Comparison of Soot Measurement Instruments during Transient and Steady State Operation

Christophe Barro, Philipp Vögelin, Pascal Wilhelm, Peter Obrecht, Konstantinos Boulouchos (Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich)

Extended Summary to the Presentation Slides

Measurement Equipment and Testbench

The particulate emissions from a diesel engine can be characterised from formation and oxidations process as well as at the tail pipe. To prove an engines legal conformity, mass concentration and particle number in the exhaust stream need to be analysed where the size and the number of particles becomes more and more important regarding health effects and future legislations.

For a more detailed investigation, particulate size distribution analysis as well as optical methods – both, in-cylinder and tail pipe measurement – can be used to characterise the diesel engines operation in terms of exhaust gas particulate emissions.

The presented setup uses simultaneously the following four measurement systems: A smoke meter to find the filter smoke number (FSN) from AVL, where a white filter paper with exactly defined properties is passed by exhaust gases. The resulted scattering, additional species on the carbon particles included, gives a so called FSN value which is transferred to a soot mass concentration (mg/m^3) by an empirical formula from AVL.

A Micro Soot Sensor from AVL (PASS, Photo acoustic soot sensor) delivers a second soot mass concentration value. Exhaust gases pass a chamber and the high absorbing dark soot particles are heated up by using modulated laser light. A microphone records the resulting sound waves (photo acoustic effect) from the expansion and contraction of the surrounding gases. The soot mass concentration can then be derived from the detected elementary carbon.

A diffusion size classifier (Matter Aerosol) is able to derive the number of soot particles and their mean diffusion mobility size. The incoming soot particles are electrically charged by a corona and then pass an induction, diffusion and filter stage. In every stage the resulting electrical current is measured. This allows to calculate the number and the mean size of the particles per volume. A correlation from M. M. Maricq [1] was used in order to find a soot mass concentration.

The in-cylinder optical light probe (OLP) from Kistler Instruments is a 3-Color-Pyrometer which allows adapting the two-colour pyrometry technique 3-times for cross reference. It consists of a lens with a light conductor mounted in the cylinder head aligned with the combustion chamber. During the diffusion combustion formatted soot particles glow due to the high temperature of the combustion gases, the gathered radiation is then split in three different wavelength intensities by filters and finally converted to crank angle resolved voltage signals by photodiodes. The so called two-colour pyrometry can then be applied. Intensities of two wavelengths are needed in order to calculate the radiating soot density represented by the KL factor (concentration · optical length). The OLP is a prototype and still in development.

All measurements were executed at ETH's test facilities. The single cylinder DI diesel research engine of the MTU 396 series type, equipped with a common rail injection system has an independent pressurised and thermal controlled air supply and an exhaust throttle. The displacement volume is 3.96 litres defined by a bore of 165 mm and a stroke of 185 mm. The maximal injection pressure is around 1400 bars and the injector is controlled by ECU from Bodensee Steuergeräte (BSG).

Steady State Observations

A load of 50% (10 bar mean effective pressure) was chosen for all steady state and used as the base for the transient measurements. Good quantitative agreement was found between the different measurement instruments during steady state operation.

All measured soot concentrations in the exhaust were transferred from mg/m^3 to g/kWh. The heat release curve is generally stable with only slight derivations from cycle to cycle. In contrast to the heat release the KL trace varies clearly from cycle to cycle. A reason for that could be either different soot formation / oxidation for every cycle or changing soot radiation in the visible field of the OLP.

27 operating points in the field of 900, 1200 and 1440 rpm with 50 % load (10 bar mean effective pressure) were measured with changing rail pressure (800 – 1200 bar) and start of injection (5 – 15° CA BTDC). The engine produced generally low soot concentrations what leads to quite narrow range of FSN numbers (0.25 – 1.2).

