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AVL Micro Soot Sensor Applications

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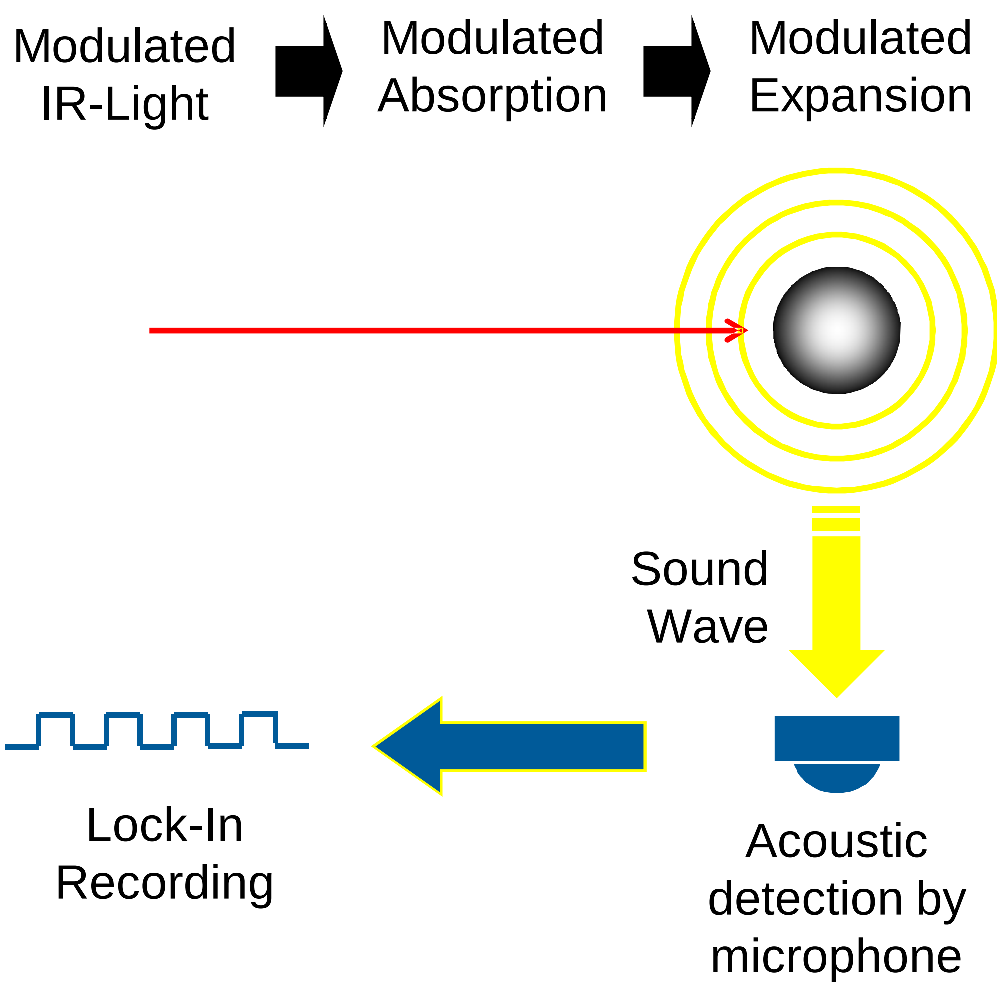
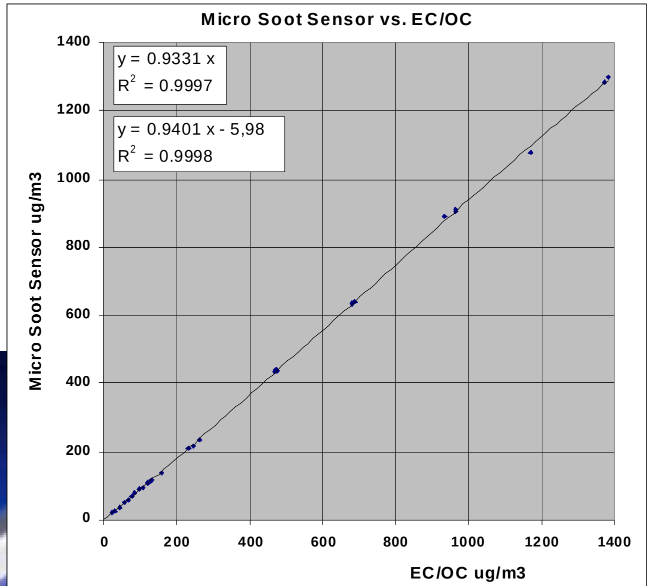
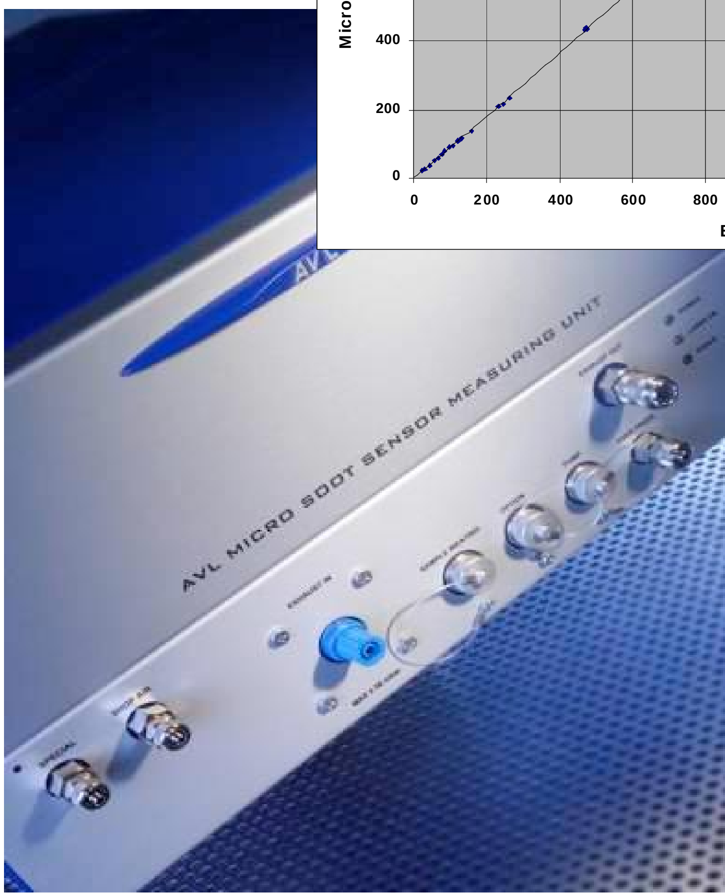
THE MEASURING PRINCIPLE - PHOTOACOUSTICS



- Sample diluted exhaust (from CVS, SPC, or Conditioning Unit), through a measuring chamber
- Black absorbing particles in the exhaust gas are thermally animated by a modulated laser beam
- Modulated heating produces periodic pressure pulsation, which will be detected by a microphone as acoustic wave
- Signal will be amplified in a pre-amplifier and filtered in a „Lock-In“- amplifier.

AVL MICRO SOOT SENSOR





Measurement of
soot mass concentration

The sensor signal is <u>directly proportional</u>
to the soot concentration,
with excellent *intrinsic* linearity.
(Advantage against opacity, where
no soot = 100% signal)

Time resolution: 1 sec

<u>Sensitivity:</u>
Zero point noise: ~ 2 µg/m³ (1 σ)
Zero point drift: < 2 µg/m³ / hr
various influences < 5 µg/m³ typically

data rate: 10 Hz

Standard interfaces
RS232 or TCP/IP with AK protocol, DIO,
Analogue I/O,)

DETECTION LIMITS

Assume a continuous exhaust concentration of 10 µg/m³ PM or soot.

This corresponds to:

- typically 0.1 mg/kWh - PM limit EU VI: 10 mg/kWh
- typically 0.2 mg/km - PM limit EU 6: 4.5 mg/km

⇒ The detection limit of the photoacoustic measurement is
20 to 100 times lower
than the EU particulate limits

The detection limit of the EU 5 (improved) standard gravimetric PM measuring method is

- typically 1 mg/km, or 1 mg/kWh (acc. to PMP measurements)

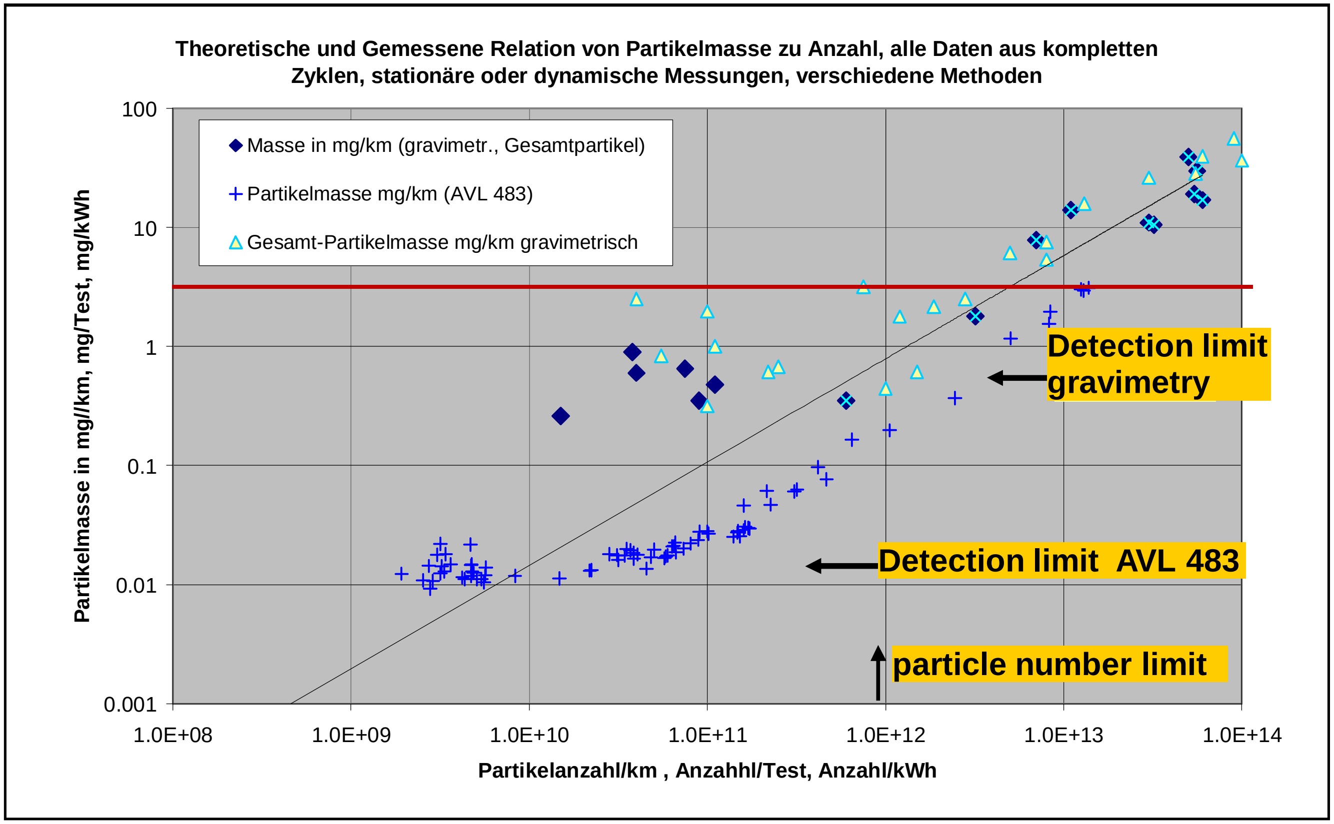
⇒ The typical detection limit of the photoacoustic measurement is
more than 20 times better
than the detection limit of the standard PM measurement.

DETECTION LIMITS

Practical Determination of the detection limits:
From the relation to more sensitive methods, e.g. particle counting

The detection limit of the photoacoustic measurement is **more than 20 times better** than the detection limit of the standard PM measurement.

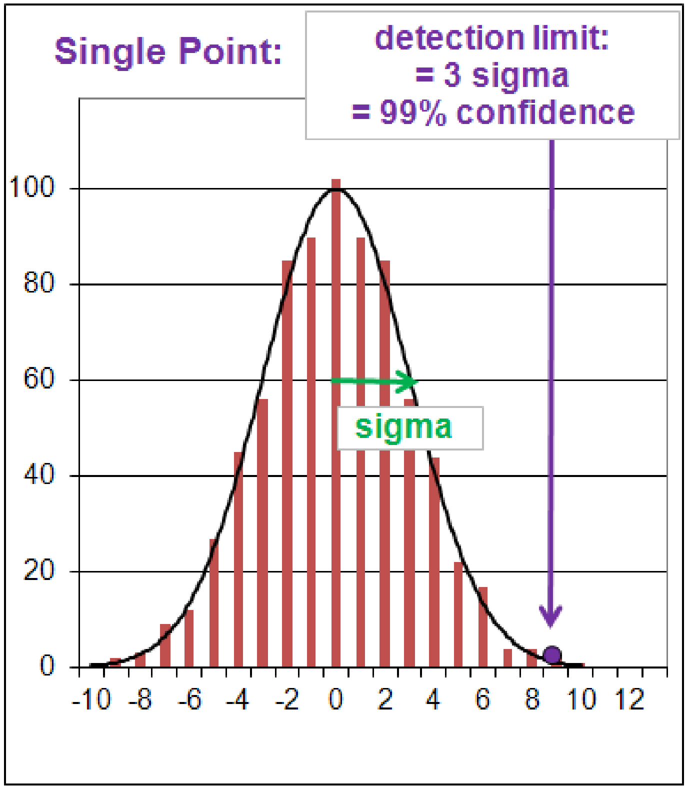
It is also below the emission corres-ponding to the Particle number limit.



