12th ETH Conference on Combustion Generated Nanoparticles, Zurich, June 23-25, 2008

Growth in road traffic, off-cycle emissions, aggressive driving, and real-world PM emissions: Can the benefits of new vehicles keep up?

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Fine particulate matter (PM) is considered one of the most harmful pollutants originating from internal combustion engines, causing considerable health damages. Historically, reductions in emissions were achieved primarily through the combination of increasingly strict standards for new vehicles, and technological improvements to the engine and exhaust gas aftertreatment technology to meet these standards. These reductions were counteracted, to varying extent, by a gradual and persistent increase in traffic intensity. A combination of several current trends is, however, creating conditions where the health damages due to increasing PM emissions can be expected, in many locations, to get worse. In the Czech Republic, diesel fuel sales increase at a rate corresponding to doubling every fifteen years. The contribution of transport to total PM_{10} emissions is approximately one half and gradually increasing. Considering that particles from road transport are generally very fine and that they are emitted relatively close to large number of people, and that rates of respiratory ailments are on the rise, this is an alarming trend.

One contributing factor is the decreasing stability of diesel engine emissions, given primarily by a shift from open-loop, mechanically controlled engines with no aftertreatment to sophisticated controls utilizing high-pressure injection, variable geometry turbochargers, exhaust gas recirculation, and a variety of exhaust gas aftertreatment devices. Experience with similar improvements on gasoline engines throughout last three decades suggest that such sophisticated systems are prone to relatively high emissions levels during highly transient operation (i.e., effect of time lag in closed-loop control), and operation at extreme high or low loads (overfueling at full throttle, poor combustion and low exhaust gas temperature at idle). Also, drifts in calibration, wear of components, and various malfunctions tend to increase emissions over the useful life of the vehicle. As a result, large portion of total fleet emissions originate from a disportionately small number of vehicles, and large portion of total emissions from a vehicle originate during a disproportionately small fraction of its operating time.

Another factor is the rapid increase in traffic intensity, notably in the areas with growing economy, driven by a trend towards widespread use of automobile as the primary means of individual transport (also called “automobilism”, with associated phenomena of migration of cities into their surrounding areas, known in North America as “suburban sprawl”), and of heavy trucks as the primary means of cargo transport. Such increase in traffic intensity overloads the transportation network, to the point where the the volume of vehicular traffic reaches and exceeds the carrying capacity of the road. The relative traffic density is referred to, in transportation engineering, as volume-to-capacity ratio, V/C or VCR. At low VCR, the traffic flow is relatively smooth; as VCR increases, the variations in vehicle speeds increase, causing more pronounced fluctuations in engine loads, notably in heavy vehicles. Further increases in VCR cause frequent stops and accelerations, and, finally, breakdown of the traffic flow, with resulting idling and low-speed “crawl”. Extended low-load operation then leads to lower efficiency of exhaust gas aftertreatment devices, lower benefits of EGR, and higher fuel consumption per km.

Other factors are an increase in power-to-weight ratio of modern vehicles, and an increase in the occurrence of aggressive, performance and high-speed driving, characterized by highly transient operation. Idle, low-load and transient high-load operation are poorly covered by the current engine certification cycles, generally resulting in higher emissions under such conditions. Another factors are the relatively slow fleet turnover, the migration of used vehicles from richer to poorer regions, and the rapid rise in road transport in growing regions with lagging road network capacity.

Some of these factors are demonstrated on real-world emissions measurements done by the author over last twelve years, with the emphasis on recent measurements done on late-model light-duty vehicles. All measurements were done using relatively simple on-board emissions monitoring systems constructed by the author. The results show that performance driving on a mountain road and on an expressway has lead to NO_x and PM emissions, measured in grams per kg of fuel consumed, several times higher than values corresponding to certification limits. In city traffic, several times higher NO_x were observed during extended idling. Generally, rapid changes in engine load have lead to substantially higher PM emissions. The data is poorly quantifiable, as this would require extensive measurements on tens to hundreds of vehicles.

Overall, the benefits offered by new emissions standards and technology of new vehicles appear to be diminished or overcome by a combination of several interrelated phenomenae: increase in vehicle kilometers traveled, increase in volume-to-capacity ratio of roadways, increase in transiency of engine operation, reliance on advanced technologies, controls and aftertreatment, increase in power/weight ratio, increase in occurrence of aggressive or performance driving, slow fleet turnover and migration of the used vehicles to poorer regions.

Should these trends continue (situation might improve given the rising fuel prices), reduction in traffic intensity and especially congestion, retrofits of existing vehicles, and other measures should be considered along with the planned new emissions standards.

One example of the planned PM increase counter-measures is the Czech diesel retrofit programme, a joint effort of Swiss and Czech experts, Czech authorities and local fleets in two most polluted regions centered around cities of Prague and Ostrava. This program is described in detail in a separate poster.

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Can the benefits of new vehicles keep up?

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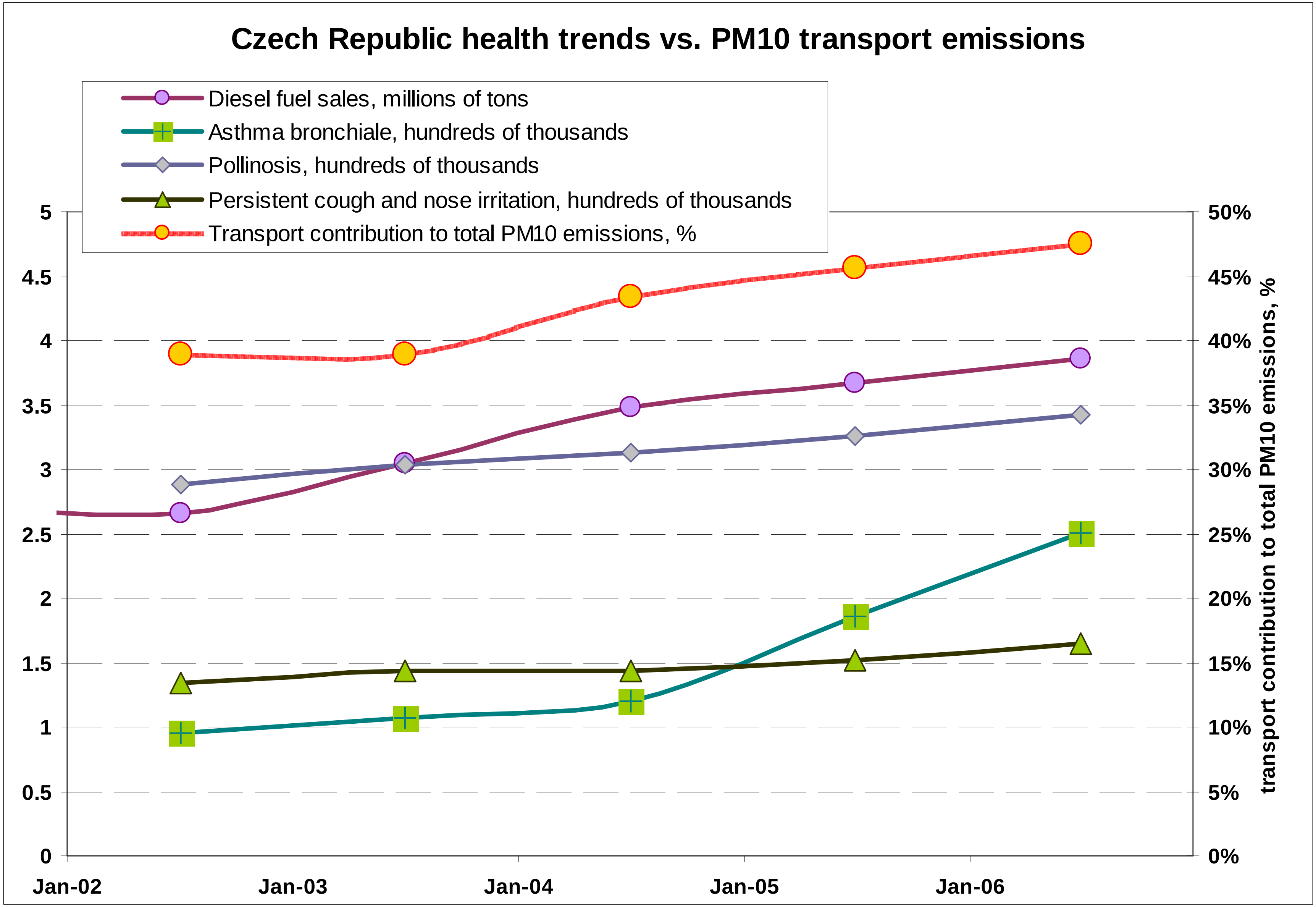
Overview

- In the Czech Republic, approximately one half of PM10 emissions is from transportation.
- Particulate matter from internal combustion engines is small in size (nanometers to hundreds of nm) and emitted in close proximity to people.
- The contribution of the transportation sector to total PM10 is steadily rising, along with health damage.

The benefits offered by new emissions standards and technology of new vehicles appear to be diminished or overcome by a combination of several interrelated phenomenae:

- *increase in vehicle kilometers traveled*
- *increase in volume-to-capacity ratio of roadways*
- *increase in transiency of engine operation*
- *reliance on advanced technologies, controls and aftertreatment*
- *increase in power/weight ratio*
- *increase in occurrence of aggressive or performance driving*
- *slow fleet turnover and migration of the used vehicles eastward*

