Acknowledgements

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Real-time, on-road measurements of diesel exhaust aftertreatment device PM removal efficiency

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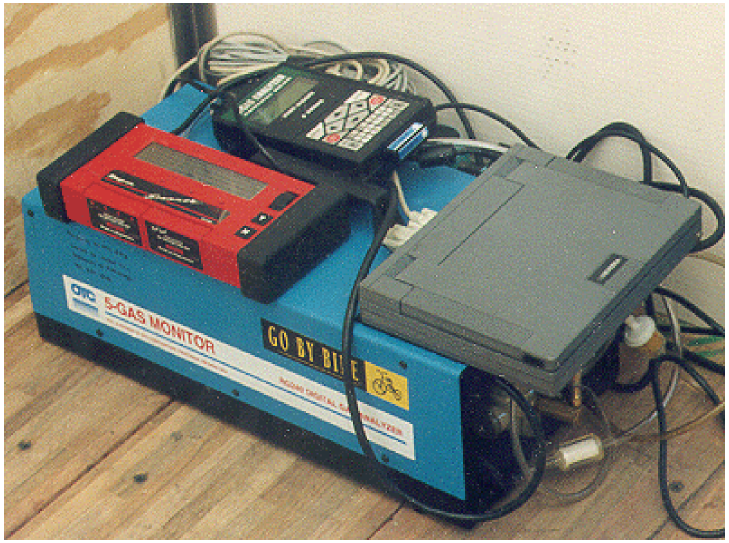
Background

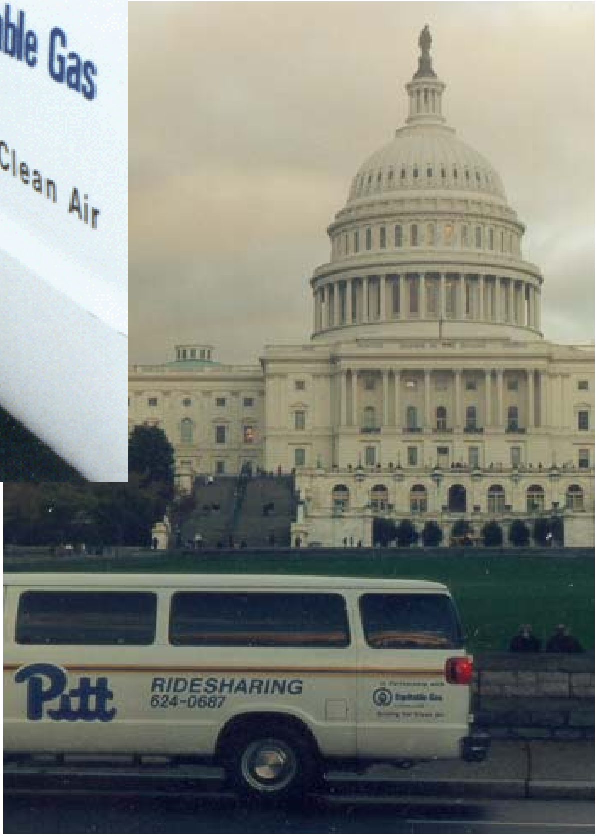
Modern engines increasingly rely on the combination of electronic engine controls and exhaust aftertreatment devices to achieve low emissions.

Various deviations from “ideal operation” typically result in substantially higher emissions.

Small number of vehicles and small portion of total operating time have a disproportionately high contribution to the total emissions.

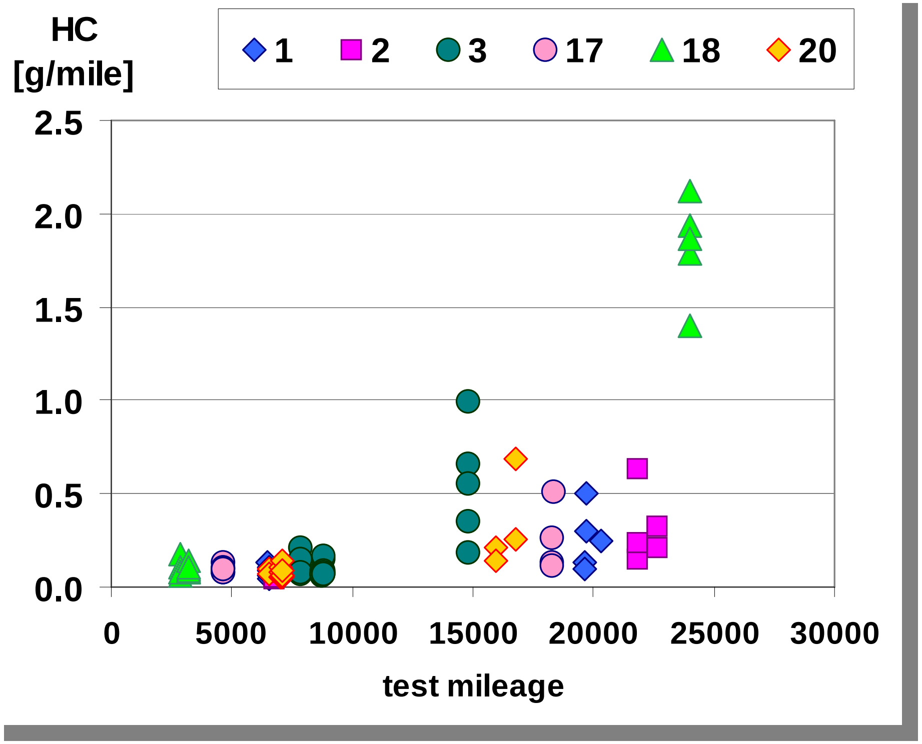
Example: On-road tests of CNG buses
(Pittsburgh, USA, 1996-99)

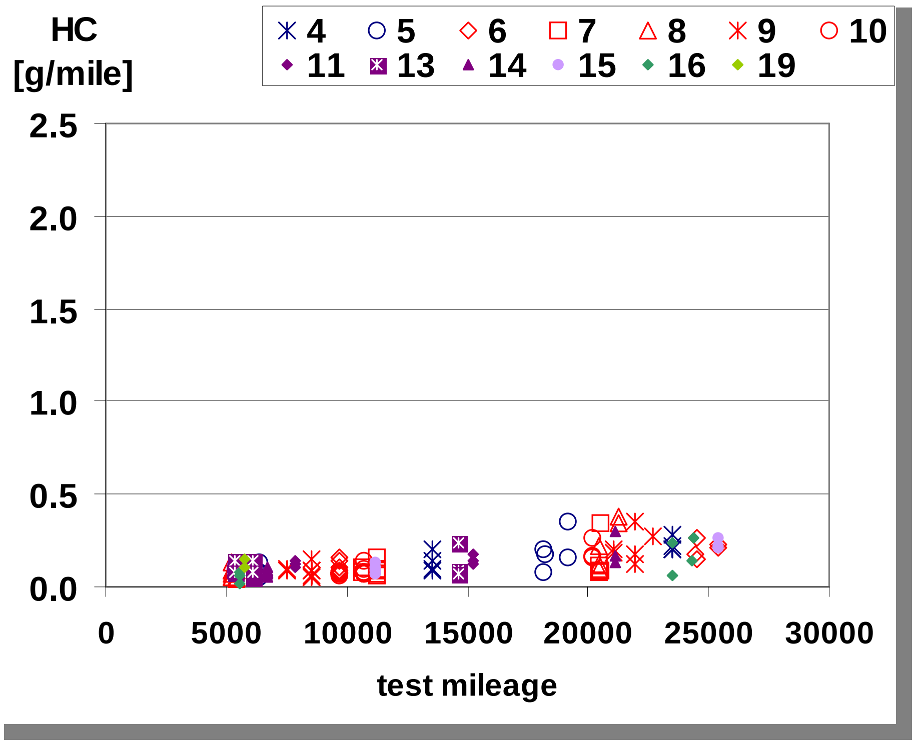




Example: On-road tests of CNG buses

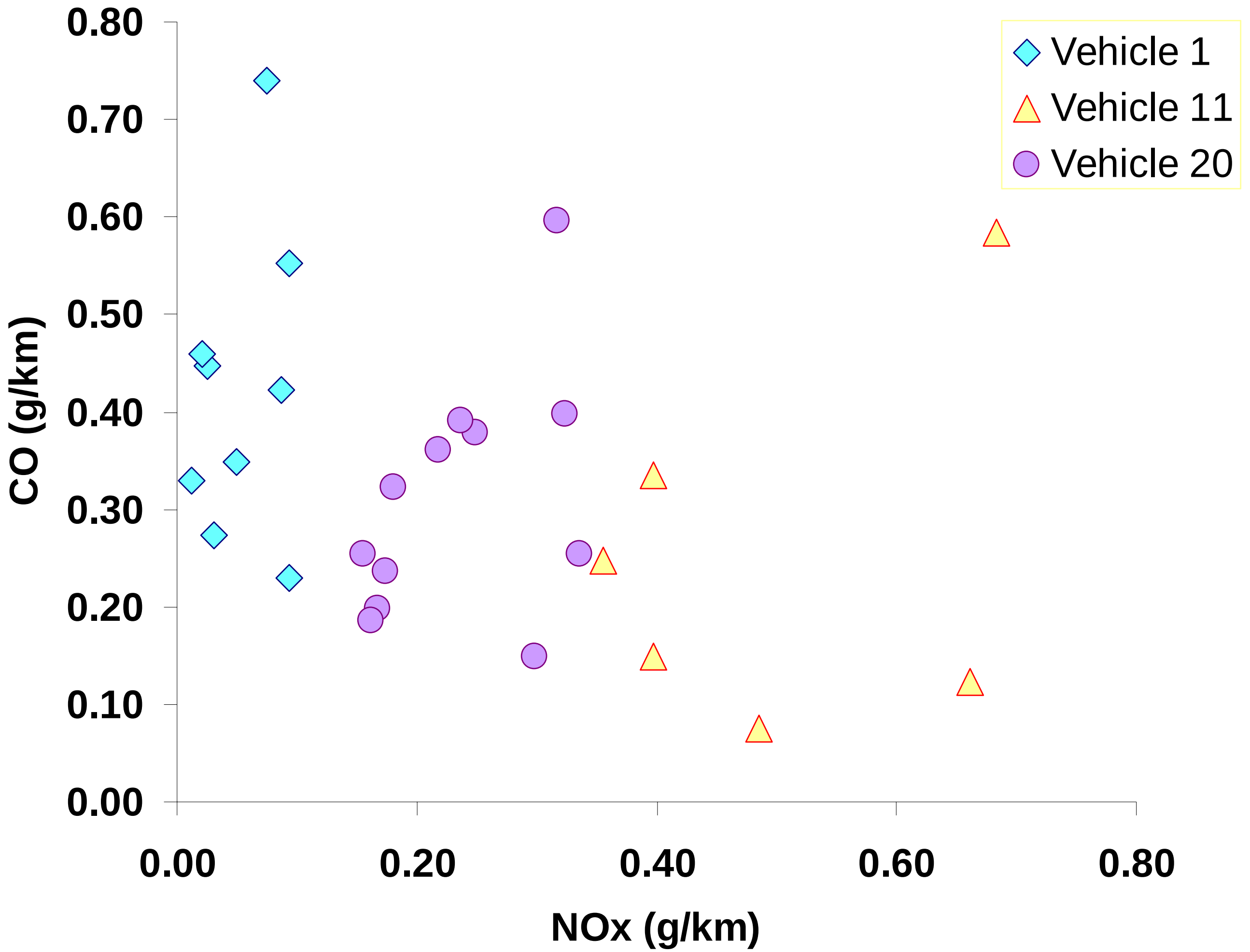
HC emissions deterioration rates





Example: On-road tests of CNG buses

Differences among identical vehicles



Why on-road measurements?

When evaluating benefits of a fleet-wide deployment of a new technology, high emissions vehicles and high emissions episodes cannot be ignored as “outliers”, but must be characterized and accounted for.

On-road measurements using portable on-board systems allow for testing of a large set of vehicles under a wide range of operating conditions.

Measurements can be done during normal everyday operation of the tested equipment.

Evaluation of aftertreatment devices

Use one monitoring system. Run separate identical tests with and without aftertreatment, compare.