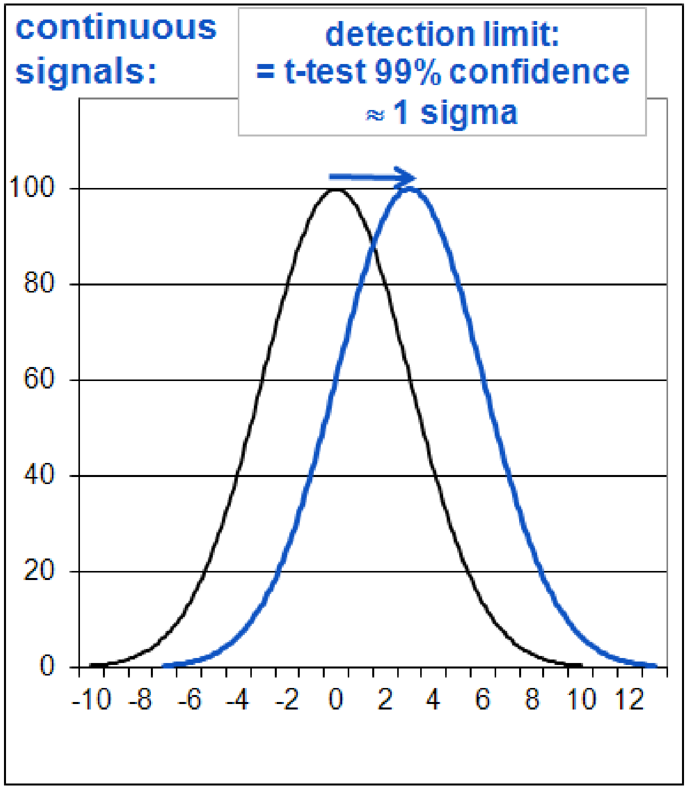
Correctly understanding detection limits

The detection limits for an experiments is defined as the value which can be discriminated from zero noise with 99% confidence

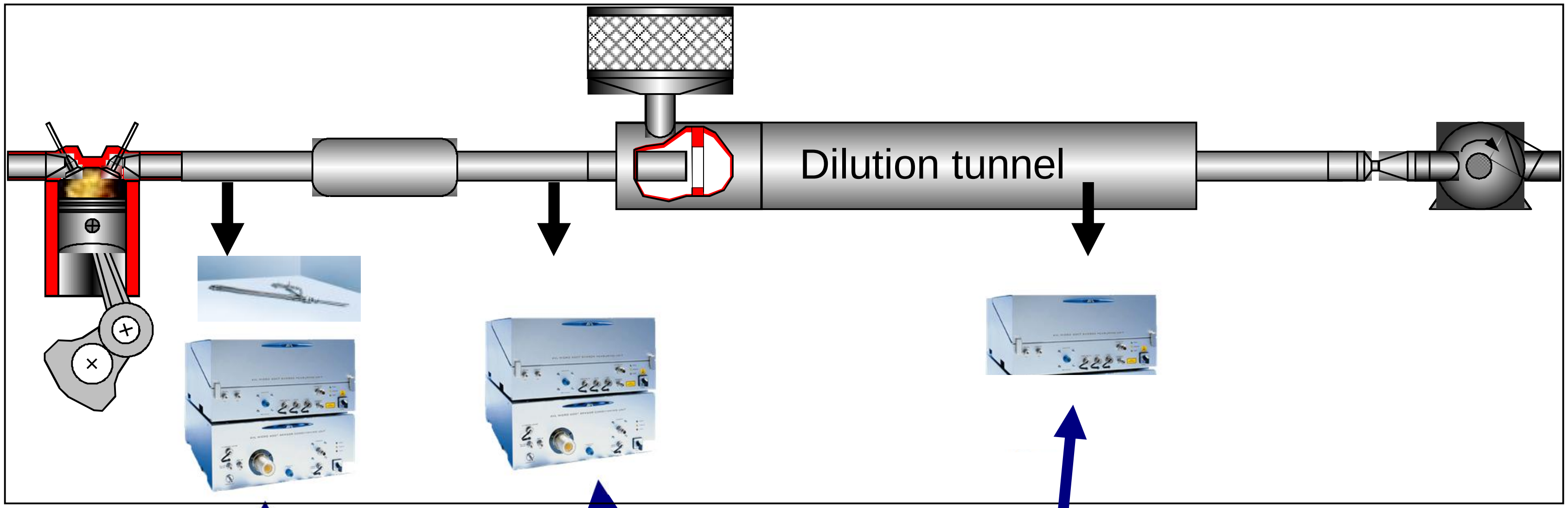
"Single value" chemical analysis



"Continuous reading"



EMISSIONS SAMPLING POSITIONS



- Transient soot Emissions optimisation
- Cold start measurement
- Endurance tests

- DPF soot loading

- DPF Filter efficiency and/or fault detection

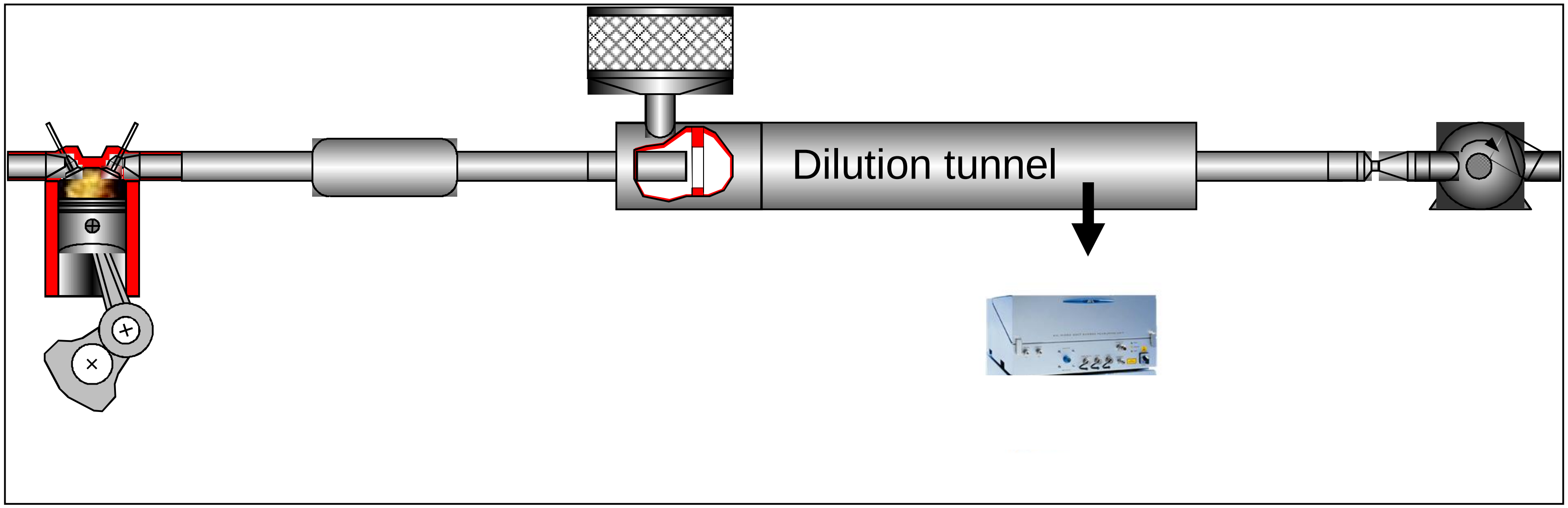
Application examples

High pressure (up to 1 bar)
High Soot and HC concentr.
Temperature up to 800°C

Low Soot concentration
Temperature:
≤400(600)°C ≤ 52°C

Technological aspects and challenges

Sampling from the CVS

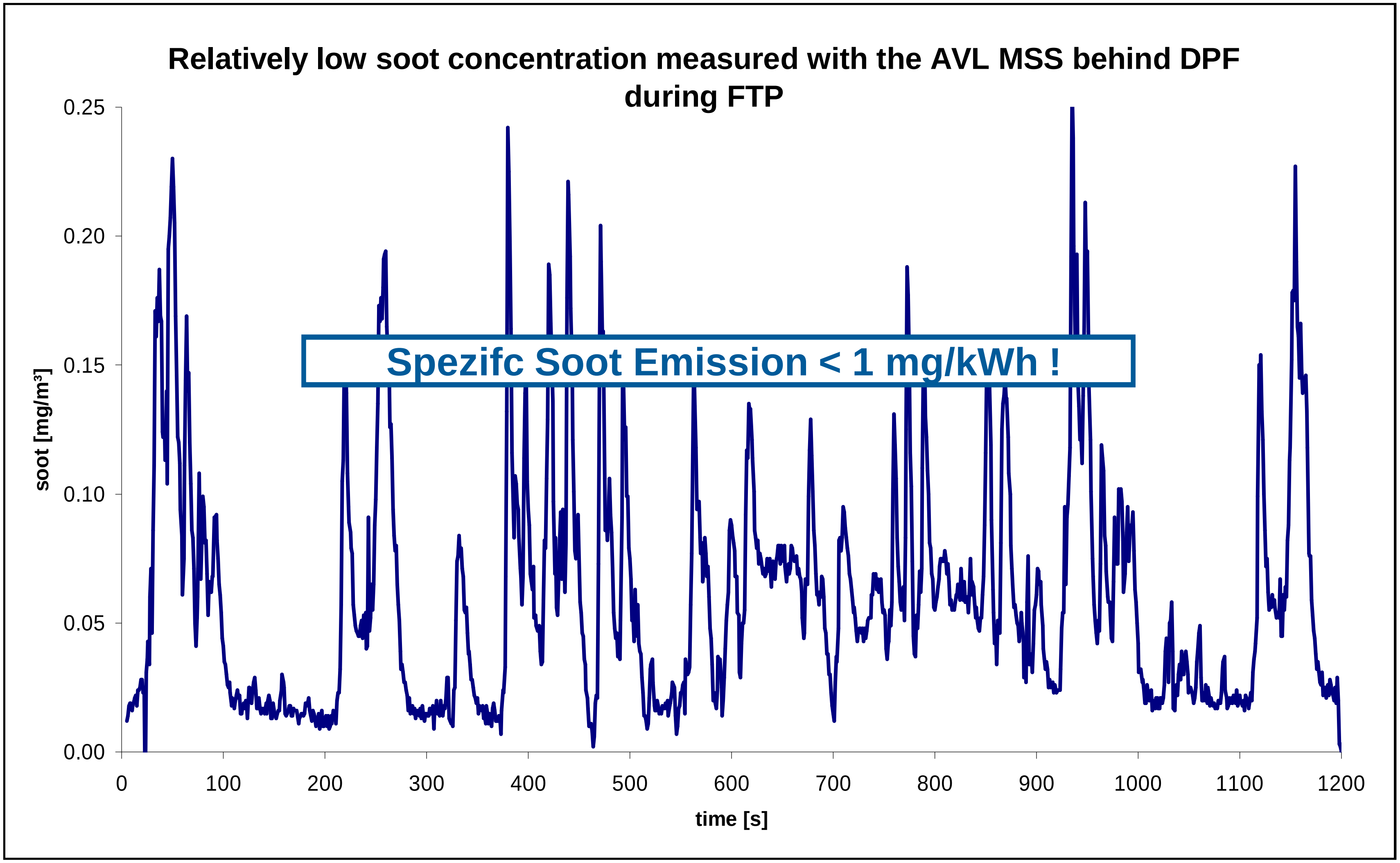


- Transient soot Emissions optimisation
- Cold start measurement
- Endurance tests

