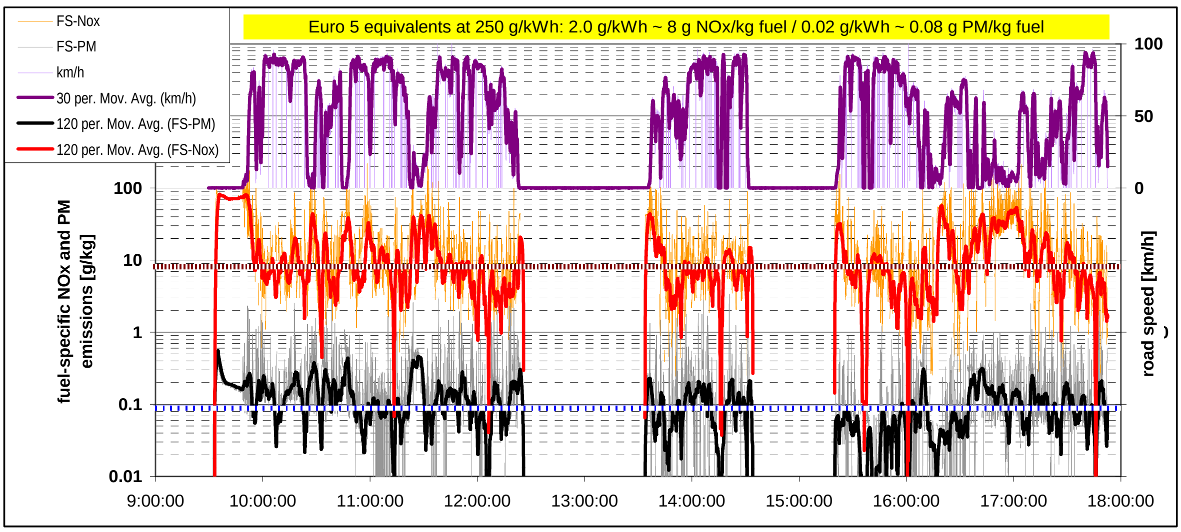


Figure 4: PM emissions from a DAF Euro 5 truck with a trailer (39 tons total weight) during operation on Prague perimeter road. NOx (middle line, red) and PM (bottom line, black) emissions per kg of fuel increase (note the logarithmic scale) when travel speed (upper line, violet, right axis) decreases due to congestion.

The problem of extended idle extends to subsequent operation, during which catalytic devices operate at reduced (or zero) efficiency until their working temperature is increased, and during which matter deposited in the exhaust system undergoes gradual removal through a combination of physical forcing, evaporation, thermal chemical transition (pyrolysis or oxidation) to gaseous form, and (not necessarily complete) combustion.

The effects of the deposits and their transformations on exhaust toxicity are yet to be fully understood, especially for emerging fuels. Removal of a puddle of fuel in an exhaust system by the flow of hot exhaust gas may be a sufficiently different process from the combustion of homogeneous mixture or finely atomized fuel to warrant such investigation. For example, non-esterified vegetable oils are known for poor combustion at idle due to their high viscosity and high boiling point (many transtition into gas phase through chemical reaction before reaching the boiling point), resulting in liquid matter deposited in the exhaust system at idle. These deposits are then driven off at higher loads in the form of white smoke with characteristic odor.

Closed particle filters seem to retain their efficiency at idle and low loads, and the extended idling problem shifts from excessive emissions to that of ensuring regeneration. However, filters can be viewed as a privilege of increasing number of countries or regions with progressive air quality policy, not a European norm, as a filter is not necessary to comply with the Euro 5 limits. For example, in Czech Republic, removal of particle filters on imported vehicles has been openly offered as a service, while in Poland, devices have been patented to emulate to the engine control unit a (removed or destroyed) particle filter.

It should be noted that the degree to which urban operating conditions affect vehicle emissions depends on the engine design and calibration, which are heavily affected by the emissions legislation applicable in the country in which the engine is sold. In the United States, excessive “off-cycle emissions” have been relatively successfully addressed by supplemental cycles (US06) for light-duty vehicles and not-to-exceed (NTE) limits for in-use emissions for heavy-duty vehicles.

It can be postulated that the question of “are we better off” (with a new emissions standard), often posed at previous ETH conferences, is likely to remain in the repertoire of the conference. Advanced engine designs tend to eliminate larger particles and elemental carbon, increasing the relative prevalence of nanoparticles and organic carbon. Both are significant from a toxicological view: nanoparticles have higher probability of deposition in the lung and can penetrate into the bloodstream, and organic carbon generally poses a higher risk than elemental carbon. The current particle number standards include only particles which are non-volatile and larger than 23 nm. Further, they are applicable only to standardized engine operating conditions. Very small, semi-volatile particles, emitted in congested city areas, are therefore likely to at least partially escape the current legislation.

The presented combination of factors suggests that a closer look at the relative toxicity of engine exhaust during typical low speed operation in congested urban areas is well warranted.

It is proposed here that the assessment of the toxicity of engine exhaust is not performed at “NEDC sweet spots” of relatively steady engine operation at intermediate rpm and load, nor at conditions representative of average operation of vehicles, but in conditions representative of realistic operation in densely populated areas, perhaps with a focus on less favorable operating conditions.

Not only such operating conditions can be viewed, in many cases, as the worst-case emissions, but also, in many cases, such conditions can be viewed as being the most representative of the exposure, with exposure measured as a combination of traffic intensity (source density) and population density (receptor density).

Measurement and sampling of exhaust during realistic urban operation, and subsequent toxicity assessments, will be the focus of the recently started European project LIFE10 ENV/CZ/651 – MEDETOX, Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic. This is a Czech national project of the Institute of Experimental Medicine of the Czech Academy of Sciences (toxicology partner, coordinator of the project), Technical University of Liberec (engine testing partner) and the Ministry of Environment of the Czech Republic (national regulatory body). This project has evolved out of a national contribution to a larger international effort to bring together engine emissions and toxicity experts and to discuss and harmonize the methodology for the assessment of the relative toxicological potential of emerging engine and aftertreatment technologies and emerging fuels.

This work was sponsored by the EU LIFE+ programme, LIFE10 ENV/CZ/651 – MEDETOX, Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic. Data shown here were collected by the author using a portable on-board emissions monitoring system.

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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 – focus of this work

Test conditions – NEDC driving cycle, moderate accelerations & loads

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
  - <u>most of these are outside of the current driving cycles</u>
  - <u>most of these are common in congested urban areas</u>

Coindicence of problems in dense / congested urban areas

High concentration of vehicles

-> high ambient concentrations

High population density

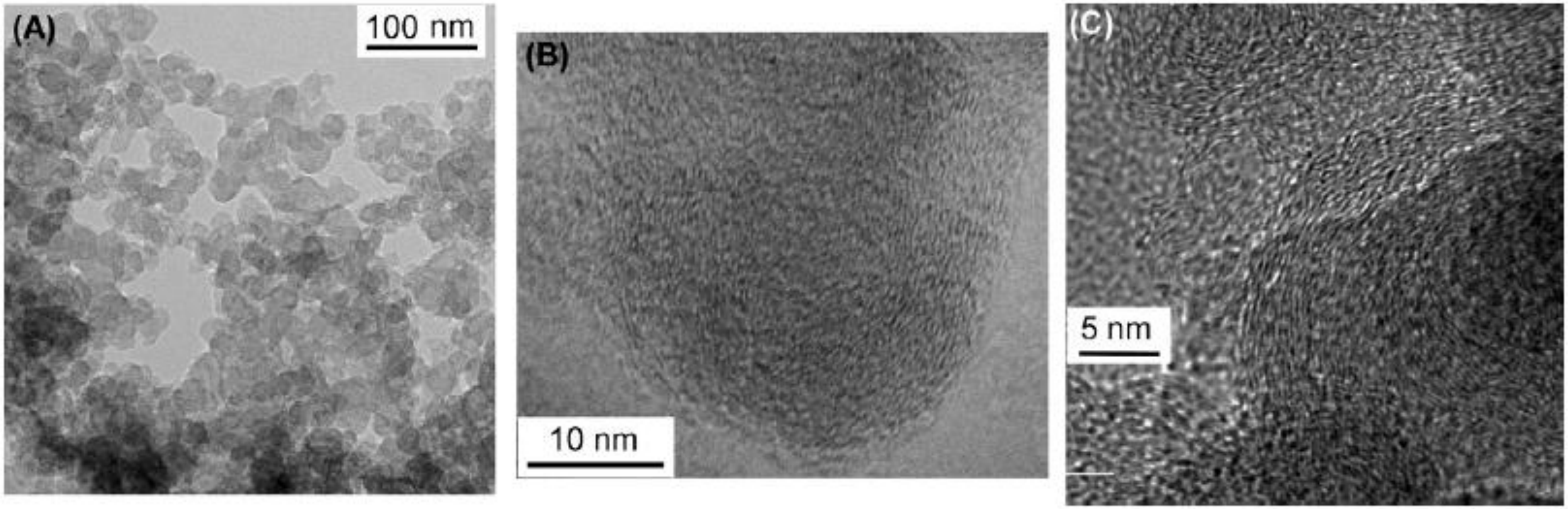
-> high number of people exposed

High frequency of problematic operating modes

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

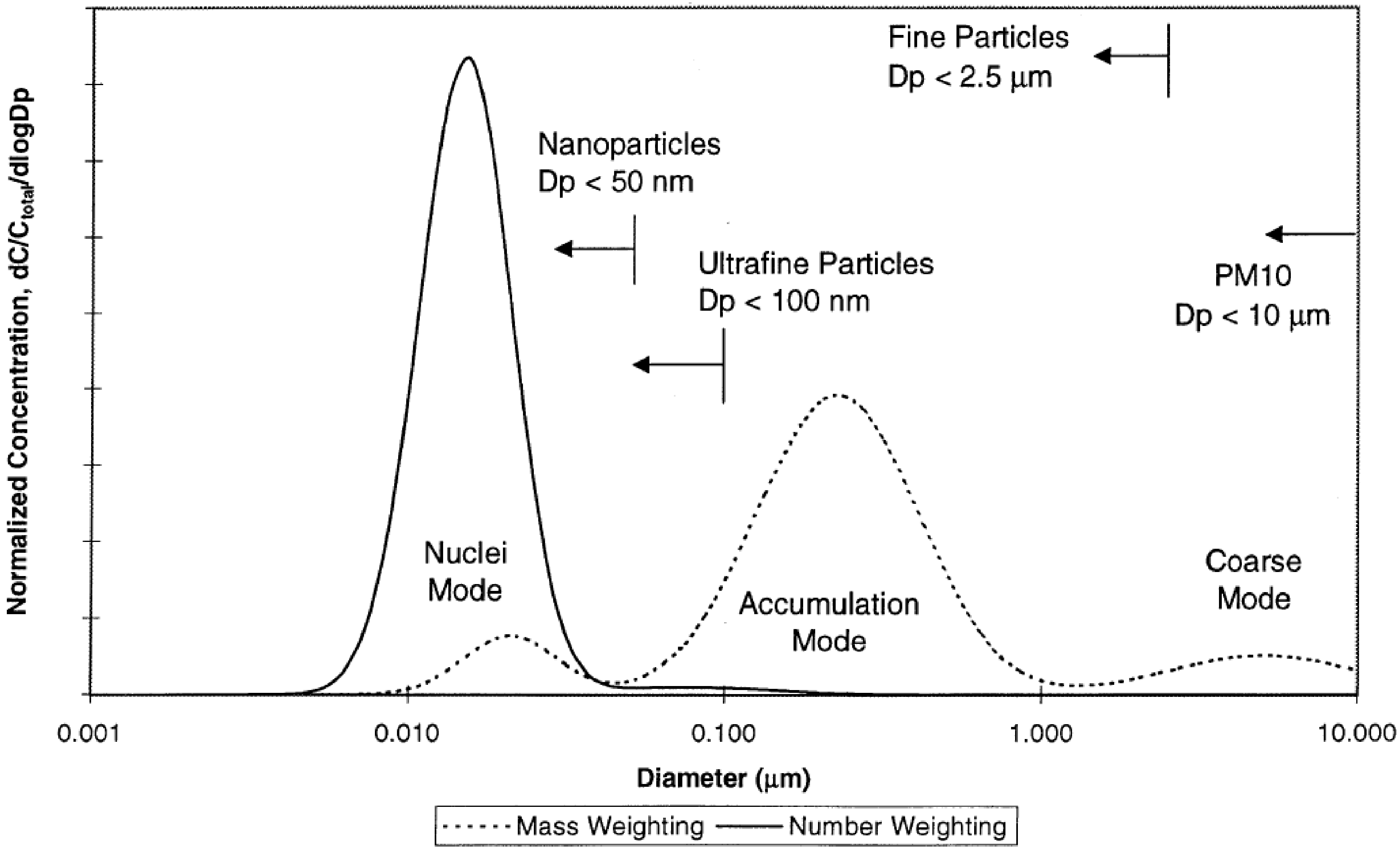
-> higher and/or more hazardous emissions

Diesel exhaust particulate matter



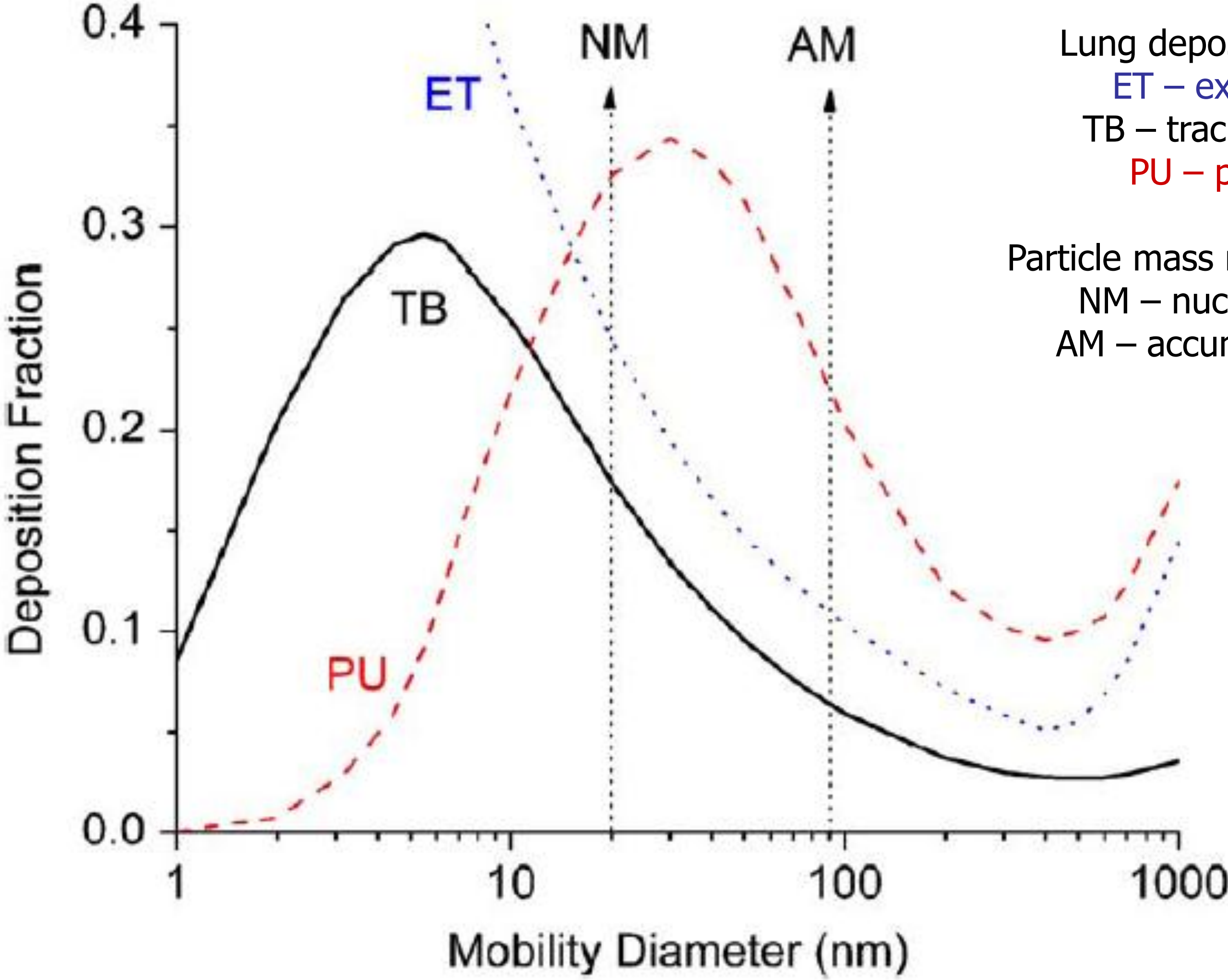
Liati A., Dimopoulos P.E., Combustion and Flame 157 (2010) 1658–1670.