+ Relatively easy test

– Tests have to be repeatable

Real-time or proportional sampling instrumentation

Use two monitoring systems, one upstream, one downstream of the aftertreatment

+ Tests do not have to be repeatable

– More difficult realization of the test

Instrumentation has to measure in real-time (1 Hz)

Repeatability of on-road measurements

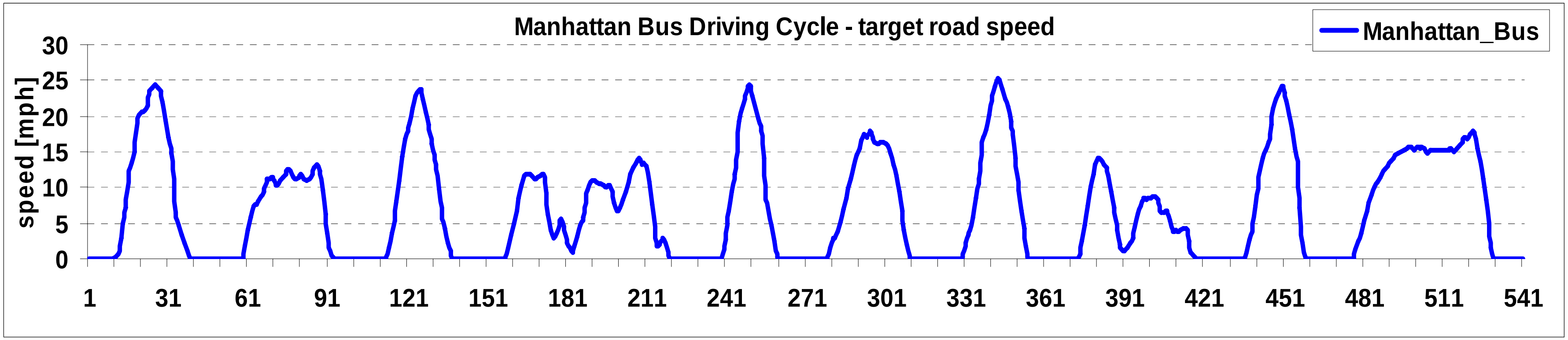
Instrumentation:

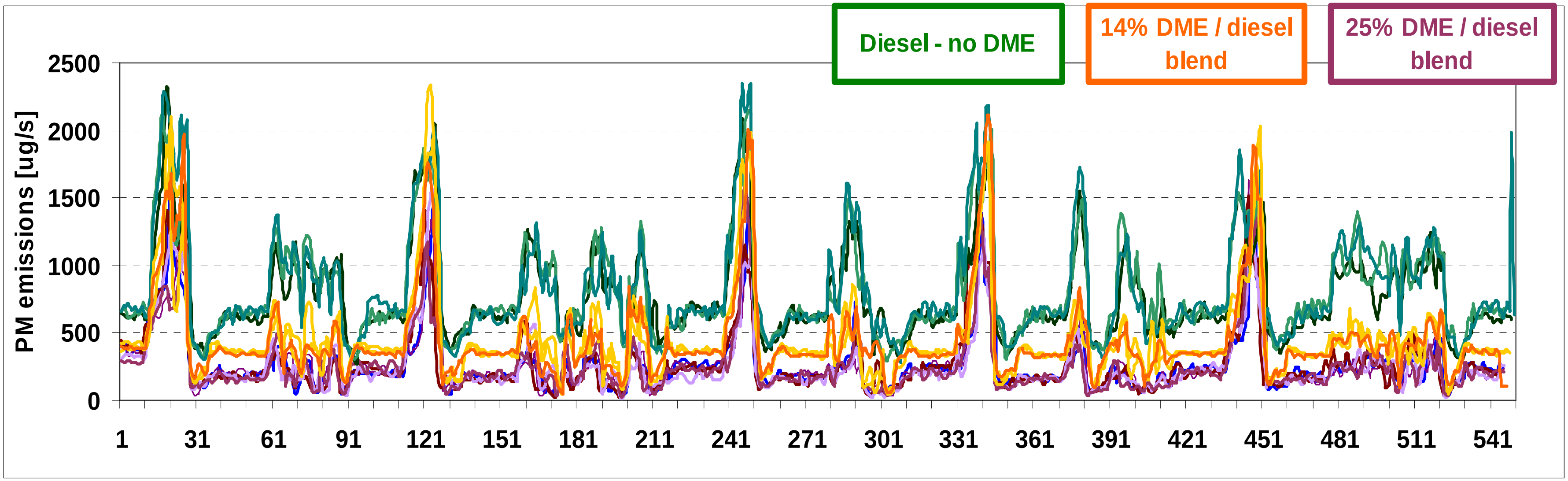
- Five-gas (HC, CO, NO, CO_2, O_2) “garage” analyzer
- Light scattering device for PM concentration measurements
- Sampling: No dilution, no heating of the line
- Exhaust flow: Computation based on engine rpm, intake air temperature and pressure, engine parameters and exhaust composition
- Second-by-second data

Vehicle: 1999 International 24-passenger bus, DT-444-E 145 kW, 7.3-liter V-8 electronically controlled direct-injection turbodiesel

On-road tests on a test track can be repeatable

Bus operating on different blends of diesel fuel and di-methyl ether (DME)
Emissions measured using Manhattan Bus cycle driven on a 1,6 km test track



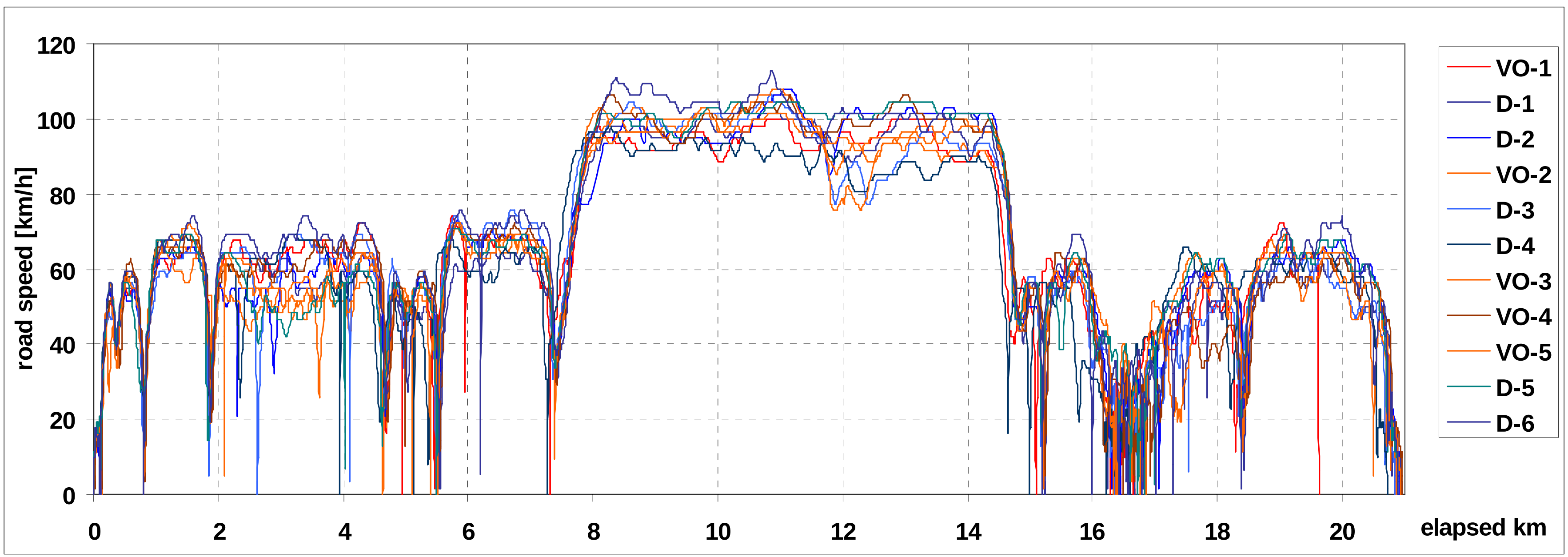


Test-to-test variance: < 10 % for computed total PM mass

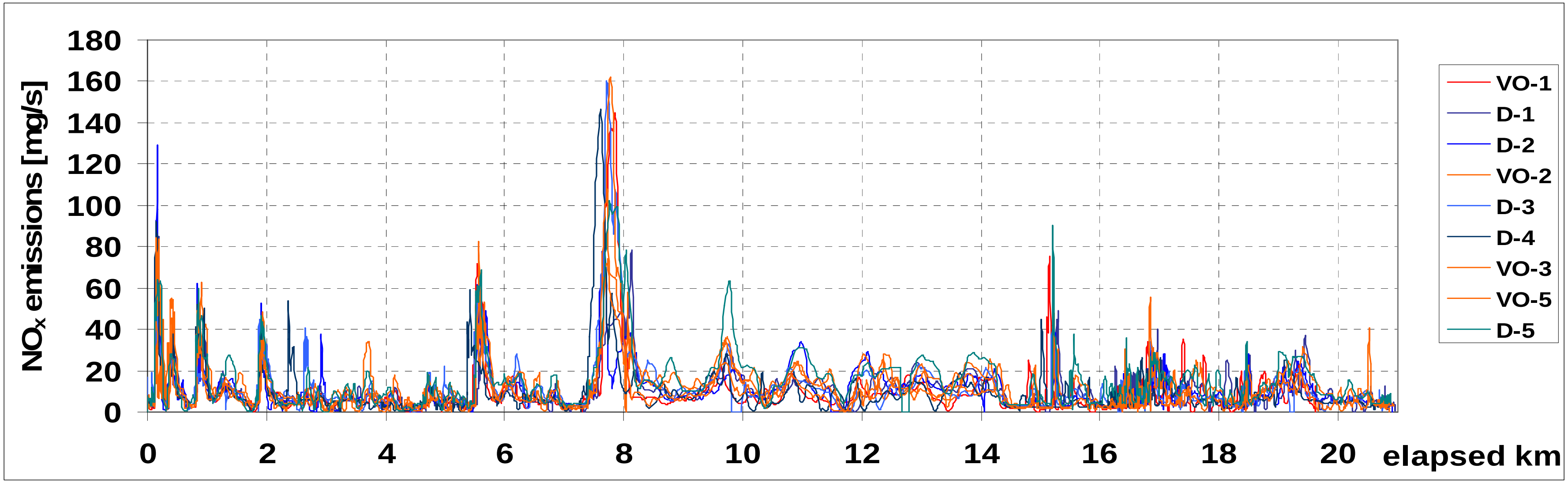
Measurements in ordinary traffic are poorly repeatable

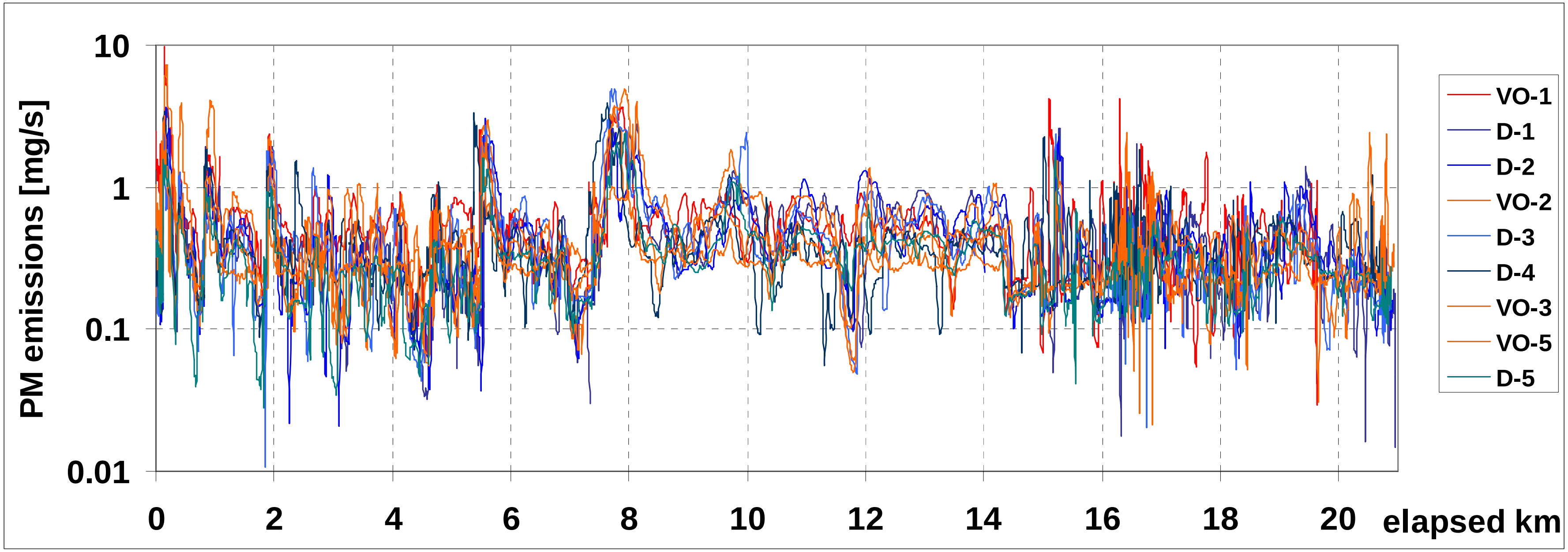
Example: VW Golf / Jetta cars powered by diesel fuel and vegetable oil. Multiple runs along a 20,9 km suburban-highway-city route.

Unlike in laboratory tests, comparison is done on a distance basis (x-axis: distance from start of the test)



Example: VW Golf car powered by diesel fuel and vegetable oil.
Multiple runs along a 20,9 km suburban-highway-city route.





Simultaneous upstream-downstream sampling

More weight, higher power consumption, decreased system reliability

Impossible to sample from a laminar flow upstream of the aftertreatment due to exhaust system geometry of most engines

But: Most diesel particles < 1 um; if sampling PM_1 or $PM_{0.5}$, sampling error is relatively small compared to other factors

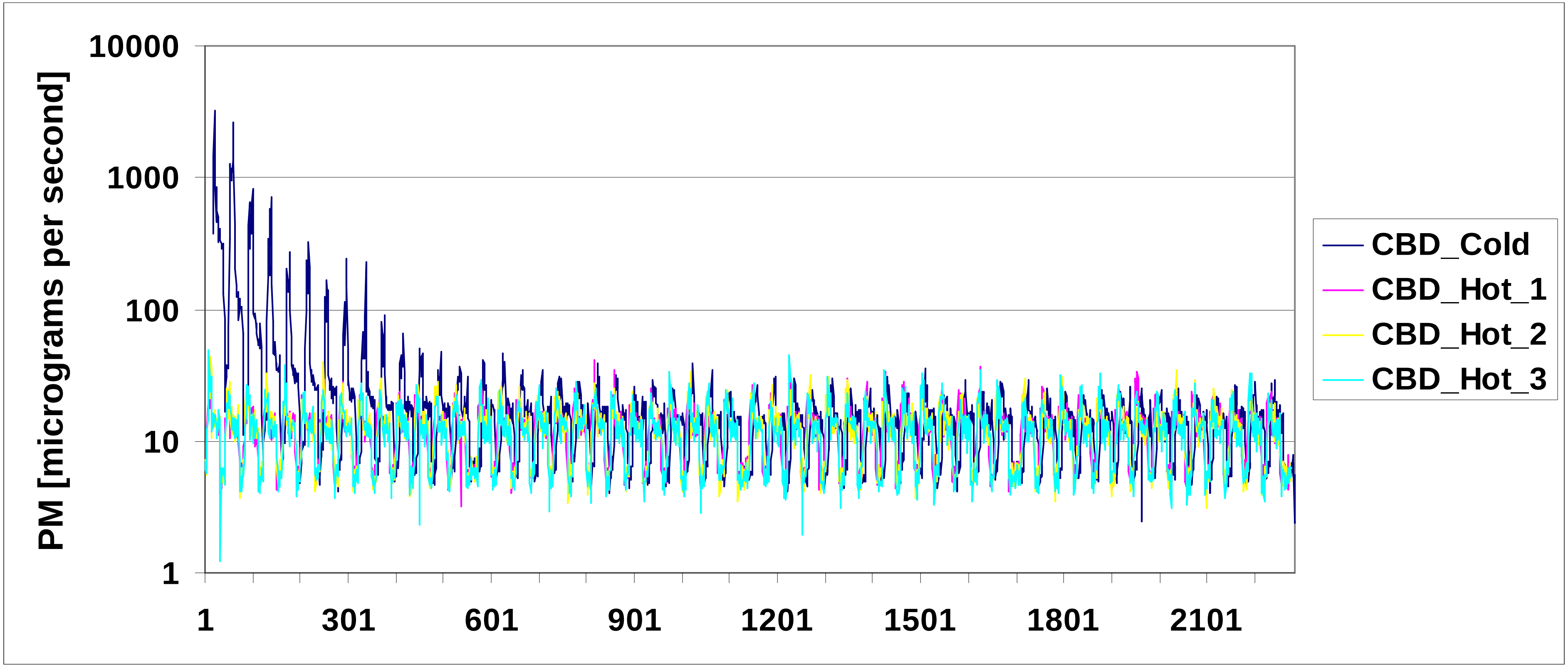
Pilot studies done using a simple light-scattering device