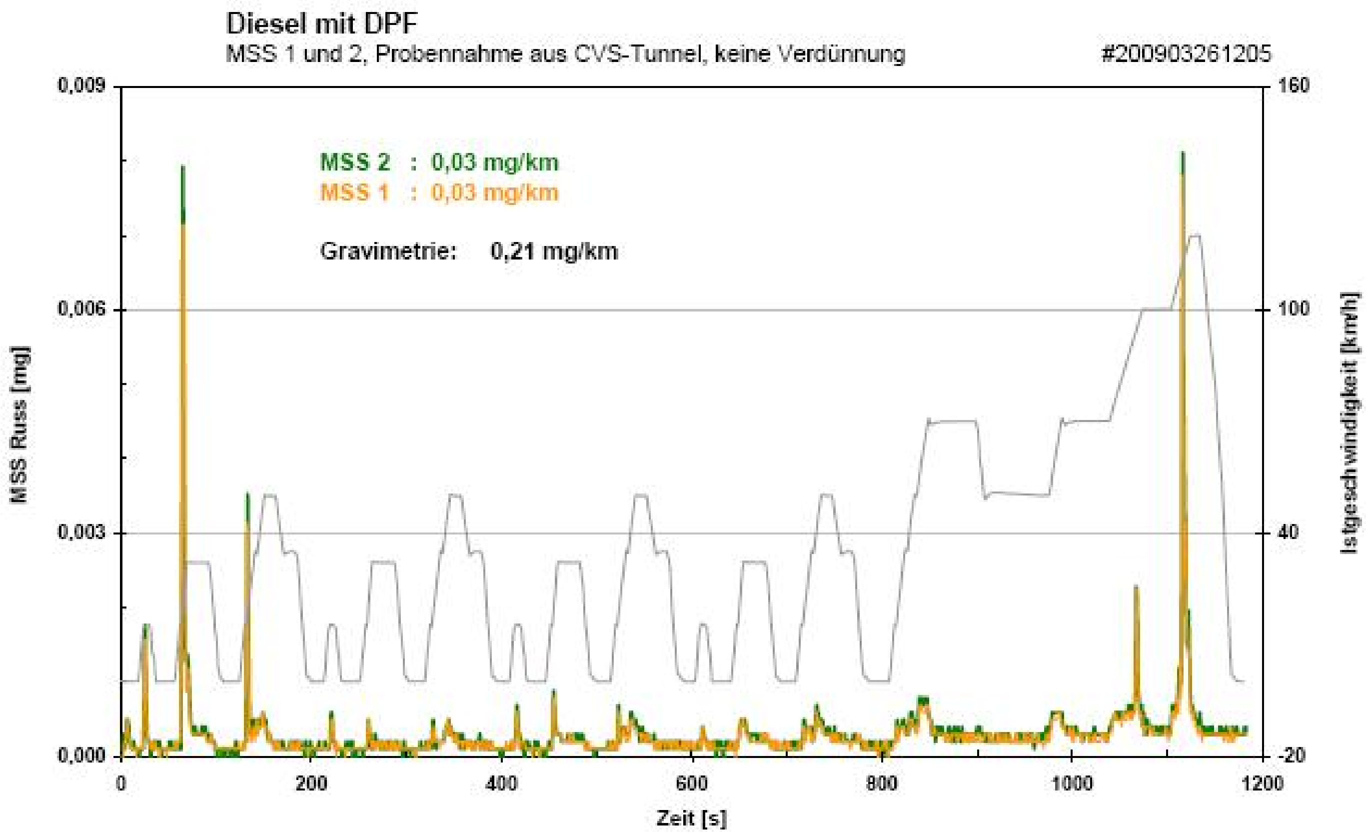
Challenge: Low Soot concentration

Advantage: Temperature:≤ 52°C

Application example:
Dynamic soot emission measurement from CVS



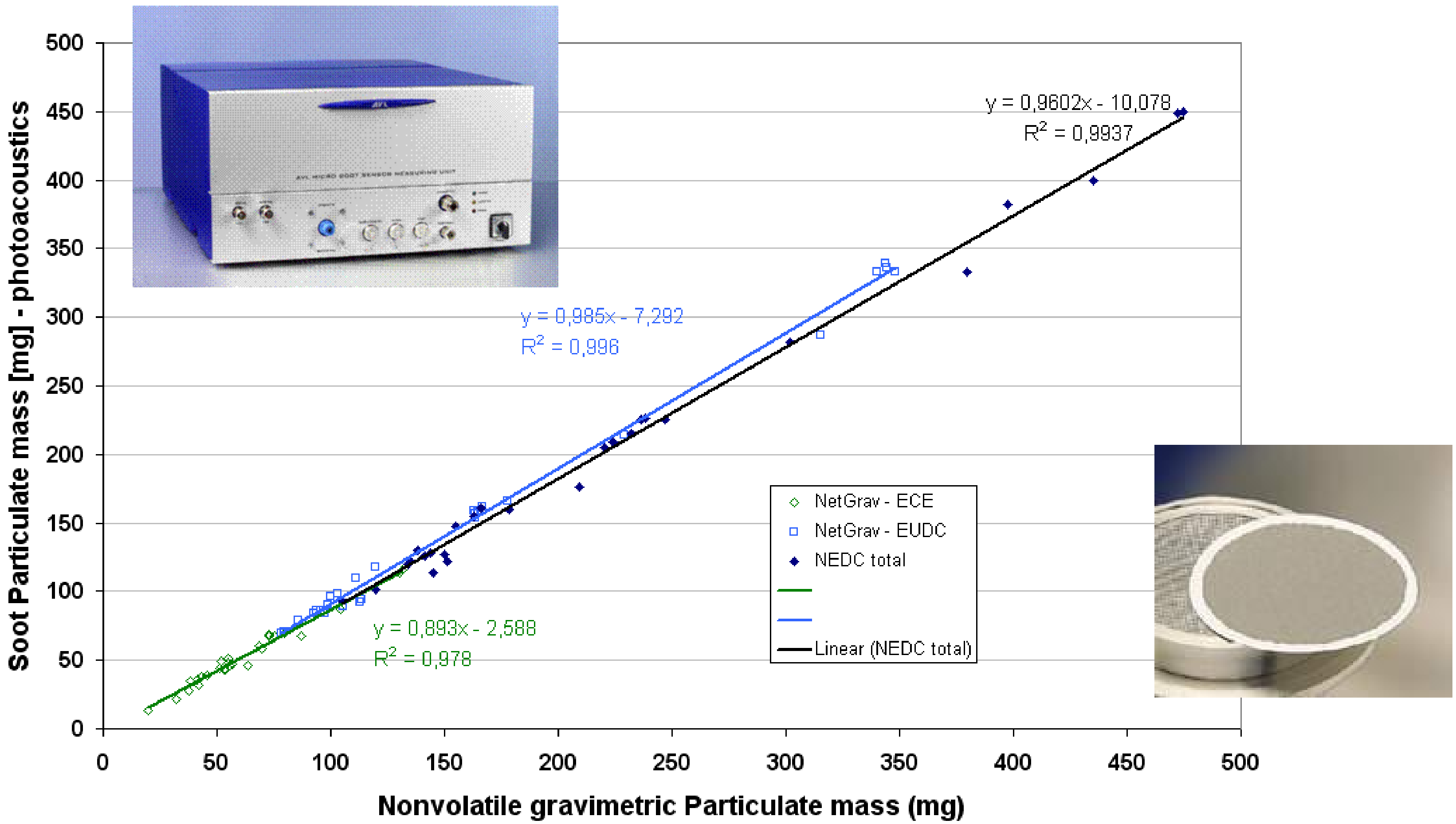
Application example:
Dynamic soot emission measurement from CVS



The post-DPF soot emission is reproducibly measureable at levels 2 orders of magnitude smaller than the certification limit.

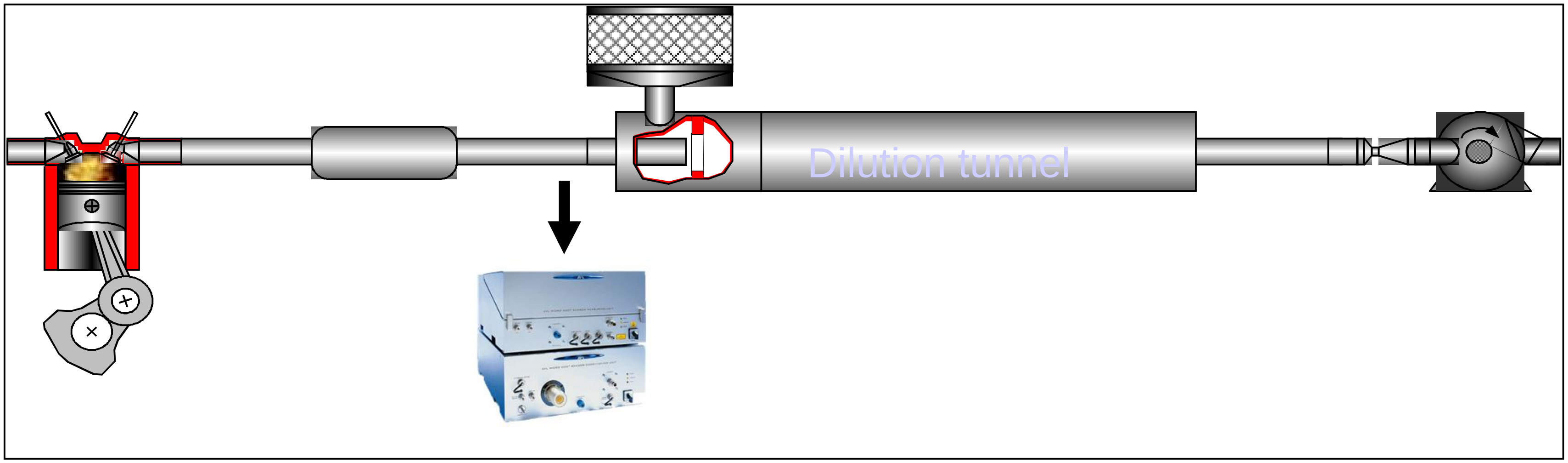
Only particulate **<u>and</u>** soot emissions measurements allow to quantify and optimize the performance of a DPF.

Application example:
Dynamic soot emission measurement from CVS



The soot emission calculated from the photoacoustic measurement correlates excellently with the non-volatile gravimetric Particulate emissions.

SAMPLING from the RAW EXHAUST (post-DPF)

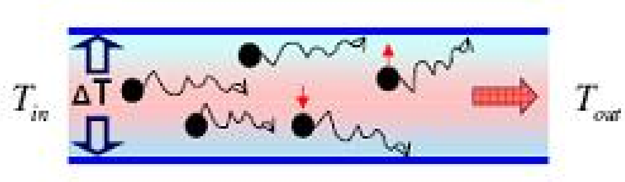


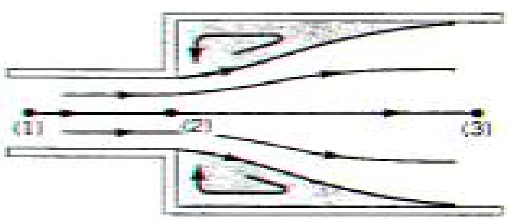
- Transient soot Emissions optimisation
- Cold start measurement
- Endurance tests
- DPF Filter fault detection

Challenges:
- Low Soot concentration
- Sampling Temperature: up to 400(600)°C -> **sampling artifacts**

Advantage: No CVS required

SAMPLING ARTEFACTS ARE FALSIFYING MEASUREMENT RESULTS





Ø At the sample point:

- Inhomogeneous particle distribution in the exhaust duct
- Pressure effects

Ø After sampling:

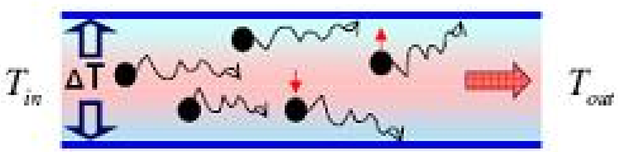
- Thermophoresis
- Condensation of HC and Water

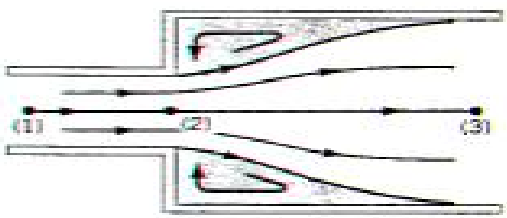
Ø During transport:

- Diffusive losses
- Turbulent losses
- Water condensation

Soot measurement from the RAW exhaust
Sampling effects

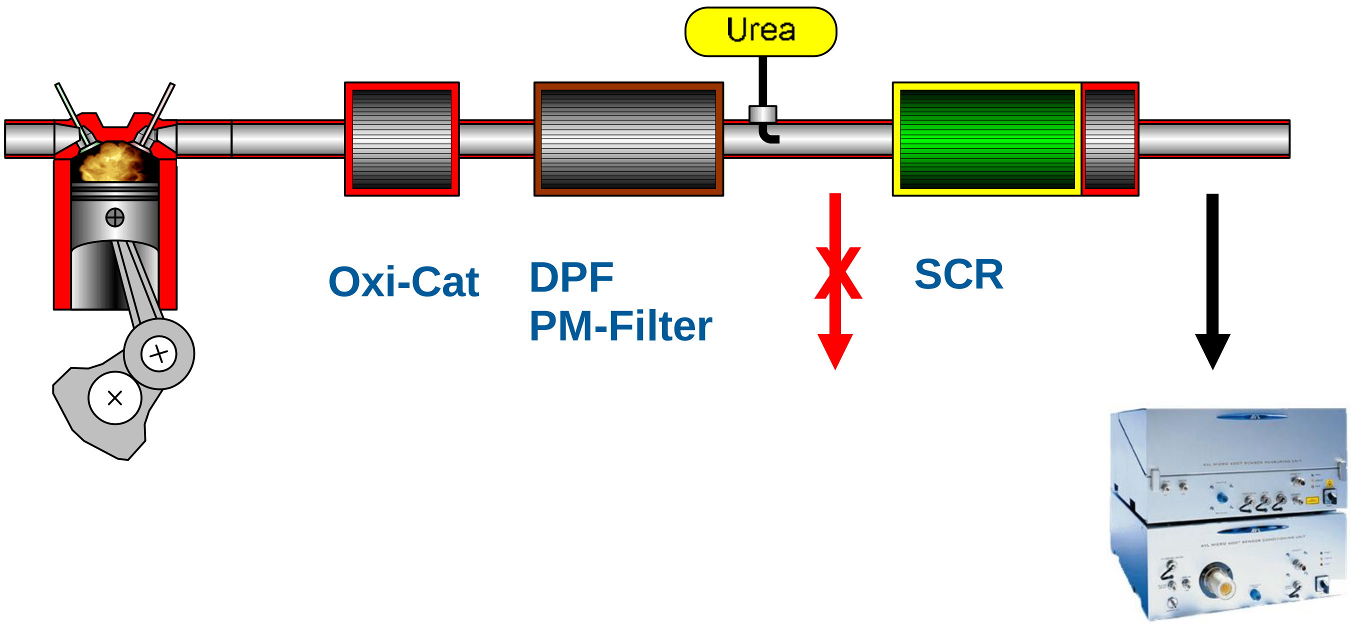
Aerosol sampling, especially from the raw exhaust, is a difficult topic, involving several technical challenges based on the physics of aerosols.
The critical effect is particle deposition: due to the Brownian motion particulates can hit the walls, where they stick (in contrast to gas molecules).