Typical diesel exhaust PM size distribution



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

Lung particle capture efficiency



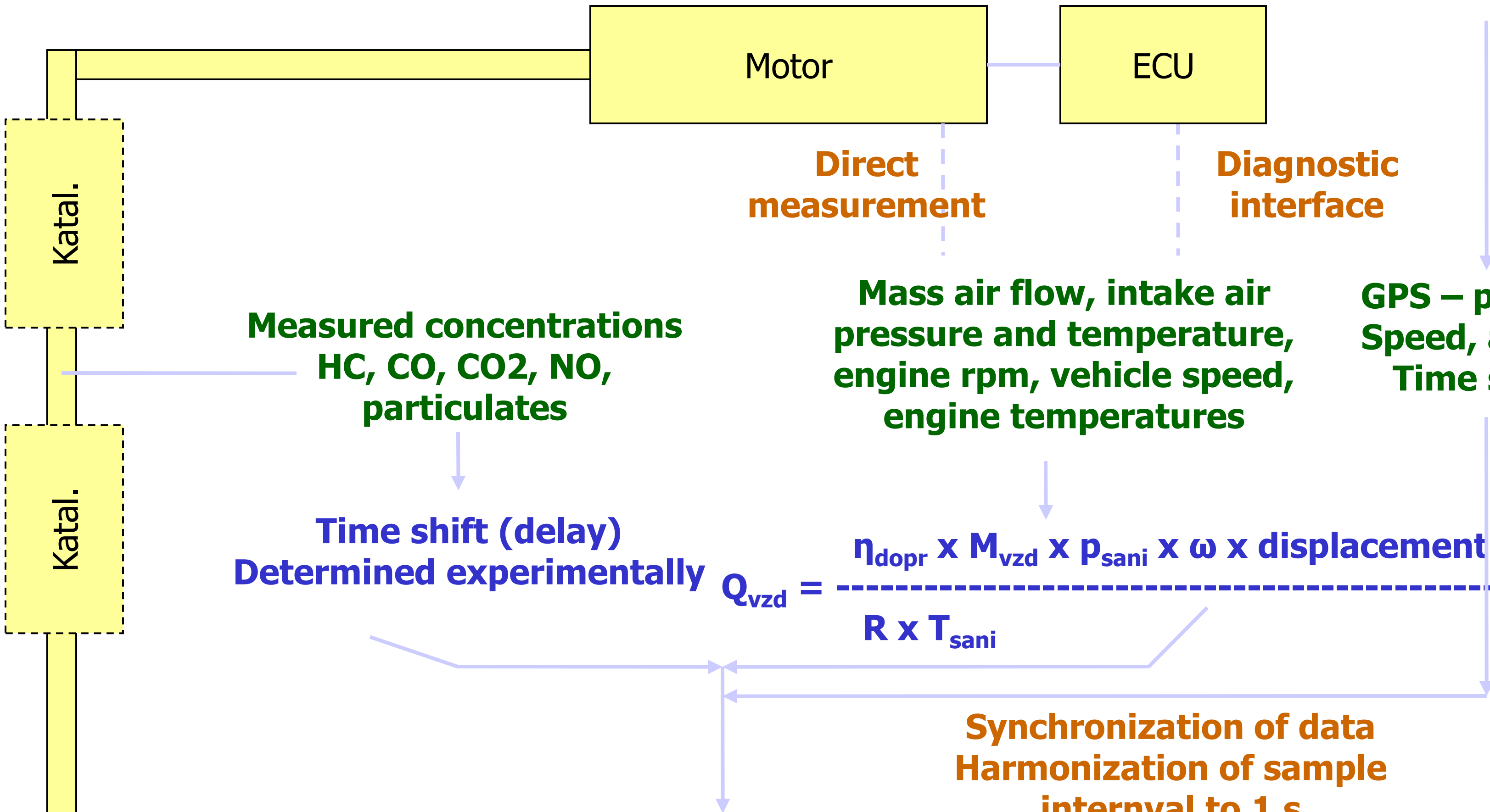
Lung deposition fraction:
ET – extrathoracic
TB – tracheobronchial
PU – pulmonary

Particle mass median diameter:
NM – nucleation mode
AM – accumulation mode

B. Alfoldy et al., Aerosol Science 40 (2009) 652—663.

Examples shown here measured with on-board monitoring system

Monitoring system functional diagram



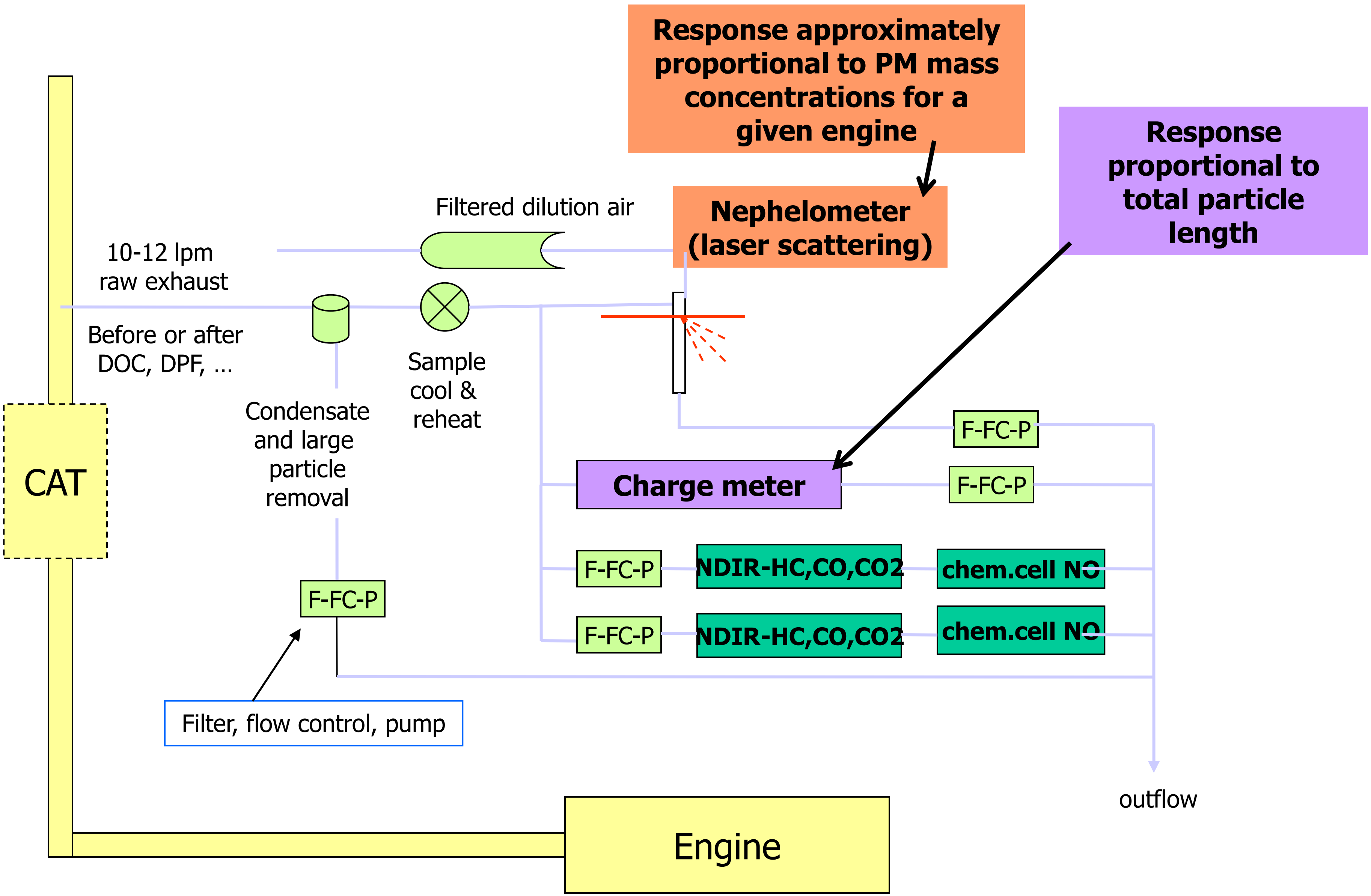
1. Exhaust gas flow calculations
2. Mass emissions = const. x concentration x exhaust flow
3. Fuel consumption = C emissions (PM, HC, CO, CO2) / C in fuel

Integrating: Emissions per test, distance, kg of fuel

Data recording

Examples shown here measured with on-board monitoring system

Monitoring system analytical part



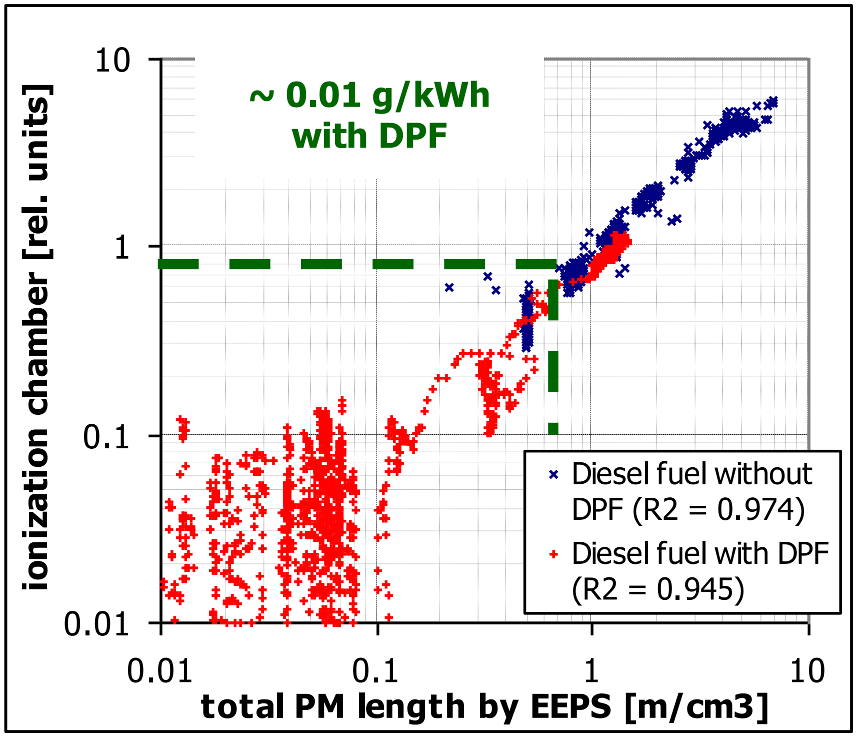
PEMS PM measurement comparison
– Zetor 1505 engine, steady-state tests, 2008-2010

Measuring ionization chamber - total particle length

[Vojtíšek, Journal of the Air & Waste Management Association, 61, 2011, 126-134]

comparison with electrostatic classifier

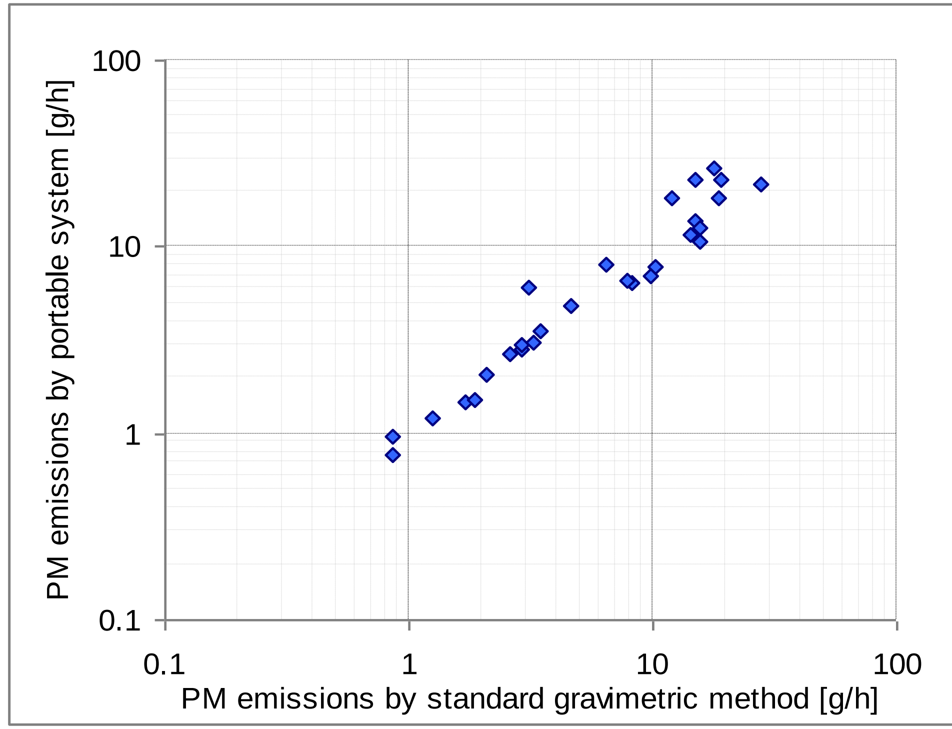
(Engine Exhaust Particulate Sizer, TSI, St. Paul, MN, USA)



Light scattering device (semi-condensating integrating nephelometer) – approximation of total particle mass

[Vojtíšek, Society of Automotive Engineers Technical Paper Series, 2001-01-3641 (2001) a 2009-24-0148 (2009)]

comparison with gravimetric measurement



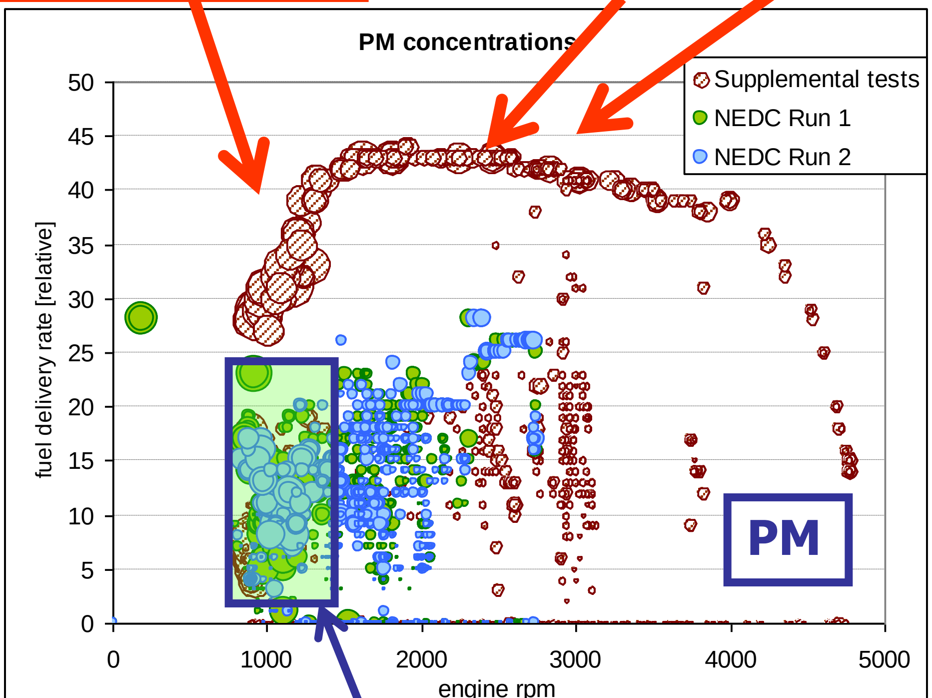
Challenges of EU automobile diesel engines
Euro 4 Skoda Fabia – chassis dynamometer runs
NEDC vs. full-power loaded accelerations