Simple on-board systems can be capable of <u>repeatable</u> measurements in the lab even at ~0.01 g/kWh levels (but no claims about accuracy)

2000 International 3400 truck, DT-466-E turbodiesel, CRT trap

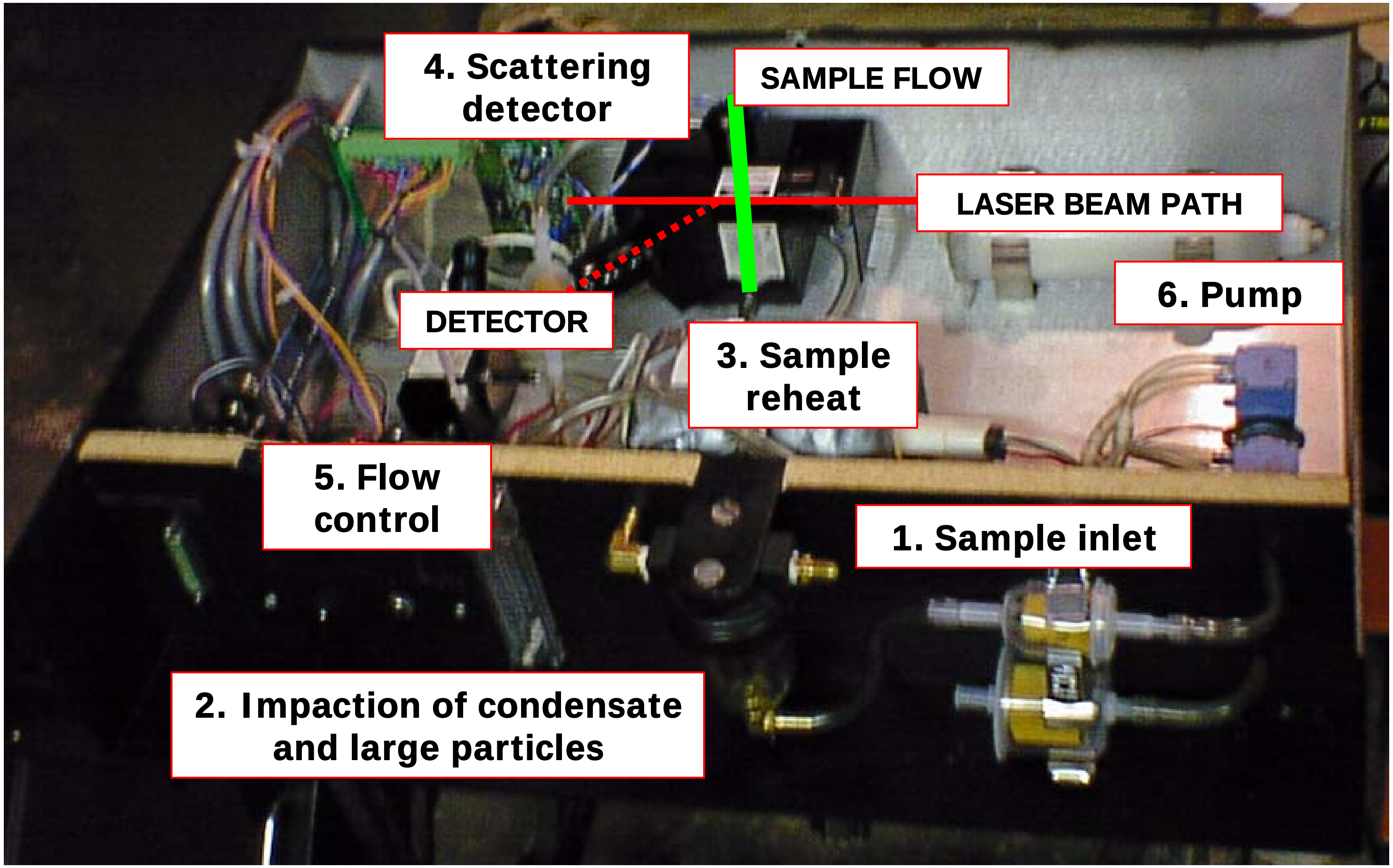
CBD cycle driven on a chassis dynamometer

PM concentrations measured with a light scattering device, exhaust flow computed



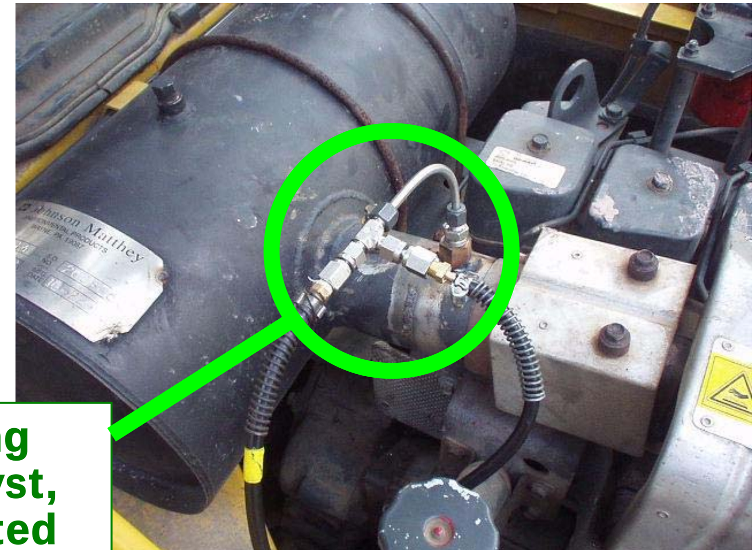
On-board PM concentrations measurement using a light scattering instrument

- Samples raw, undiluted exhaust from the tailpipe using 6 mm sample line
- Real-time measurements of PM scattering efficiency
- Robust, easy to use, low power consumption
- Data requires considerable interpretation



On-line diesel oxidation catalyst evaluation

Simultaneous Upstream / Downstream Sampling (2 monitoring Systems)



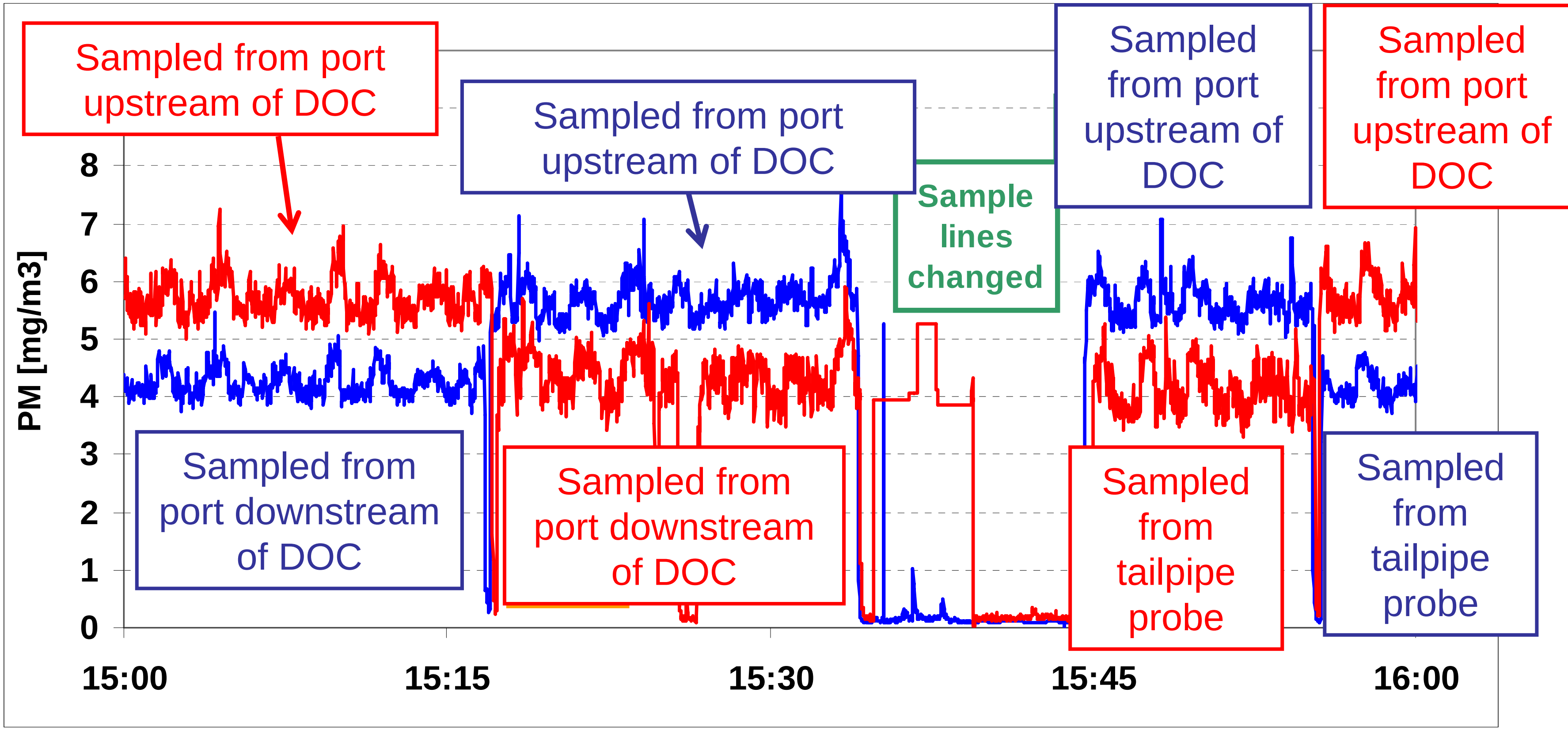
Exhaust sampling port before catalyst, ¼” probe, unheated line, no dilution

Exhaust sampling at tailpipe ¼” probe, unheated line, no dilution

Construction equipment, World Trade Center, New York

On-line diesel oxidation catalyst evaluation

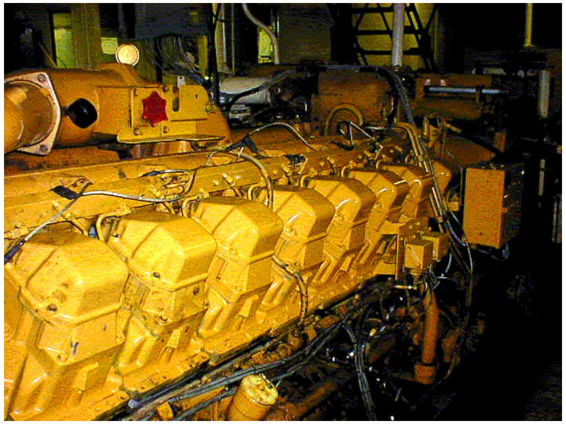
Three sampling locations: Identical sample ports upstream and downstream of DOC, ordinary probe at the tailpipe
Two monitoring systems (light scattering device for PM concentrations)

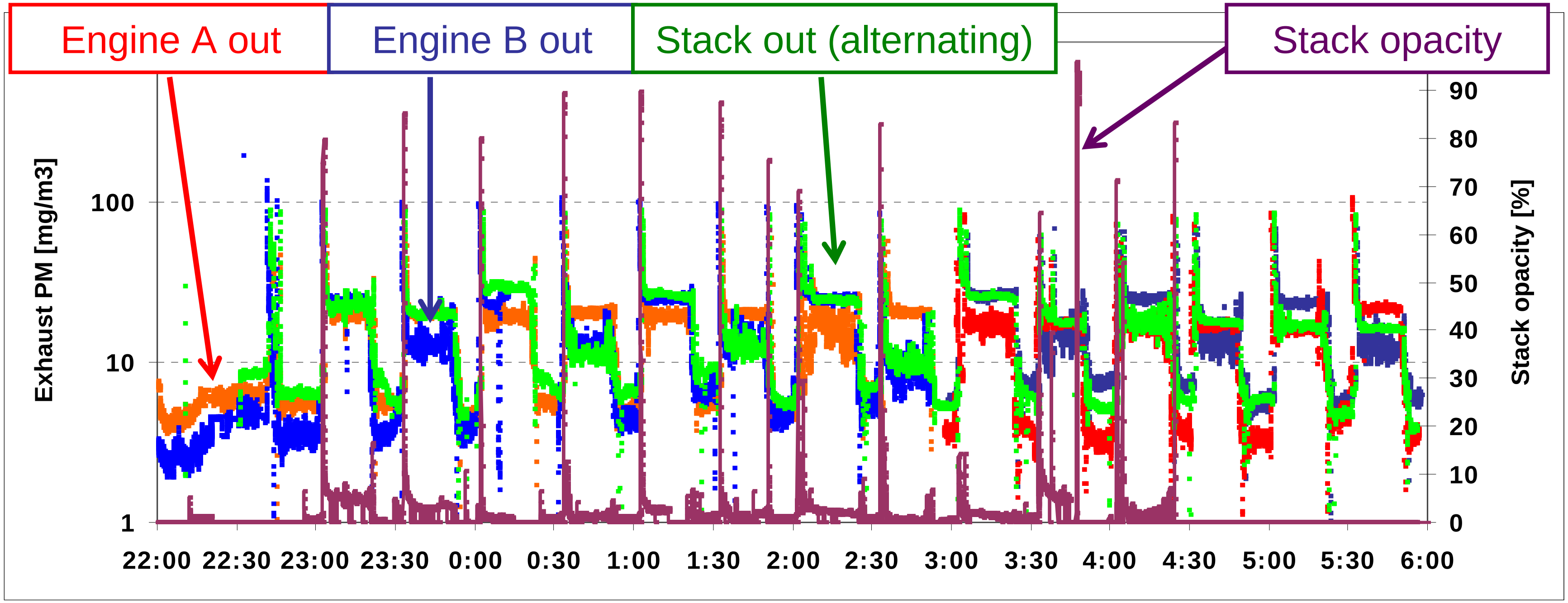


(MQ 100 kVA electric generator, 6.8-liter, 135-hp John Deere engine)