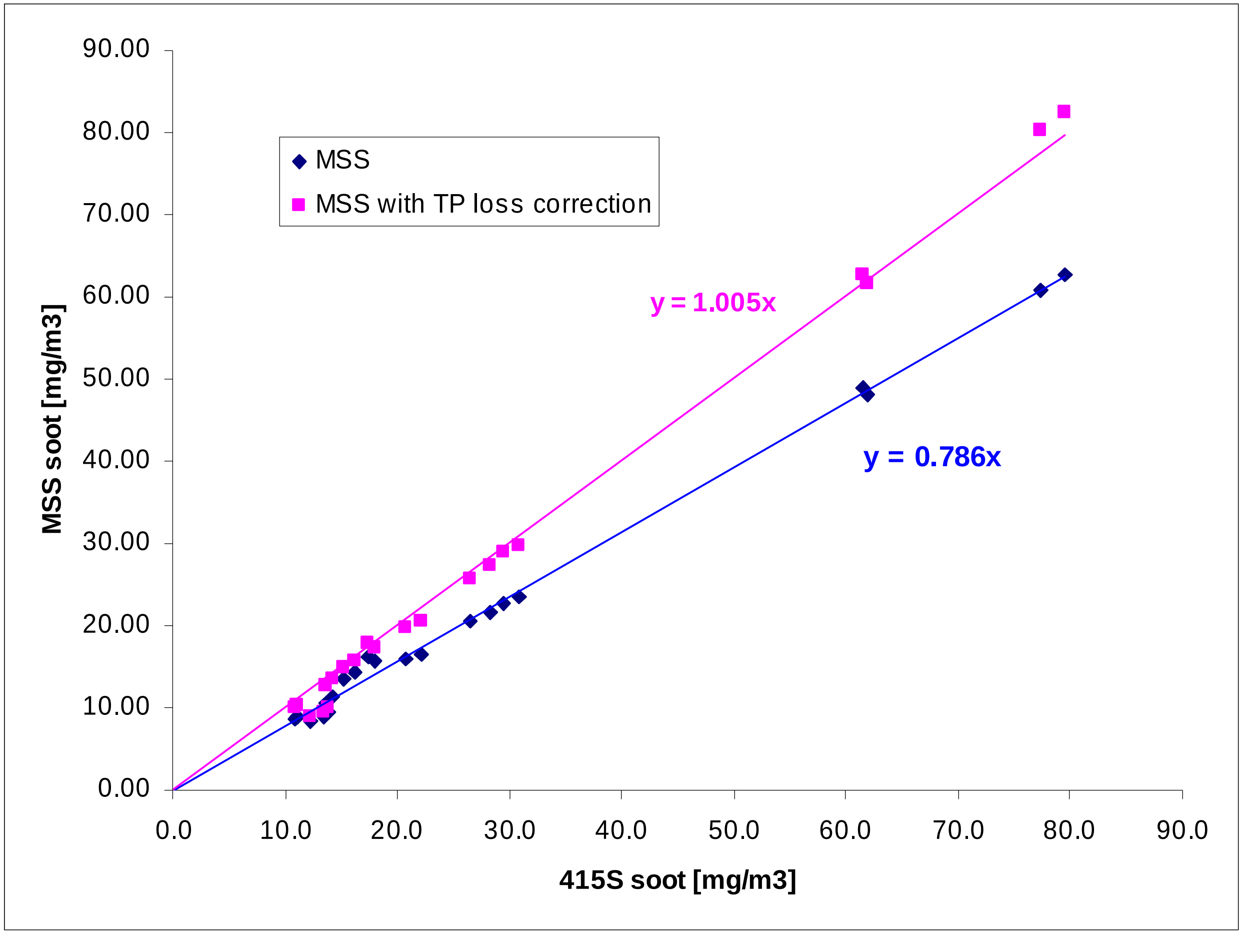
- Thermophoresis:
  If temperature gradients exists, the Brownian motion has a preferred direction to the cold walls. It can be quantitatively calculated from T_{in} and T_{out}.
- Particle deposition in transfer lines:
  For tubes the effect is typically <0.5%/m, small compared to thermophoresis, but for diameter changes (orifices!) it may be substantial.
- Inhomogeneous particle concentration at the sampling point may lead to non-representative concentrations.
- Pressure pulsations may lead to “backflow” from dilution cells mounted too closely to the exhaust stack.

How to ruin your emissions measuring equipment



Sampling after Urea injection, before the SCR, will result in solid urea particle deposition and therefore plug your sample lines, particulate filters, measuring cells, etc…, destroy e.g. optical components (windows) and result in severe instrument impairment.
Specialized equipment is required if emissions should be measured at this point.

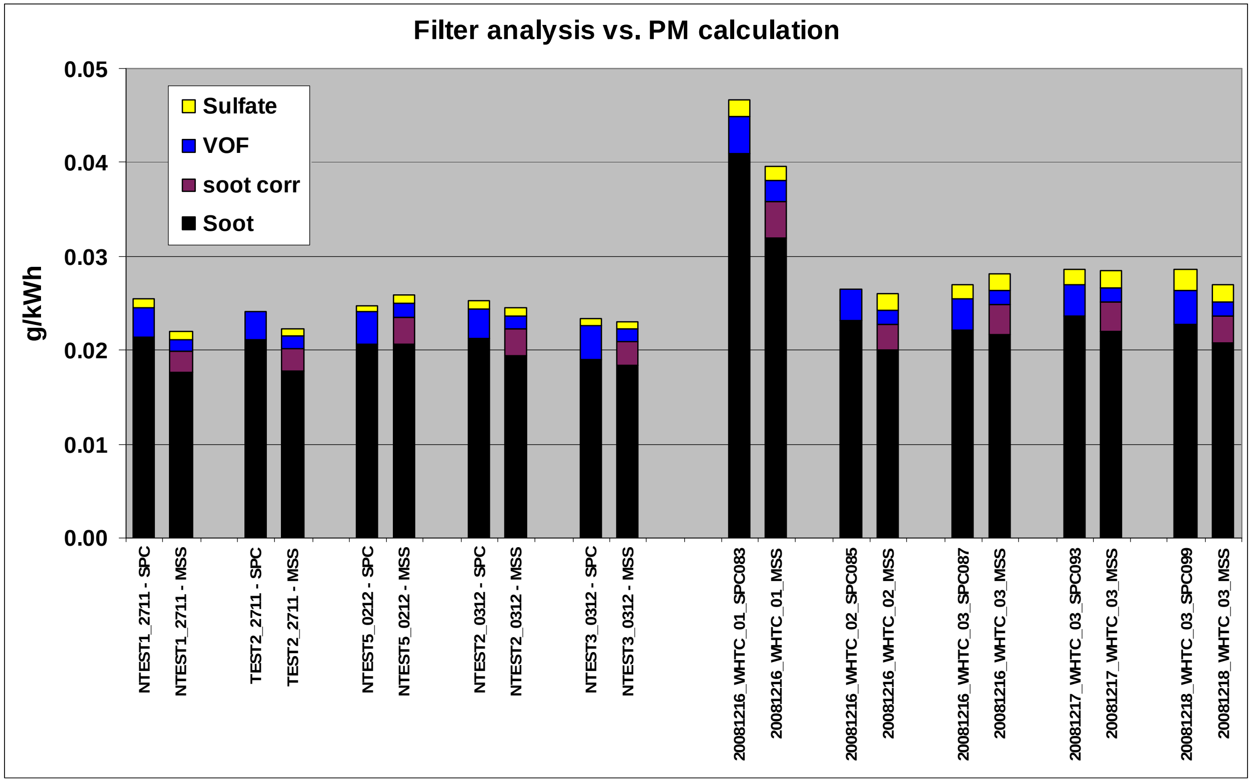
Application example:
Soot measurement from the raw exhaust



The uncorrected results are typical 20 to 40% low due to thermophoresis.

The equations given in previous presentations can fully compensate for the deposition.

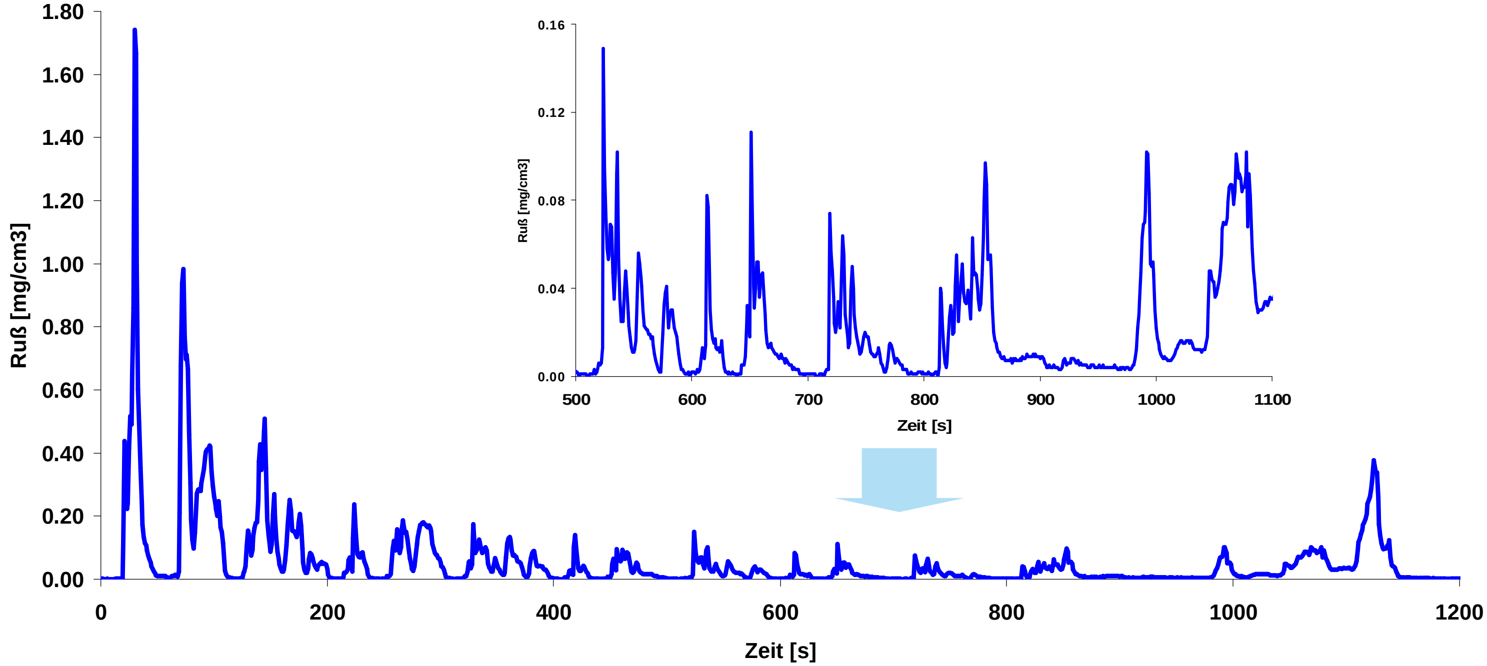
Application example:
Soot measurement from the raw exhaust



When rather cool exhaust is sampled from the tailpipe, thermophoresis is small, the results correlate well to the soot emissions determined by the gravimetric method