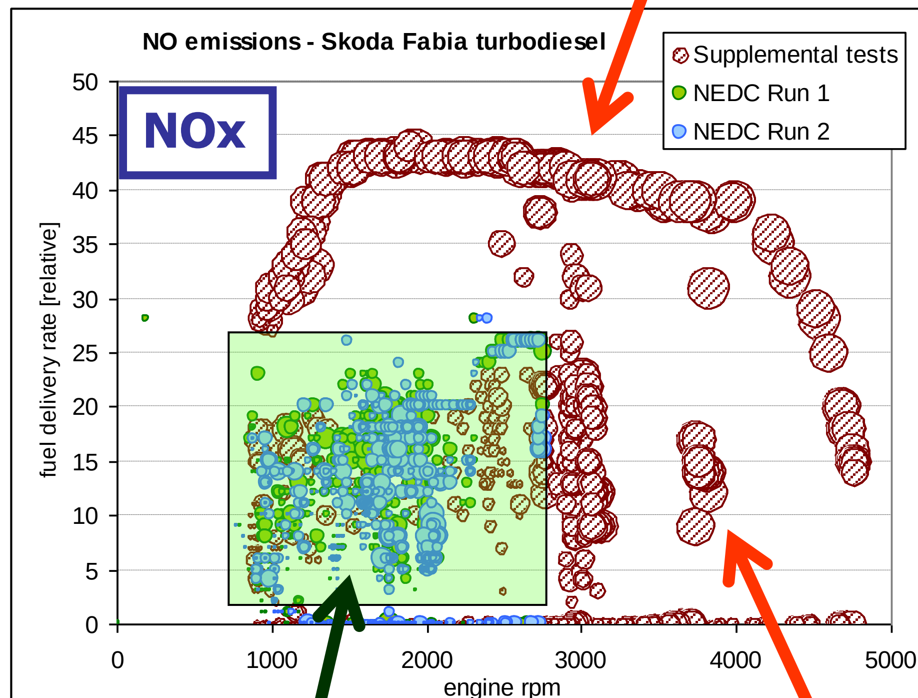
Problem compounded by downsizing & turbocharging: Relatively low torque at idle.

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



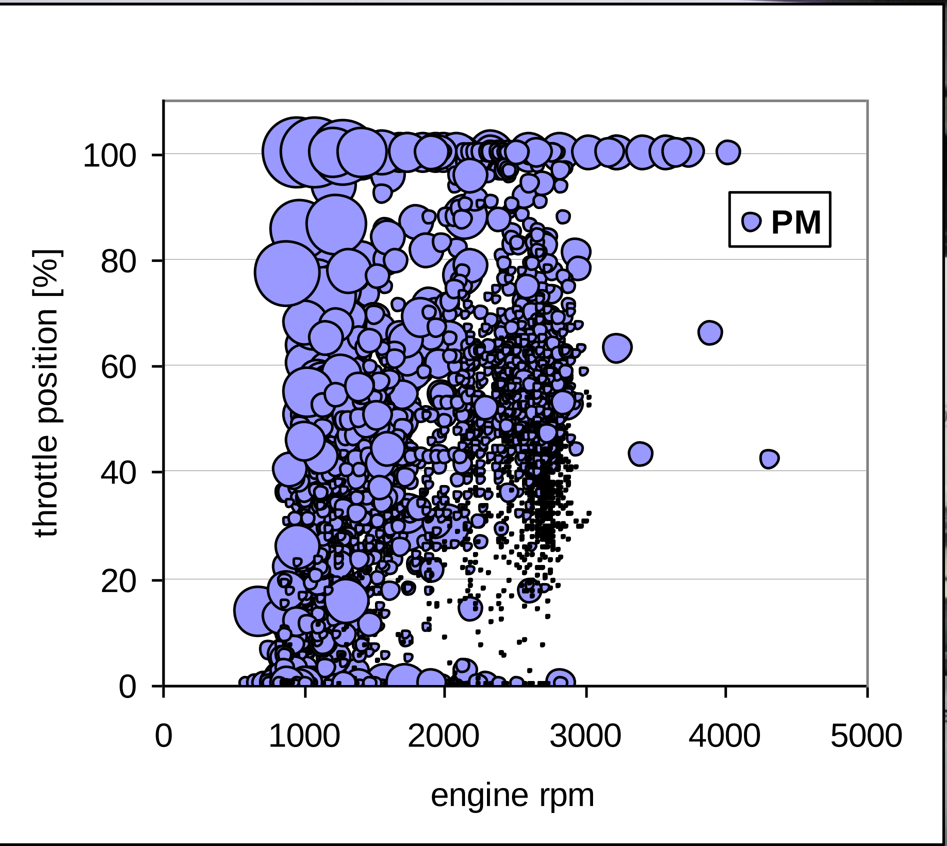


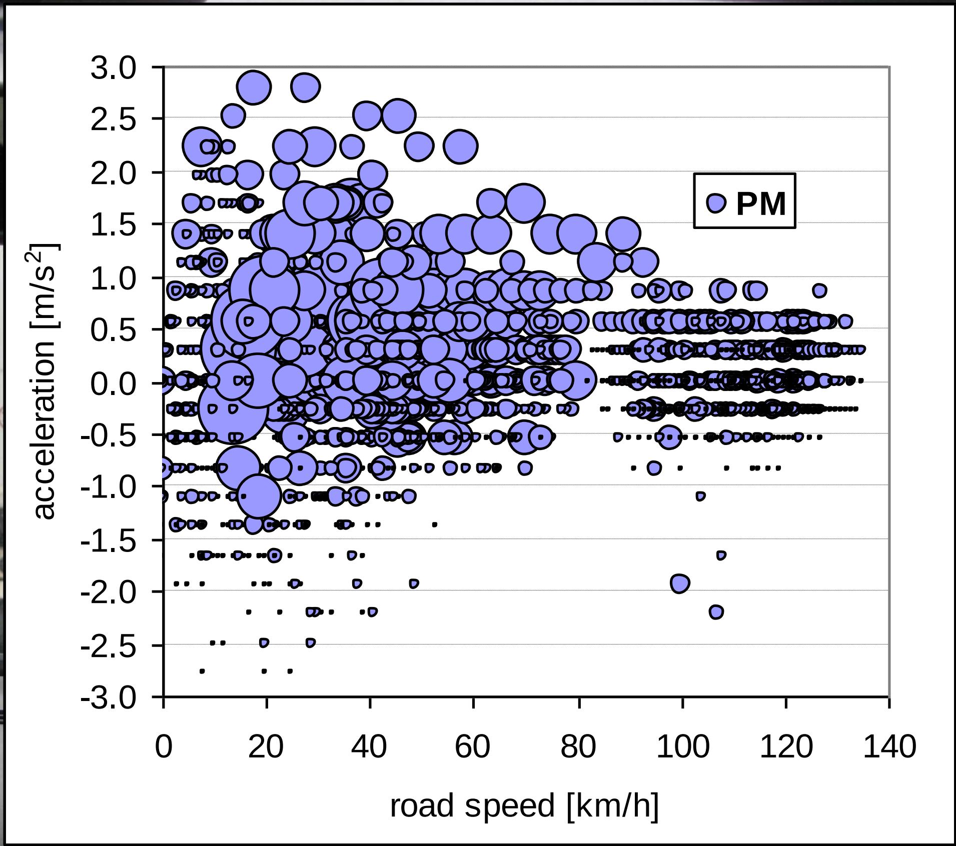
Long idle / low load: DOC cooldown, combustion deterioration, high fraction of OC in PM

NOx reduced by EGR

?

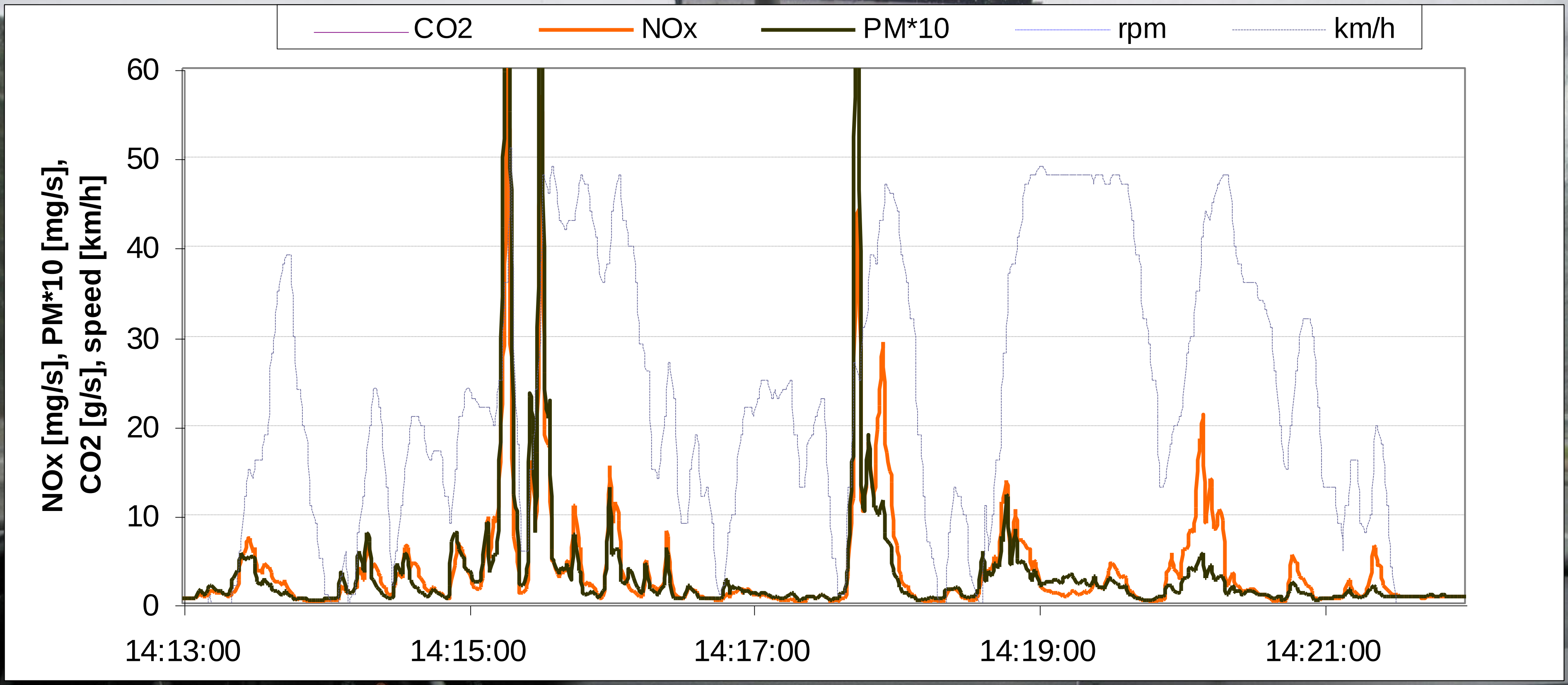
Euro 4 Skoda Octavia – real-world city driving tests





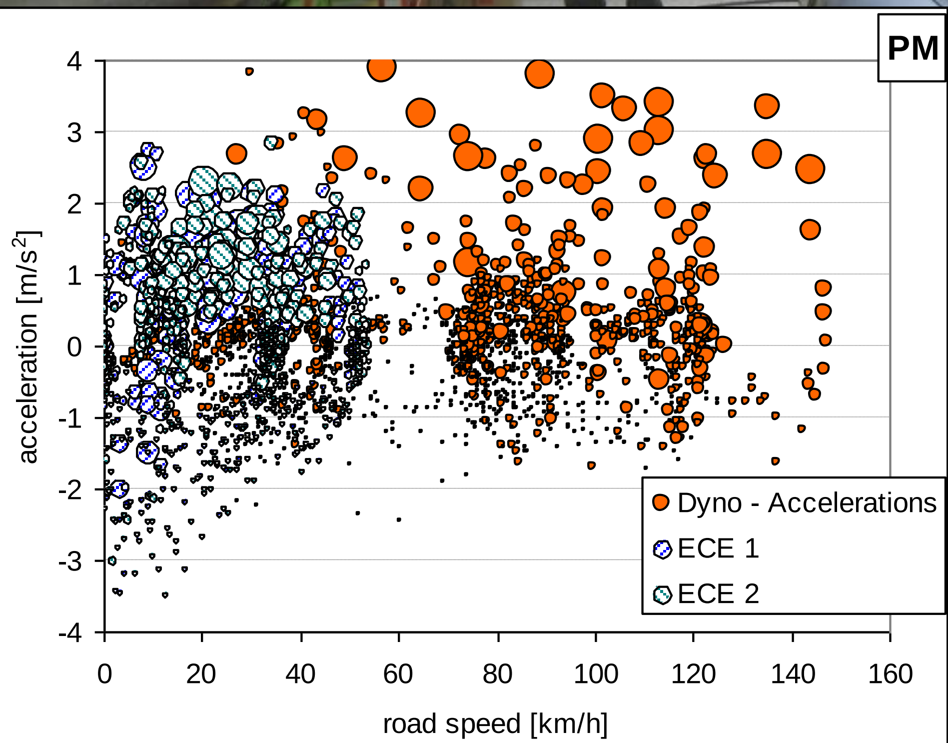
Source data: Vojtíšek-Lom et al., Society of Automotive Engineers Technical Paper 2009-24-0148

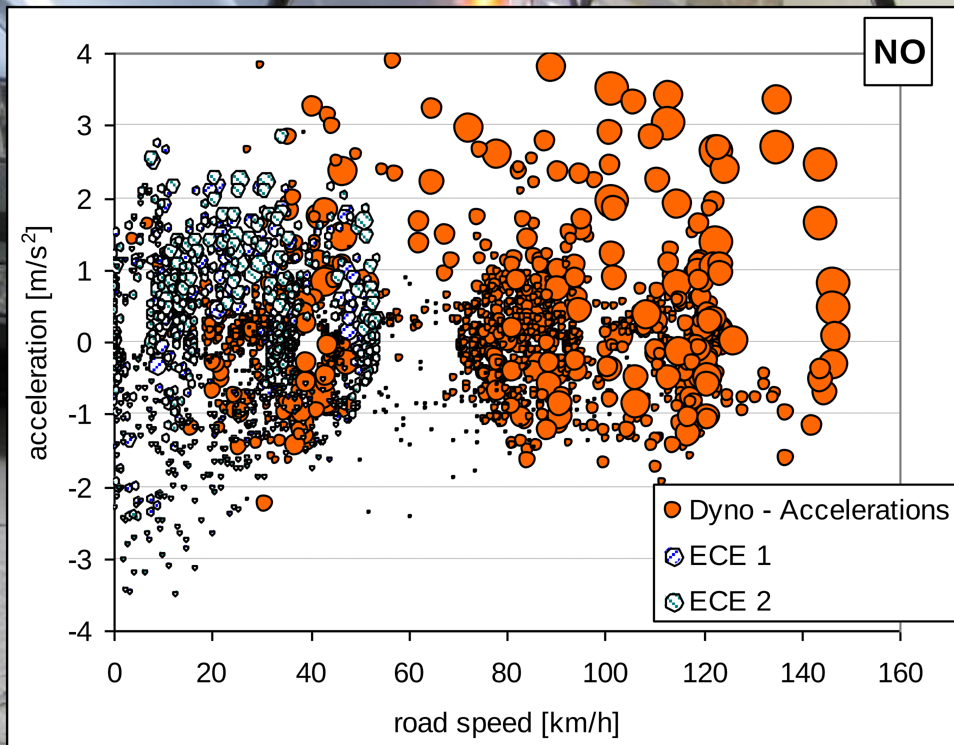
Euro 4 Skoda Octavia – real-world city driving tests



Measurement by the author.