Engine-out vs. tailpipe-out: New York City ferries
(Staten Island Ferry, Manhattan <-> Staten Island)

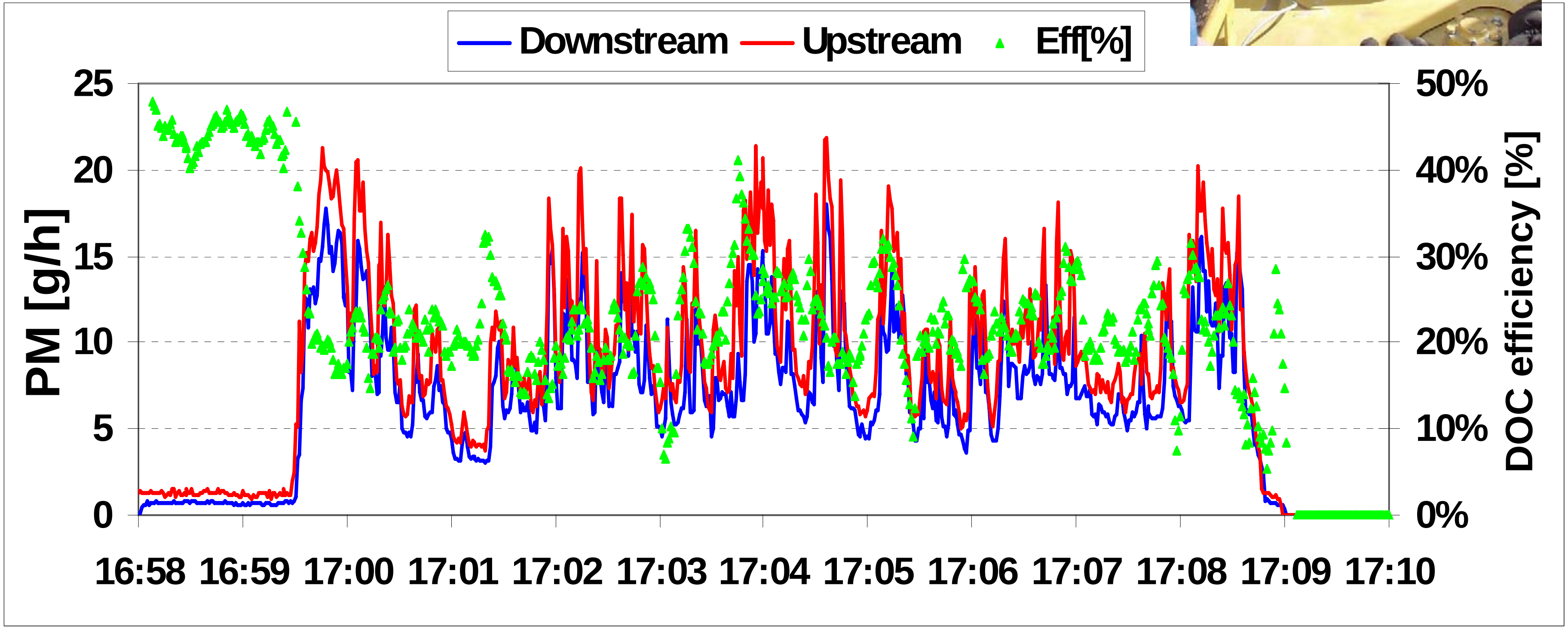
- True in-use testing
- 2 x Caterpillar 3516 V-16 1155 kW drive engines
- Baseline for biofuels and SCR evaluation
- Sampling at turbocharger outlet AND at stack end





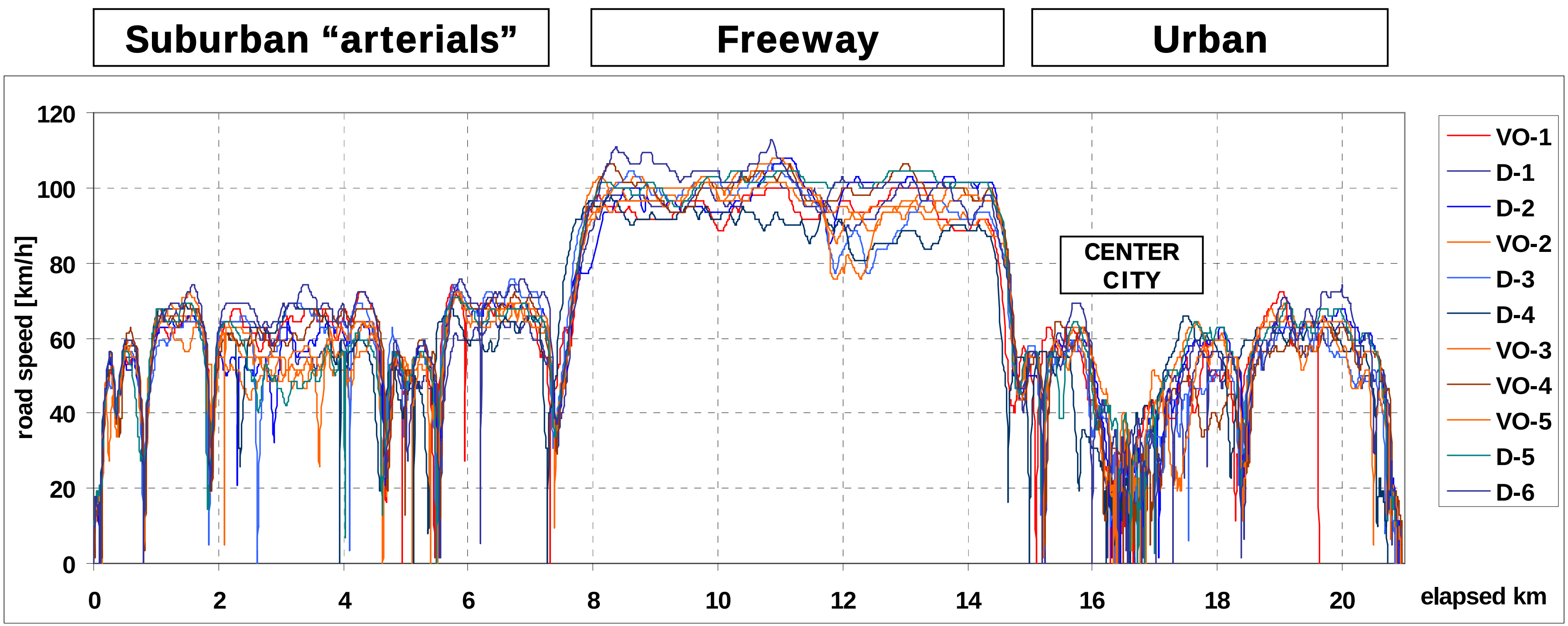
On-line diesel oxidation catalyst evaluation

- In-use emissions testing on construction equipment during regular operation at the World Trade Center no. 7 site, New York, NY
- Operation not repeatable and difficult to simulate
- Simultaneous upstream and downstream sampling



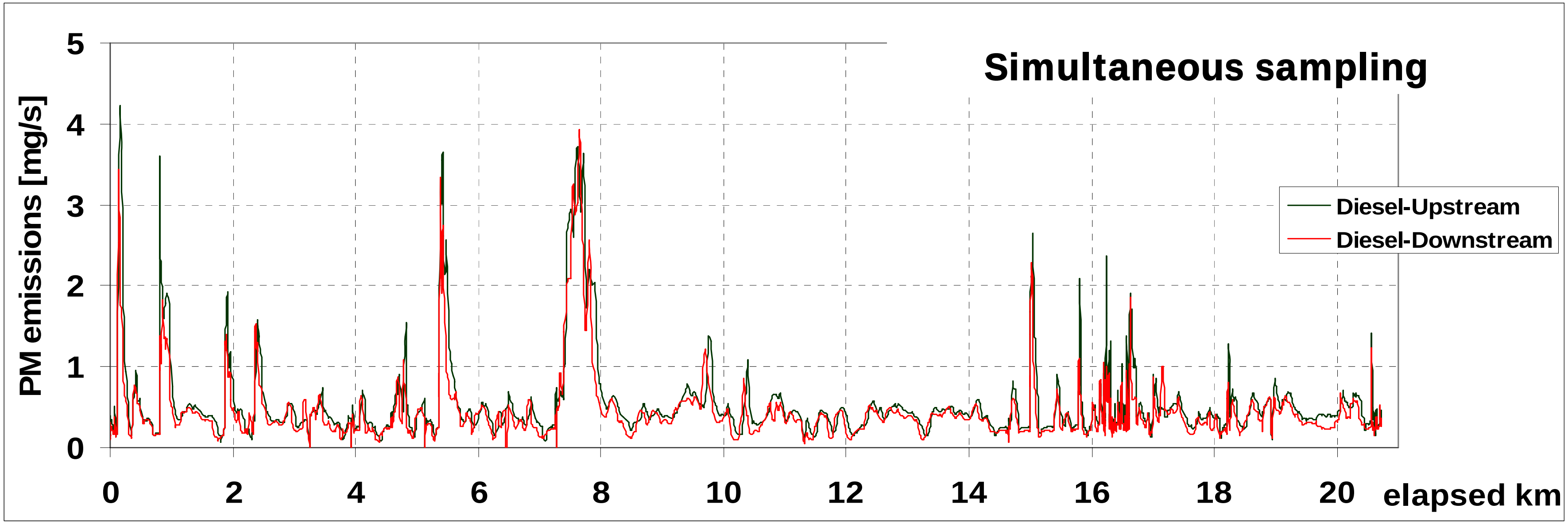
On-road emissions from recycled frying oil study

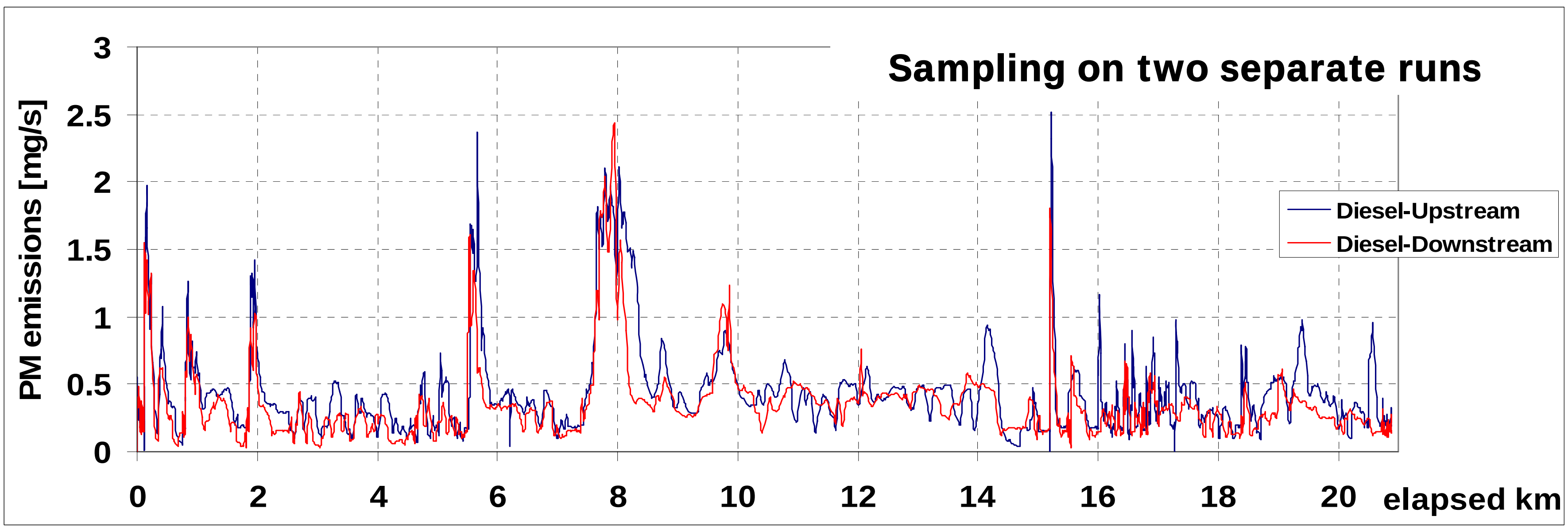
VW Golf / Jetta 1,9 TDI cars with GreaseCar vegetable oil conversion
Fuels: Highway diesel fuel and a mix of recycled frying oil from different sources
Vegetable oil heated to ~60 C fuel temperature at injection pump inlet
20,9 km suburban / highway / urban test route
Emissions measurements upstream and downstream of DOC
Data still being analyzed