Application example:
Soot concentration in the exhaust of a GDI engine

1.6 l GDI Cold Start Tests

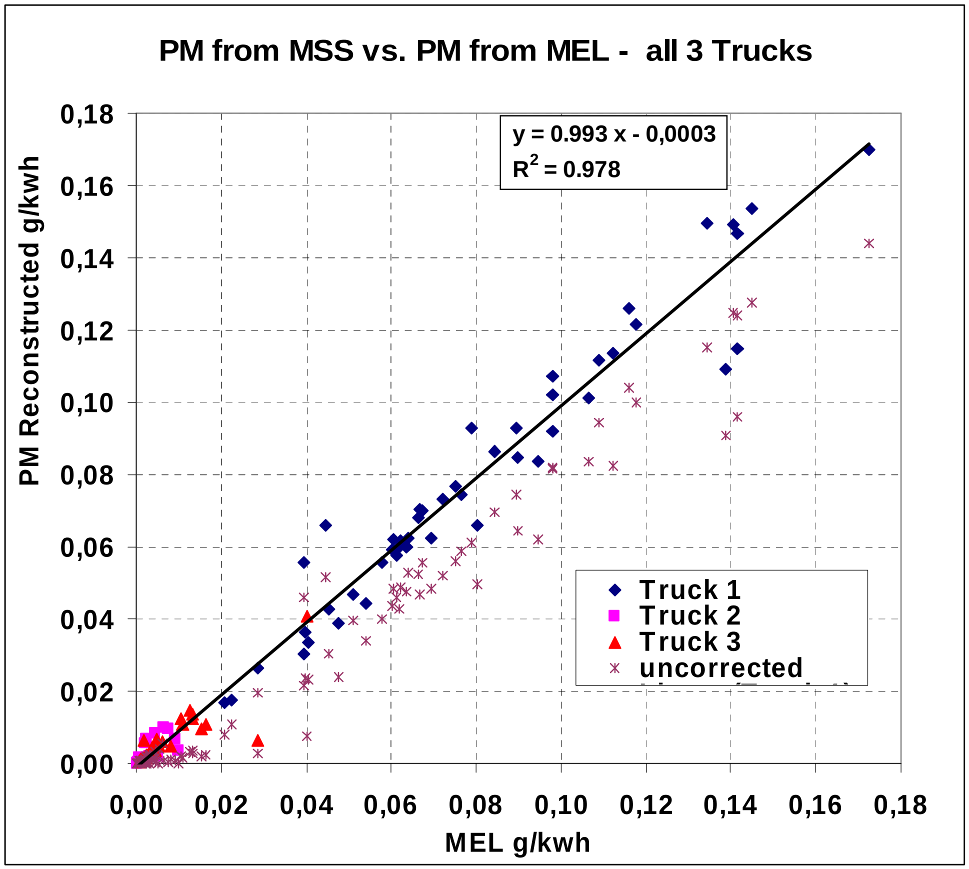


GDI emissions are currently a major topic of investigation, because the nonvolatile particle concentration in the exhaust of many GDI engines have been found to be substantially larger than in the post-DPF exhaust of Diesel engines.

Optimisation of the particle emission is possible with the simpler and cheaper soot sensor**, <u>if</u>** the change in relation between mass and number (compared to this relation for Diesel engines) is taken into account (see below).

Application example:
Dynamic soot emission measurement from CVS

Results of correlation testing between the PM based on MSS measurement and CVS measurements with the Mobile Emissions Lab (MEL) of CE-CERT (University of Riverside, Ca)



Statistical analysis:

the error of k (0.993) and d (-0.0003) is calculated.

The t-statistics is applied in analogy to CFR 40, part 1065.602

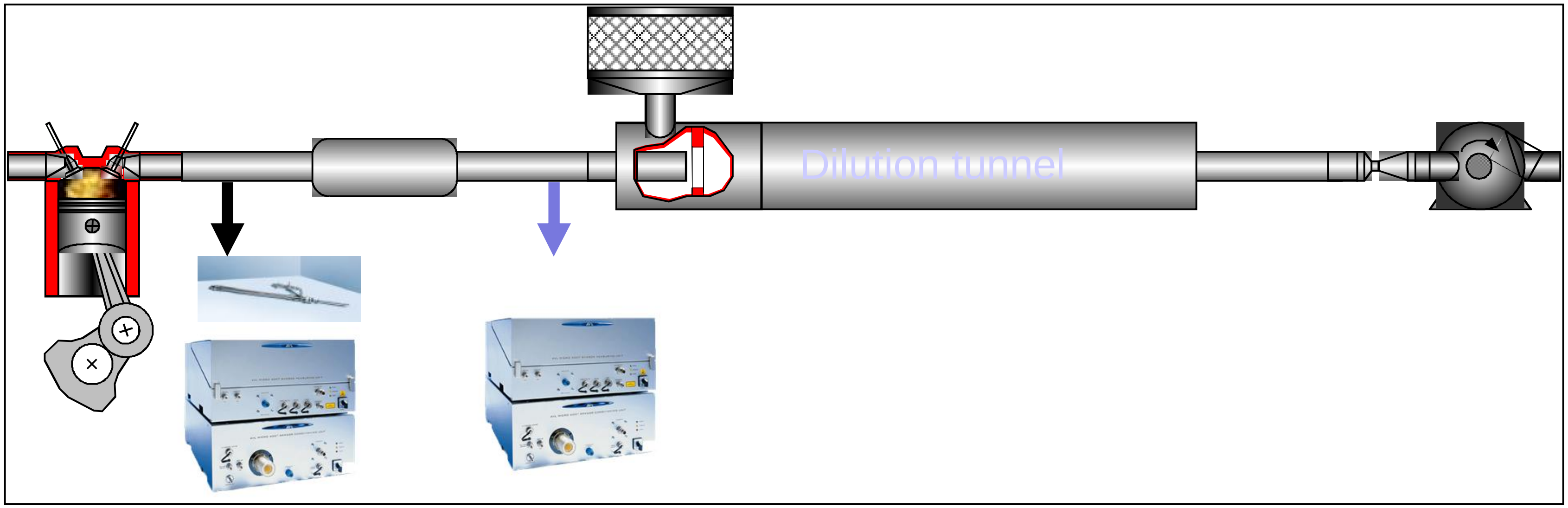
109 points,

95% t_limit = ±1.982

t(k) = -0.503

t(d) = -0.393

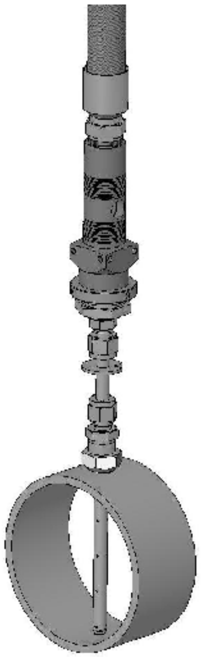
SAMPLING pre-DPF (RAW EXHAUST)

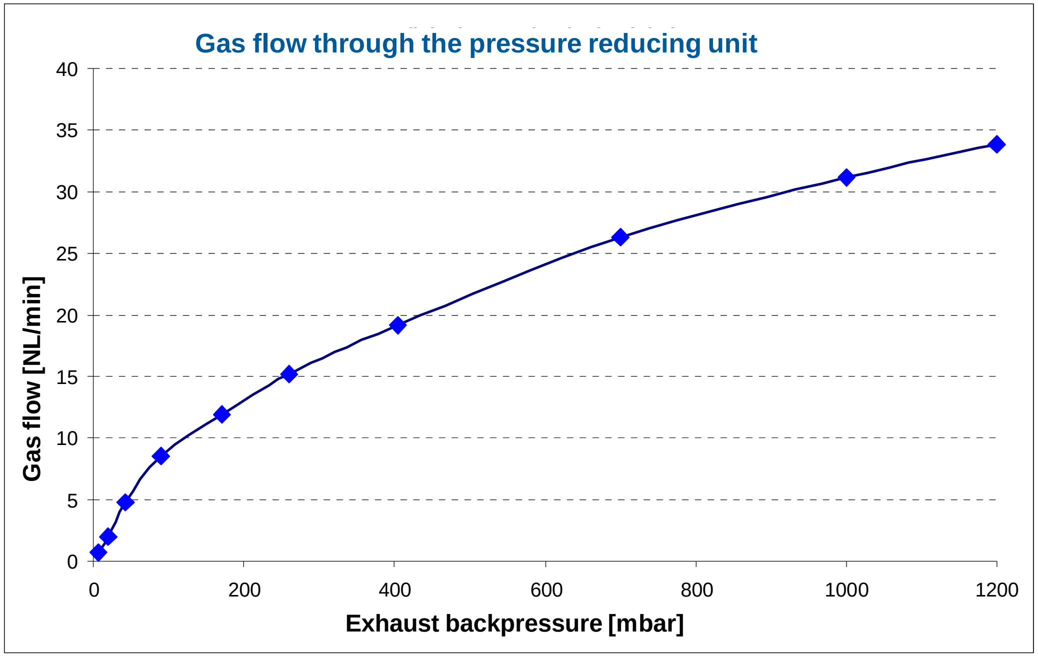


- Combustion analysis
- DPF soot loading measurement
- DPF Filter efficiency determination

Challenges:
- High pressures, up to 1 bar
- High Soot and HC concentr.
- Temperature up to 800°C

HIGH PRESSURE SAMPLING



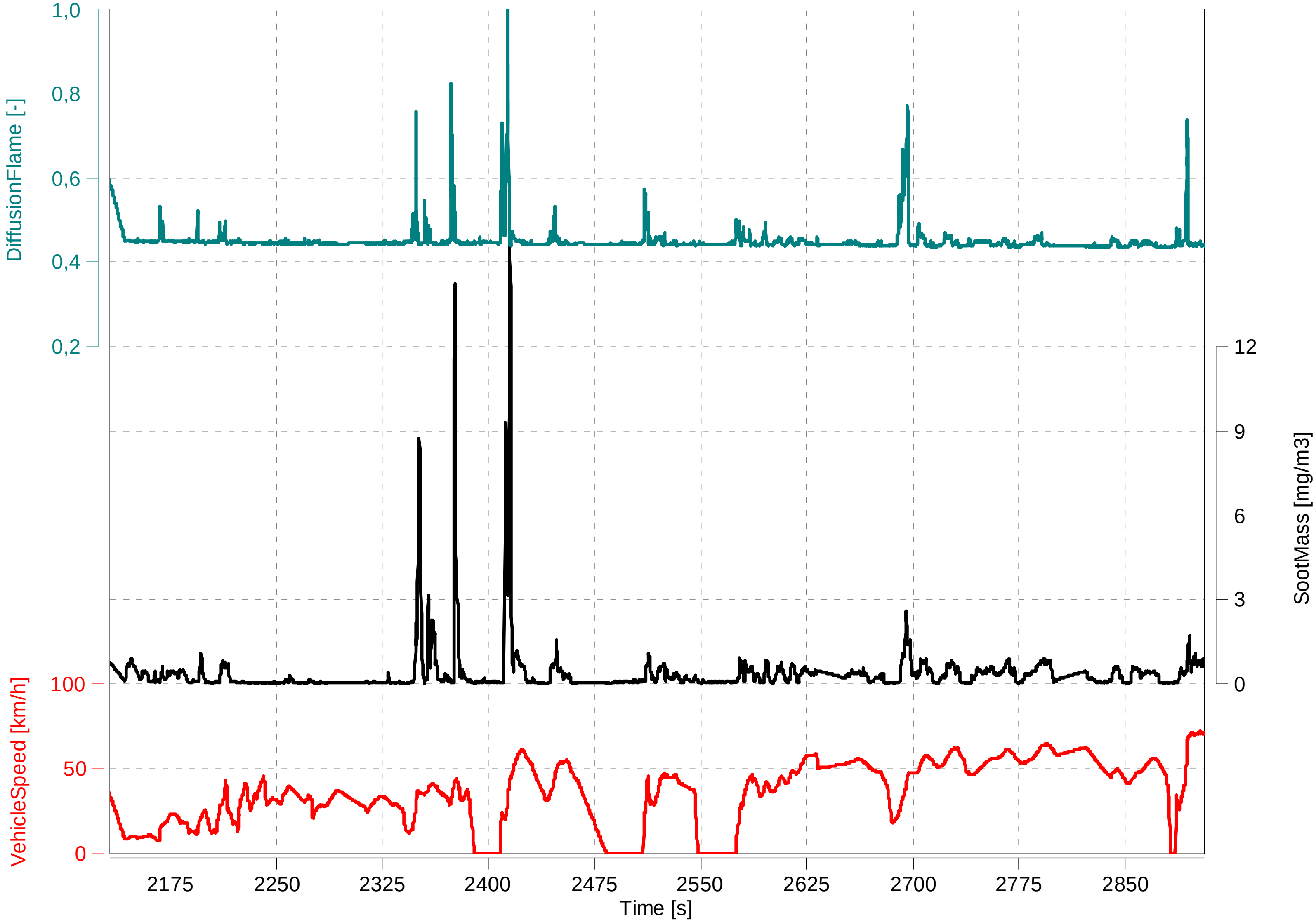


Multihole probe!