Mounting health problems: Relationship with transport intensity



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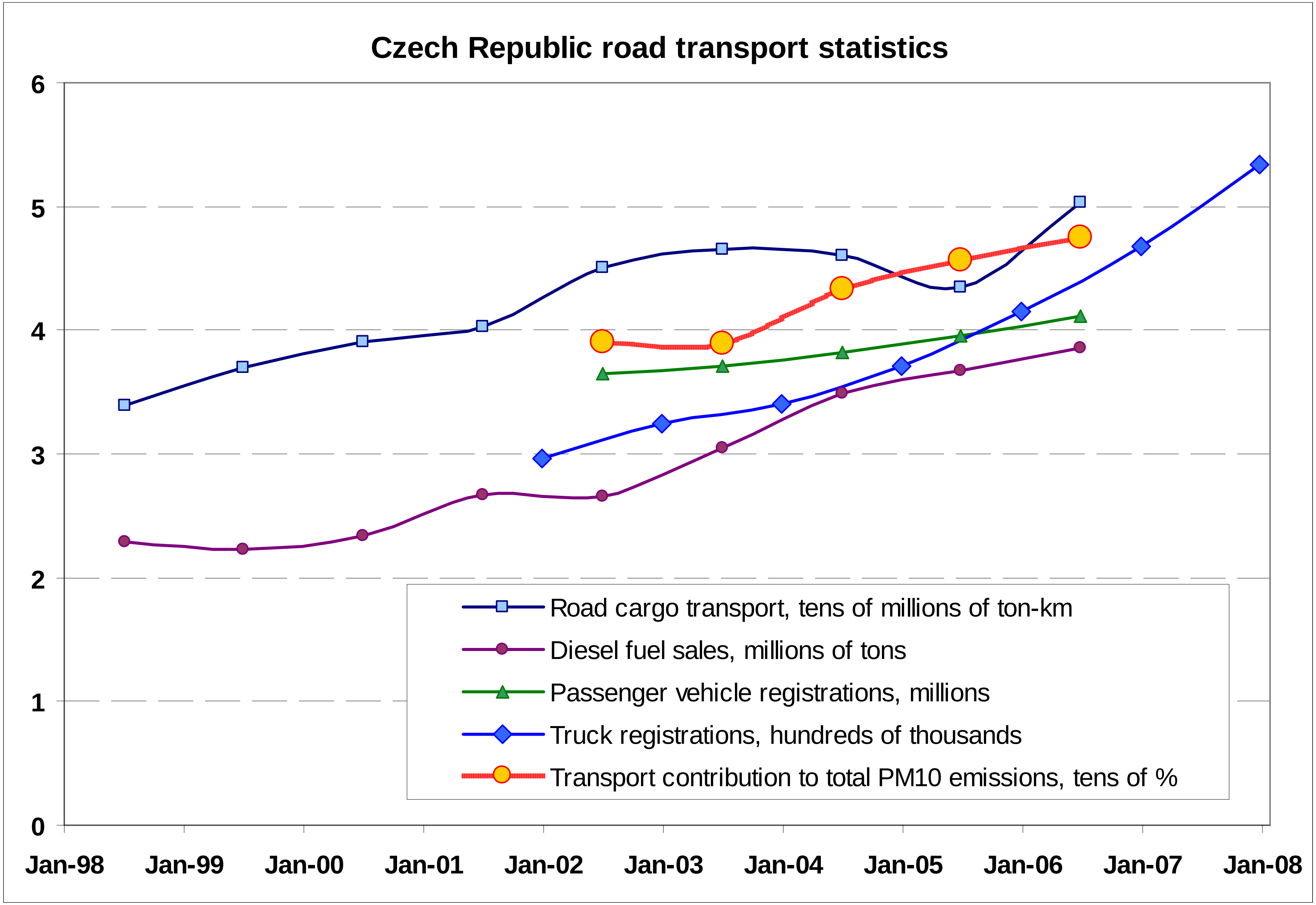
Increasing transport intensity...



Automobilismus


Automobilismus


In the Czech Republic, in the period from 1990 to 2004, energy consumed by transport rose by almost 100%, increasing by 6.7 percent from 2003 to 2004.
Ministry of the Environment
(Report on The Environment in the Czech Republic in 2004 – December 2005)

Rising transport intensity

- Rise of the volume-to-capacity ratio (VCR) of the roadways
- At very low VCR (no or little traffic), traffic flows efficently, with minimum delays, engines operate at “high speed cruise” (but far from steady state)
- As VCR increases, traffic flow becomes less steady, transiency of engine operation increases (accelerating and braking to keep with the flow of the traffic) – especially with heavy vehicles
- At VCR > 1, breakdown occurs – frequent idling, low-speed “creep”, frequent accelerations and braking; the actual throughput of the roadway actually decreases, causing further backups and delays
- Low-load operation, transient operation, and speed fluctuations are all known to increase emissions

With roadways operating at VCR close to and beyond 1 (near or above their capacity), small increases in traffic volumes can lead to large increases in emissions.

Increasing reliance of diesel engines on sophisticated technology, electronic control and aftertreatment

- Similar to gasoline engines with three-way catalyst and closed-loop air-fuel ratio control
- Similar patterns expected:
    - Design or operational anomalies leading to high emissions
        - Transient and off-cycle operation optimized to lesser extent
        - Sensor and component drift and malfunction
    - Fleet emissions dominated by small fraction of high-emitting vehicles
    - Trip emissions dominated by high emissions episodes
    - Idling and low-load operation decreases efficiency of aftertreatment devices

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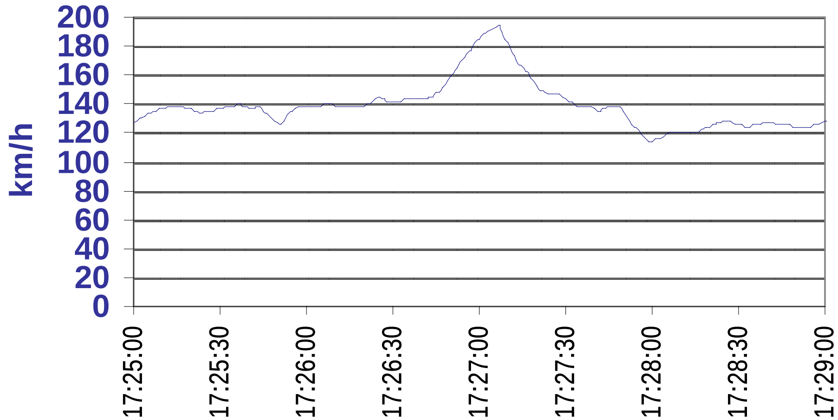
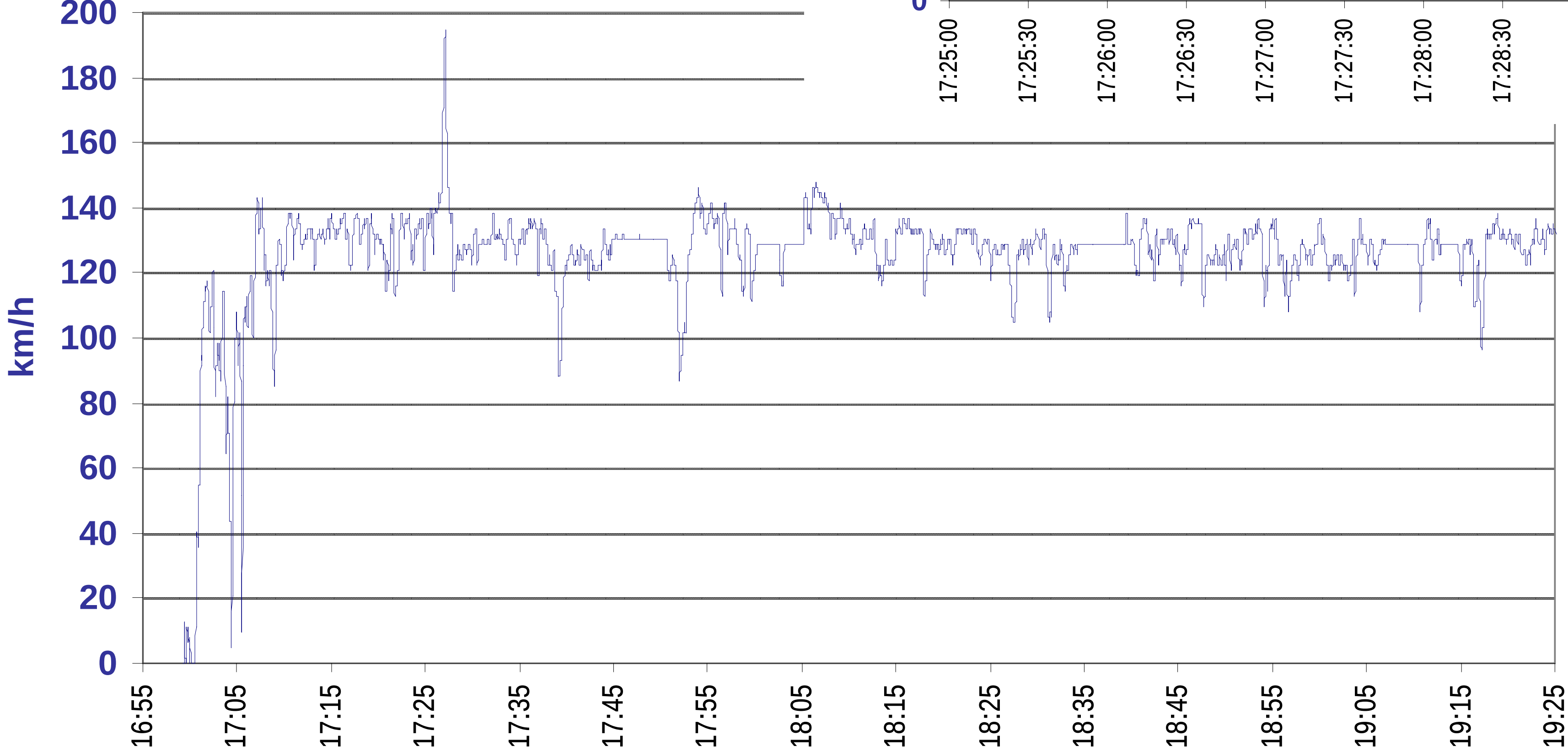
Example: High-speed cruise

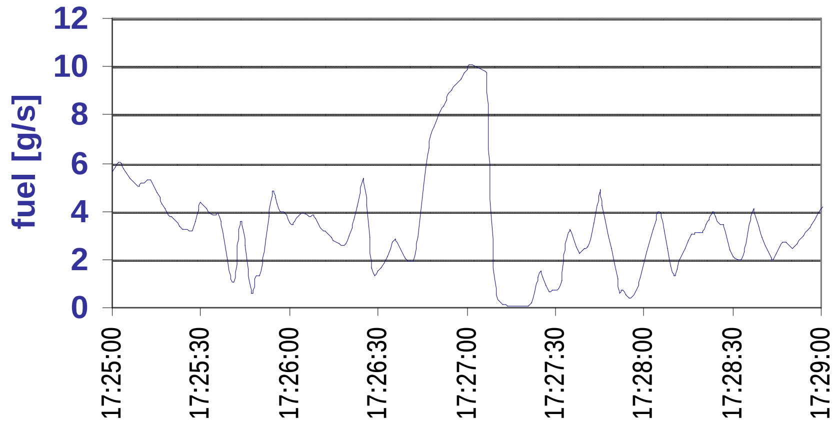
Passenger car, 138 kW turbocharged gasoline engine