Passenger car DOC efficiency – diesel fuel

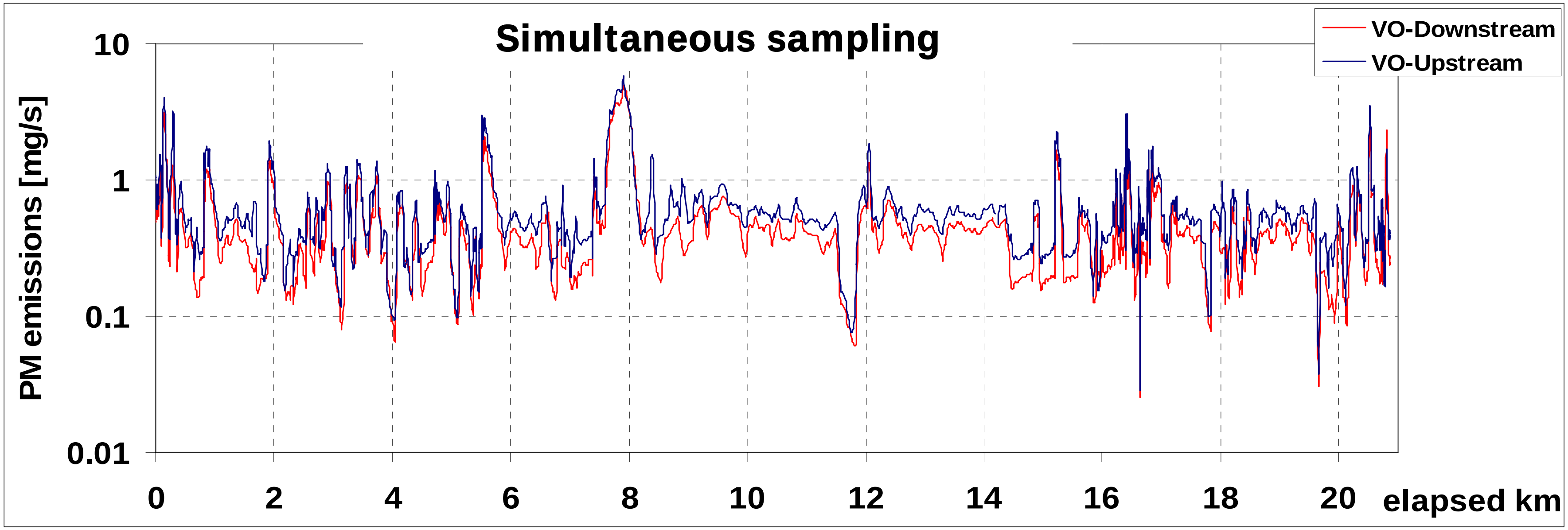
VW Jetta 1,9 TDI, 20,9 km test route in ordinary traffic

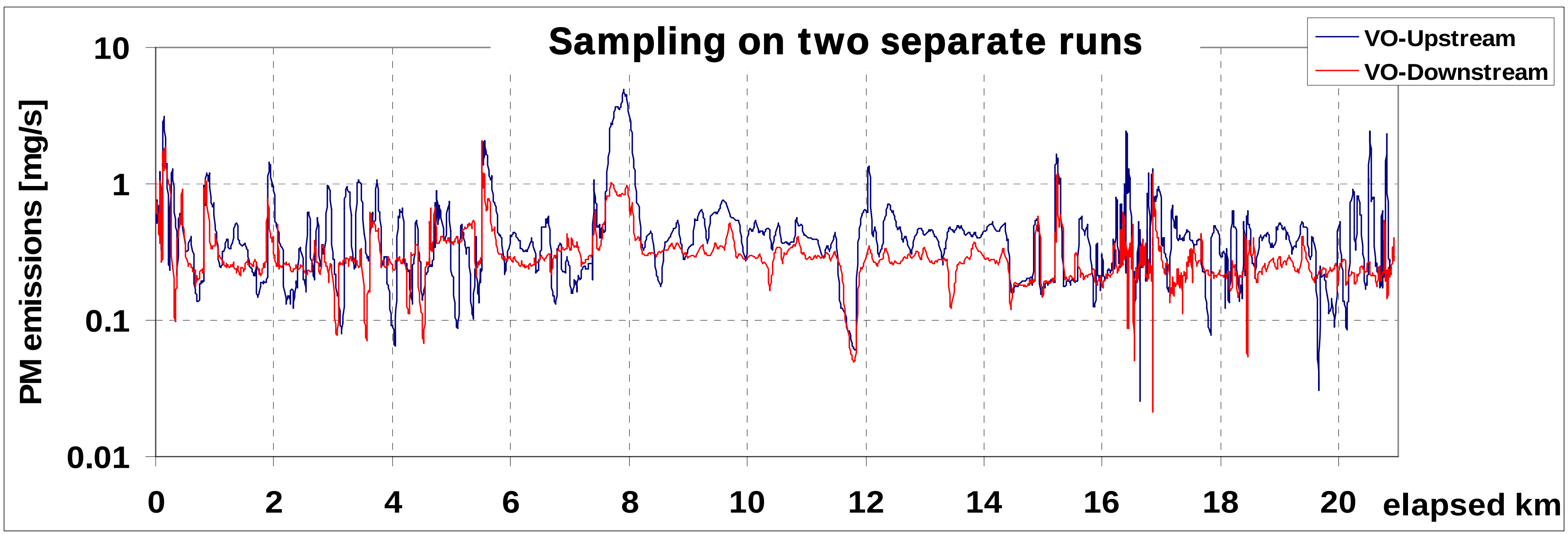




Passenger car DOC efficiency – vegetable oil

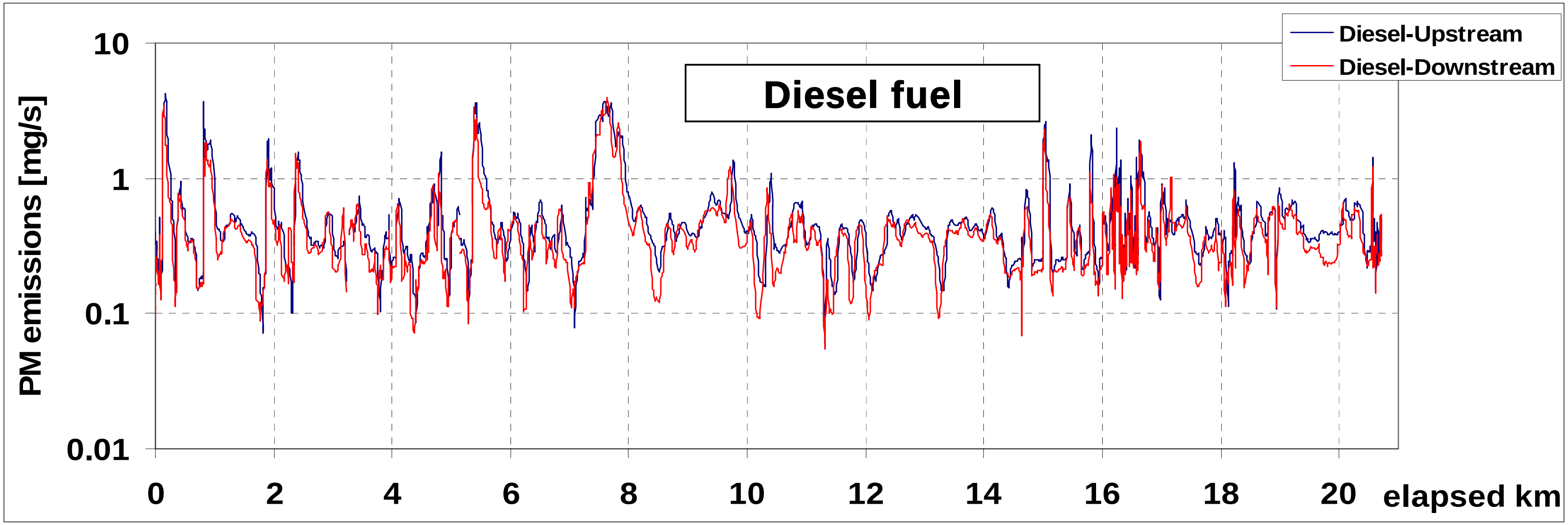
VW Jetta, 20,9 km test route in ordinary traffic

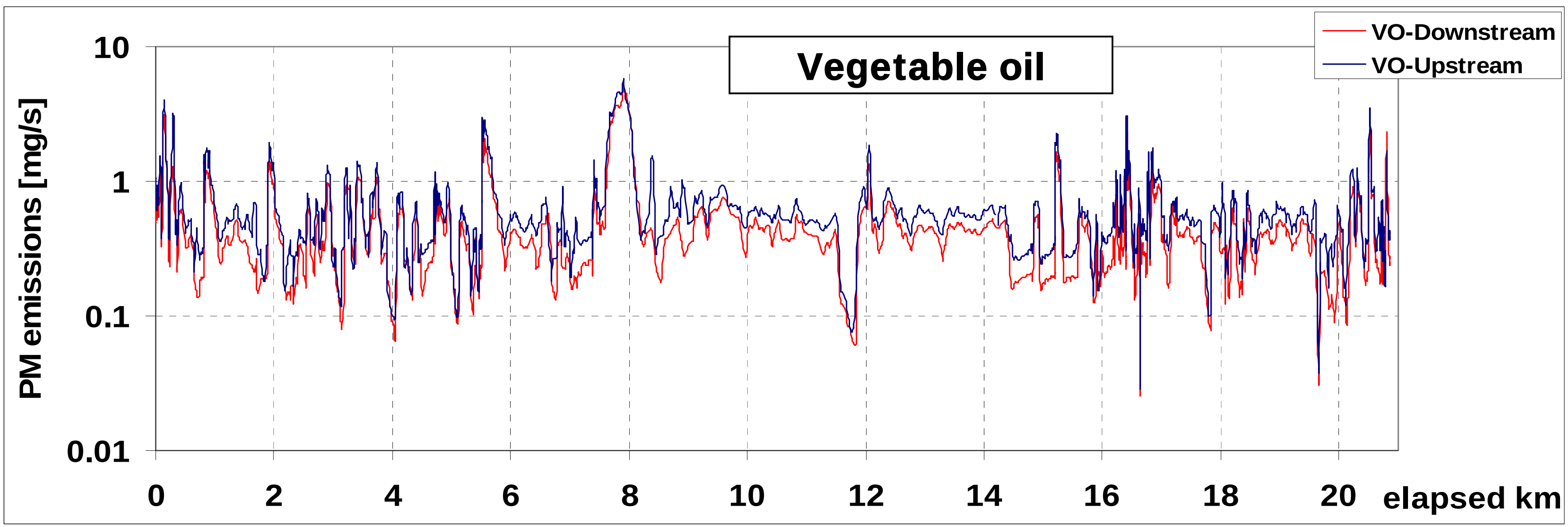




Passenger car DOC efficiency – diesel vs. vegetable oil

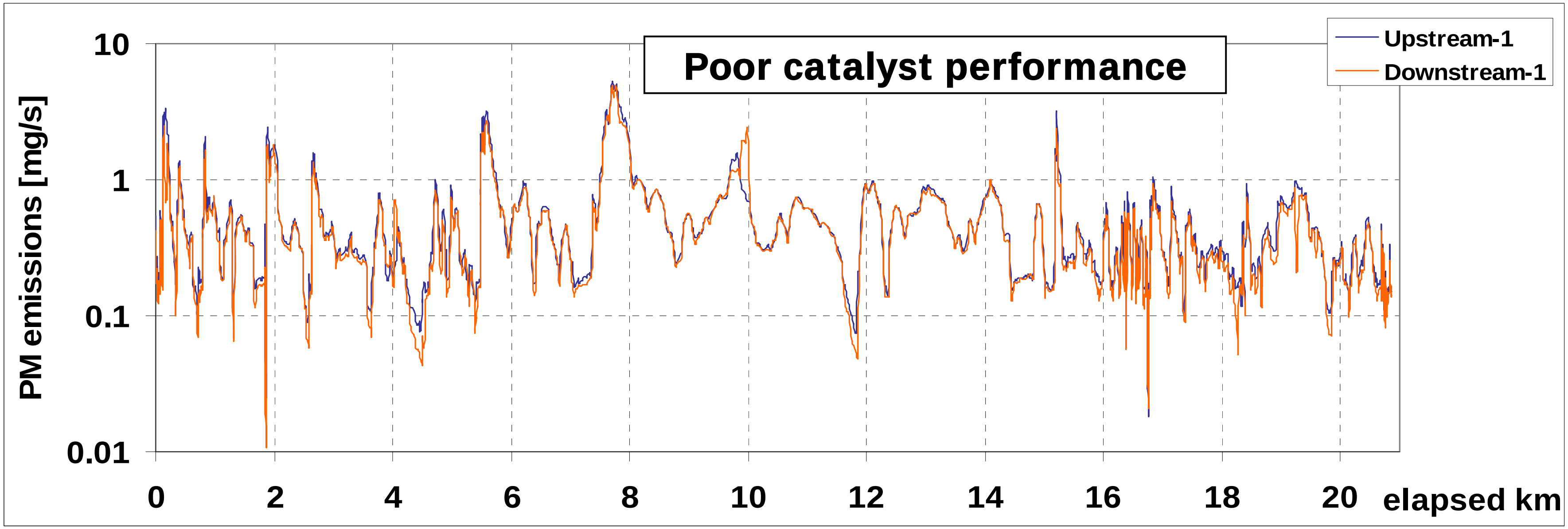
VW Jetta, 20,9 km test route in ordinary traffic