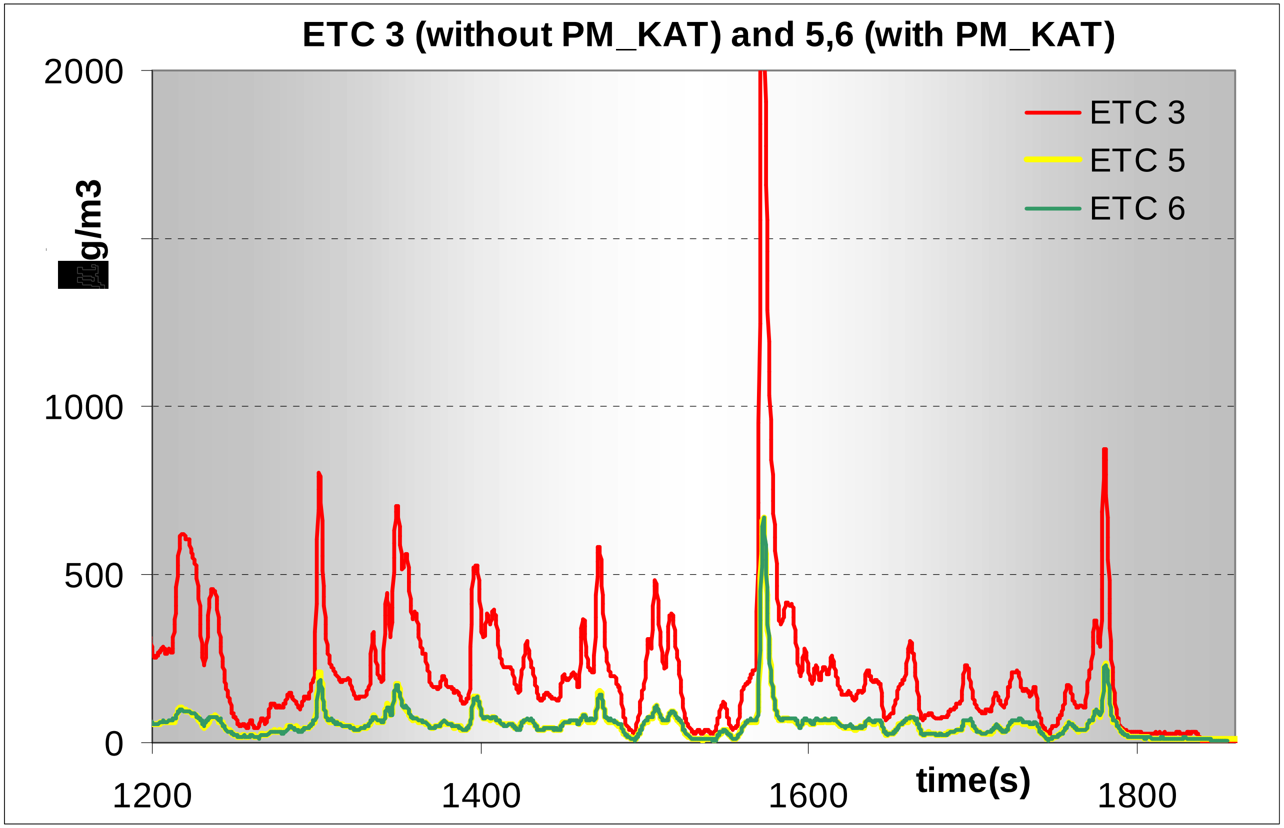
<u>Soot measurement shows losses</u>

Correction factor of 1.35 is applicable

Combustion analysis:
Relation between soot flame and soot mass emission



Application example:
efficiency measurement of a POC („PM-Kat“)

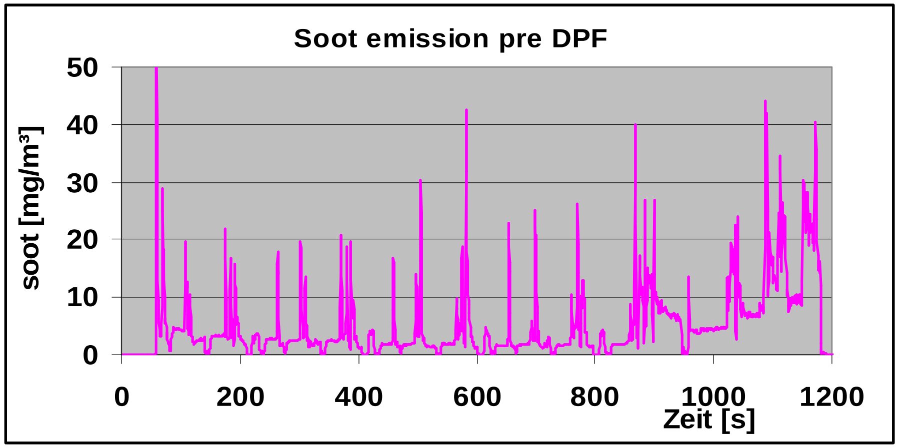


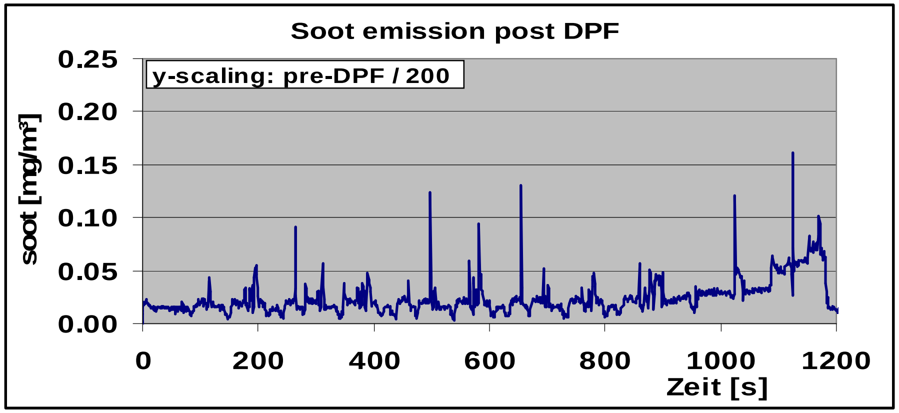
“open” filters like the so-called “PM Kat” have << 99% efficiency, but still can achieve a substantial reduction of the soot emission, especially for Heavy-Duty engines.

Since Heavy-duty engines typically have lower engine-out concentrations than light Duty engines, the reduction may be sufficient to reach the certification limit for EU VI (proposed: 10 mg/kW-hr).

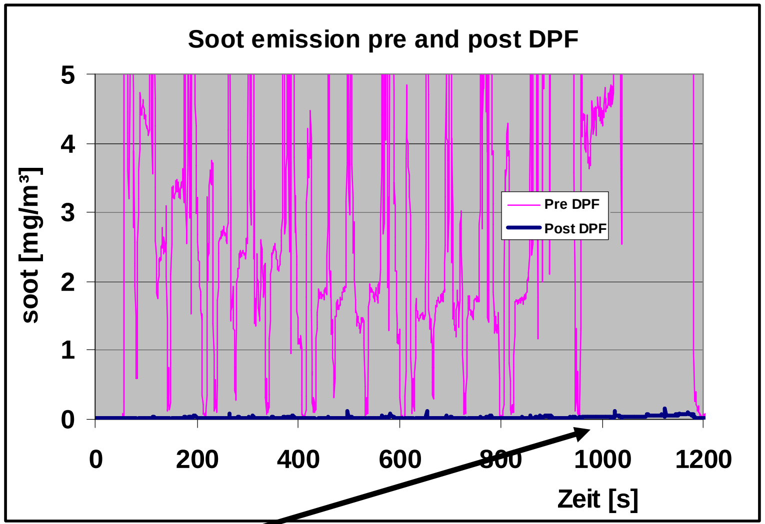
Application Example:
DPF efficiency measurement

Comparison of the Diesel soot emissions for a LD vehicle with and without DPF
(engine out: EU4 level)





Plotted on the same scale:

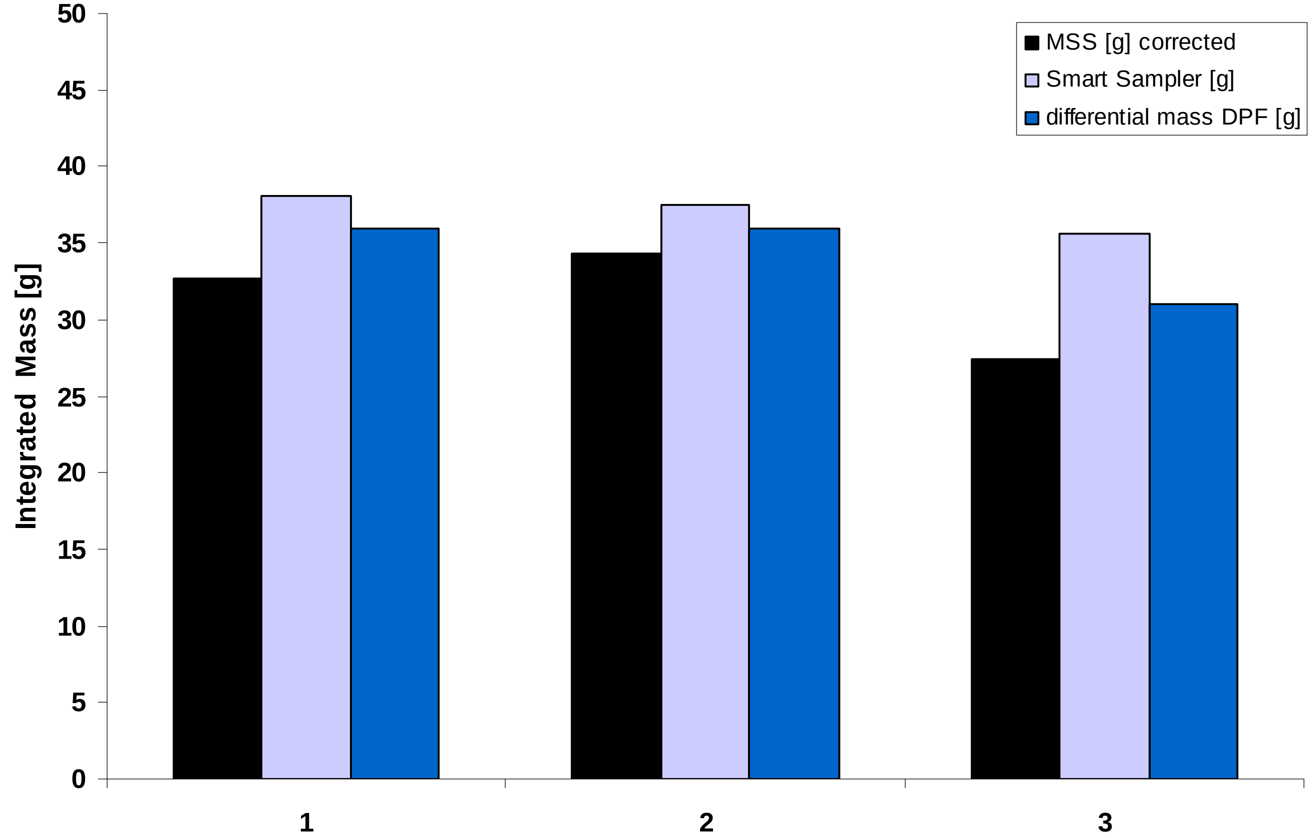


Post-DPF is hardly visible:

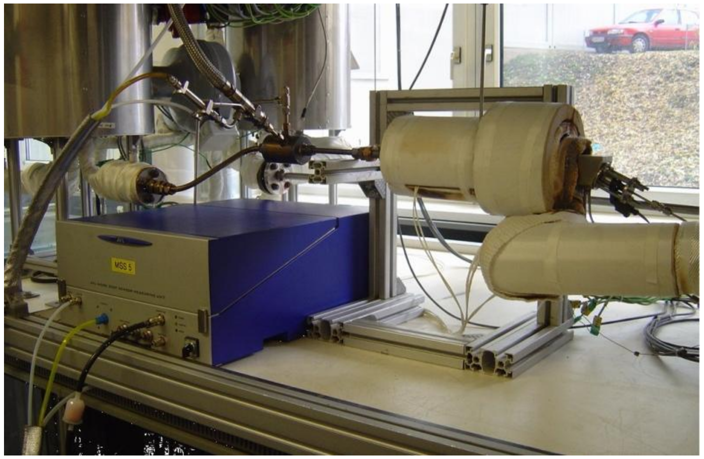
<u>Note:</u> the pre-DPF scale is 200 times the post-DPF scale.
=> The Filter efficiency is > 99%.