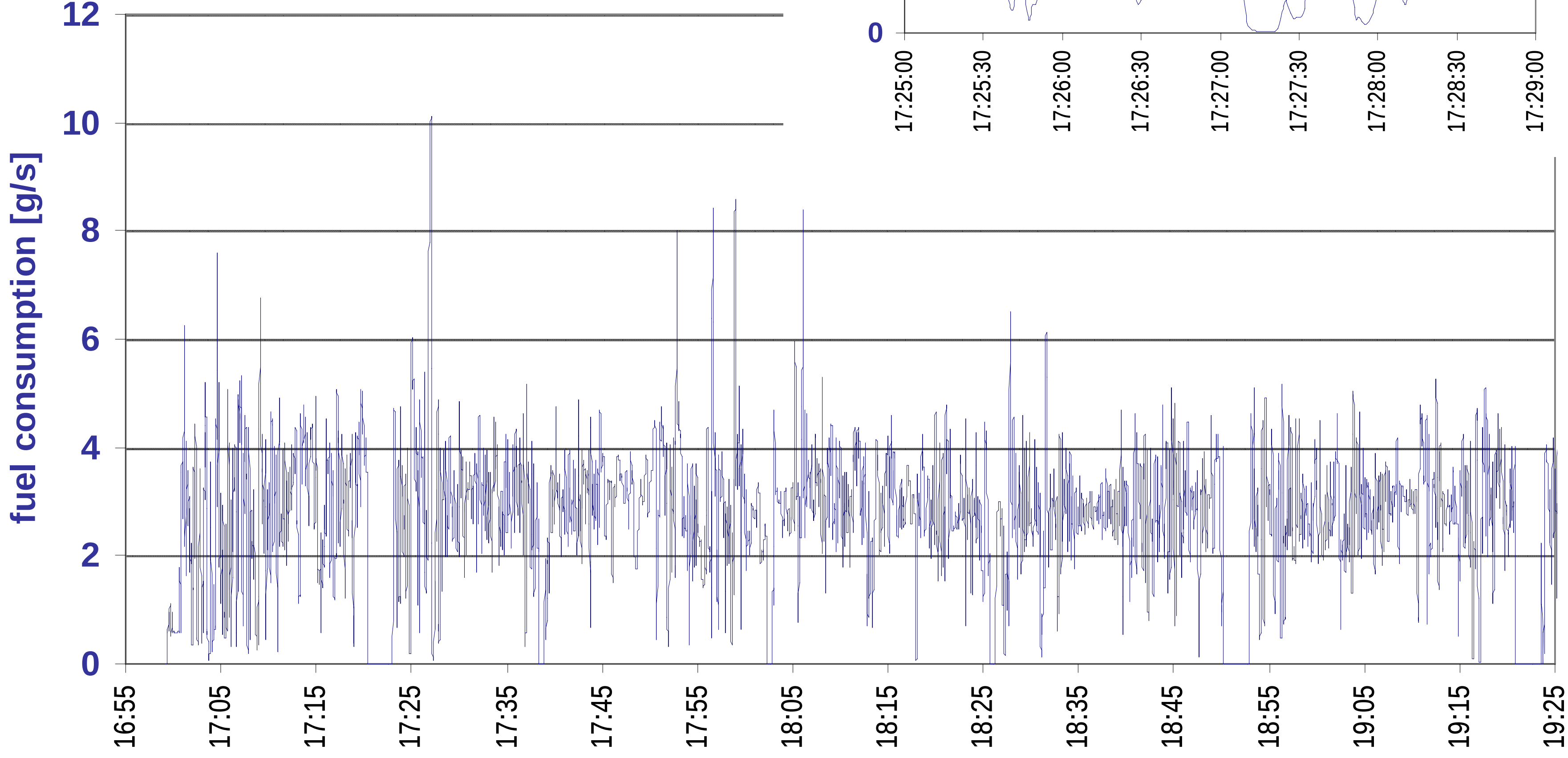




Example: High-speed cruise

Passenger car, 138 kW turbocharged gasoline engine





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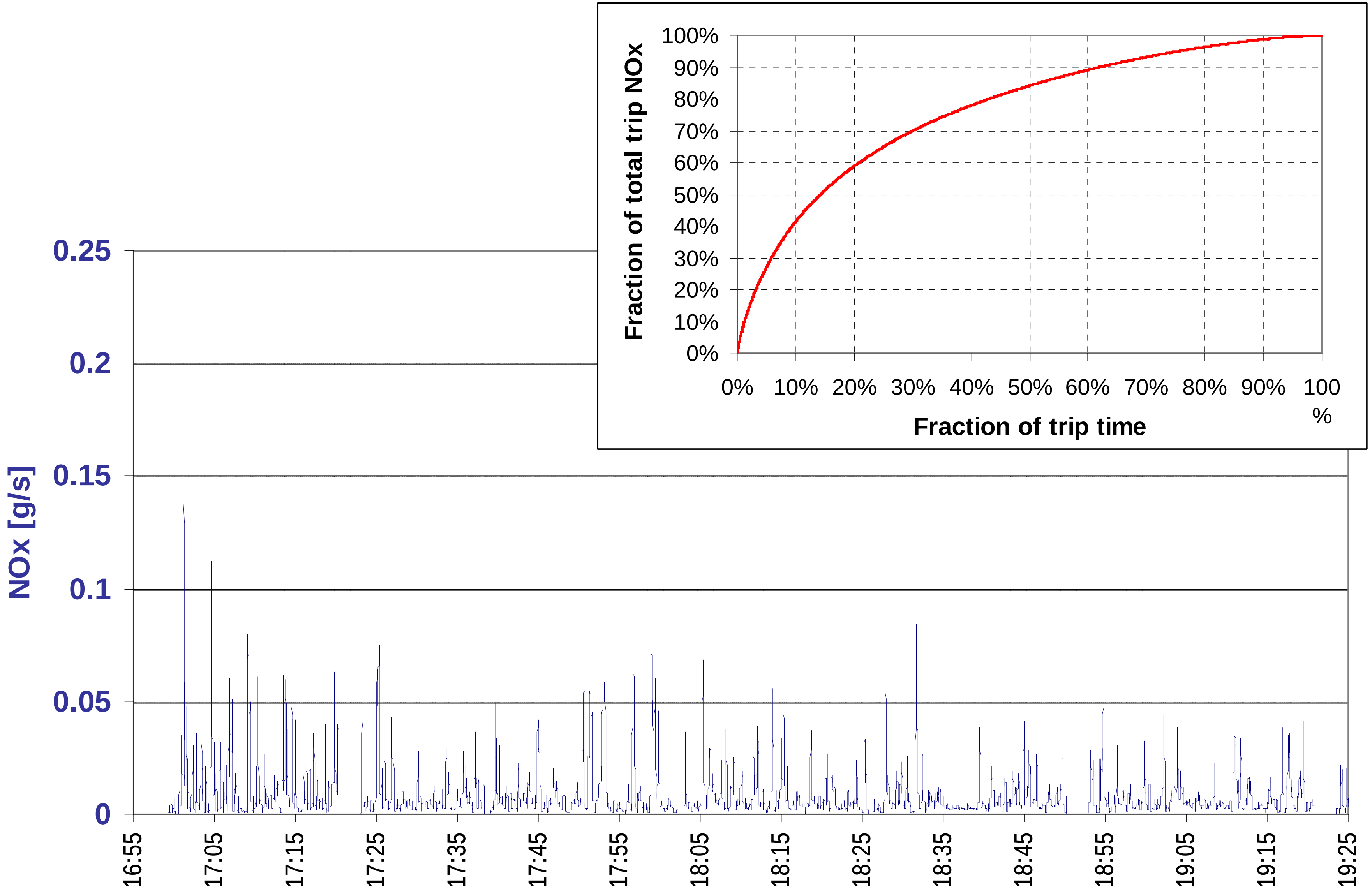
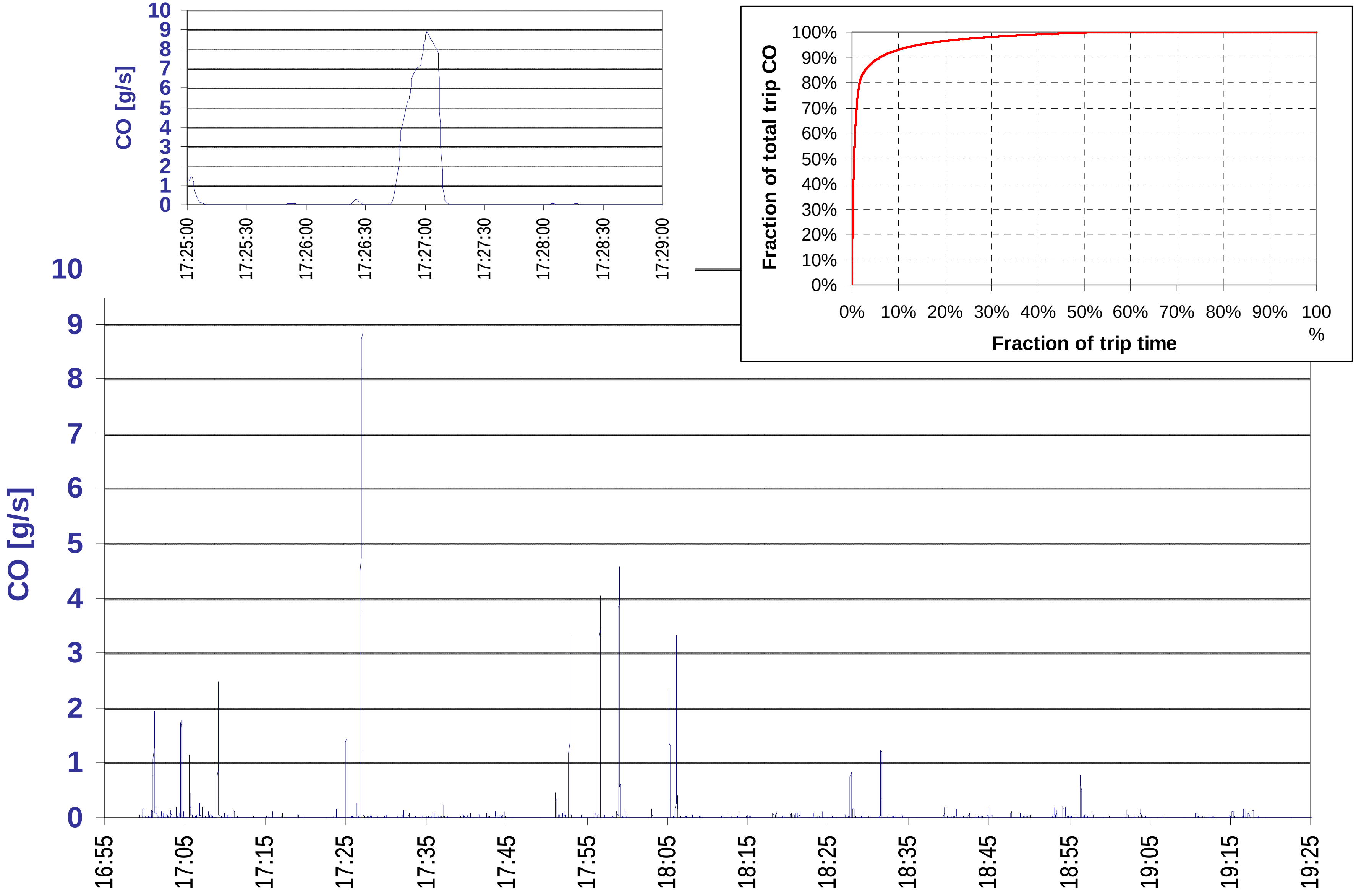