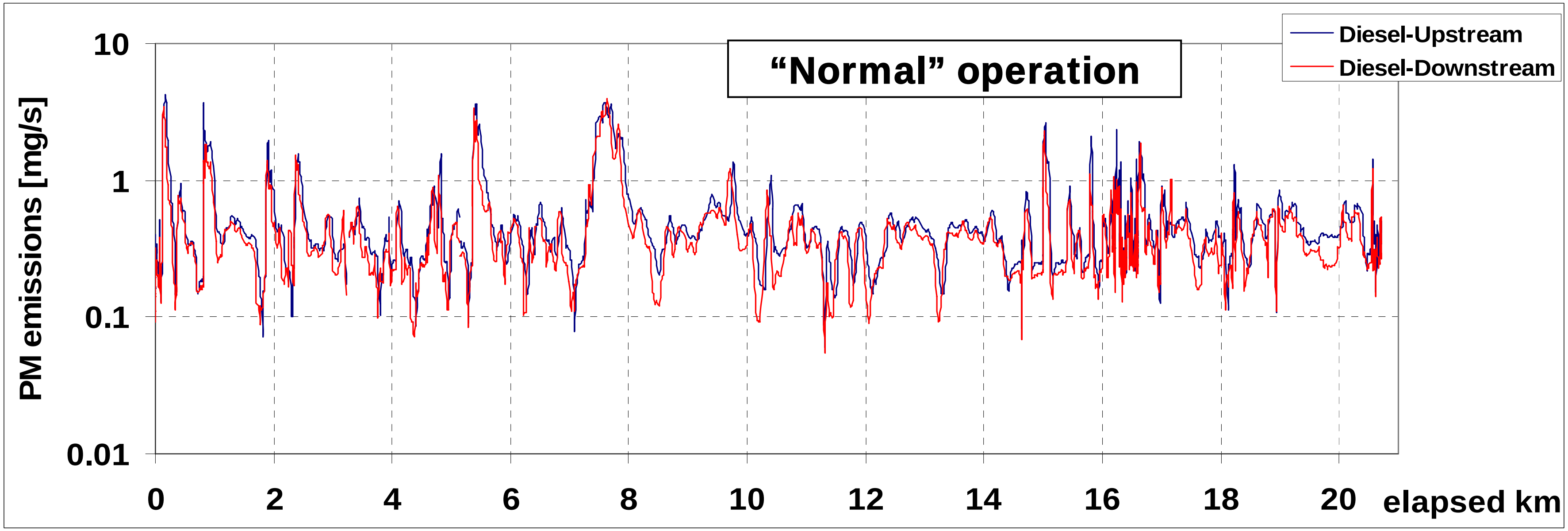




Passenger car DOC efficiency – difference in catalysts

20,9 km test route in ordinary traffic



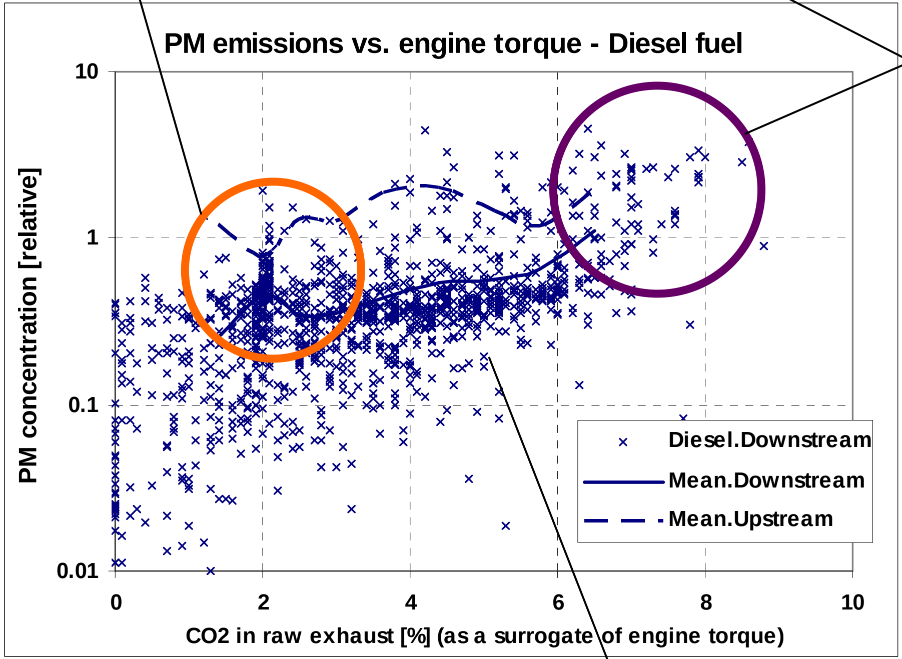


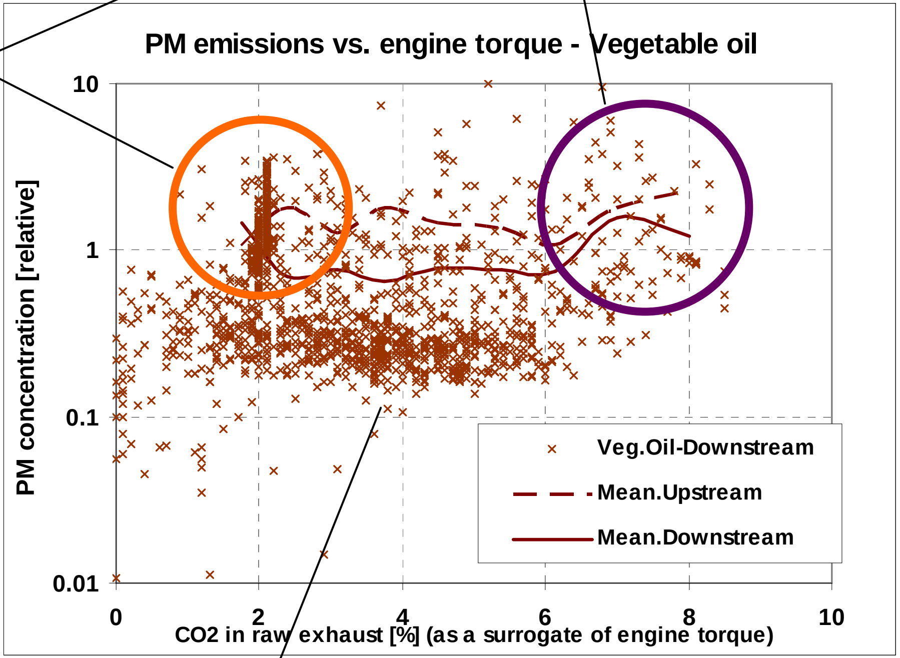
Passenger car DOC efficiency – diesel fuel vs. vegetable oil

20,9 km test route in ordinary traffic

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

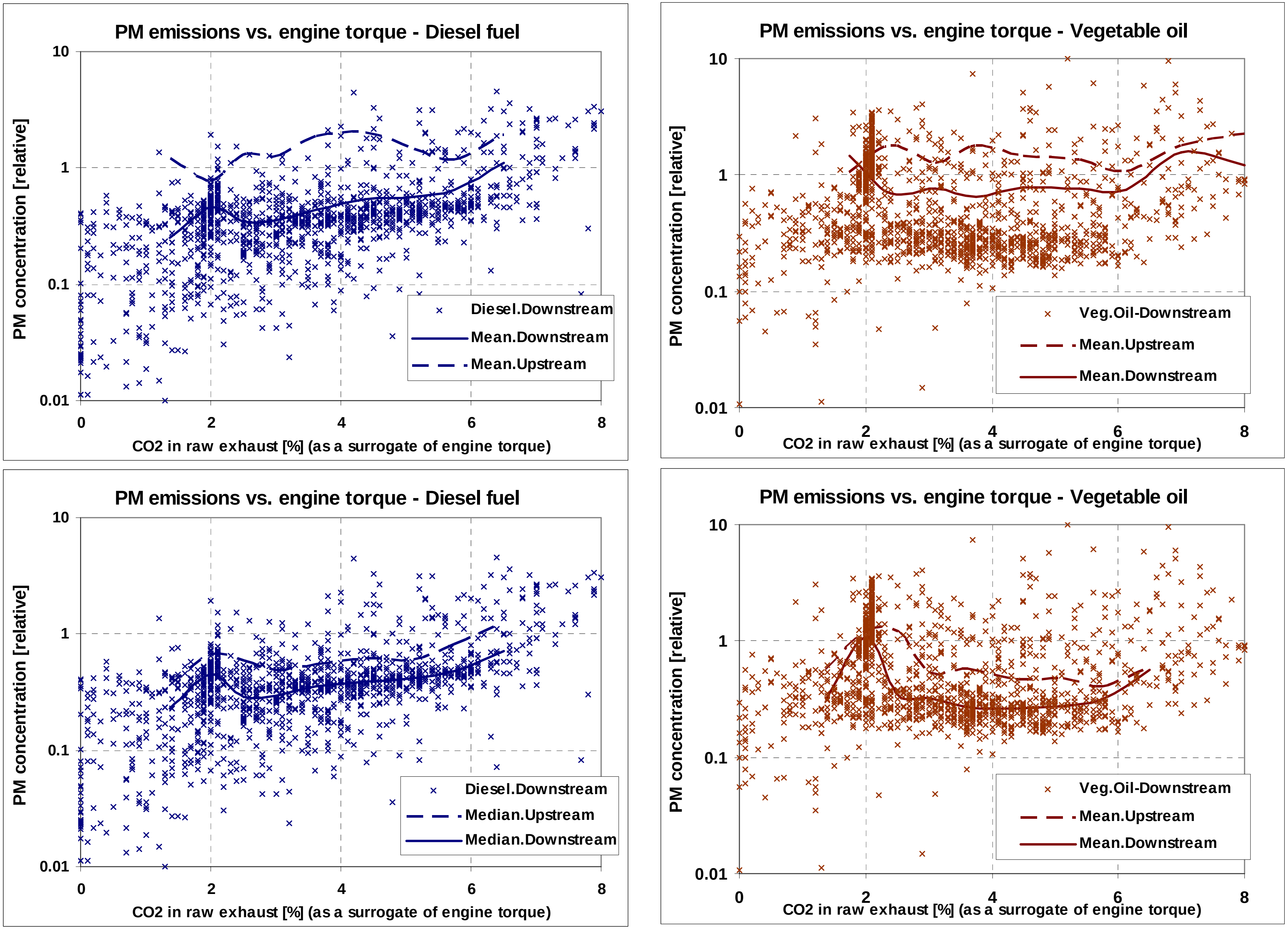
Transient high loads
Overfueling conditions
Relatively infrequent
PM dominated by soot



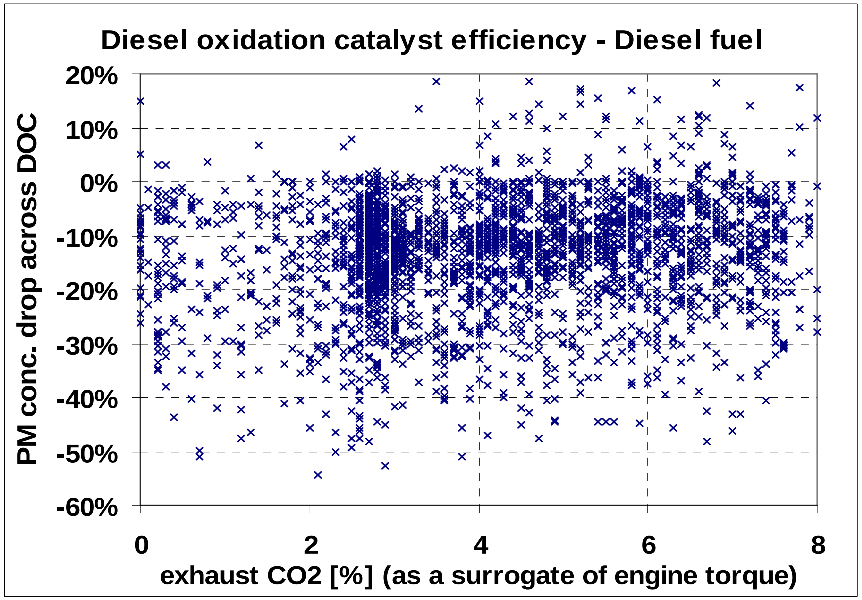


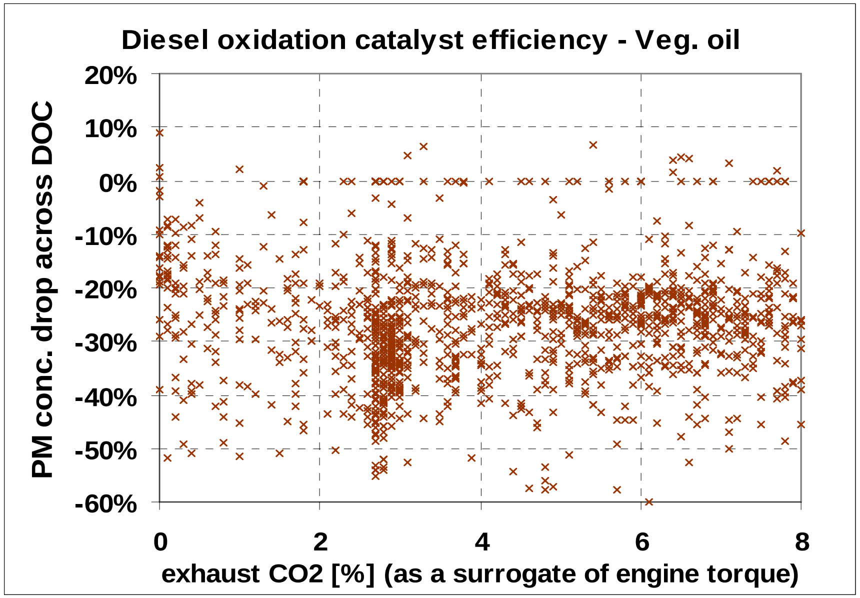
During bulk of the medium load operation, PM concentrations are lower for vegetable oil; but mean PM concentrations are higher, suggesting that a large contribution to the total comes from transients