Euro 4 Škoda Octavia – chassis dynamometer tests
ECE cycle +
full-load accelerations at speeds up to 190 km/h

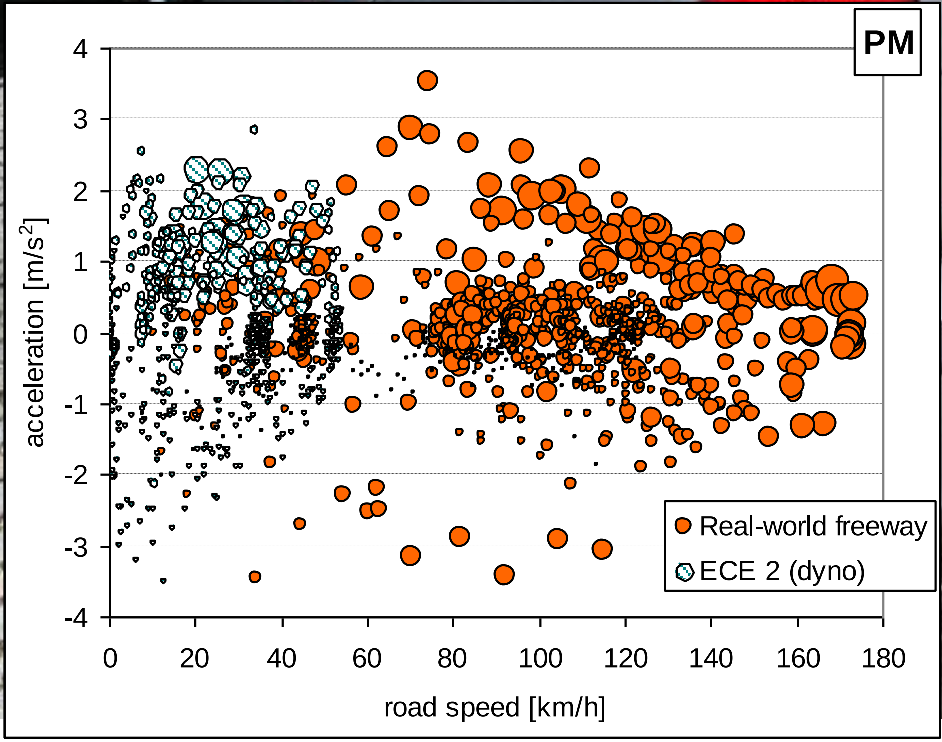


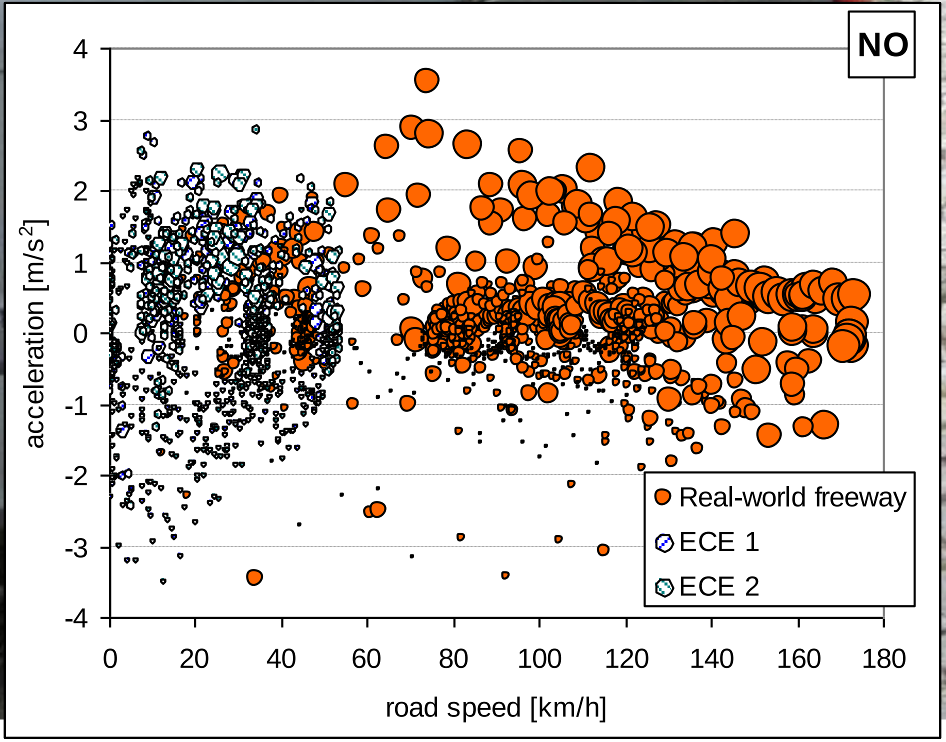


Vojtíšek-Lom et al., Society of Automotive Engineers Technical Paper 2009-24-0148

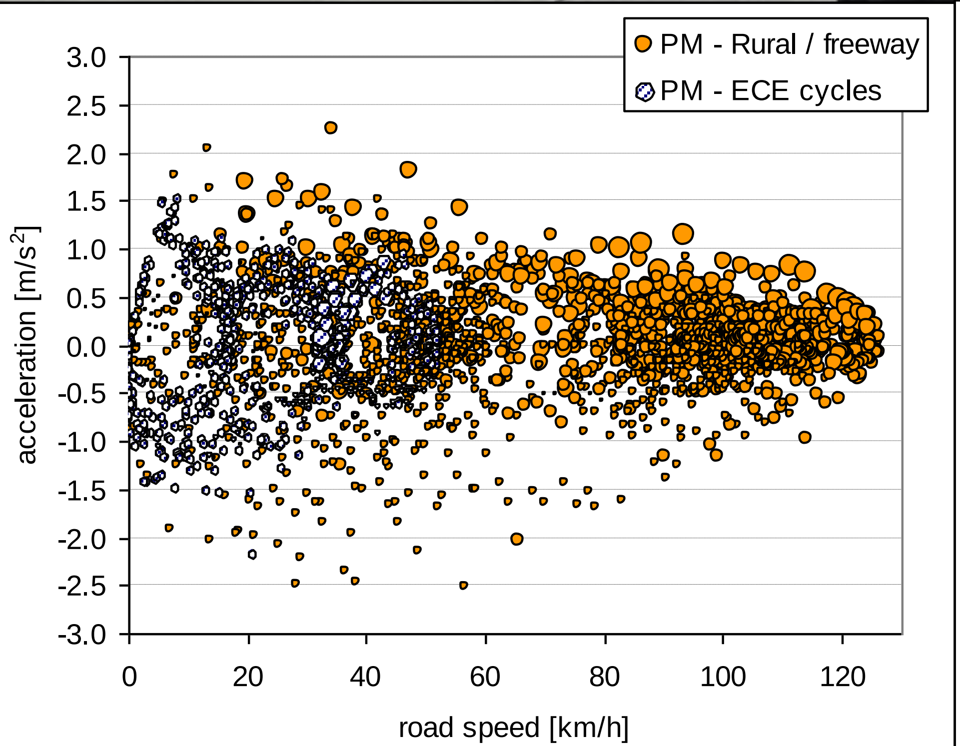
Euro 4 Škoda Octavia – high-speed freeway tests

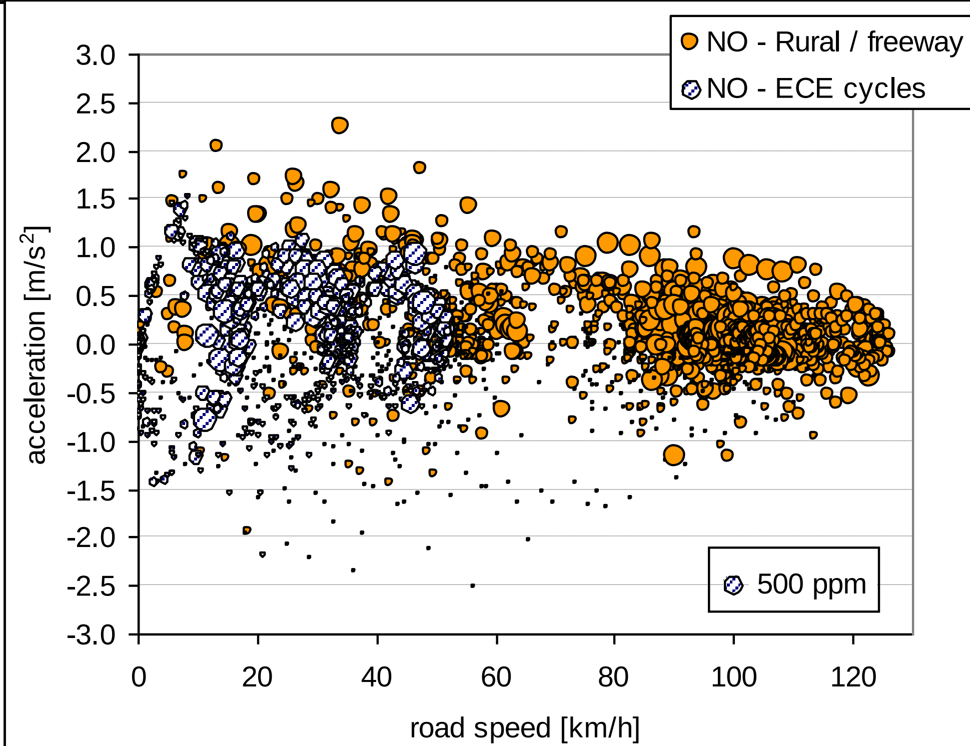
Aggressive, high-speed driving on a freeway, not atypical for Czech roads
Results contrasted with ECE cycle test on a chassis dynamometer



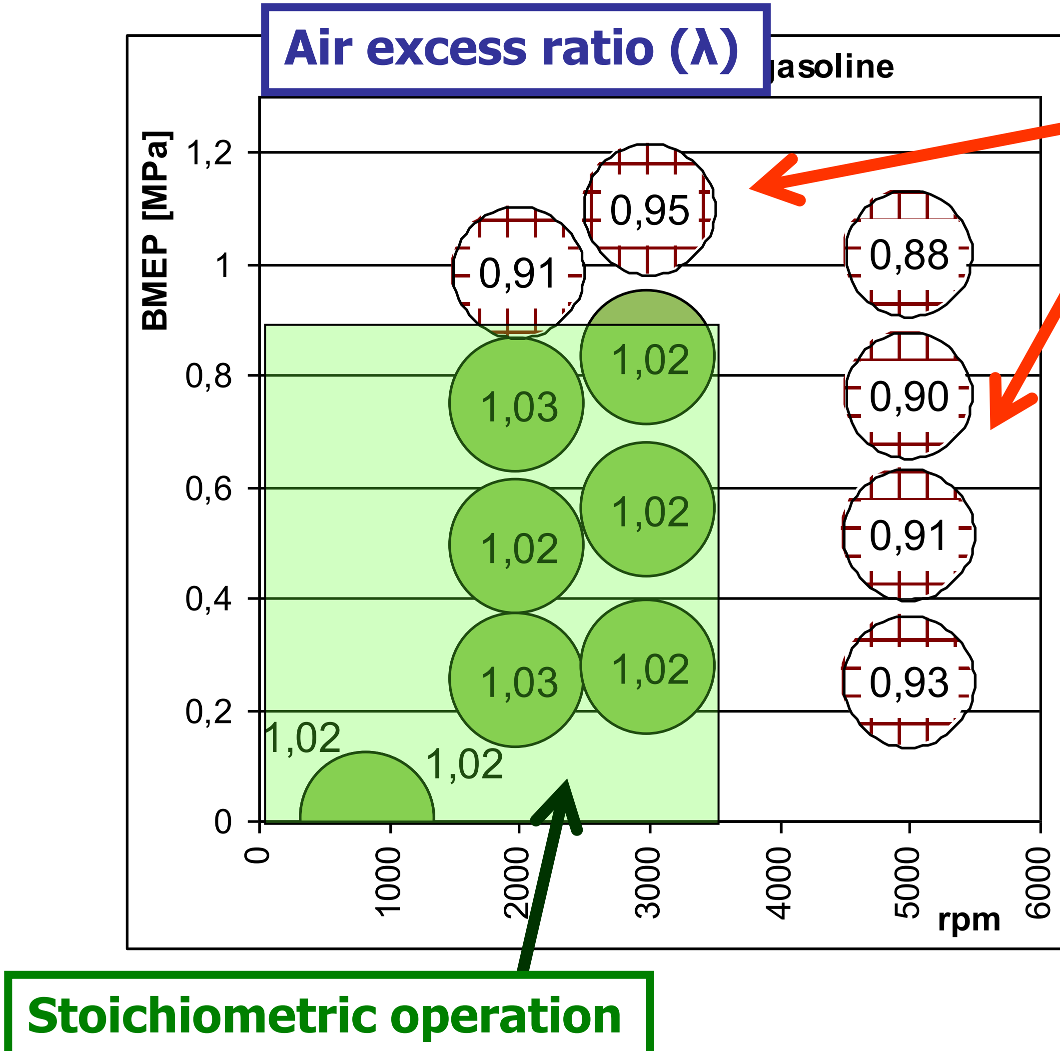


Euro 4 Renault van – real-world driving
No "off-cycle" emissions observed.