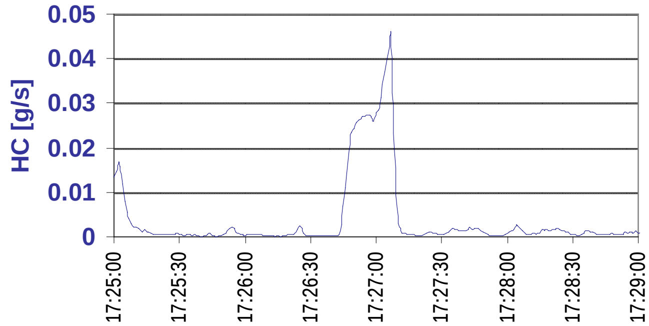
Example: High-speed cruise

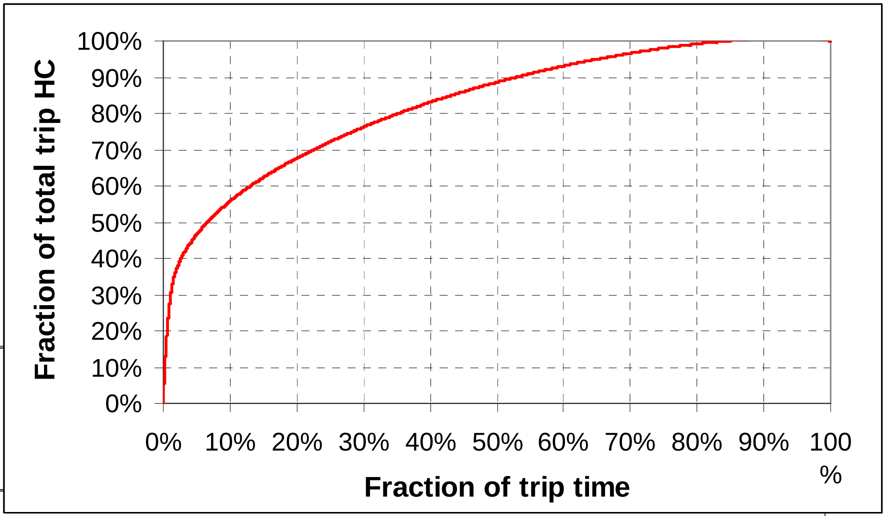
Passenger car, 138 kW turbocharged gasoline engine

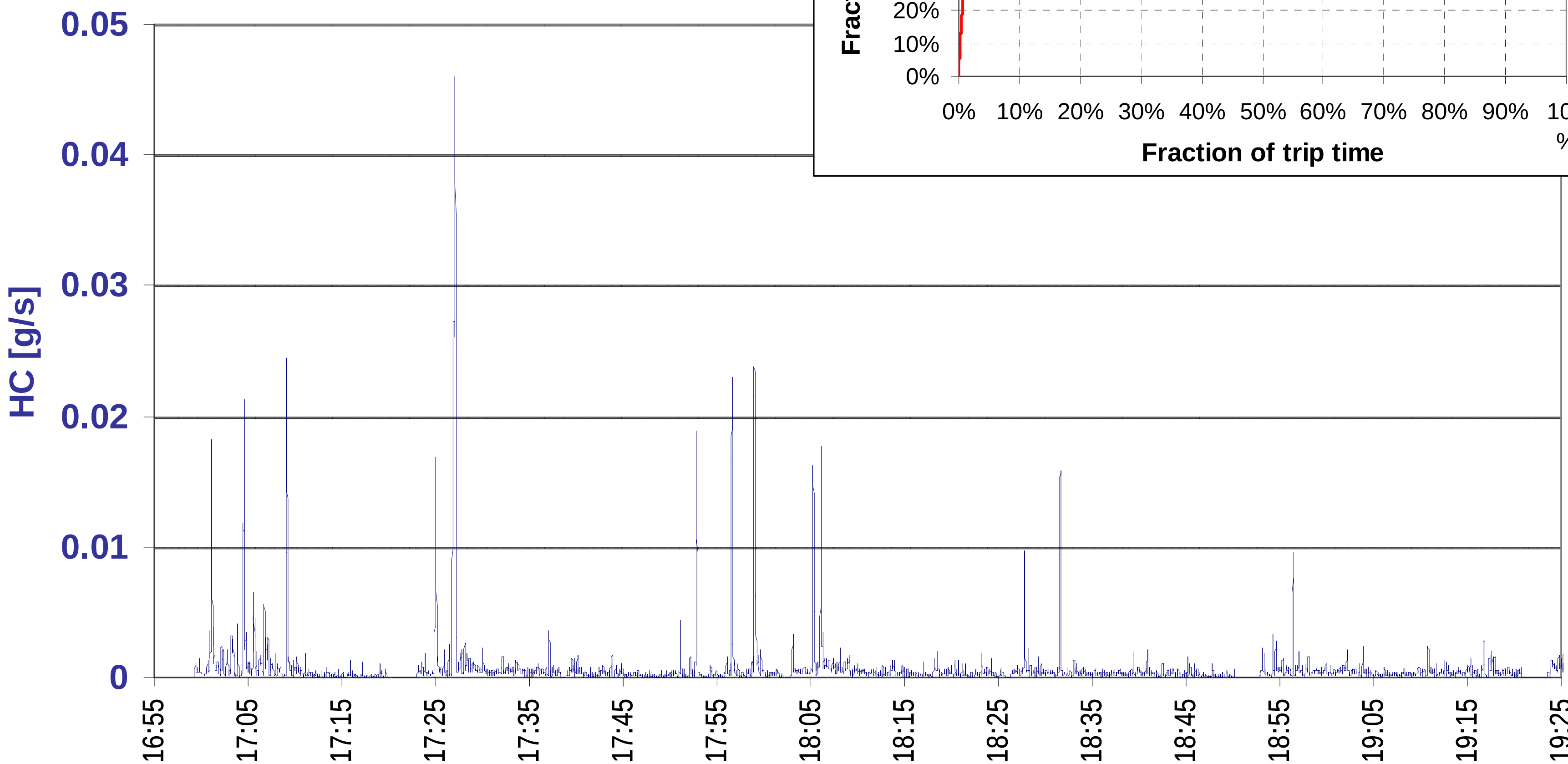


Example: High-speed cruise

Passenger car, 138 kW turbocharged gasoline engine







PM emissions as a function of engine load
2001 VW Golf, 1.9 TDI engine

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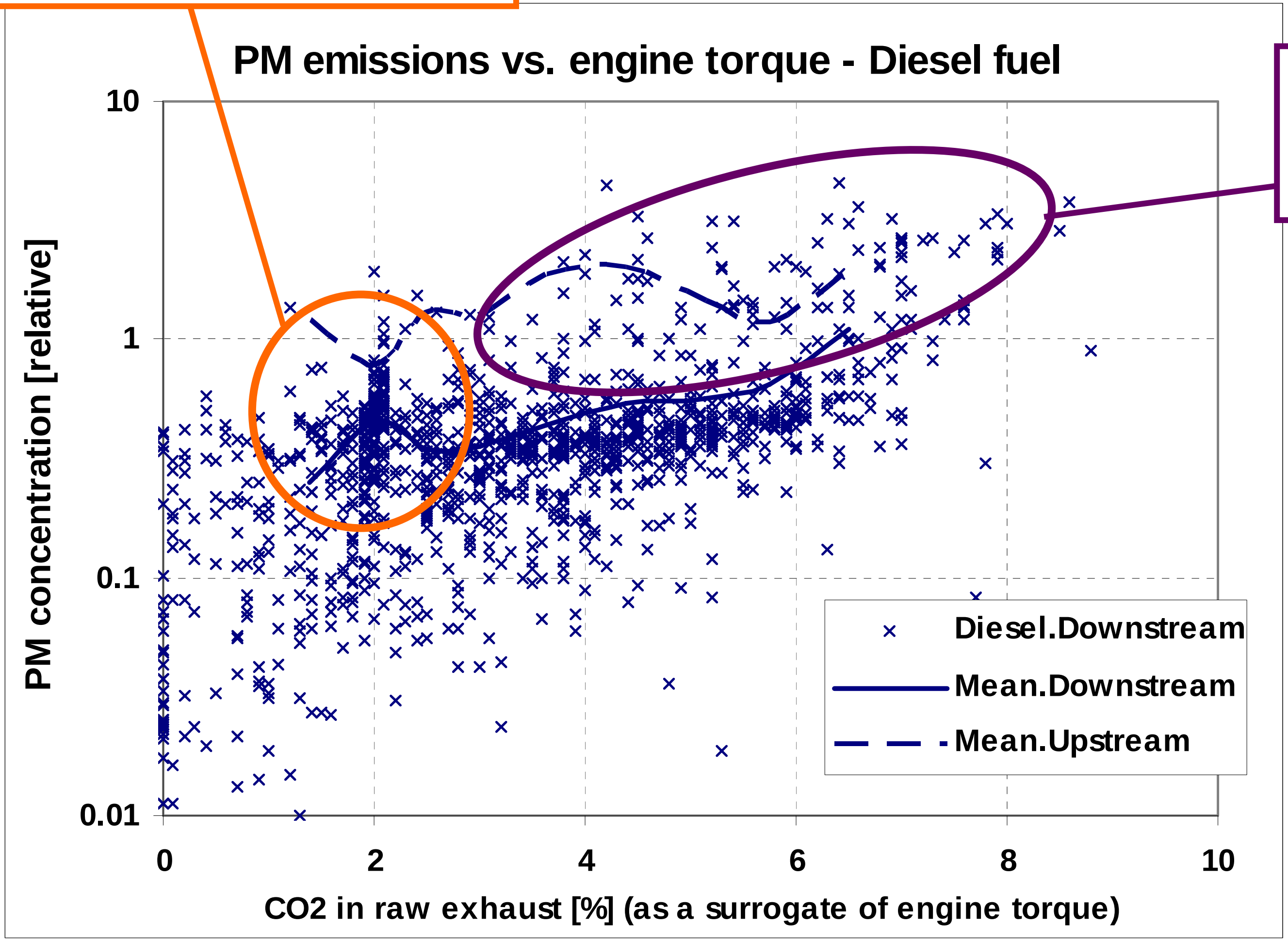
Idle (also prolonged idling)
Low exhaust and catalyst temperatures
PM dominated by organics