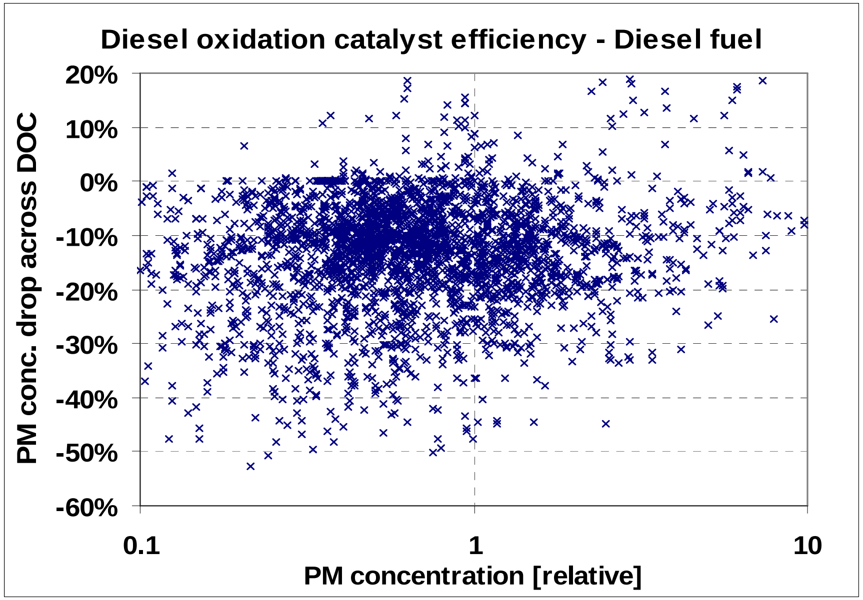
Passenger car DOC efficiency – diesel fuel vs. vegetable oil
Mean vs. median values – median values suppress transients

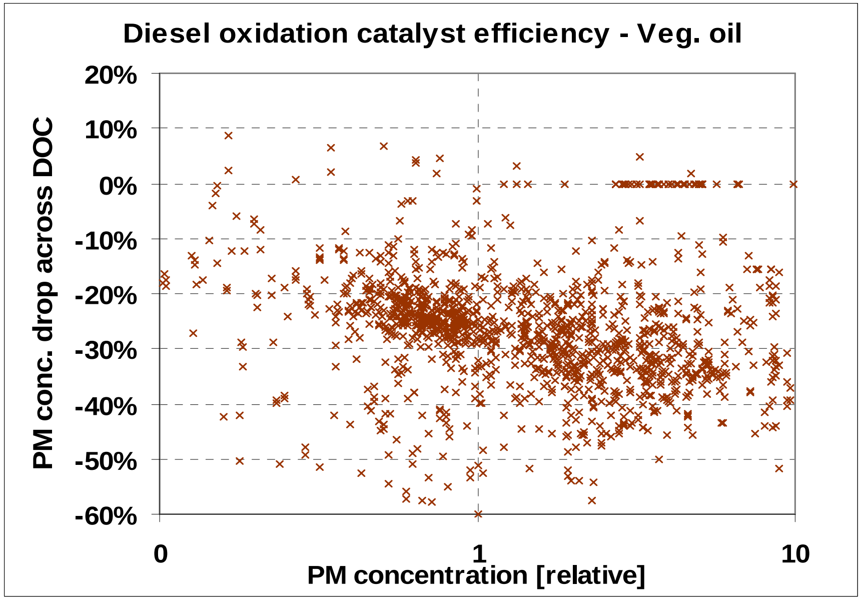


Passenger car DOC efficiency – diesel fuel vs. vegetable oil









PM dynamics within the exhaust system

- Secondary growth of PM
- Deposition, storage and re-entrainment of PM

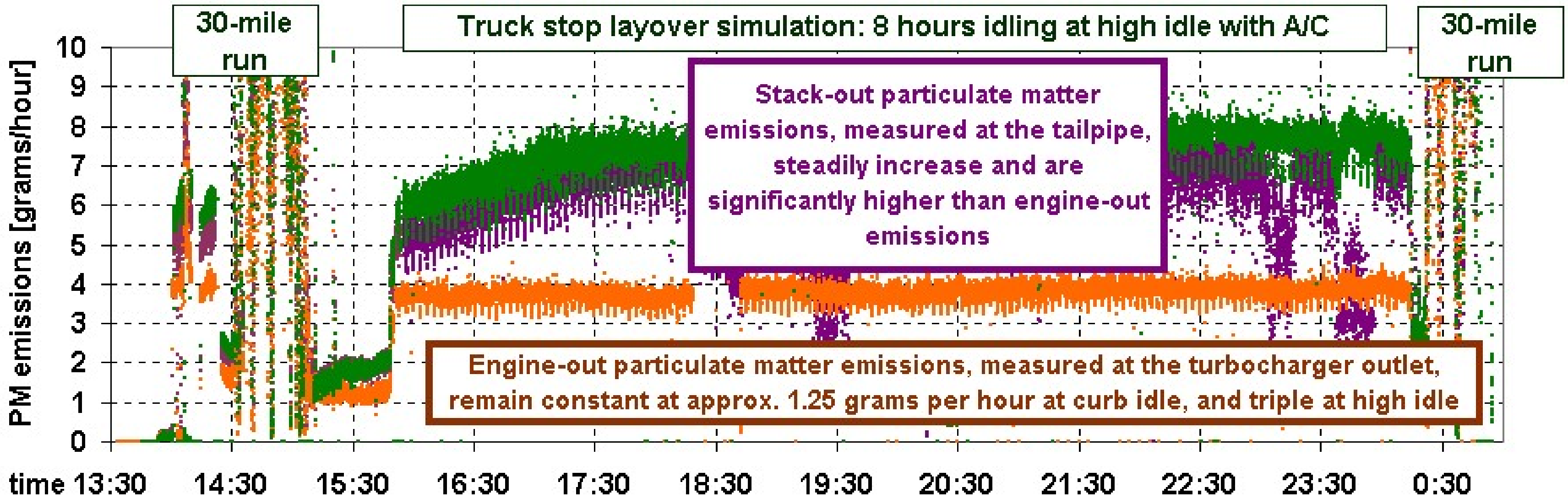
Most pronounced

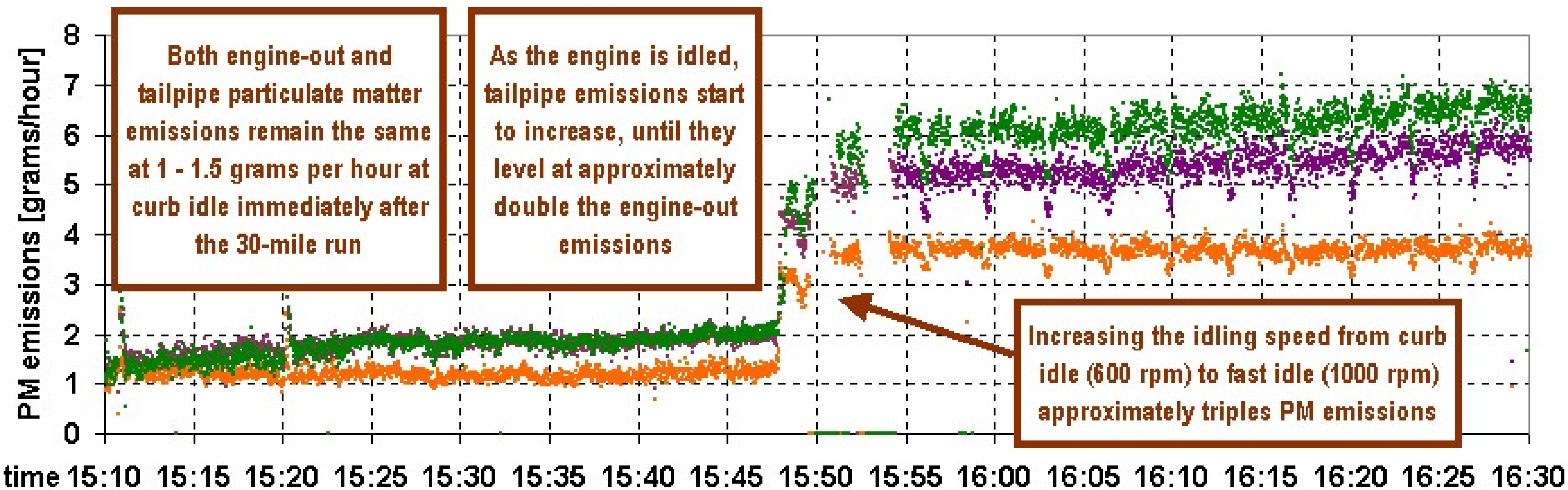
- during and following idle and low loads
- with long exhaust systems
- with high aerosol fraction of PM

Must be differentiated from the aftertreatment device effects

Effect of prolonged idling on PM emissions

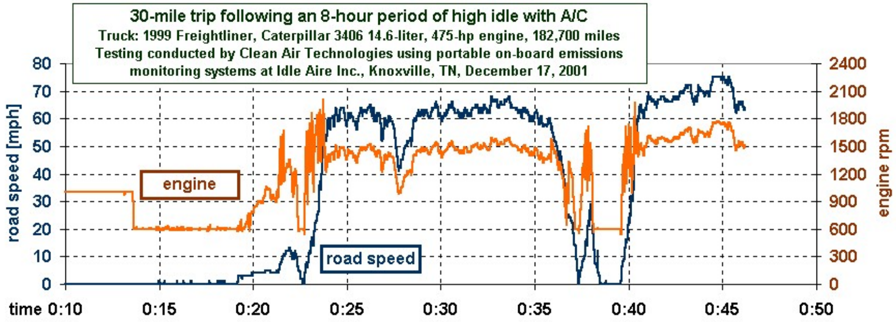
1999 Freightliner truck, CAT 3406 engine, ~150,000 miles 8-hour extended idling test Idle Aire Technologies, Knoxville, TN, December 17, 2001

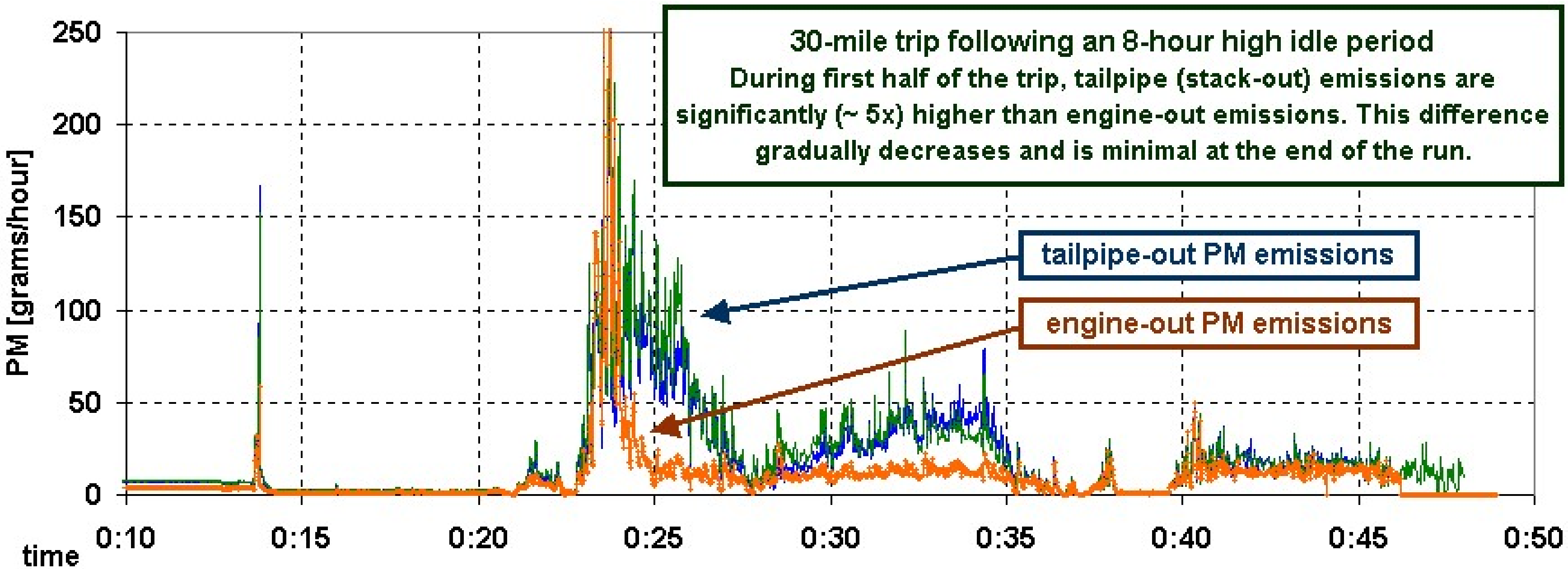




Effect of prolonged idling on emissions during subsequent driving

- 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



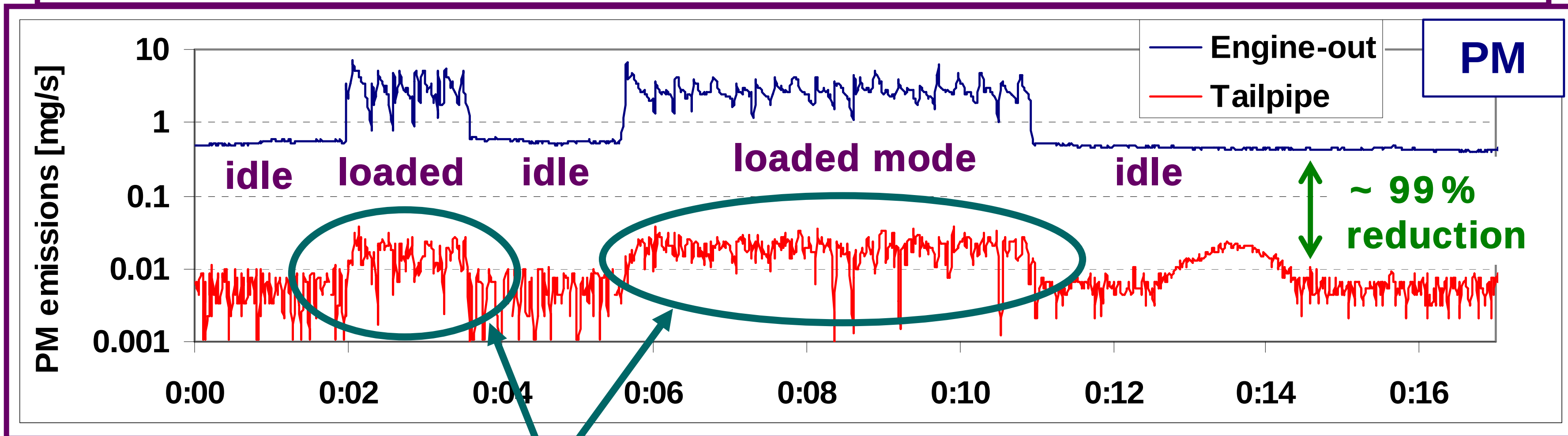


1999 Freightliner truck, CAT 3406 engine, ~150,000 miles 8-hour extended idling test Idle Aire Technologies, Knoxville, TN, December 17, 2001