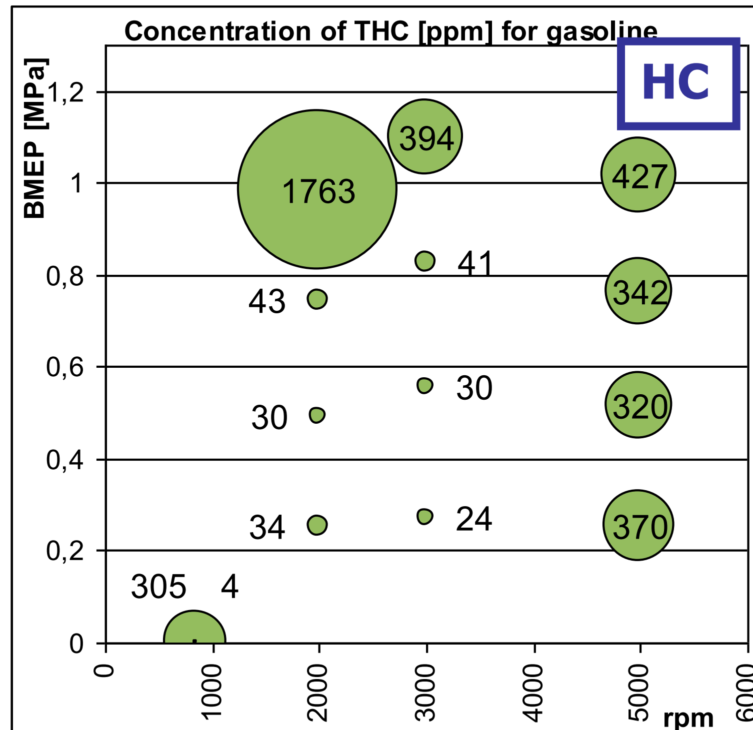


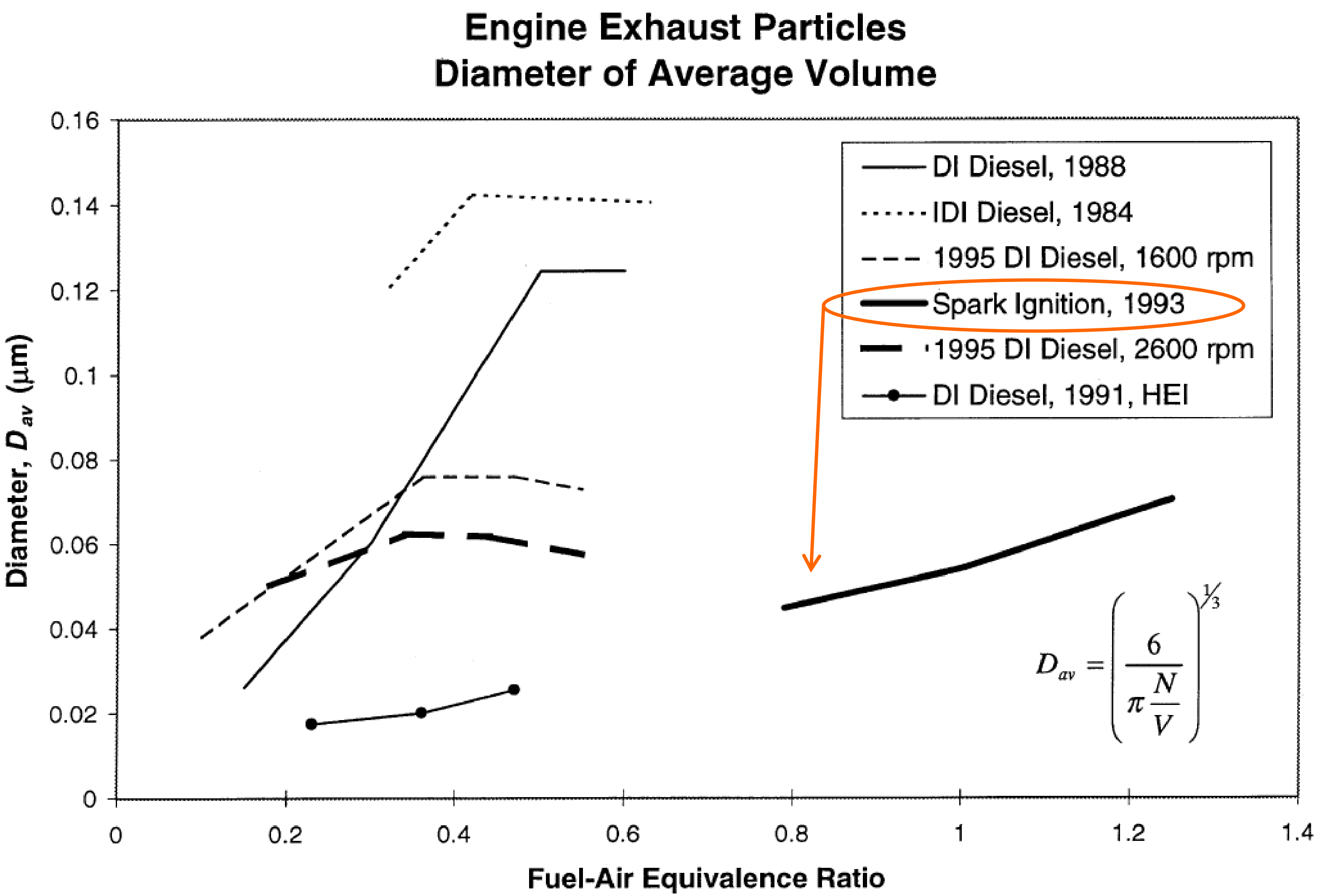


Challenges of EU automobile gasoline engines
Euro 4 Skoda Fabia – engine dynamometer runs

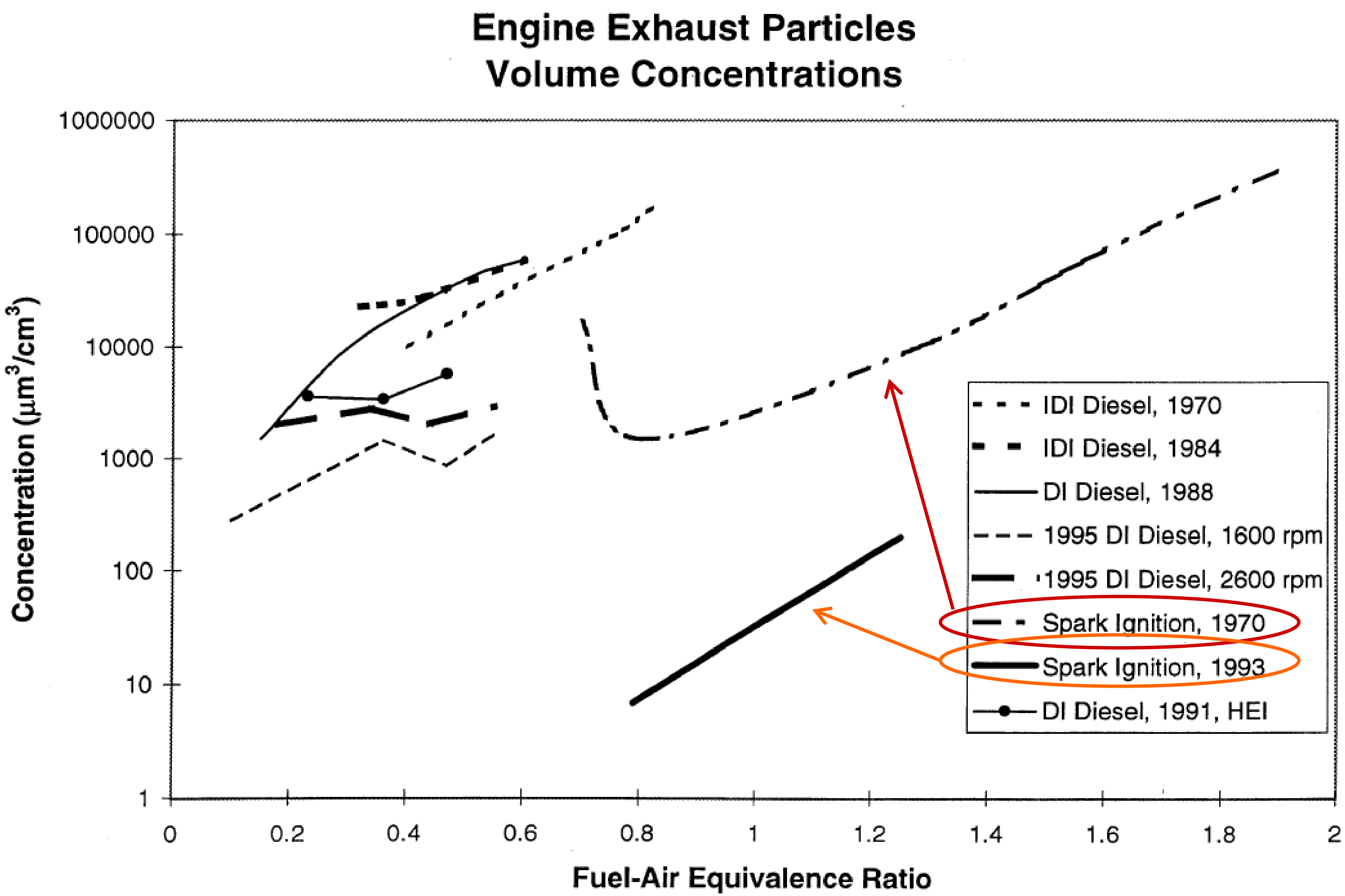


Reducing exhaust gas temperatures (catalyst protection) by fuel-rich operation at high rpm and at high loads





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



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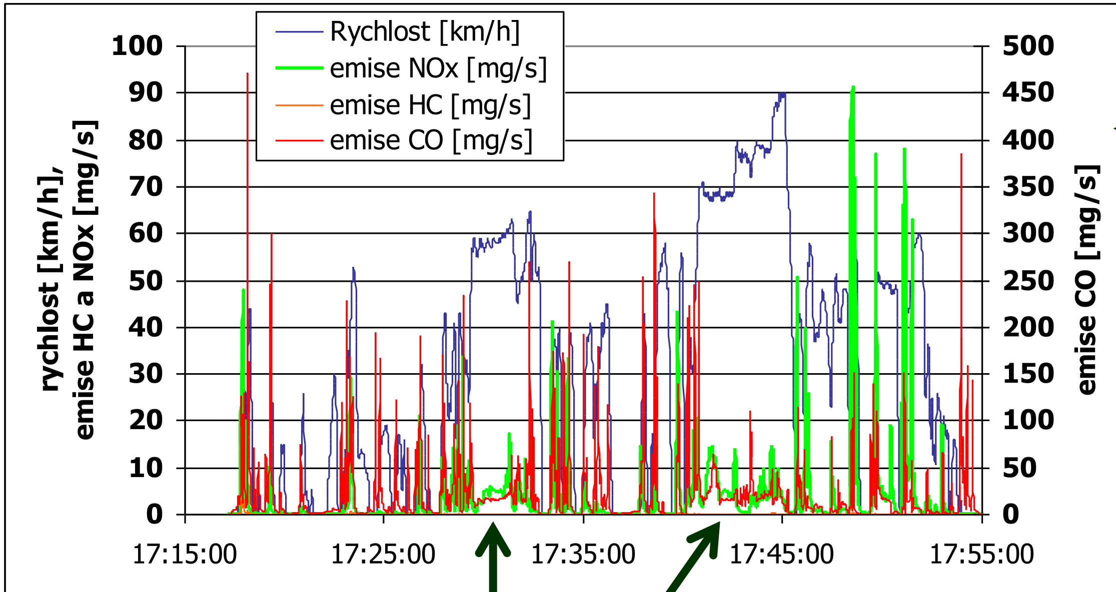
Škoda Fabia, 1,4 MPI

Škoda Fabia – 1,2 HTP

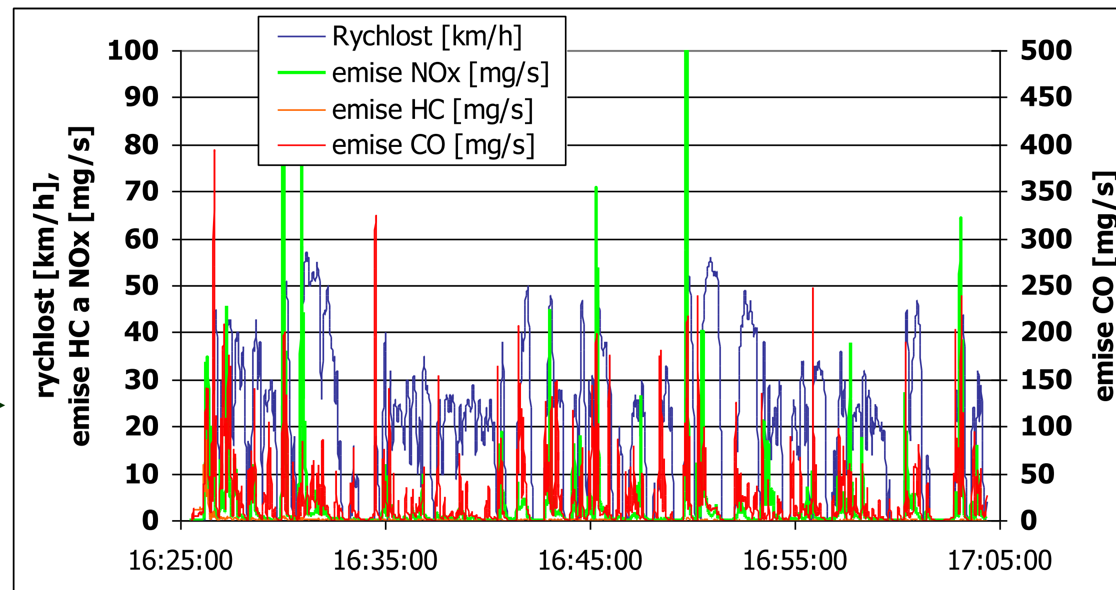


Exiting Prague on arterial roads

City driving – 0,7 - 2 liters of gasoline per hour just to keep the engine running and to power auxiliaries (only 1-2 liters / 100 km for propulsion)

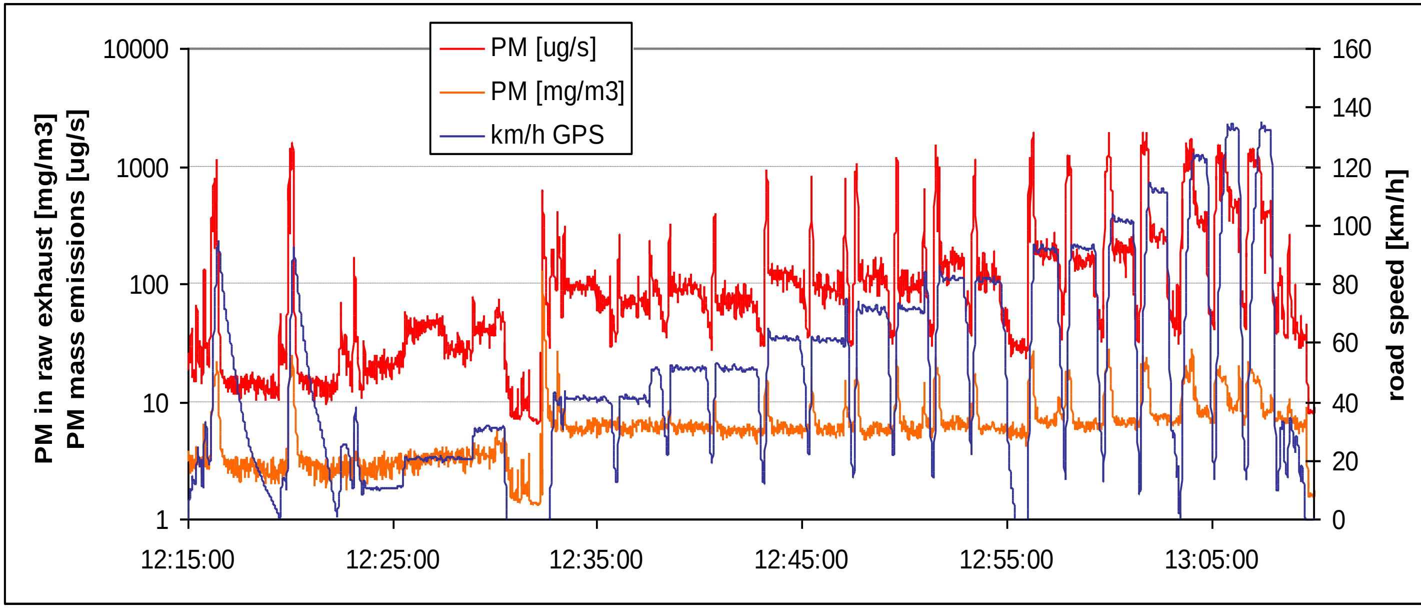
Steady-state operation (this took the driver lot of work, nobody drives like that…)