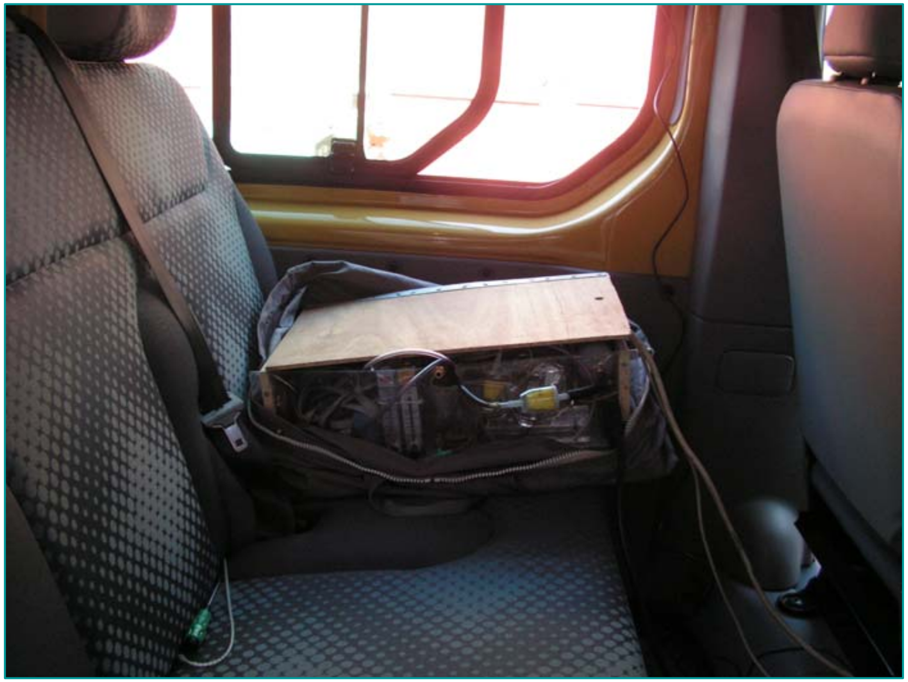
When considering second-by-second emissions data, mean emissions are higher than median emissions, suggesting high contribution of transients to total emissions

Transient high loads
Overfueling conditions
PM dominated by soot



Data: Vojtisek-Lom, 11th ETH

Example: Off-cycle and transient emissions

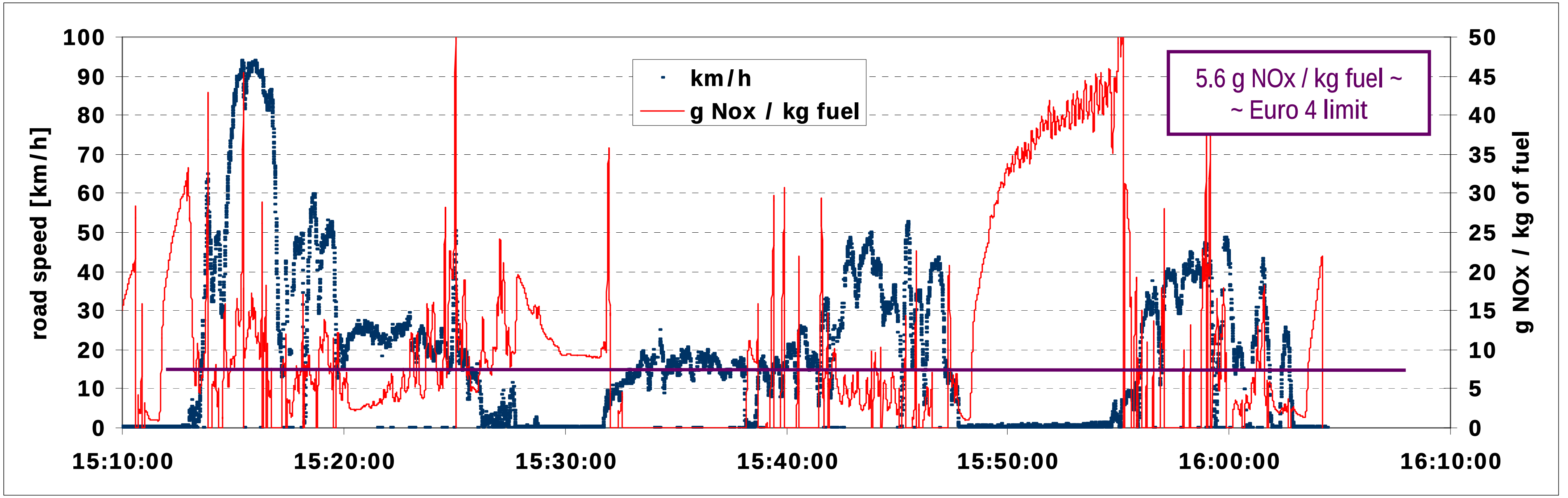


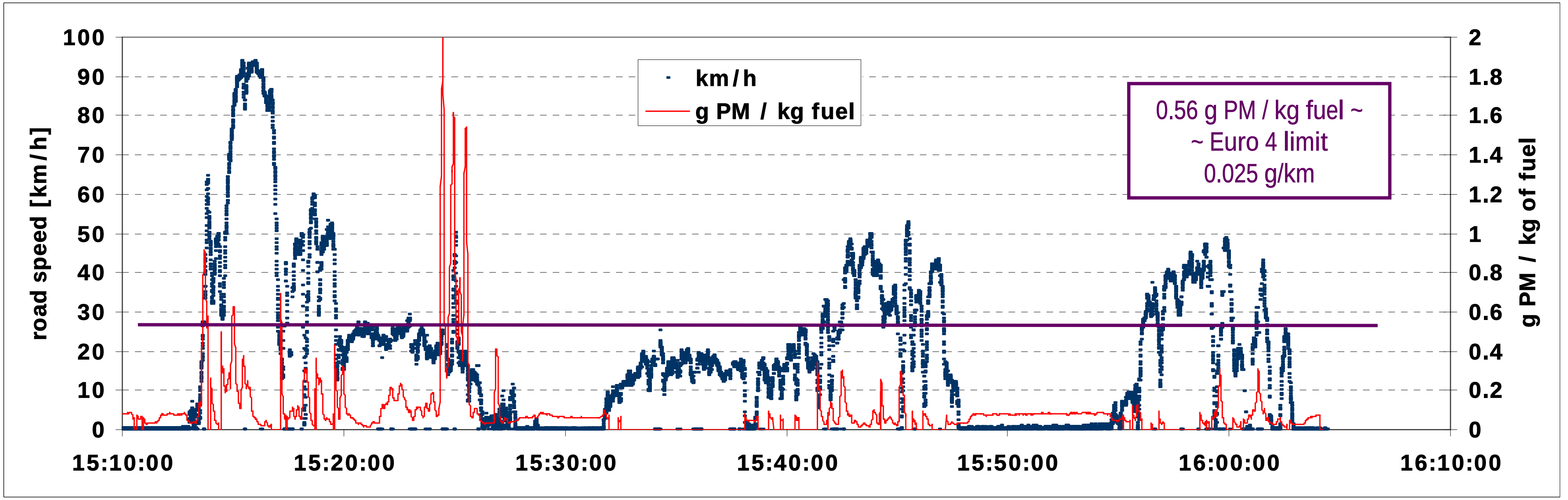
A 2007 Renault Master van equipped with a portable on-board emissions monitoring system

Ordinary operation, moderately hilly urban and semi-rural area

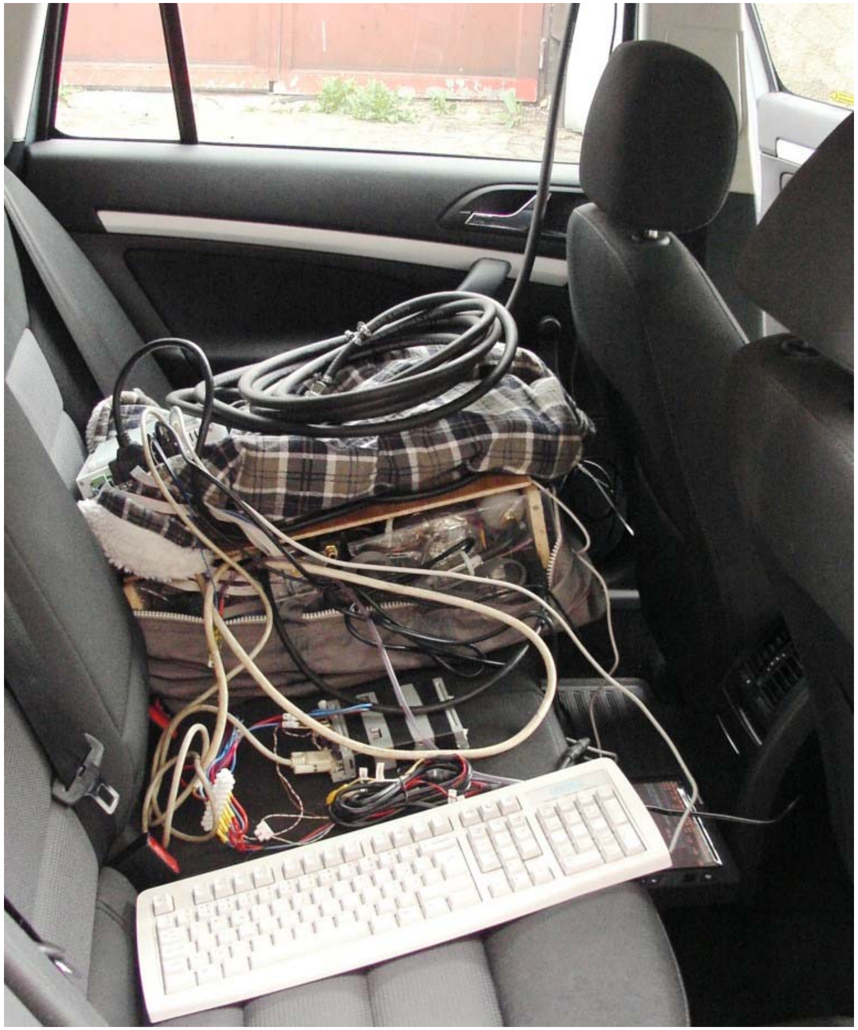
Emissions expressed in grams per kg of fuel
(deemed to be the most univerzal unit for comparison among various vehicle types and operational patterns)

Example: Off-cycle and transient emissions





Example: Effect of “performance” driving



A 2006 Škoda Octavia with 2,0-liter, 103 kW turbocharged diesel engine, instrumented with a portable on-board emissions monitoring system.