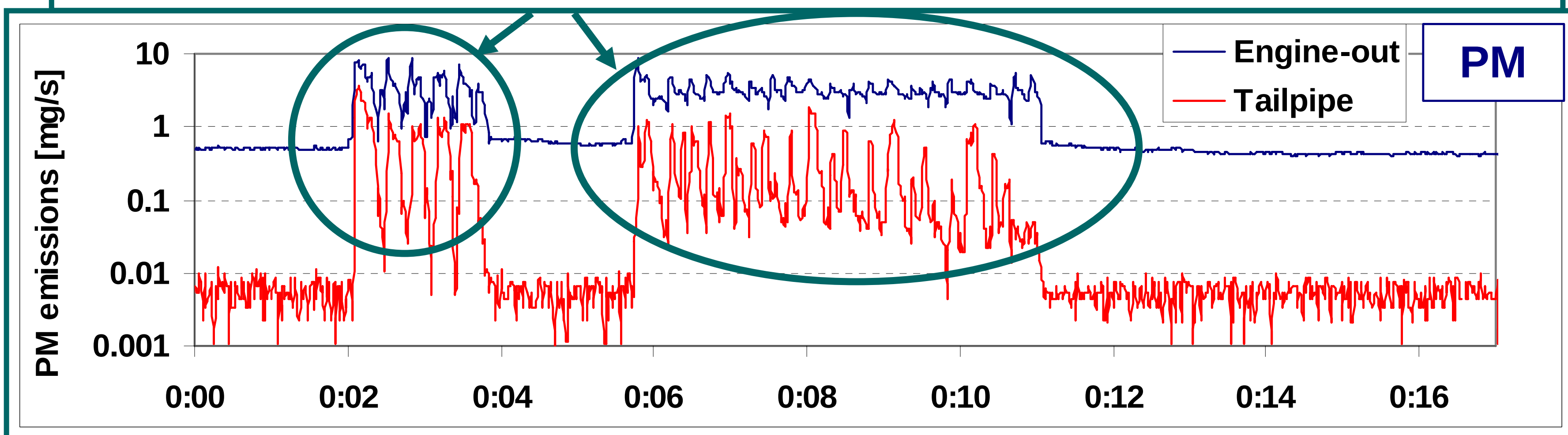
Field test – excavator with diesel particulate filter

Emissions measured simultaneously upstream & downstream of DPF during a field test designed to mimic real-world operation

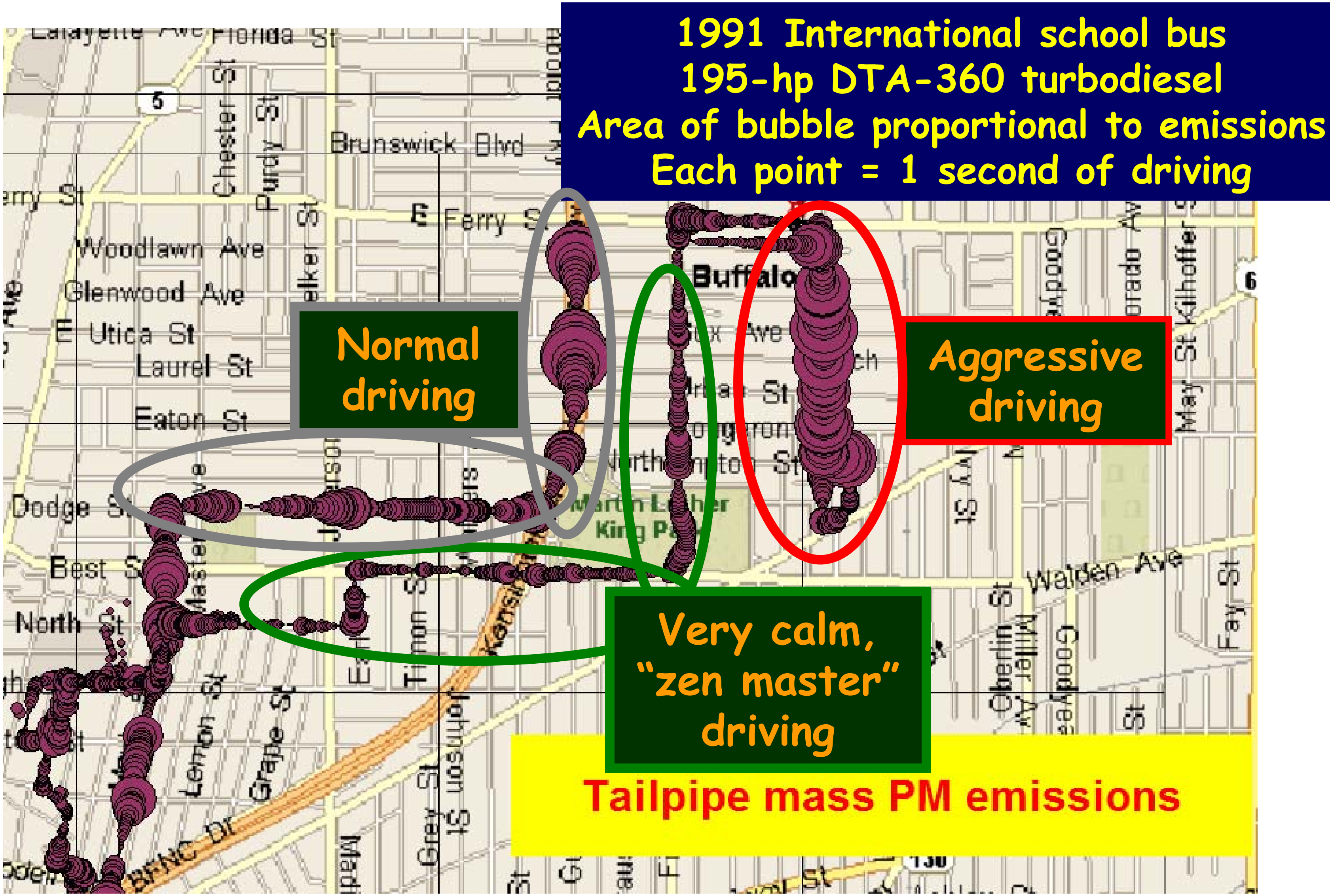
Typical test run, construction equipment with diesel particulate trap



Test run after prolonged idling: Elevated PM during high load operation



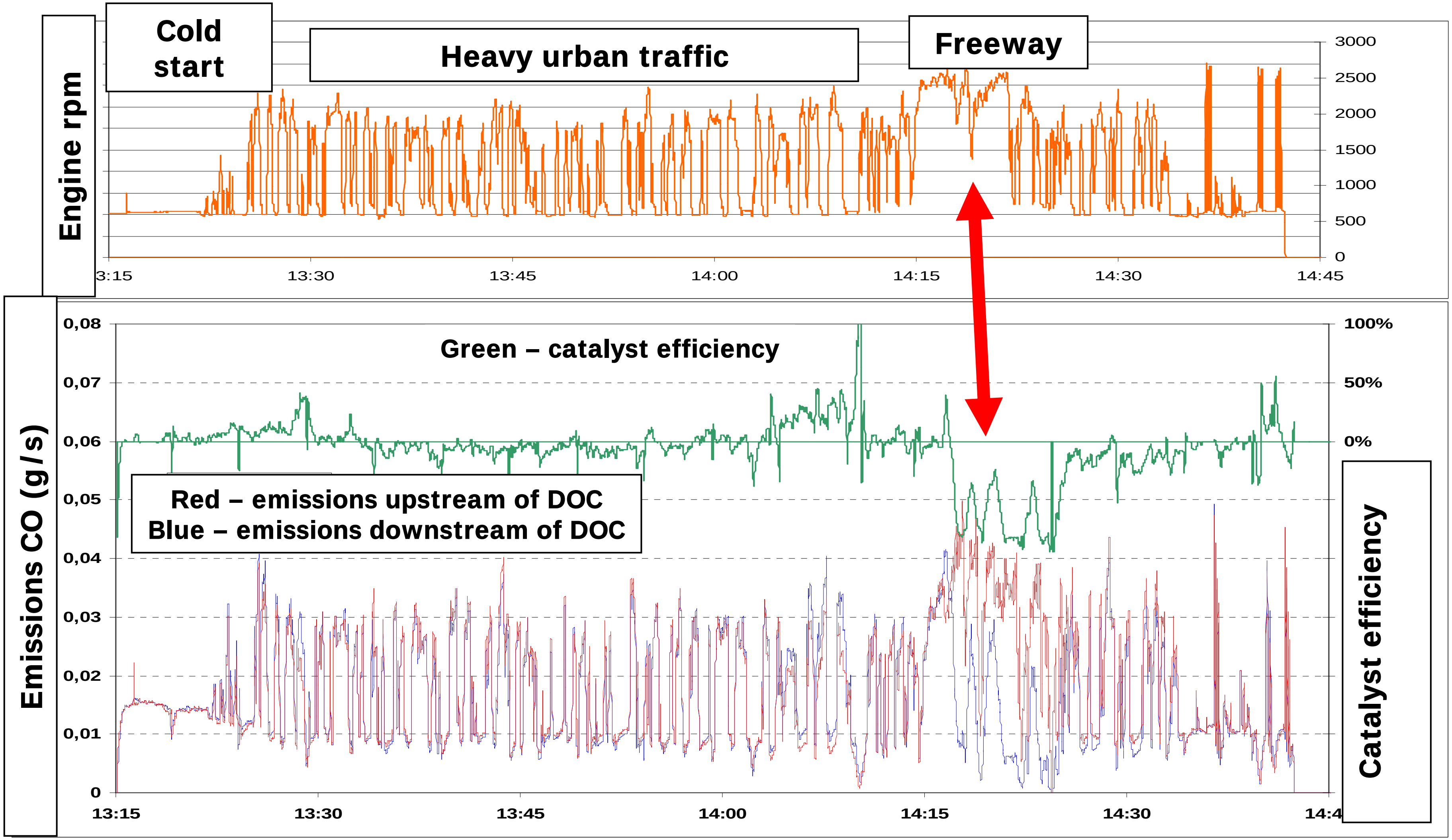
Example: Effect of driving style on particulate matter emissions



Source: Author data, personal research

Crude evaluation of overall diesel oxidation catalyst function by CO measurements

Extreme case: Bus catalyst operational only during sustained high load operation
Measurement is far from accurate (repair-grade analyzer used), but useful for the purpose.



Discussion – PM sampling, PM measurement using light scattering

- Dilution at the sampling port upstream of aftertreatment adds to the complexity of the system
- No dilution, no heating of the sampling system – secondary growth of PM in the sampling system, plus condensation of water vapor contained in the exhaust on particles

- Low concentration – counting of individual particles possible but generally not possible without dilution
- High concentration – “aggregate” number but some size information can be obtained with very fast sampling

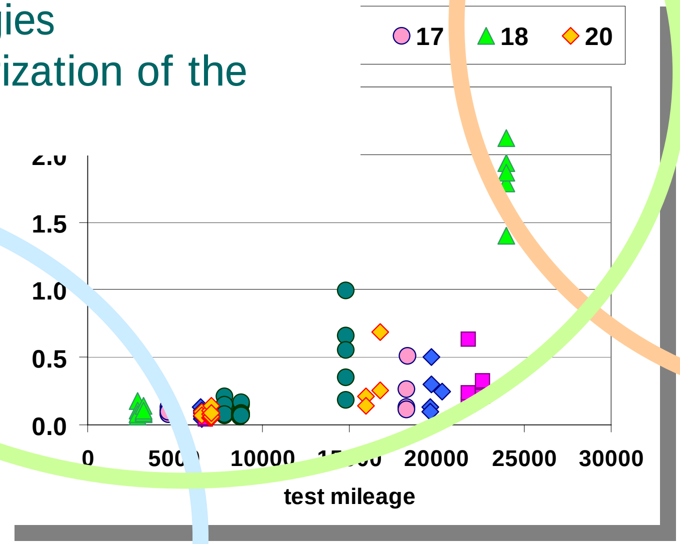
- Response ~ d^6 for particles << wavelength of light
- Response ~ d^2 for particles >> wavelength of light
- Response ~ d^0 if particles grown to uniform size
- For soot, mass ~ d^{fd}, where fd = fractal dimension of particles

- Complexity of issues requires careful use and thoughtful, application-specific calibration with other methods; still, results might not be accurate

Discussion – accuracy of on-road measurements

On-road testing
Wide intermediate area
Development and pilot deployment of new technologies
Characterization of the effects

Inspection programs
High-volume, fast, low-cost field testing
Goal is to identify high emitters (order-of-magnitude deviations)



Basic + applied research
Low-volume laboratory testing
Can be costly and complex
Goal: Laboratory quality data

Accuracy and other parameters of on-board test equipment and methods need to be carefully matched to the needs of the application.

Crude evaluation of overall particulate trap function by visual inspection

Visible soot: Signs of mechanical problem

No visible traces of soot = Trap function probably OK

Conclusions

- Aftertreatment device evaluation requires, after initial development but before mass deployment, testing of a large set of vehicles under a variety of conditions; such testing can be done on the road
- Studies done using a simple on-board system show that repeatable measurements can be obtained by replicating dynamometer driving cycles on a closed road; tests can be then done alternately with and without the aftertreatment device
- Ordinary operation (i.e., of a vehicle on the road) is generally poorly repeatable; in this case, measurements can be done by simultaneous sampling upstream and downstream of the aftertreatment device
- Studies done using a simple on-board system show that errors due to non-isokinetic sampling upstream of the device appear to be relatively small (compared to other sources of error)
- **Simultaneous emissions measurements upstream and downstream of an aftertreatment device appear to be a feasible way of evaluating its efficiency in real-world operation.**