PREDICT SOOT LOADING ON A DPF

Integrated MSS soot mass vs. DPF weighing and SPC measurement



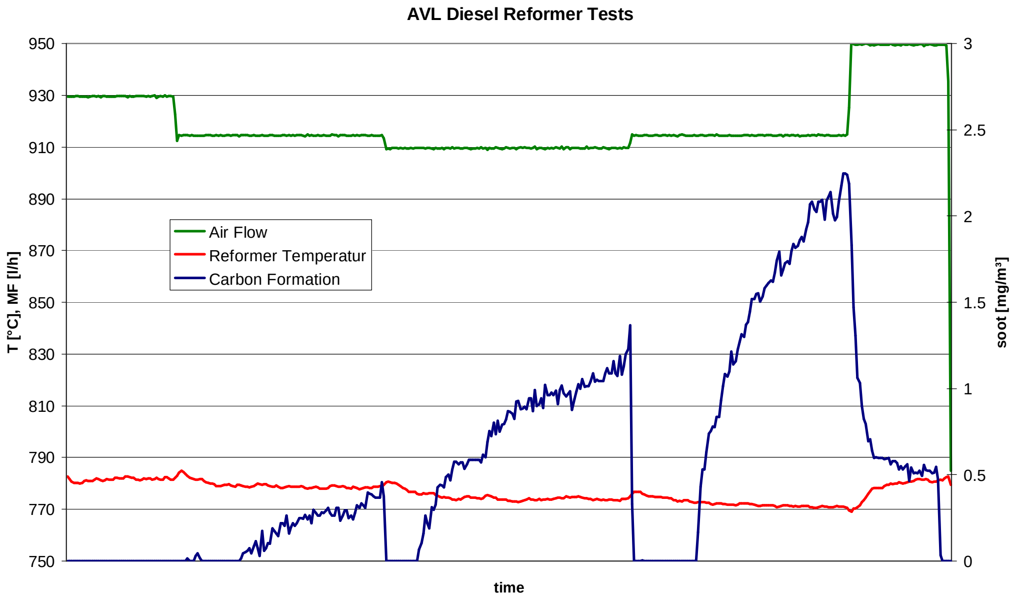
Special application:
FUEL REFORMER OPTIMIZATION



AVL Micro Soot Sensor applied on fuel cell testbed

AVL Micro Soot Sensor measures carbon fraction in reformer gas in realtime

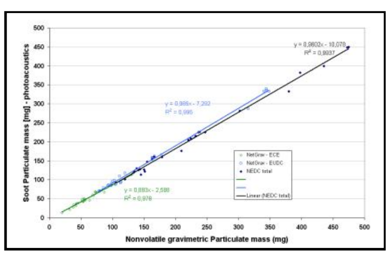
Black carbon formation is critical since it blocks the catalytic reaction in the reformer



Comparison and relations:
non-volatile particle emissions measurements

Filter analysis

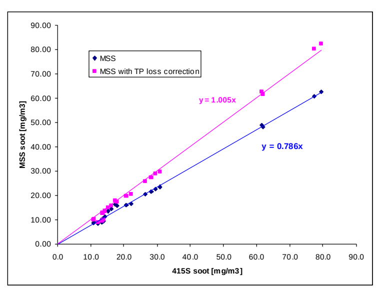
no generally applicable correlation to PM, good correlation to Insolubles.
Analysis uncertain for low soot fraction.



Smokemeter

Steady-state only!

A good correlation is achievable if particle losses are taken into account .



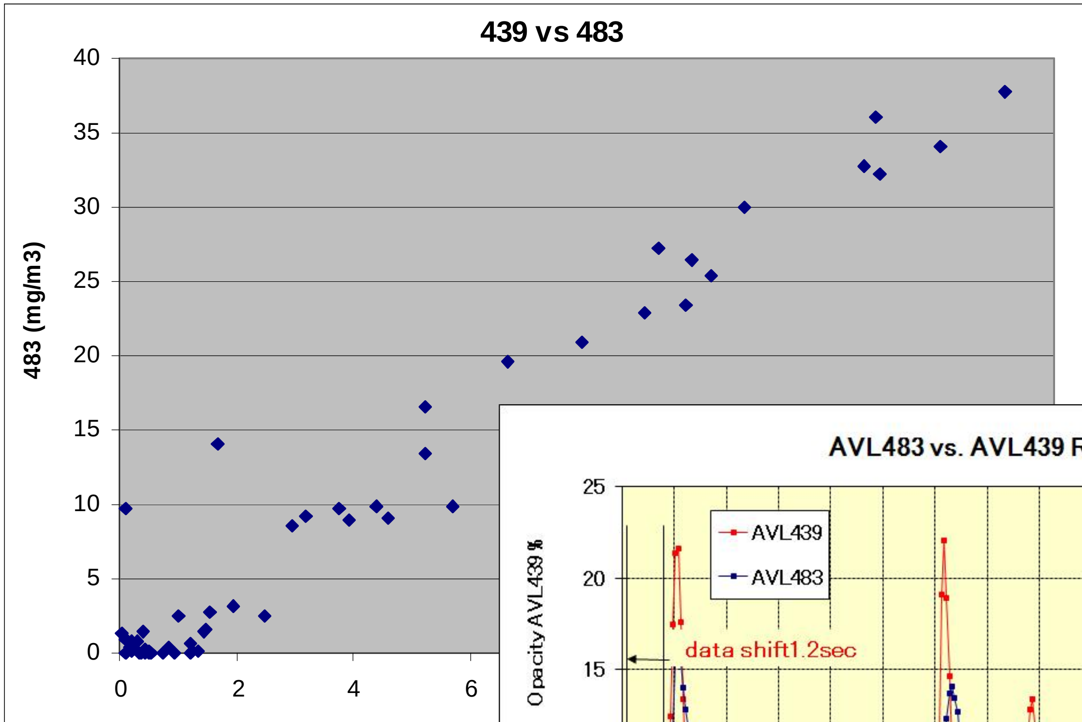
Opacimeter

The rise time of the opacimeter is an order of magnitude better, the detection limit more than an order of magnitude less.
The two instrumets yield proportional results if the PM emission is dominated by soot

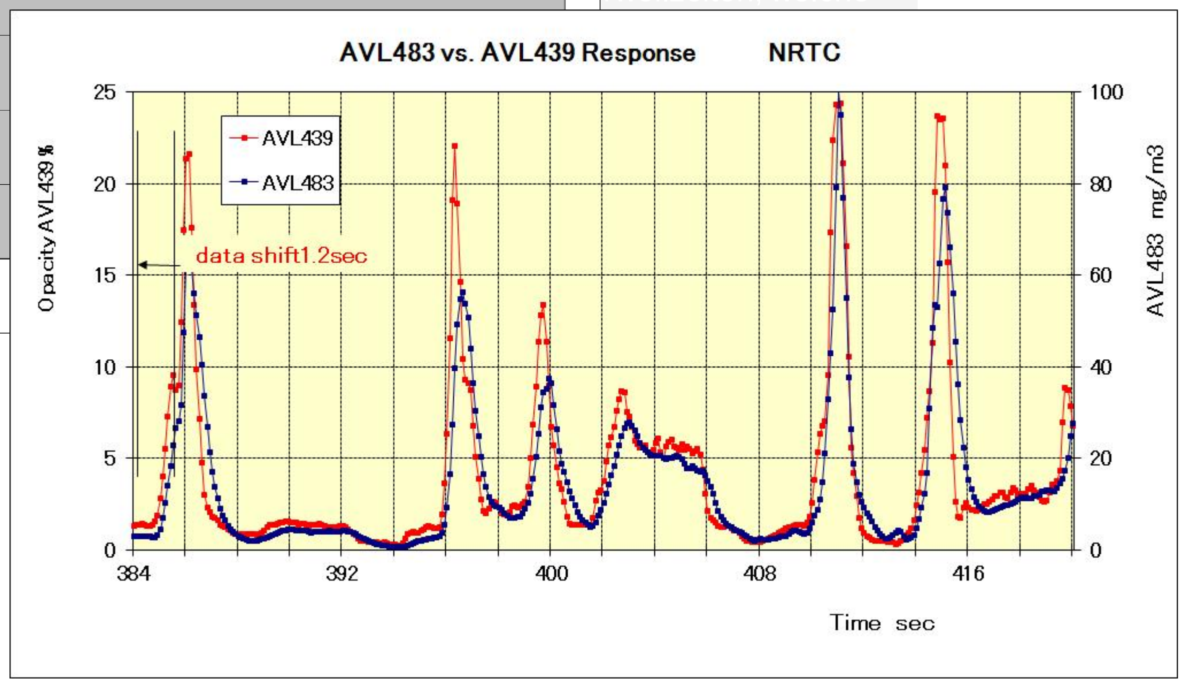
Particle Counter

Several Authors report good correlation between soot and particle number –
On a log-log scale!
The relation between soot and particle number is usually good for the average over transient test cycles, but may vary substantially depending on the driving conditions.

Comparison Micro Soot Sensor - Opacity



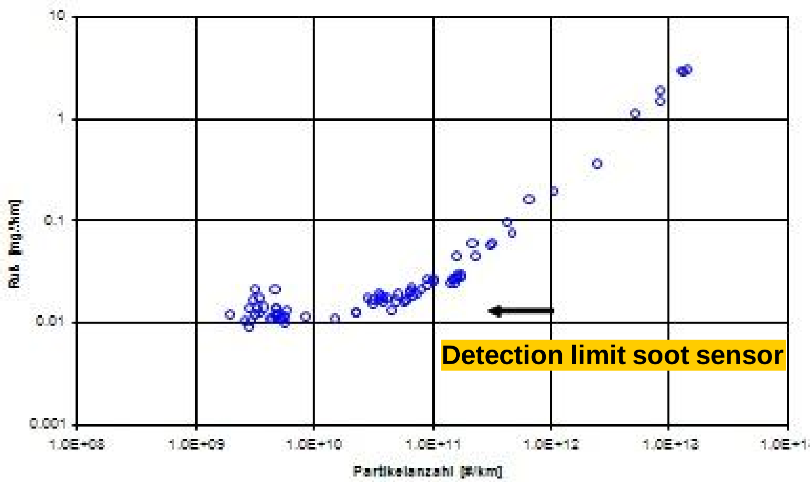
The linear relationship is expected for particle emissions which are dominated by soot.
The data scatter at low opacity is expected on the basis of the larger zero point noise.

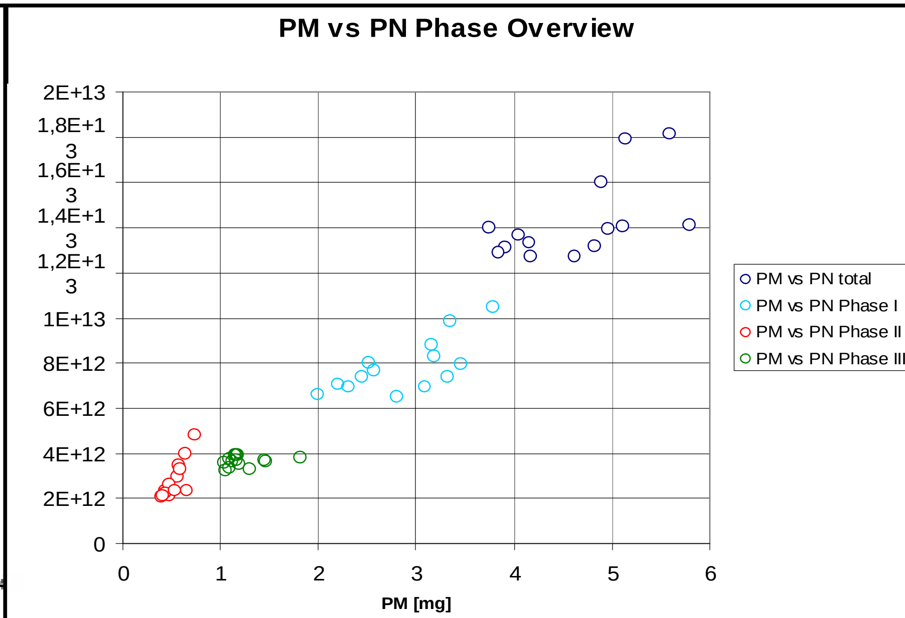


The traces of the two instruments are similar.
Rise time and delay time of the opacimeter is shorter than those of the Micro Soot Sensor.