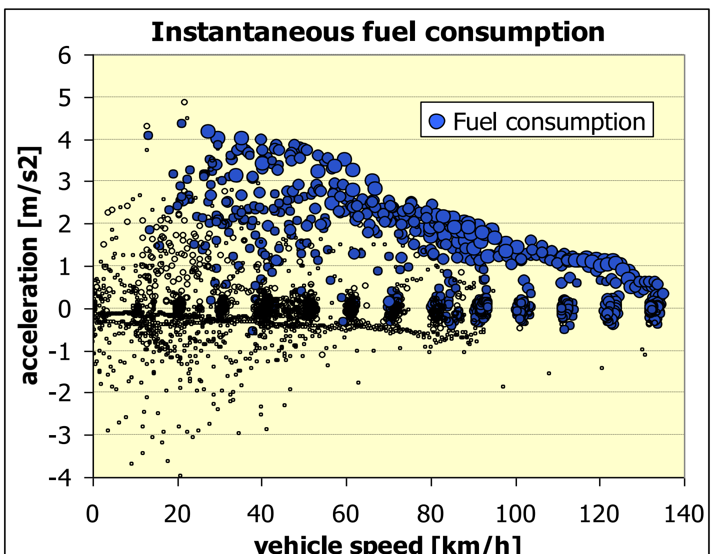
Driving through the city (Prague, CZ)

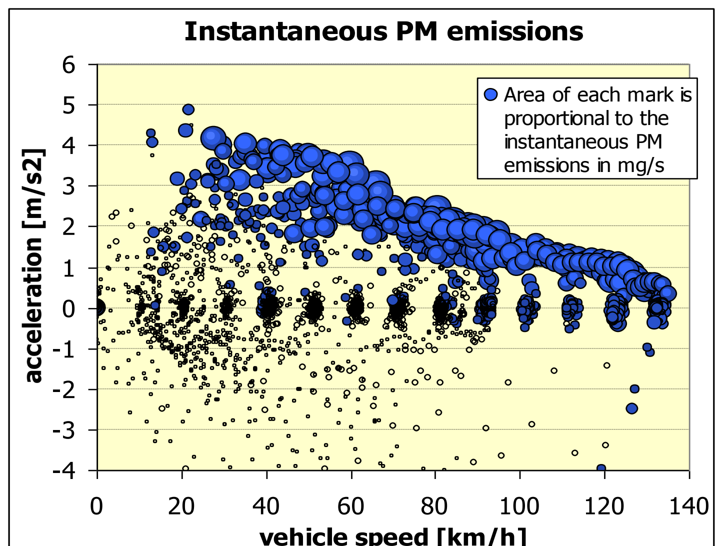


Škoda Fabia, 1,4 MPI

Airport runway experiments – steady-state vs. accelerations

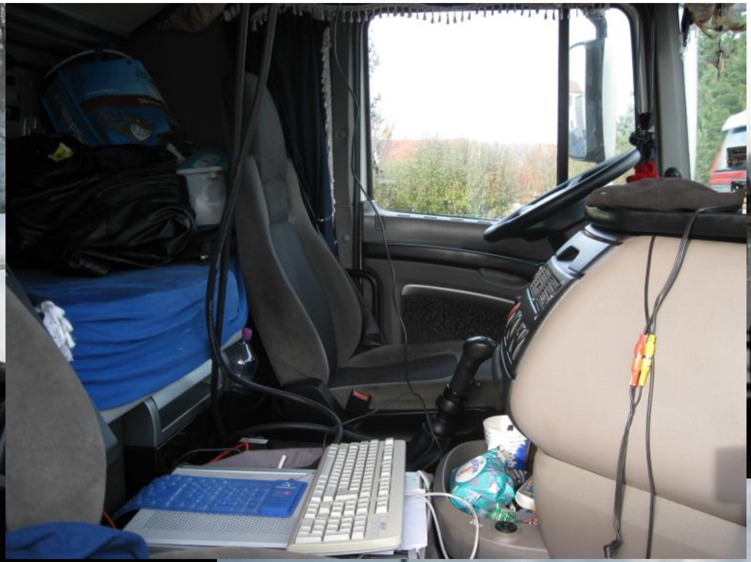


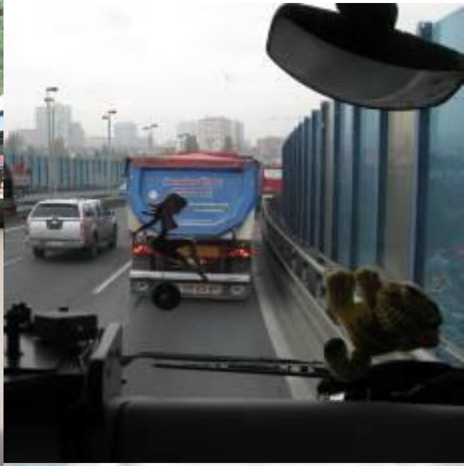




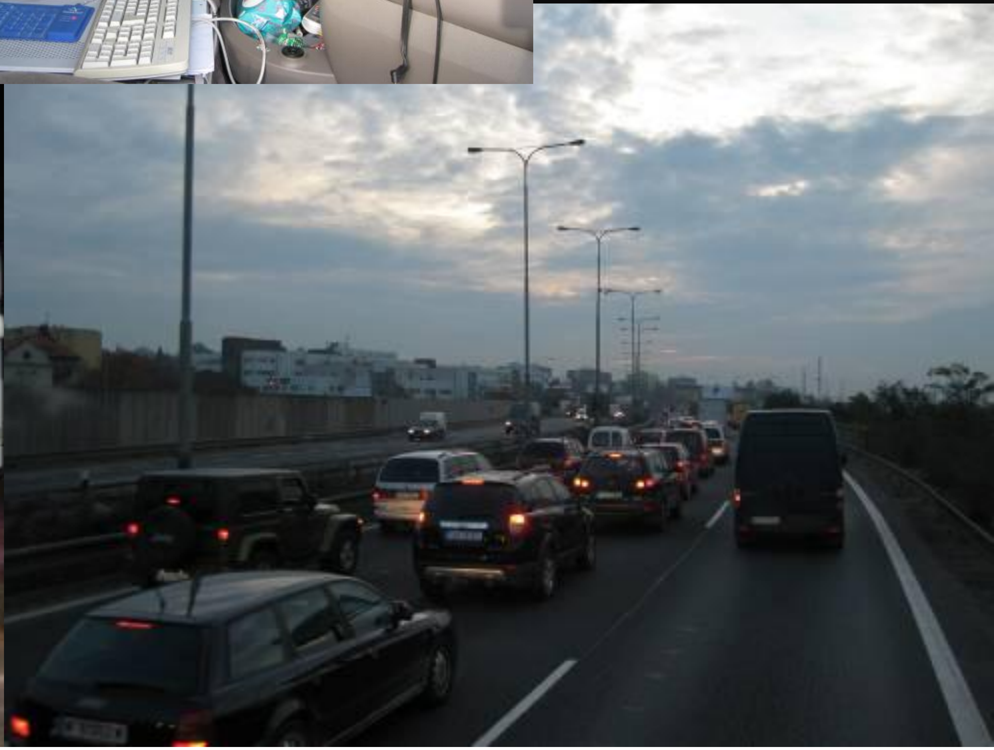
At high acceleration rates, instantaneous PM are much, much higher than during cruise – absolutely as well as per kg of fuel

Challenges of EU heavy engines: Euro 3,4,5 attained without DPF
Combustion, DOC and SCR efficiency deteriorate at idle





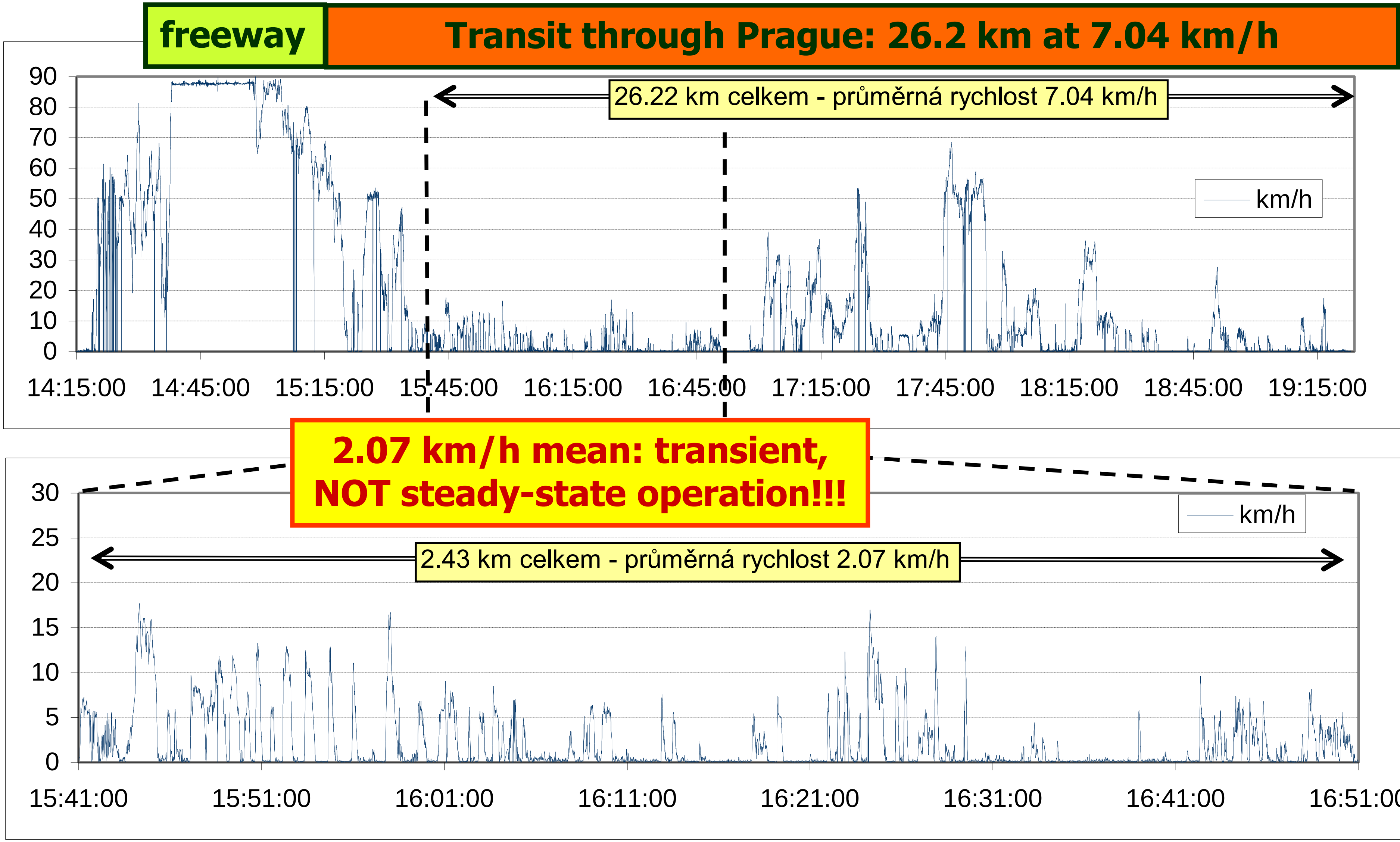
"The horror of transit truck traffic"



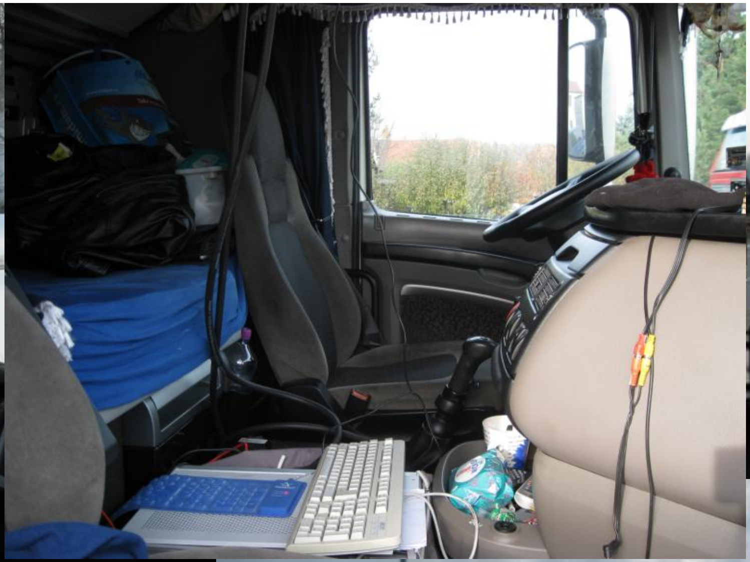
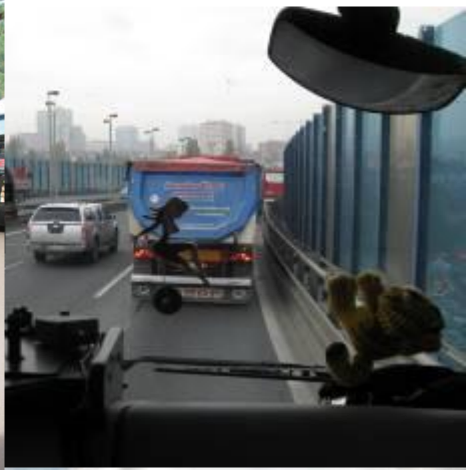
Challenges of EU heavy engines: Euro 3,4,5 attained without DPF
Combustion, DOC and SCR efficiency deteriorate at idle

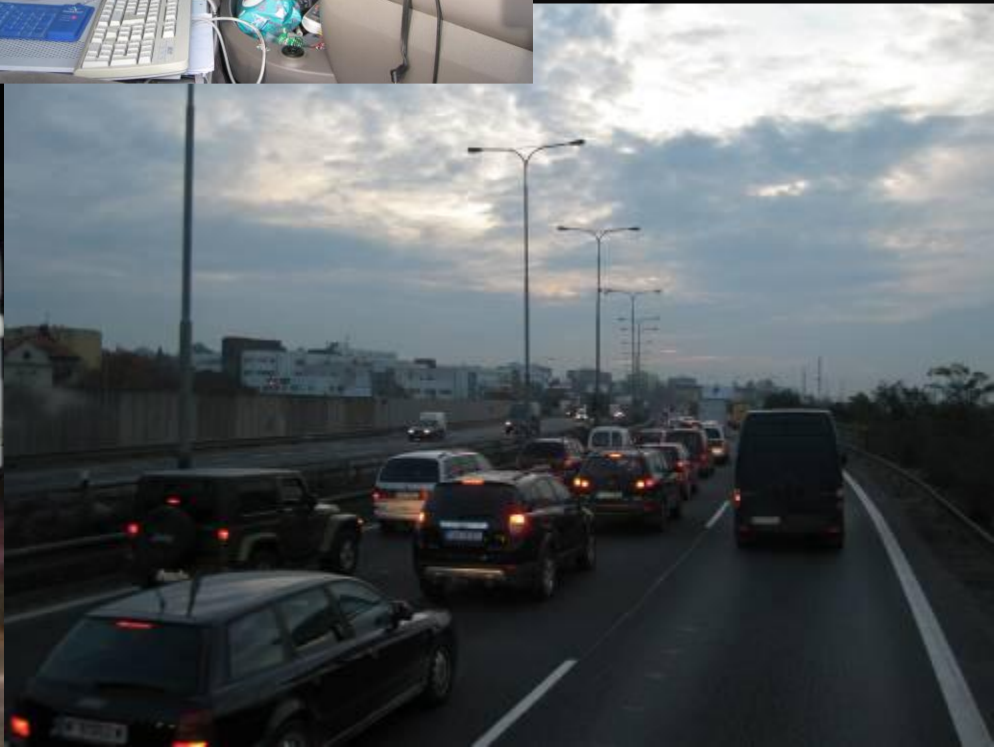
Idle and "urban creep": The horror of transit truck traffic

(Measurement by the author, Iveco EuroCargo, Euro 3, 7 ton gross weight)