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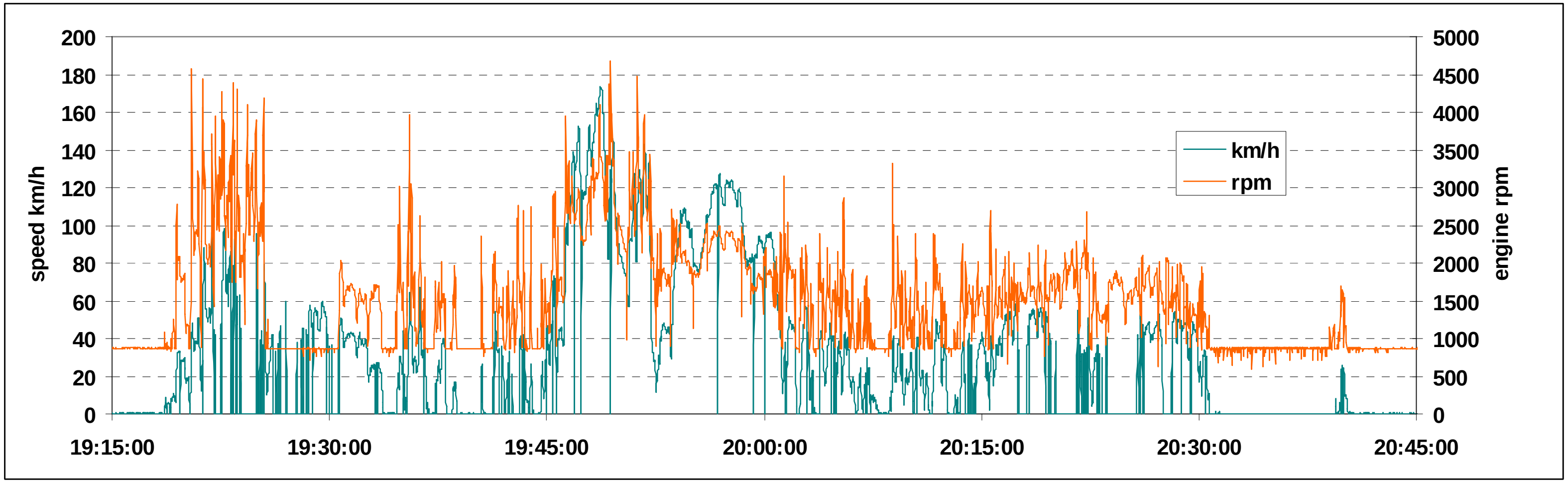
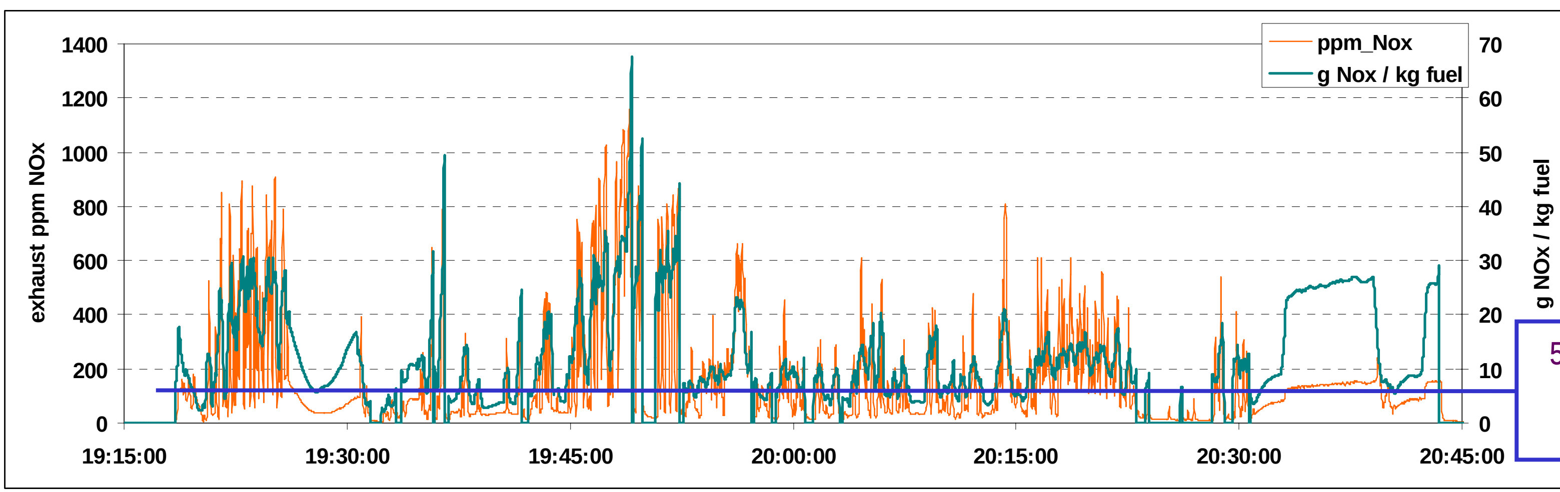
Example: Effect of “performance” driving



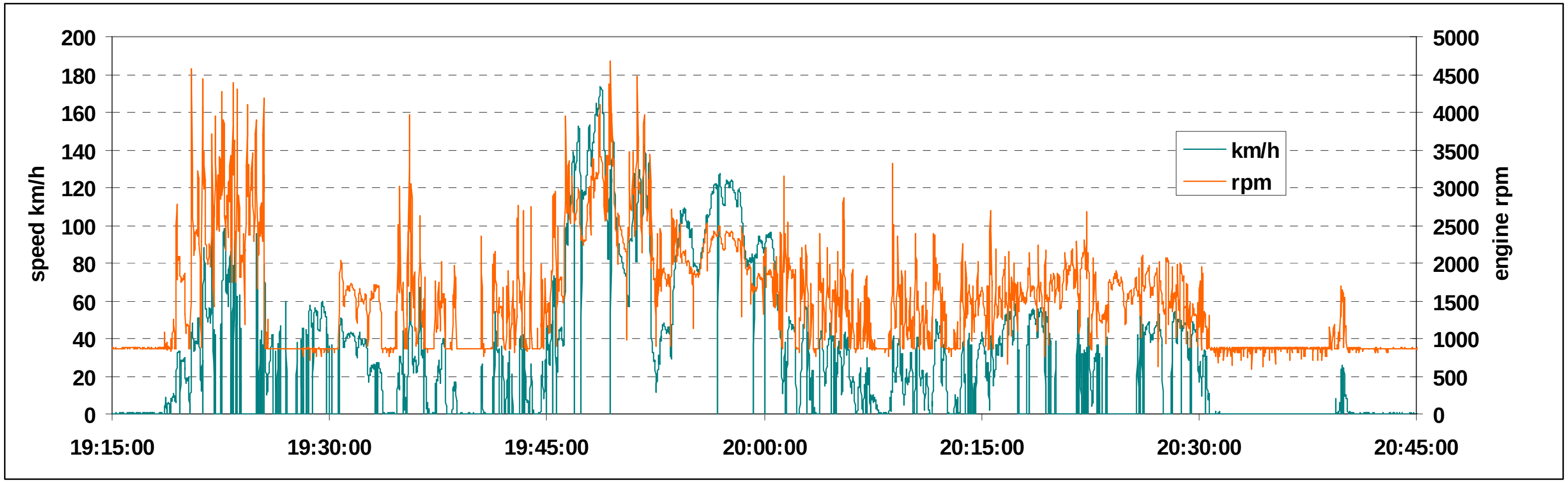
Mountain road - performance | City driving | Expressway | City driving | Mountain road - ordinary | idling

climb | descend | perf. | normal | climb | descend

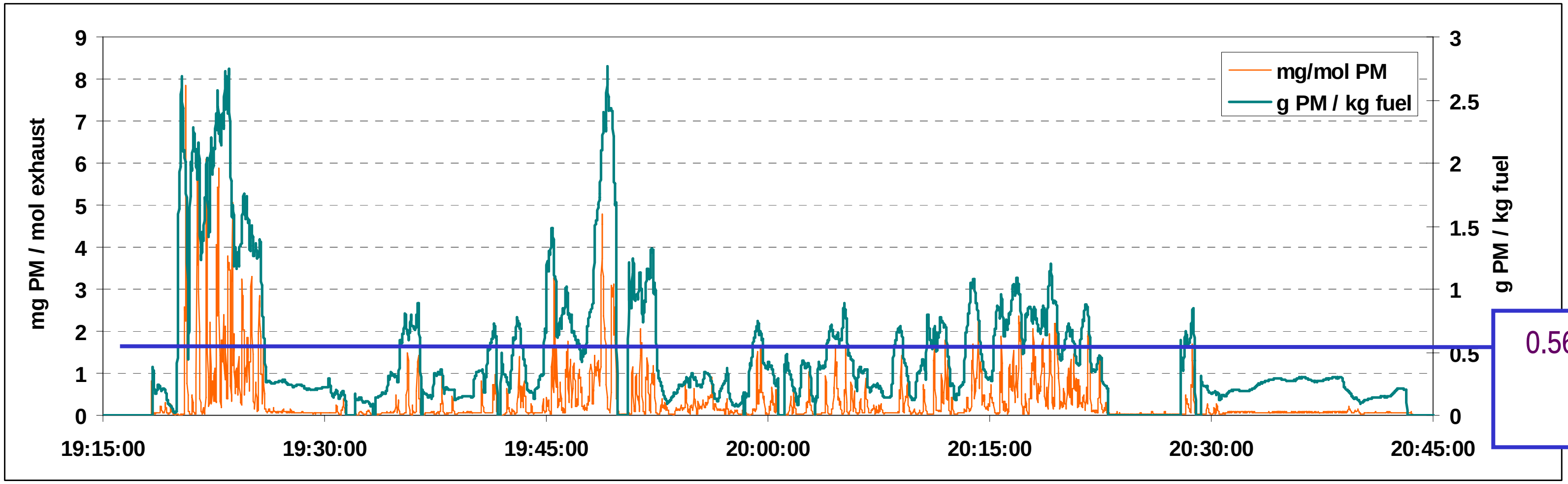


5.6 g NOx / kg fuel ~ ~ Euro 4 limit 0.25 g/km

Example: Effect of "performance" driving



Mountain road - performance: climb, descend
City driving
Expressway: perf., normal
City driving
Mountain road - ordinary: climb, descend
idling



0.56 g PM / kg fuel ~
~ Euro 4 limit
0.025 g/km

Aggressive driving: Not just cars!
Example: New York City Staten Island Ferry

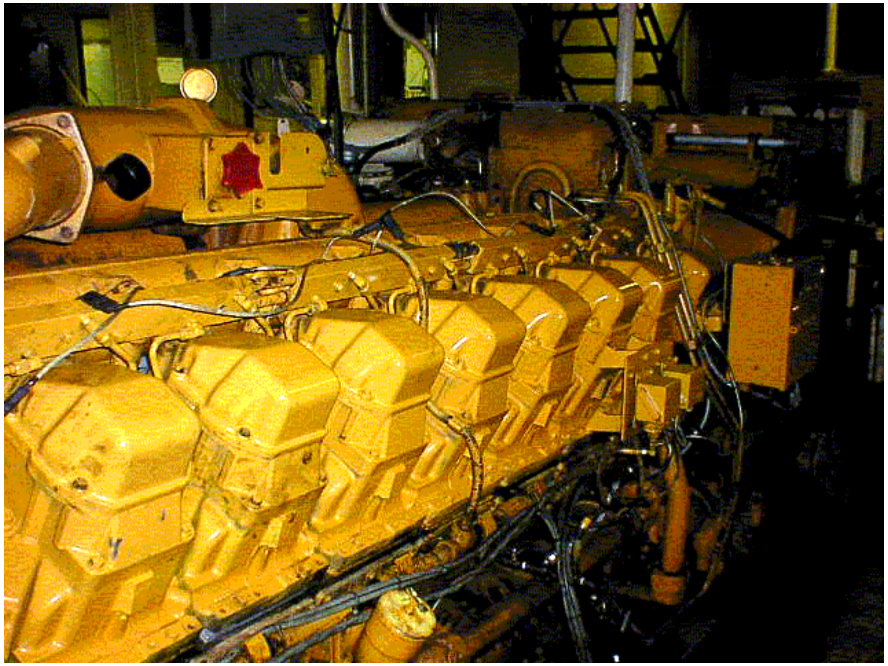
Vessels: Alice Austen and John N. Noble, 499 ton, 207’, 1288 passengers