Every single KL trace of a measured load point was evaluated regarding a KL end value which can be correlated with the tail pipe measurements. The KL trace was integrated and the position of the 98% value was searched. At this position the KL value was taken as the KL end value of the cycle. These values were then averaged in order to get a KL_{end} value of the operating point. The result is a $R^2 = 0.785$ correlation to FSN with matching KL end and FSN value at the reference operating point. At operating conditions with higher soot emission, the soot mass obtained by the KL end was underestimated compared to the FSN measurements.

In a second step the KL end values were multiplied with measured particle size and this additional information leads to a $R^2 = 0.872$ correlation to FSN. The KL_{end} underestimation of the soot mass compared to the first correlation is not anymore present. The thought behind this size correction is an assumed dependency between the radiation intensity and the surface-to-volume fraction of the soot particles. The soot particle mean size increases in this particular measurement series generally with increased exhaust soot emissions.

Transient Observations

The response time of each instrument during the transient operation varies between instantaneous (OLP) and a few seconds (PASS, DiSC) due to the respective sampling location and method. Due to the different units only a qualitative comparison can be made. The time delay results from different sampling positions in the exhaust pipe, but the KL value, smoothed by a moving average algorithm, reacts immediately.

The load step from 2.5 to 3 ms injection duration causes fluctuating curves after the step. The PASS soot mass, the particle number from DiSC and the KL end value show similar fluctuations with respect to the reaction time. The mean size stayed almost constant after the first increase. It seems that the engine doesn’t operate stable during the measured time range after the step.

Conclusions and Outlook

The understanding and analysis of the KL curve turns out to be quite difficult since measured radiation and the calculated KL values only stands for an averaged soot density within the viewed field of the combustion chamber.

Further investigations are planned concerning a representative and reliable analysis of the KL trace regarding a better correlation with tail pipe measurements. Not only the end values of KL trace but also the whole shape should be considered. In the best case no additional information like the particle mean size or number has to be used for the evaluation.

[1] M. M. Maricq, N. Xu / Aerosol Science 35(2004) 1251–1274

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Christophe Barro
Philipp Vögelin
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Konstantinos Boulouchos
Aerothermochemistry and Combustion Systems Laboratory
ETH Zurich

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Outline

- **Testbench**
- **Soot Measurement Instrumentation**
- **Steady State Observations**
- **Transient Observations**
- **Conclusions**
- **Outlook**

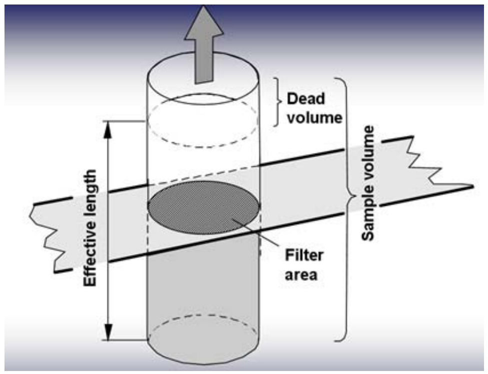
Testbench

- **Single cylinder, common rail research engine:**
  - MTU 396, independent pressurized air supply (pmax ~ 4.5 bar), Exhaust throttle
  - $p_{inj,max}$~1400 bar, BSG ECU
- **Exhaust stream soot emissions:**
  - AVL Smoke Meter (FSN)
  - AVL Micro Soot Sensor (PASS)
  - Matter Diffusion Size Classifier (DiSC)
- **In-cylinder soot:**
  - Kistler Optical Light Probe (OLP)
    - Prototyp

Soot Measurement Instrumentation (1/2)

Smoke Meter

- Principle:

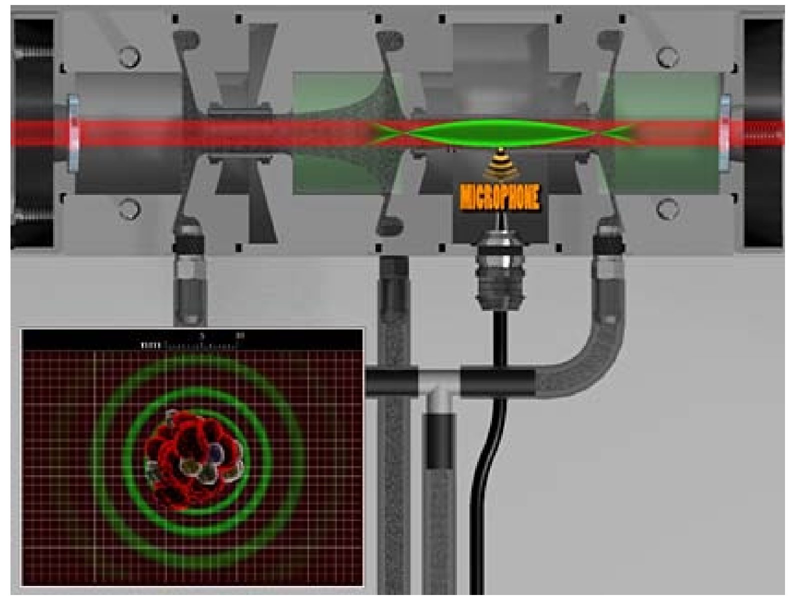


- Output:
  - FSN (Filter Smoke Number)
  - mg/m³
  - Correlation

$$"C"\ (mg/m^3) = \frac{1}{0.405} \cdot 4.95 \cdot FSN \cdot \exp(0.38 \cdot FSN)$$

Micro Soot Sensor

- Principle: Photo Acoustic Effect



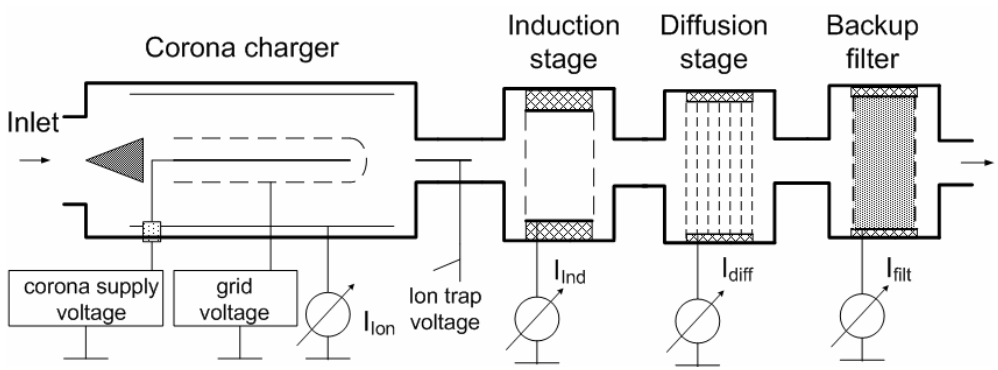
- Output:
  - mg/m³

Source: www.avl.com

Soot Measurement Instrumentation (2/2)

▪ Diffusion Size Classifier

- Principle:

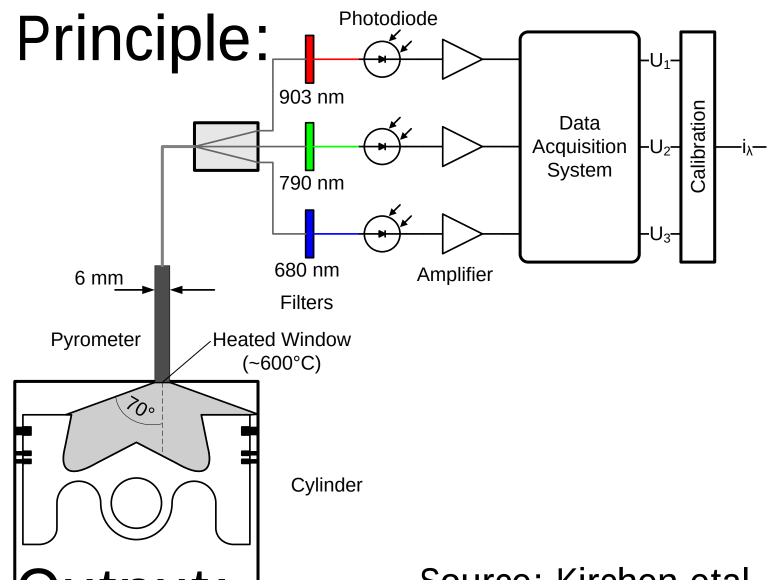


Source: Fierz etal. 2007

- Output:
  - Mean diffusion mobility size
  - Number of particles

▪ Optical Light Probe

- Principle:



Source: Kirchen etal. 2009

- Output:
  - Spectral intensity
  - Soot cloud Temperature
  - KL (optical soot density)

OLP in Detail

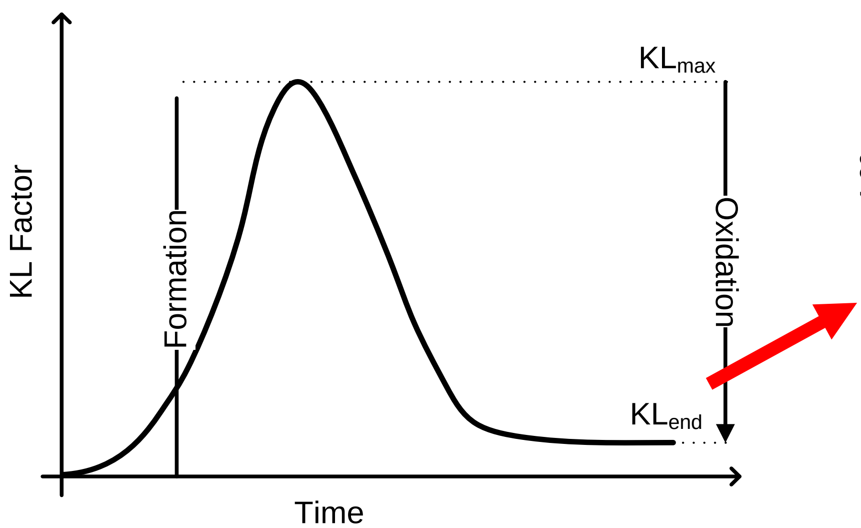
- **Multi-color pyrometry considers light intensity to determine in-cylinder:**

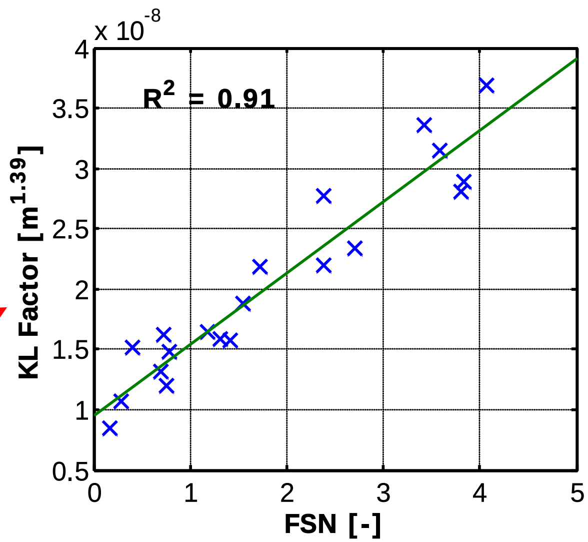
Soot cloud temperature

$$\left[1-\left(\frac{e^{\frac{C_2}{\lambda_1 T}}-1}{e^{\frac{C_2}{\lambda_1 T_{s,1}}}-1}\right)\right]^{\lambda_1^{\alpha}} = \left[1-\left(\frac{e^{\frac{C_2}{\lambda_2 T}}-1}{e^{\frac{C_2}{\lambda_1 T_{s,2}}}-1}\right)\right]^{\lambda_2^{\alpha}}$$