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



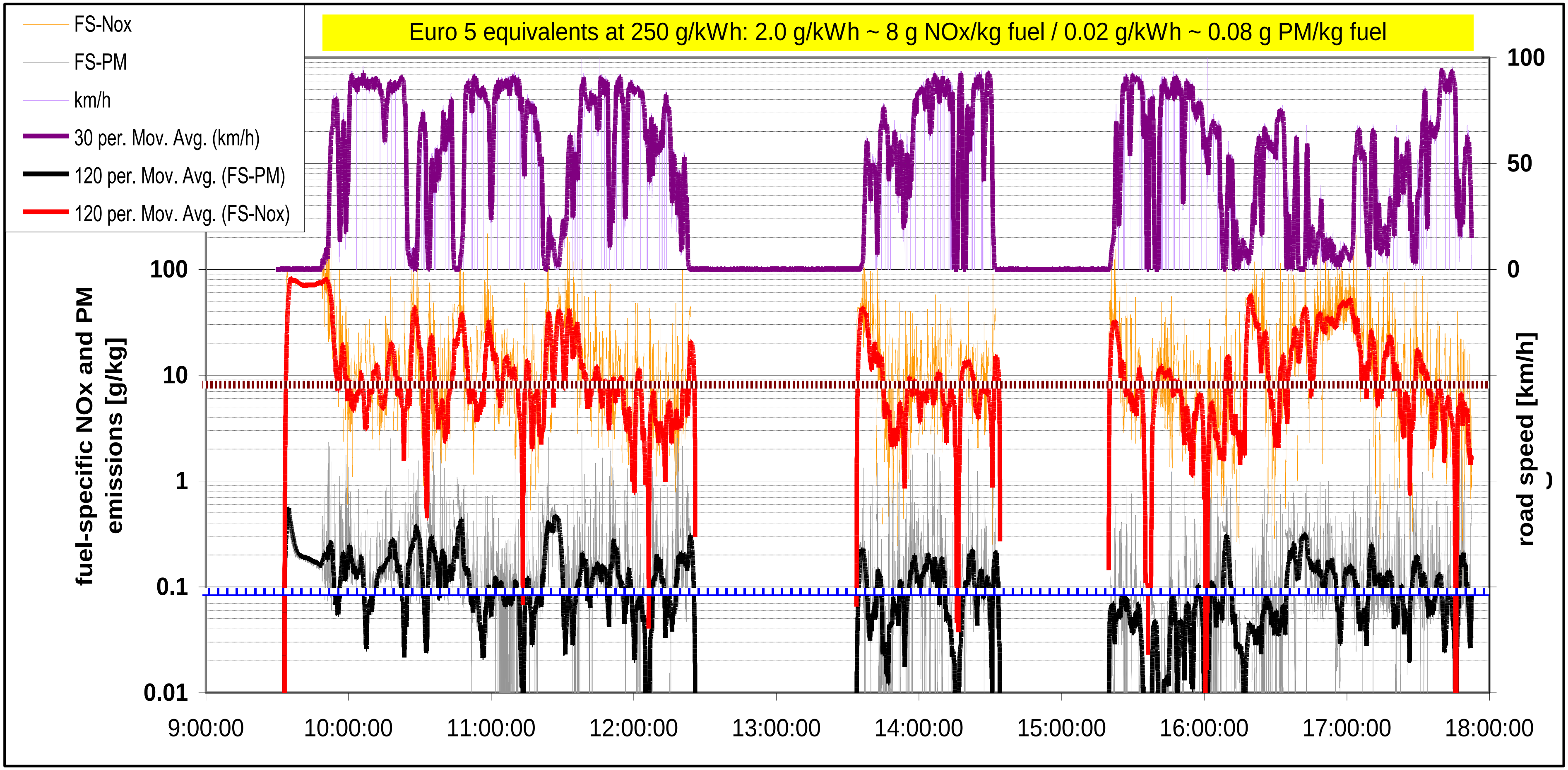
The horror of transit truck traffic

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":

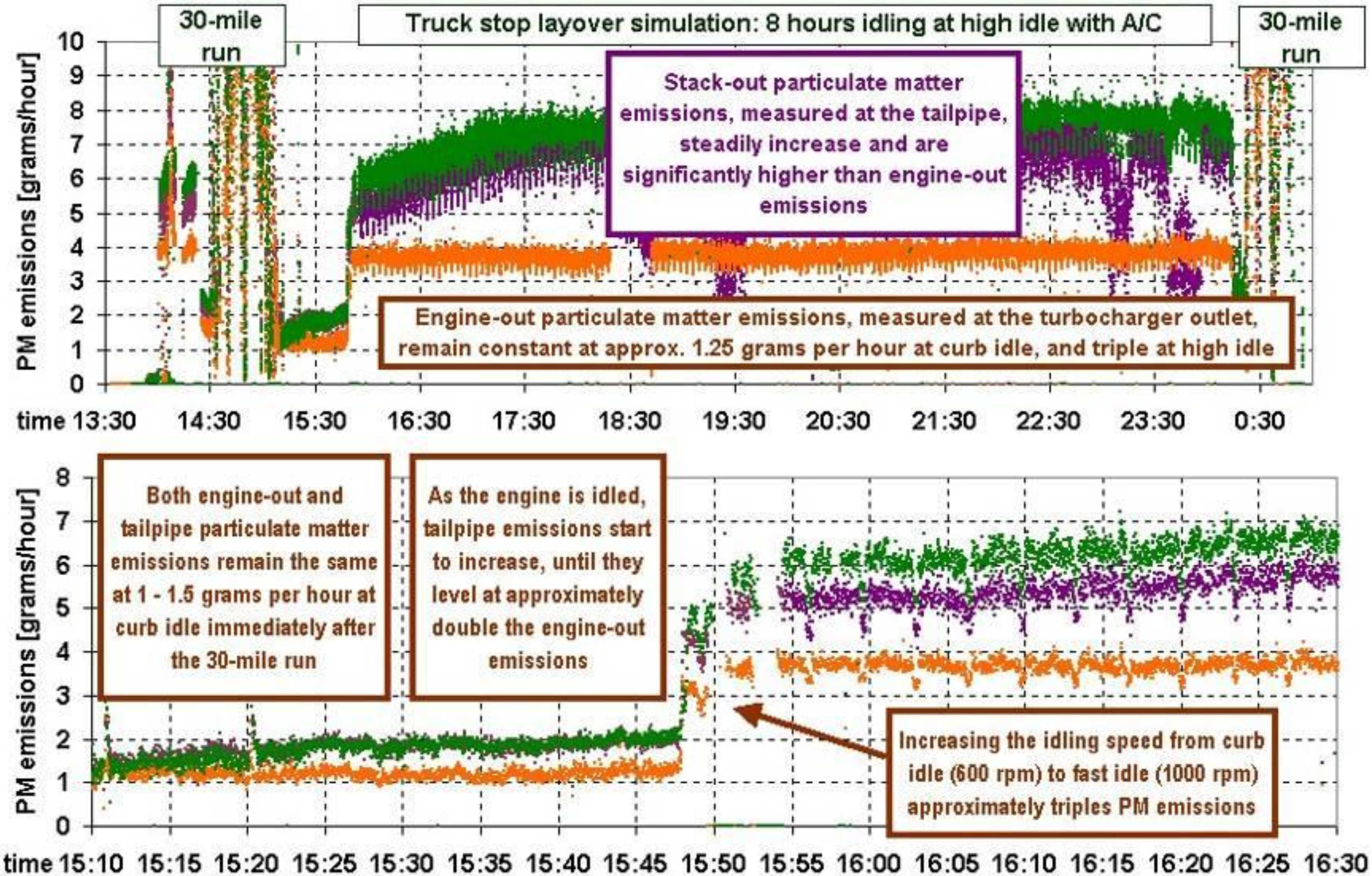
combustion worsens, DOC cools down, SCR cools down, EGR not feasible

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



Effect of prolonged idling on PM emissions

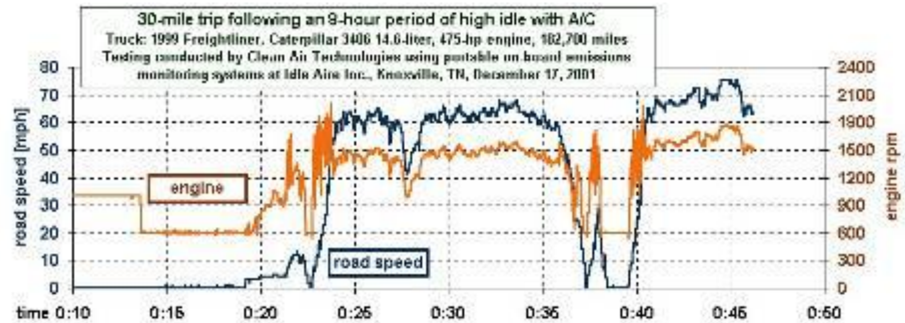
1999 Freightliner truck, CAT 3406 engine, ~150,000 miles 8-hour extended idling test Idle Aire Technologies, Knoxville, TN, December 17, 2001

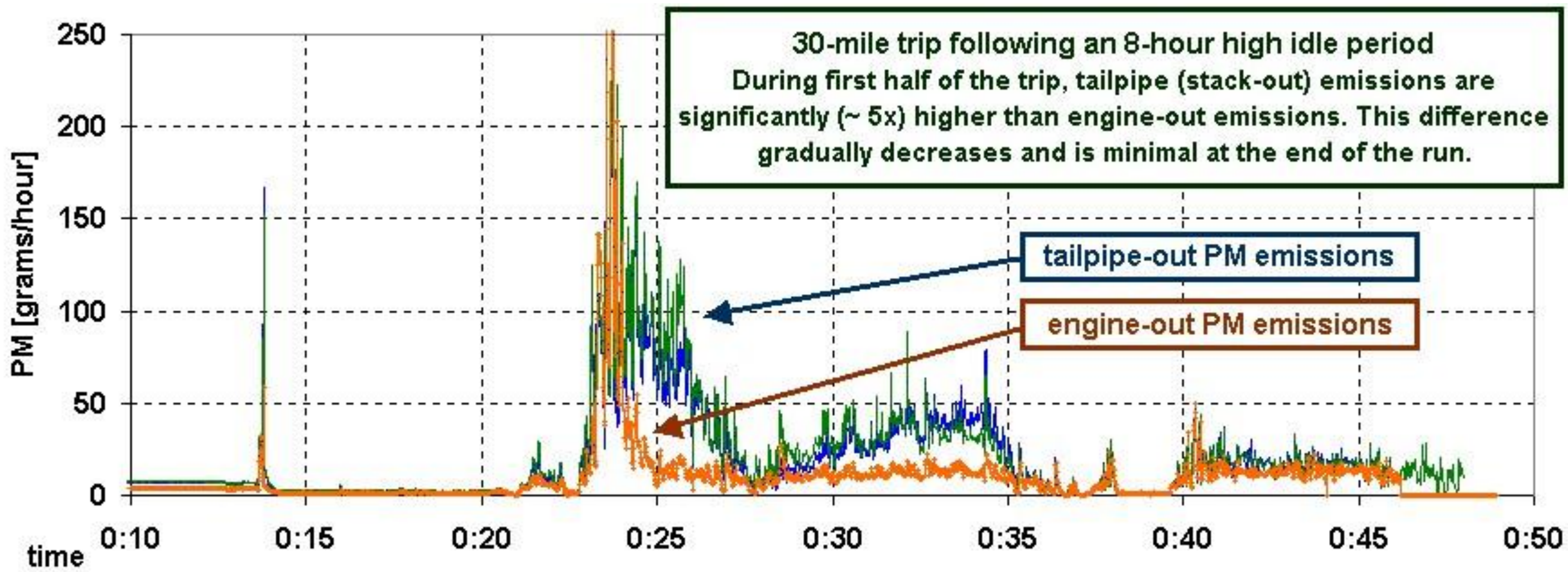


Vojtisek-Lom, CRC On-road vehicle emissions workshop, 2002

Effect of prolonged idling on emissions during subsequent driving

- **Class 8 truck idled for 8 hours at high idle, then driven for ~32 miles on an interstate highway**
- **PM emissions were sampled at the turbocharger outlet (engine-out) and at each stack (tailpipe) using three portable, on-board systems**





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Vojtisek-Lom, CRC On-road vehicle emissions workshop, 2002

USA-Canada Peace Bridge border crossing

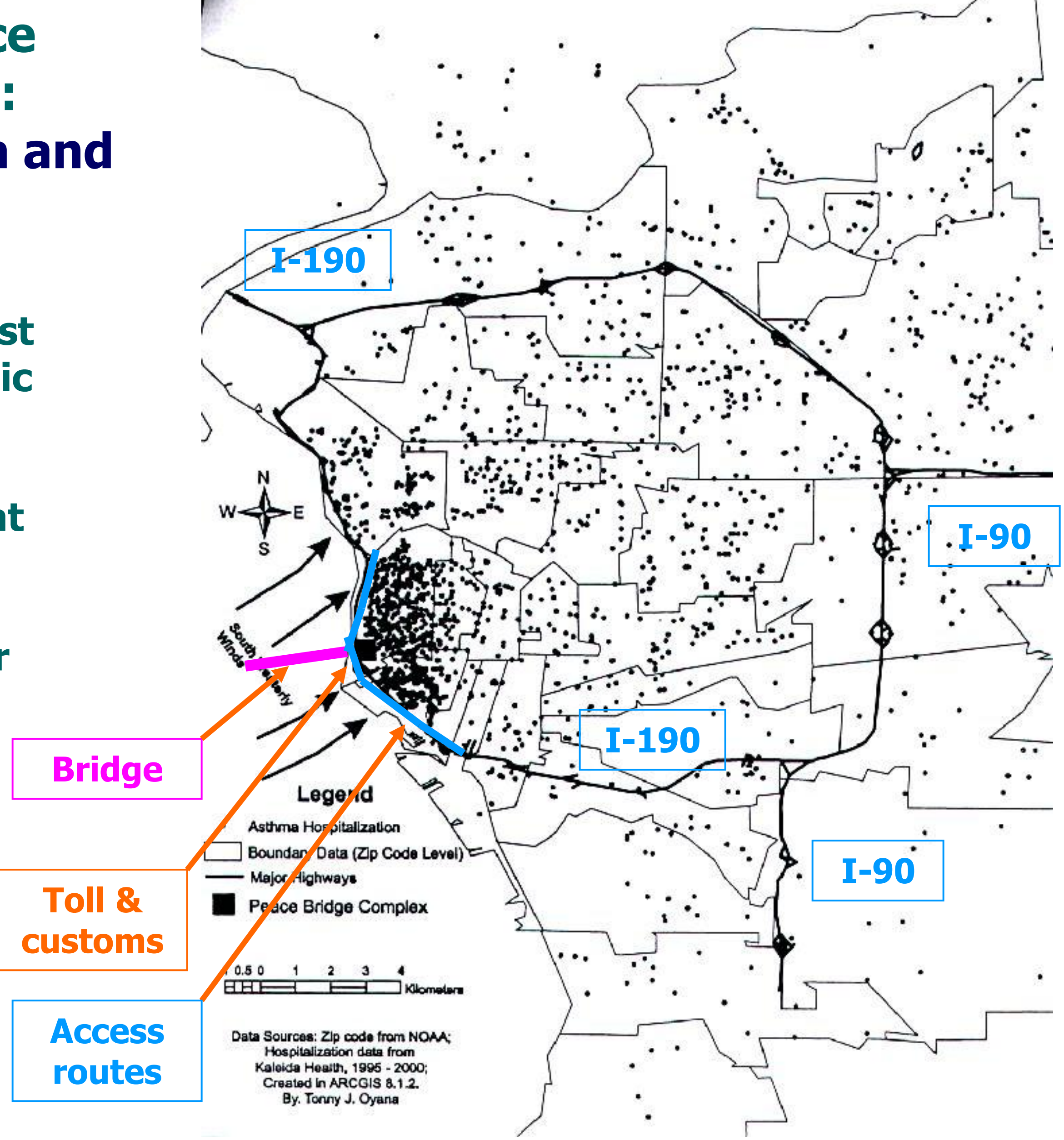
- 1.14 million heavy trucks annually (2004)
- 7.66 million private vehicles annually (2004)
- Frequent delays, during which trucks idle
- On Buffalo side, trucks often use residential streets as staging areas

Jamson S. Lwebuga-Mukasa, *Journal of Asthma*, Vol. 42, No. 5, 2005, pp.337-348.