Operation:

- Passenger ferry between Staten Island and Lower Manhattan in New York City
- 8 km, 20 minutes each way, 11 pm – 6 am, one round-trip each hour

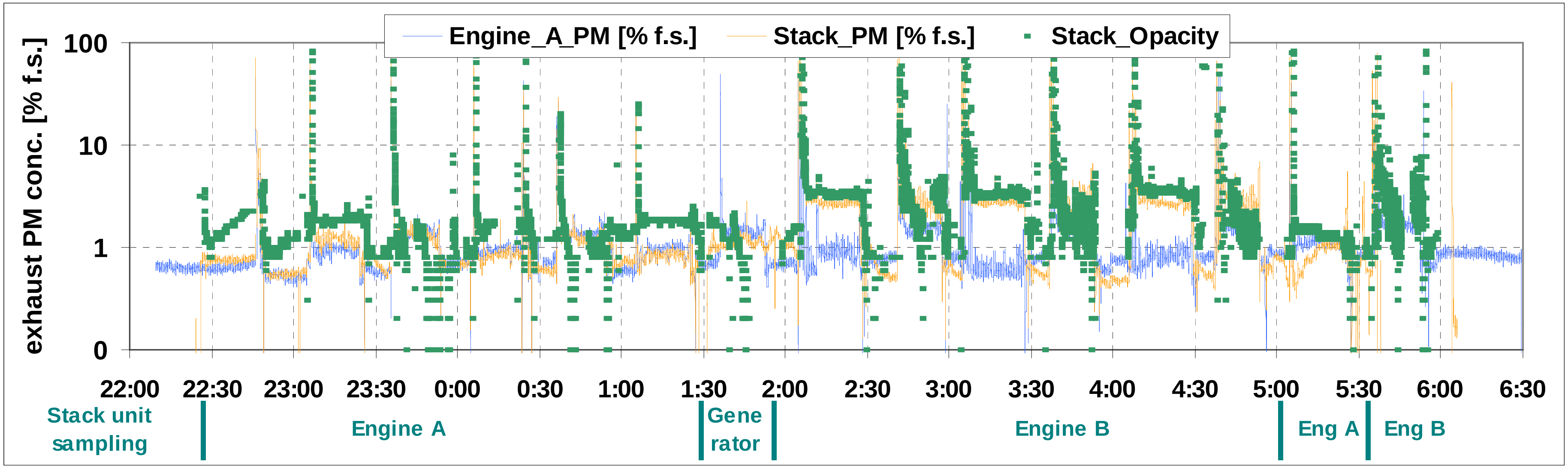
Engines (all model year 1986):

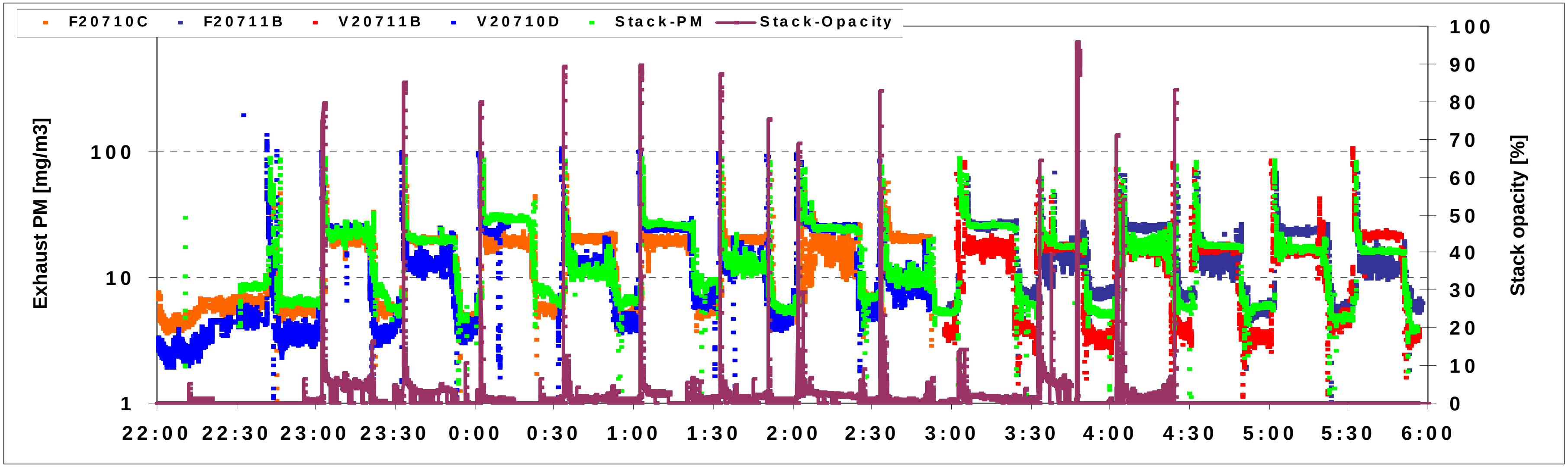
- 2 Caterpillar 3516 V-16, 69-liter, 1150 kW drive engines
  - directly coupled to Voith-Schneider cycloid drive propulsion system
- 2 generators (Caterpillar 3406); 1 used
- 1 emergency backup generator; not used



Data: Vojtisek-Lom, 13th CRC workshop on Real-world Vehicle Emisisons, San Diego, California, USA, 2003.

Example: Passenger ferry PM emissions





Concentration data over an 8-hour shift. New York City Staten Island Ferry, 2002. Author data

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Passenger ferry operation: Ways to accelerate to a cruising speed

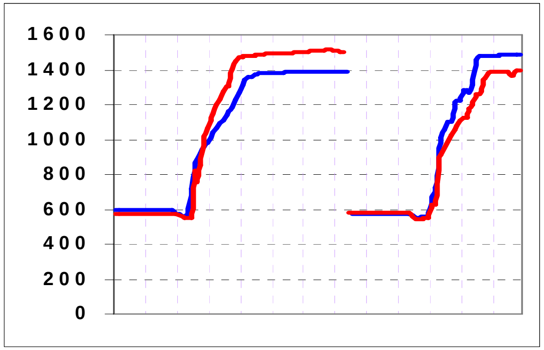
"Wild"

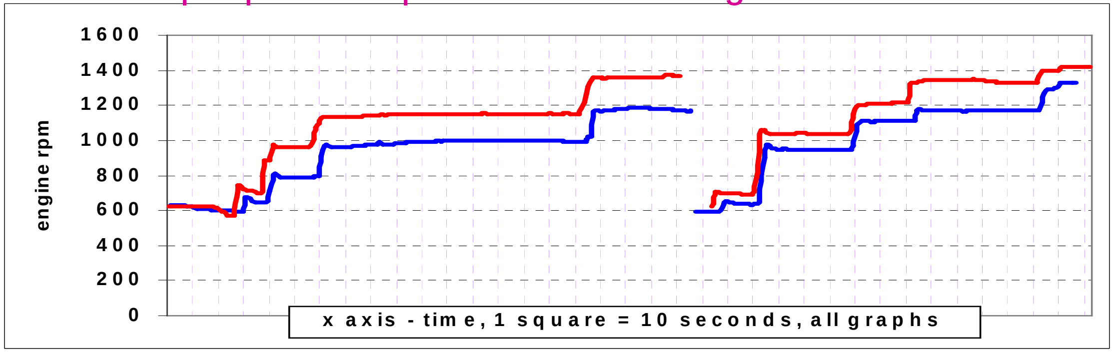
Idle to full power in one move

"Mild"

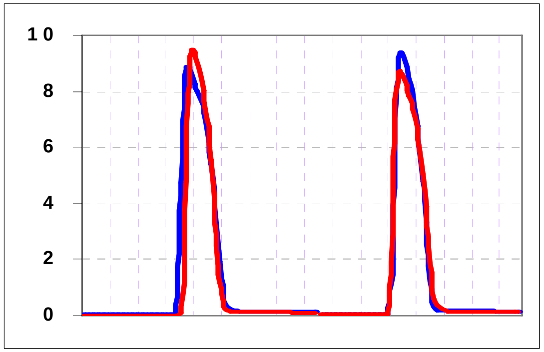
Ramp-up to full power in several gradual increments