Soot concentration (KL factor)

$$KL = -\lambda^{1.39} \ln\left[1-\left(\frac{e^{\frac{C_2}{\lambda T}}-1}{e^{\frac{C_2}{\lambda T_s}}-1}\right)\right]$$

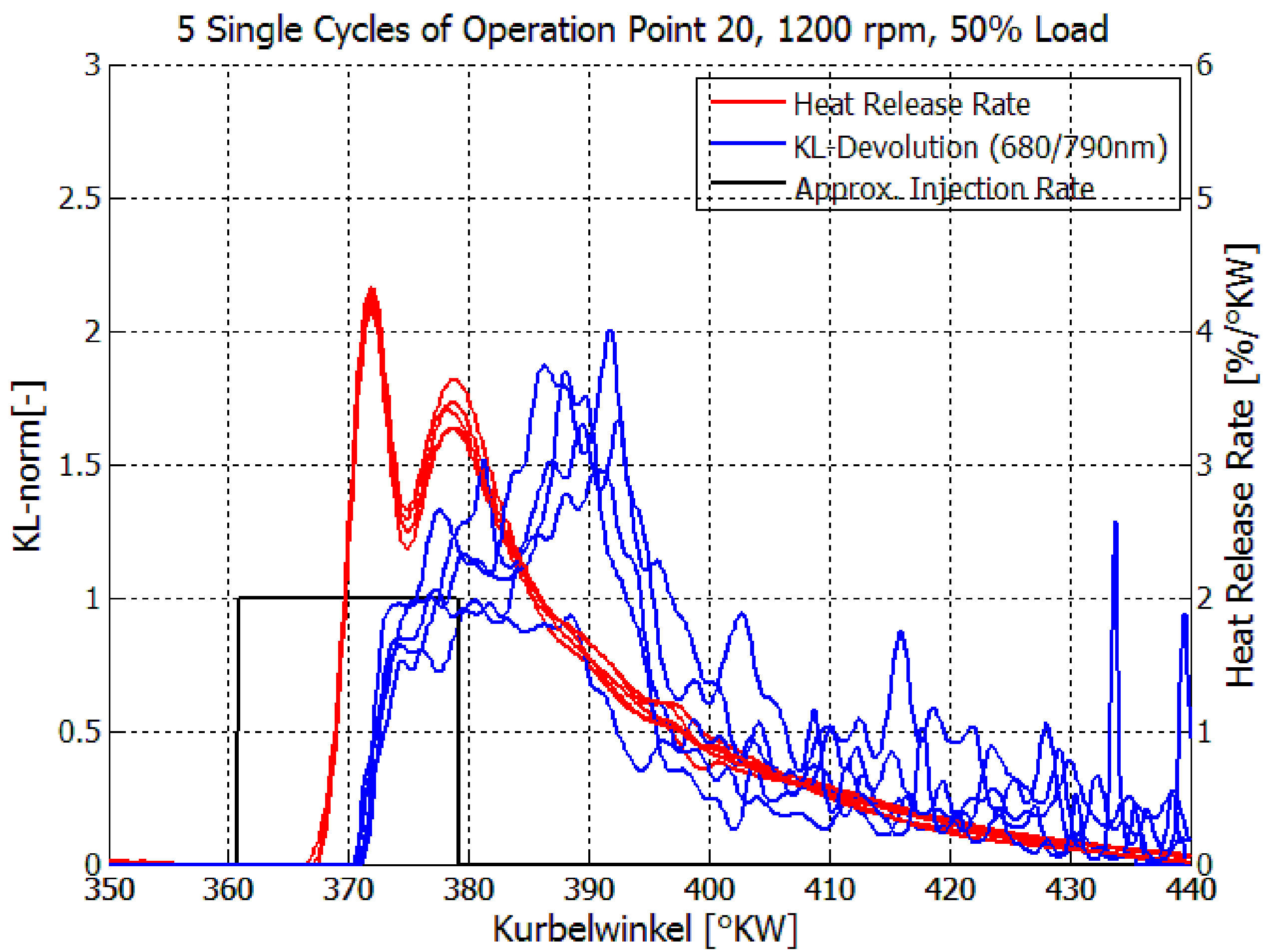




Source: Kirchen etal. 2008, Hottel and Broughton 1932

Steady State Observations (1/3)