Health issues near Peace Bridge border crossing:
Very high levels of asthma and respiratory ailments

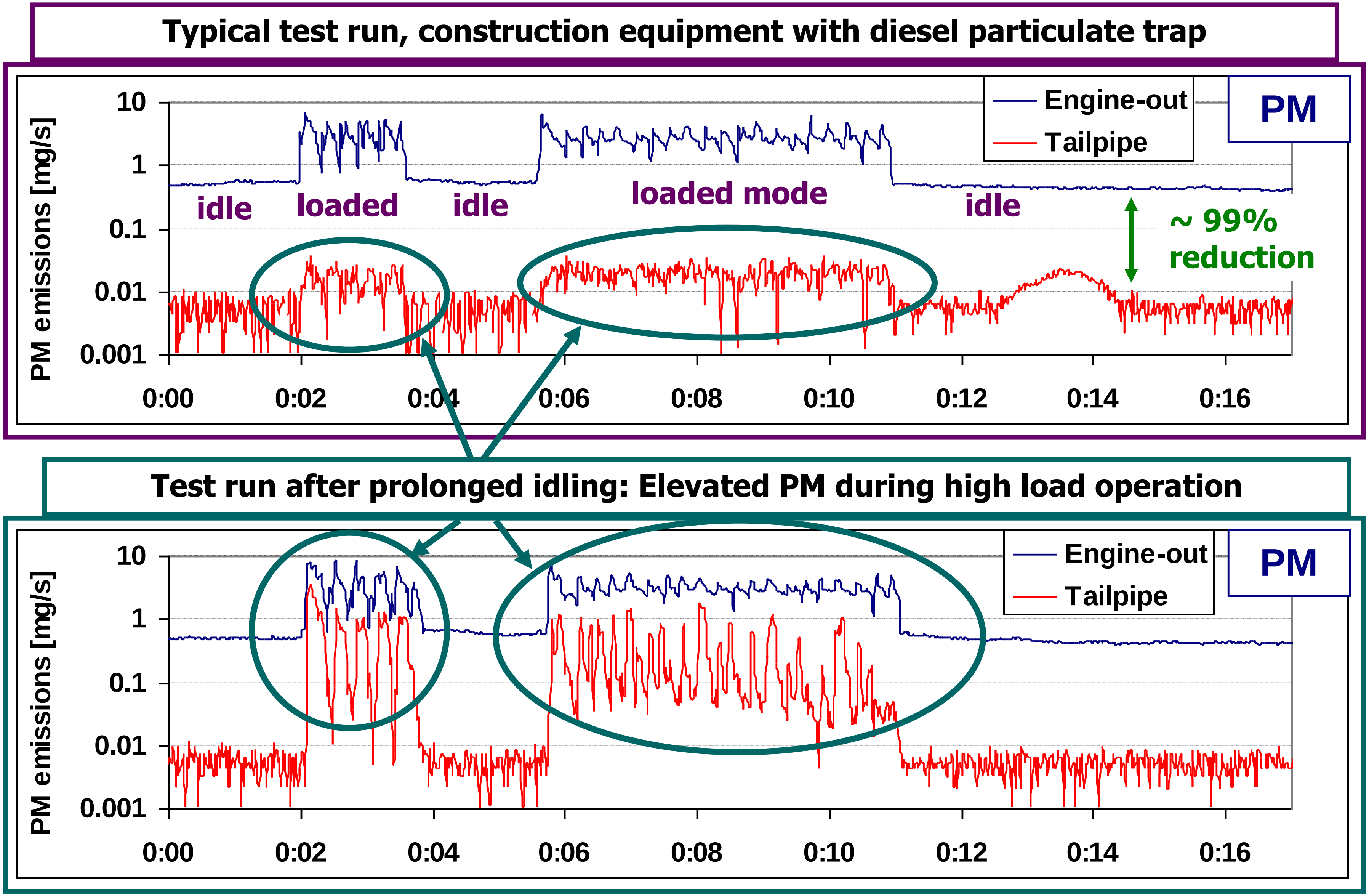
- **36% of households with at least one person suffering from chronic respiratory ailment**
- **51% of households reporting at least one asthmatic**
- **Health care utilization rates for asthma more than double in the immediate vicinity than in surrounding neighborhoods**

Spatial distribution of asthma cases in Buffalo (marked by black dots)



Jamson S. Lwebuga-Mukasa, *Journal of Asthma*, Vol. 42, No. 5, 2005, pp.337-348.

Field test – excavator with diesel particulate filter
Emissions measured simultaneously upstream & downstream of DPF



DPF work, but … are they the EU norm, or the privilege of wealthy and progressive countries and regions?

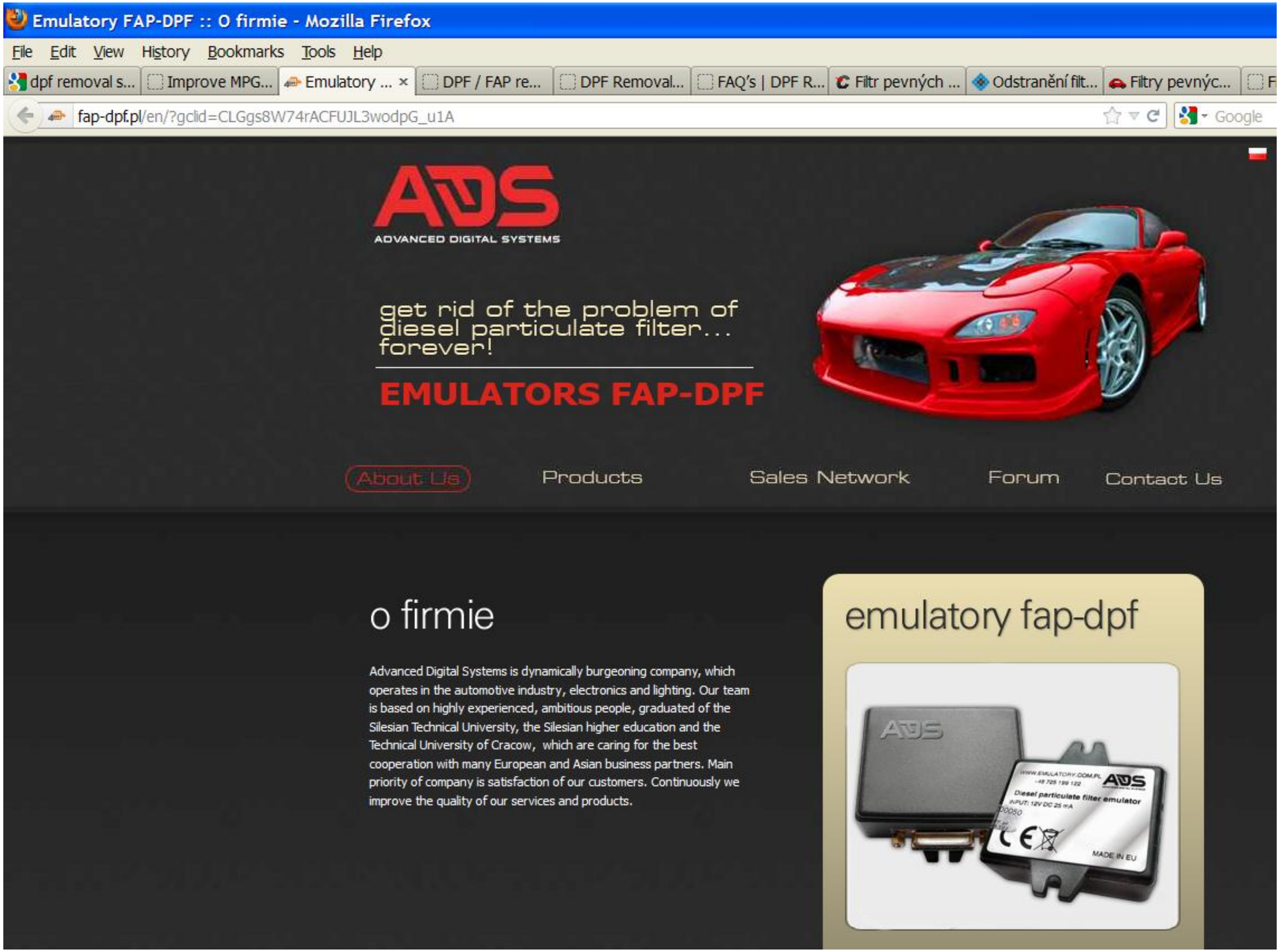
Czech advertisement for removal of DPF from imported vehicles

Advertisement:

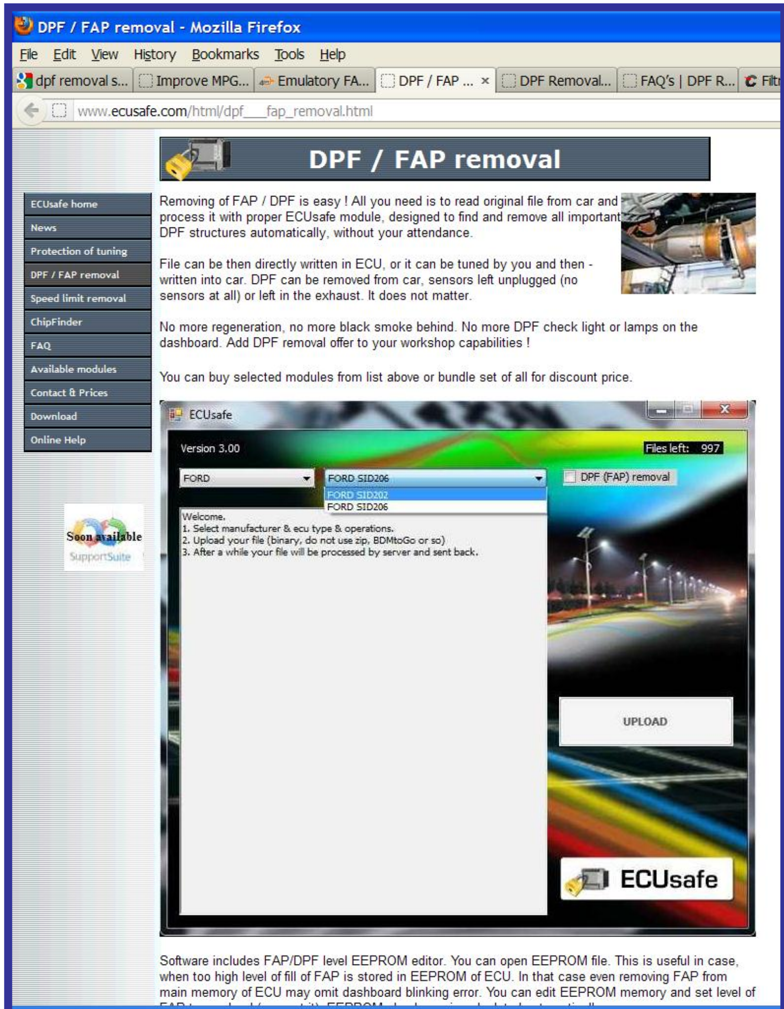
Permanent removal of DPF
Guaranteed work
Toll-free number
Compliant with Euro X
Discount for taxis

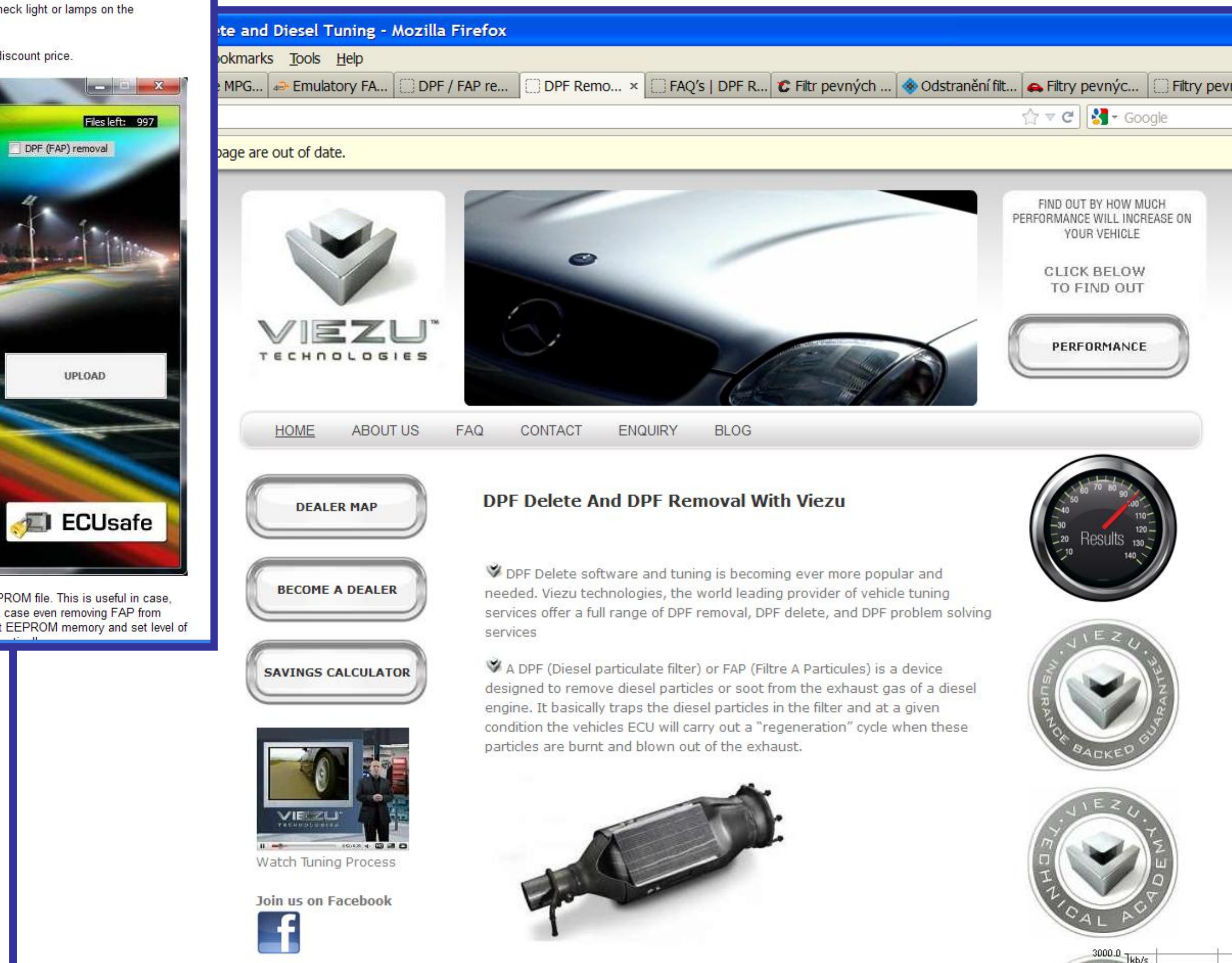
DPF work, but ... are they the EU norm, or the privilege of wealthy and progressive countries and regions?

Polish advertisement for emulation of (removed) DPF to the ECU



UK advertisement for removal of DPF and corresponding adjustments of ECU





Summary:
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

Recommendation:
Choice of realistic urban driving cycle for toxicity evaluation.

New project: MEDETOX

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

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

Czech national project – originally a national component of EngToxNet
(Under discussion ETH and elsewhere, 2006-2010.

Finding a commonly accepted exhaust toxicity test procedure still a desired task, but proposals unsuccessful so far.)

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

Department of Vehicles and Engines, 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

-> PETAS – Portable exhaust toxicity assessment system