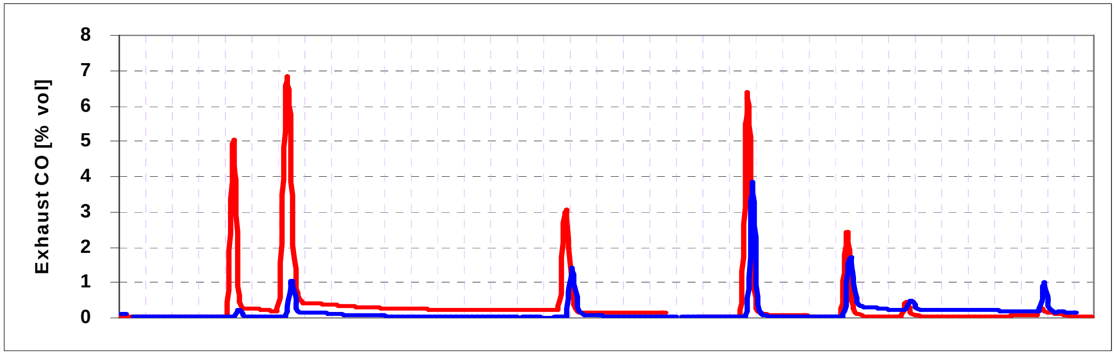
rpm



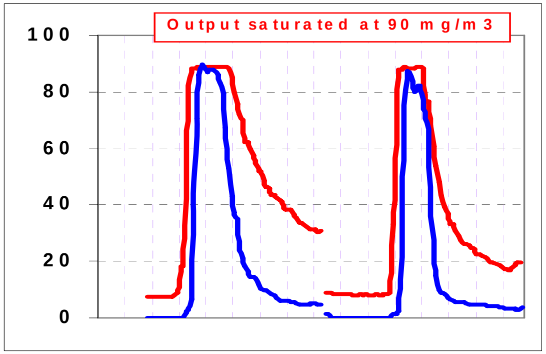


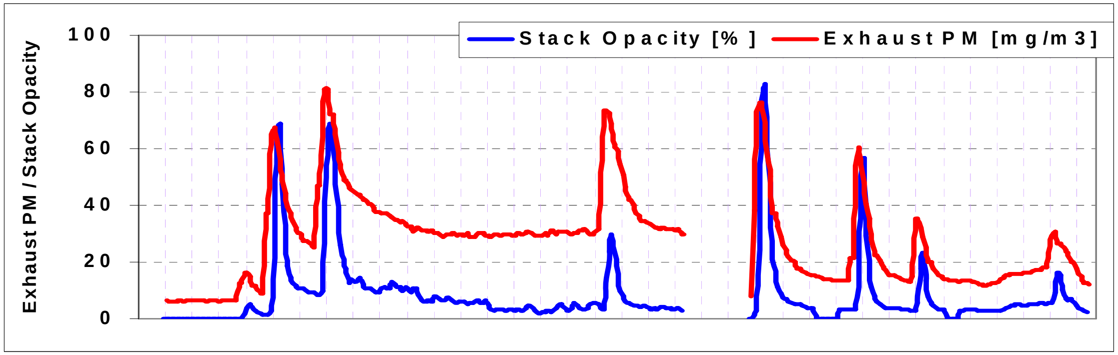
CO





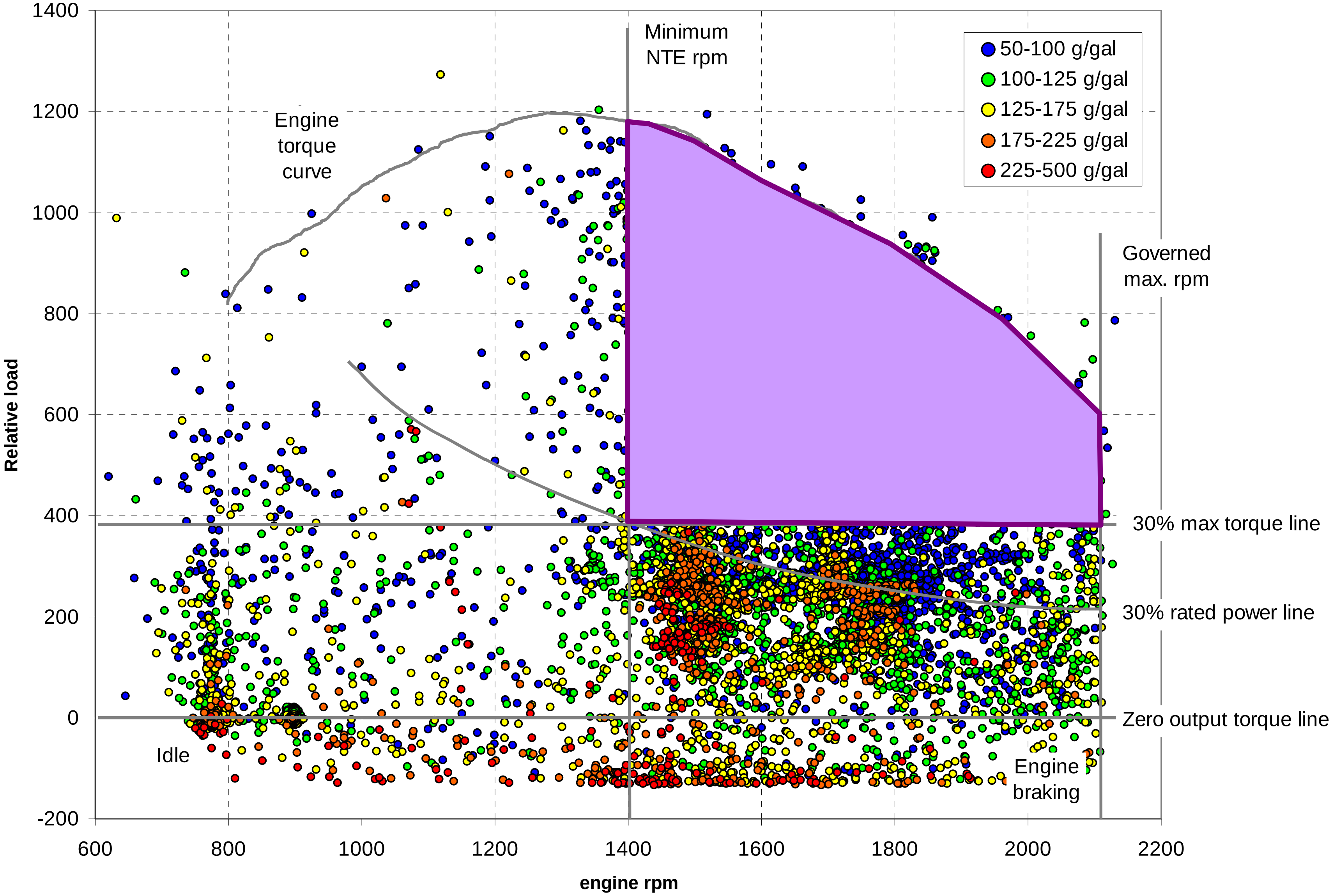
PM





Data: Vojtisek-Lom, 13th CRC workshop on Real-world Vehicle Emisisons, San Diego, California, USA, 2003.

U.S. Not-to-exceed (NTE) zones vs. NOx emissions in real-world operation of a truck



Solutions?

Better standards for new vehicles

- Emissions standards based on metrics expressing the level of danger to public (number based standards)
- Cycles representing actual operation, or, real-world testing component

Already being prepared – but – fleet turnover is slow (CZ average vehicle age is 10-15 years)!

Decreasing vehicle-km traveled

- Restrictions on vehicle travel historically difficult in democratic society
- Place- or time-specific tolls (center cities, rush hour)
- Emissions-based tolls

Implementation of cleaner fuels (FAME blends, biofuels, ...)

Retrofits of existing fleets

- Repowering with newer engines
- Installation of exhaust gas aftertreatment devices
- Variety of engine component upgrades

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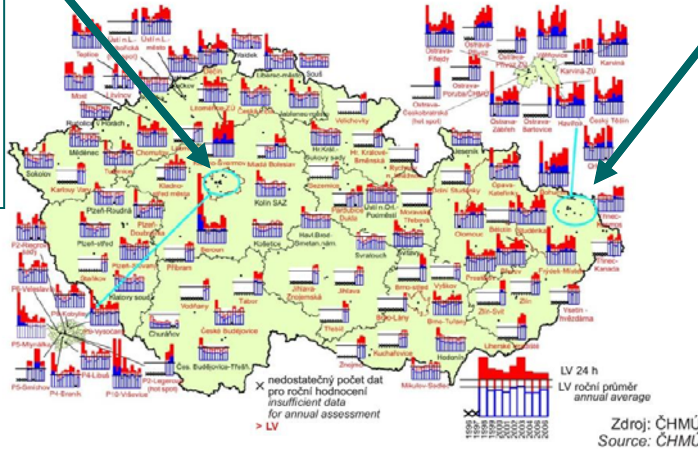
Czech diesel retrofit programme

City of Prague – Highest PM emissions per km²

- **Magistrate of Prague**
- **City-owned Prague Transit Co.** (public transit urban bus fleet)
- **City-owned Prague Services** (waste management, street maintenance)

Two regions with worst air quality:

36. nejvyšší 24h koncentrace a roční průměrné koncentrace PM_{10} na vybraných stanicích, 1996–2006
36^{th} highest 24-hour concentrations and annual average concentrations of PM_{10} at selected stations, 1996–2006



Moravskoslezský region and city of Ostrava – Highest PM concentrations

- **Regional government of the Moravskoslezský region**
- **Magistrate of Ostrava**
- **City-owned Ostrava Transit Co.** (public transit urban bus fleet)
- **Regional Highway maintenance department**

Czech diesel retrofit programme

Ideal retrofit candidate fleet

Medium to large fleets of centrally maintained vehicles
Vehicles operated entirely in the urban areas to be benefitted
Vehicles accumulating high annual service hours
Large vehicles burning large quantities of fuel
Support of the project by the fleet, at all levels

Which technology?

Previous experience exists with compressed natural gas and biodiesel blends.
In this project, focus will be on diesel particulate filters, which have not been implemented on a large scale in the country.

Which vehicles?

Vehicle in heavy service (large number of service hours)
Vehicle groups with identical or similar chassis and engine
Vehicles with at least several years of service life left
Vehicles in operating regimes suitable for filter regeneration

New vehicles (Euro V) will also be considered for retrofit. These vehicles have low PM mass emissions, but might have high PM number levels.

Photo: Tailpipe of a Euro V certified truck suggests abundant PM emissions.

Czech diesel retrofit programme

Principal partners:

Ministry of the Environment of the Czech Republic
Regional government of Moravskoslezský region
Magistrate of the city of Ostrava
Magistrate of the city of Prague
Prague Public Transit, Bus division
Prague Services (waste collection and street maintenance)
Highway maintenance authority of the Moravskoslezský region
Dept. of Vehicles and Engines, Technical University of Liberec
TUV-SUD, Prague (national certification/approval laboratory)
TTM, Niederrohrdorf, Switzerland
TerraConsult, Bern, Switzerland

Funding

- Two separate projects (Ostrava and Prague)
- Project budget about 5 million Euro or 8 million CHF for each project
- Proposal is being prepared to cover 85% costs of the project from the Swiss cohesion funds offered to newly joined EU states (CHF 100 million devoted to environment, with preference given to Moravskoslezský region)

Conclusions

The benefits offered by new emissions standards and technology of new vehicles appear to be diminished or overcome by a combination of several interrelated phenomenae:

- *increase in vehicle kilometers traveled*
- *increase in volume-to-capacity ratio of roadways*
- *increase in transiency of engine operation*
- *reliance on advanced technologies, controls and aftertreatment*
- *increase in power/weight ratio*
- *increase in occurrence of aggressive or performance driving*
- *slow fleet turnover and migration of the used vehicles eastward*

Should these trends continue (situation might improve given the rising fuel prices), reduction in traffic intensity, retrofits of existing vehicles, and other measures should be considered along with the planned new emissions standards.

Conclusions

- Rapid and persistent rise in transportation intensity increases total PM emissions not only per se, but also by increase of traffic congestion, leading to frequent idle, low-load, and transient operation. Increasing power/weight ratio of the fleet induces “performance” driving.

- Low emissions are achieved thanks to advanced technology and controls coupled with exhaust aftertreatment devices. Their malfunction or reserves in optimization, notably during extreme low and high load and transient operation, can lead to higher emissions.

- Newer, cleaner vehicles take time to replace the old ones, especially in developing regions, where old vehicles from rich regions migrate to.

Should these trends continue (situation might improve given the rising fuel prices), reduction in traffic intensity, retrofits of existing vehicles, and other measures should be considered along with the planned new emissions standards.

Acknowledgments

- Examples are from real-world emissions measurements done by the author.

- Previously unpublished measurements were financed by the author, by the Ministry of Education of the Czech Republic, project 1M0568 - Josef Bozek Research Centre for Engine and Vehicle Technologies II, and by the Czech Science Foundation grant no. 101/08/1717.

- Czech Retrofit Programme is a joint effort of the mentioned partners.

Department of Vehicles and Engines
Internal Combustion Engine Laboratory

- Engine dynamometers (up to 700 kW)
- Light duty vehicle chassis dynamometer
- Hydrogen, CNG, LPG fueling systems
- In-cylinder pressure indication, combustion visualization
- Gaseous and PM emissions measurements
- Fundamental combustion research
- Computational simulations
- Engine engineering
- Powertrain lab
- Vibrodiagnostics lab