PM & PN comparison: soot mass (MSS) versus particle number (APC)

Relation between solid particle number and soot mass

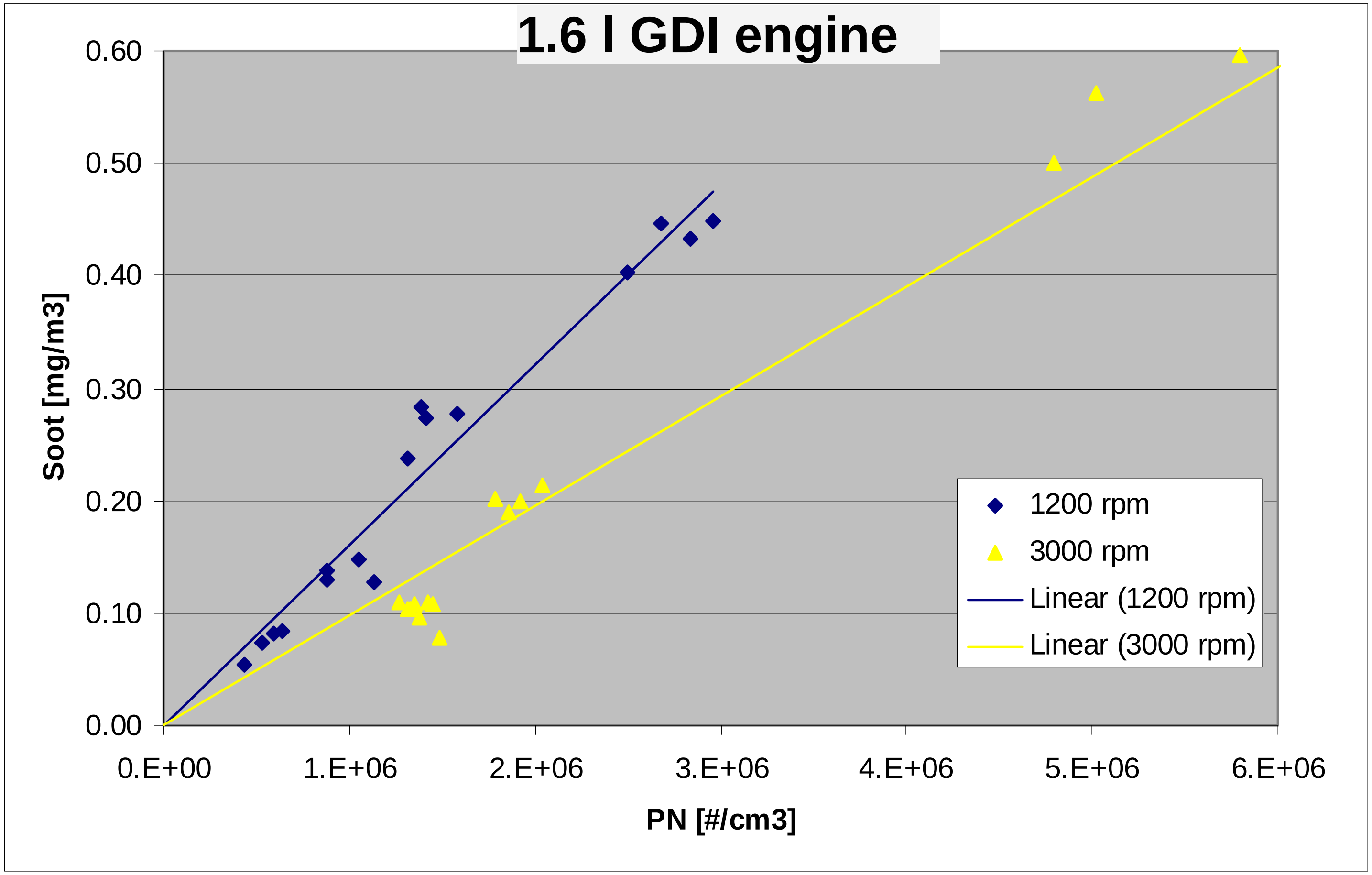




The relation between solid particle number and soot mass seems to be linear over several orders of magnitude. A widely used relation is:
$2*10^{12}$ p/km corresponds to 1 mg/km

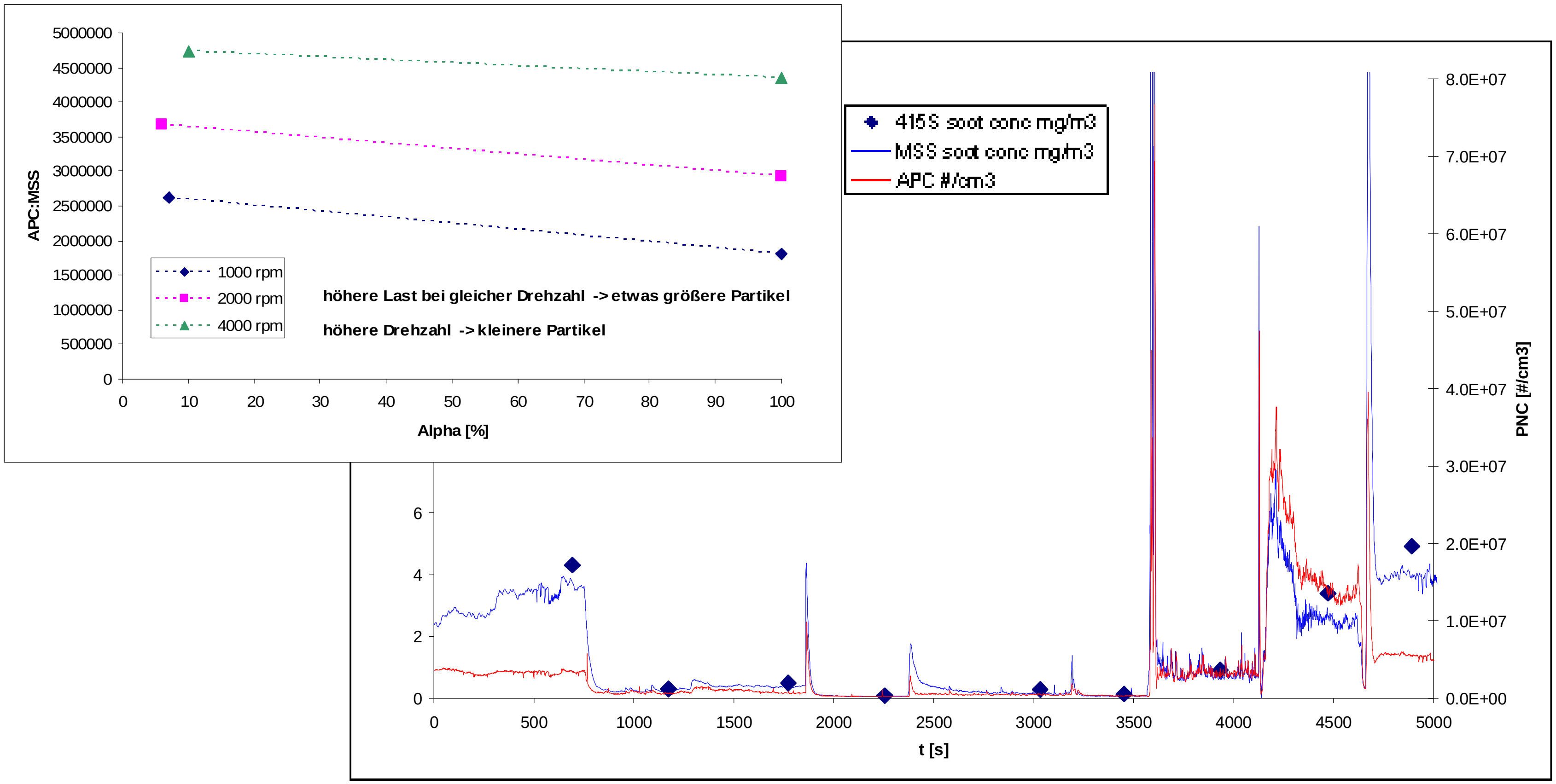
Observing PM and PN on a linear scale over only one order of magnitude sheds some doubt on the generally applicable validity of a strict correlation

PM & PN comparison:
soot mass (MSS) versus particle number (APC)



PN is influenced by engine speed due to particle agglomeration - time effect: the transport time in the exhaust duct to the sample point decreases with speed.

PM & PN comparison:
soot mass (MSS) versus particle number (APC)

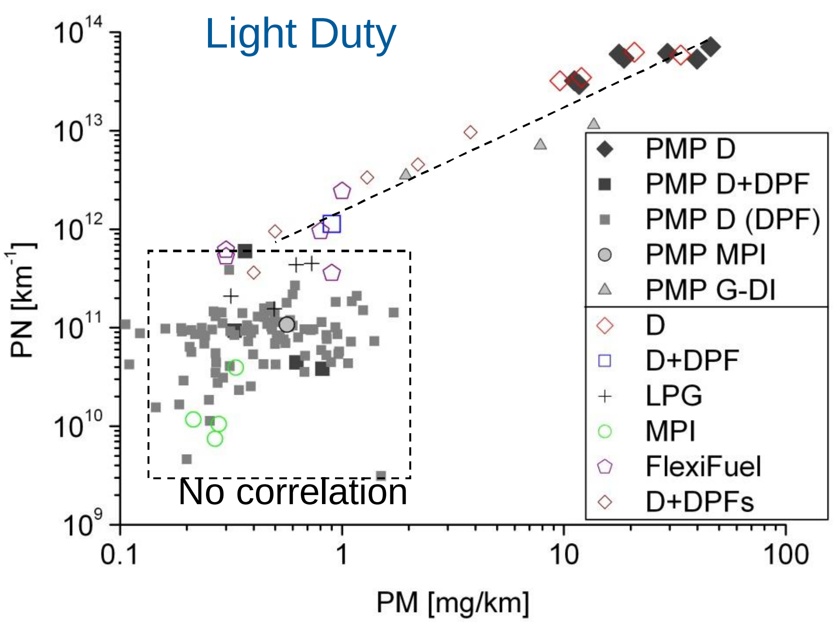


This state-resolved comparison between soot mass (MSS) and particle number (APC) at a GDI single cylinder research engines is a good example to show the applicability and the limits of the correlation method.

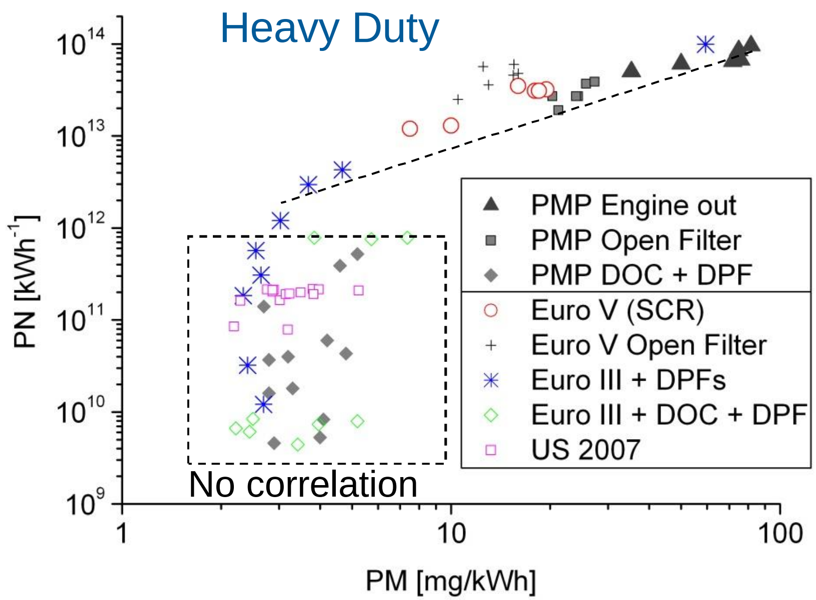
PM & PN comparison:
soot mass (MSS) versus particle number (APC)

- There is some relationship between PN and soot mass.
- When the MSS is sampling from the Tailpipe with dilution ratios between 3 and 5, it is sensitive enough to measure the soot mass when PN is at the certification limit
- When the MSS doesn‘t see any soot at all, the engine will not fail certification according to PMP

PM & PN
Vergleich zwischen Anzahl und “klassischer” Gravimetrie



Grey solid symbols are data from the PMP light duty inter-laboratory exercise with the light duty golden instrument (Rotating disk type from Matter Eng.). Colored open symbols are data with APCs at various laboratories. Each point is a different vehicle or a different fuel (exception for D (DPF) PMP, which is the golden vehicle, all labs results are given). D=Diesel, DPF=Diesel Particulate Filter, MPI=Multi Point Injection, G-DI=Gasoline Direct Injection, LPG=Liquefied Petroleum Gas.



Comparison of the PN with the regulated PM emissions for different heavy duty engine technologies. Grey solid symbols are data from the PMP heavy duty inter-laboratory exercise with the heavy duty Golden instrument (SPCS prototype). Colored open symbols are measurements with APCs at JRC and AVL. Each point is a different engine or test cycle. DOC=Diesel Oxidation Catalyst, DPF=Diesel Particulate Filter, SCR=Selective Catalytic Reduction for NOx.

Giechaskiel et al. 2010, MST

COMPARISON BETWEEN DIFFERENT MASS-BASED METHODS

	CVS – soot only (EC)	Partial Flow Dilution System with "Performance Probe" soot only (EC)	Smoke Meter 415S with heated sample line	MSS 483 from CVS or PFD	MSS 483 with Dilution unit from raw exhaust
Measured value in %	100 %	100 +/- 5%	100 +/-10%	100 +/-10%	70 +/- 10%
Measured value in mg/m3	100	95 to 105	90 to 110	90 to 110	65 to 85
Measured value in mg/m3	75	71 to 79	68 to 83	68 to 83	49 to 55
Measured value in mg/m3	50	48 to 53	45 to 55	45 to 55	33 to 43
Measured value in mg/m3	25	24 to 26	23 to 28	23 to 28	16 to 21
Measured value in mg/m3	10	9.5 to 10.5	9 to 11	9 to 11	6.5 to 8.5
Measured value in mg/m3	5	4.8 to 5.3	4.5 to 5.5	4.5 to 5.5	3.3 to 4.3

THANK YOU
for your attention

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