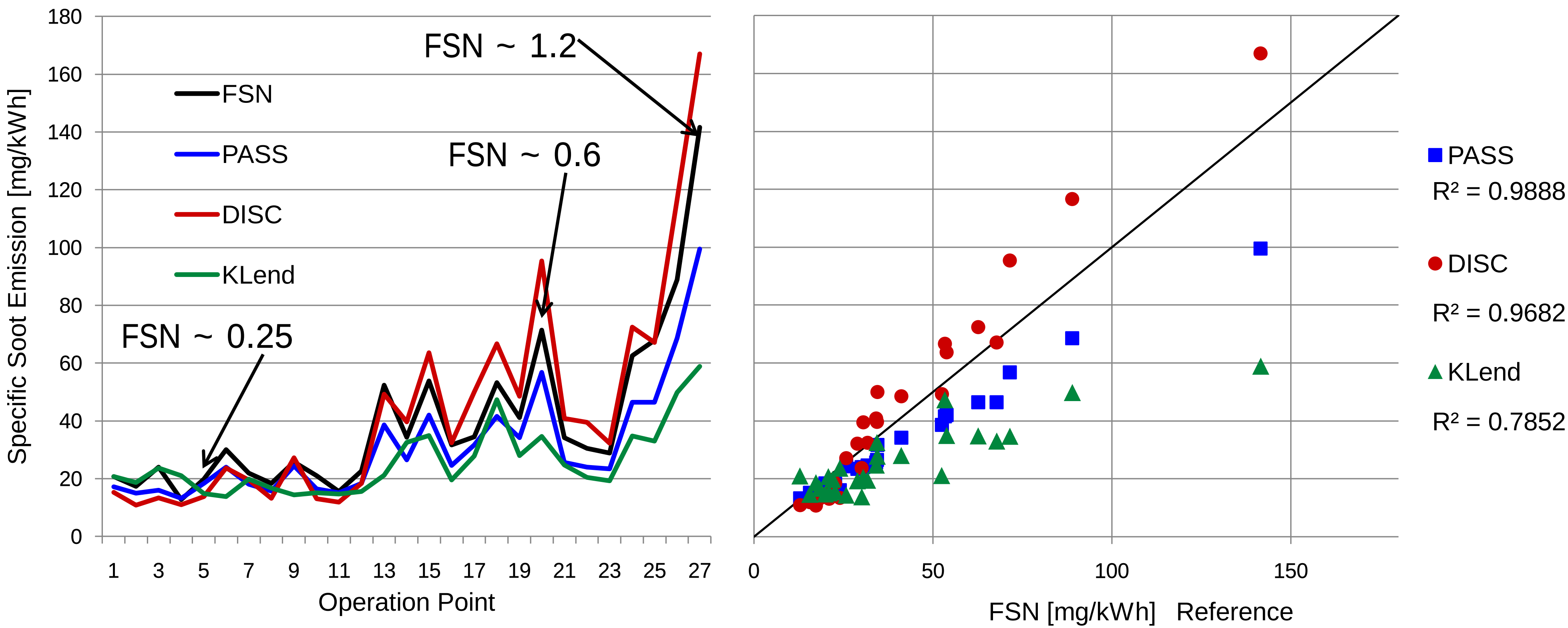
- **KL_{end} value is a mean value of cycle resolved evaluation**
  - High cycle-2-cycle fluctuations
- **PASS and FSN output transferred from mg/m³ to g/kWh**
- **DiSC correlation from Number and Size to Mass by M. M. Maricq[1]**



[1)] M. M. Maricq, N. Xu / Aerosol Science 35(2004) 1251–1274

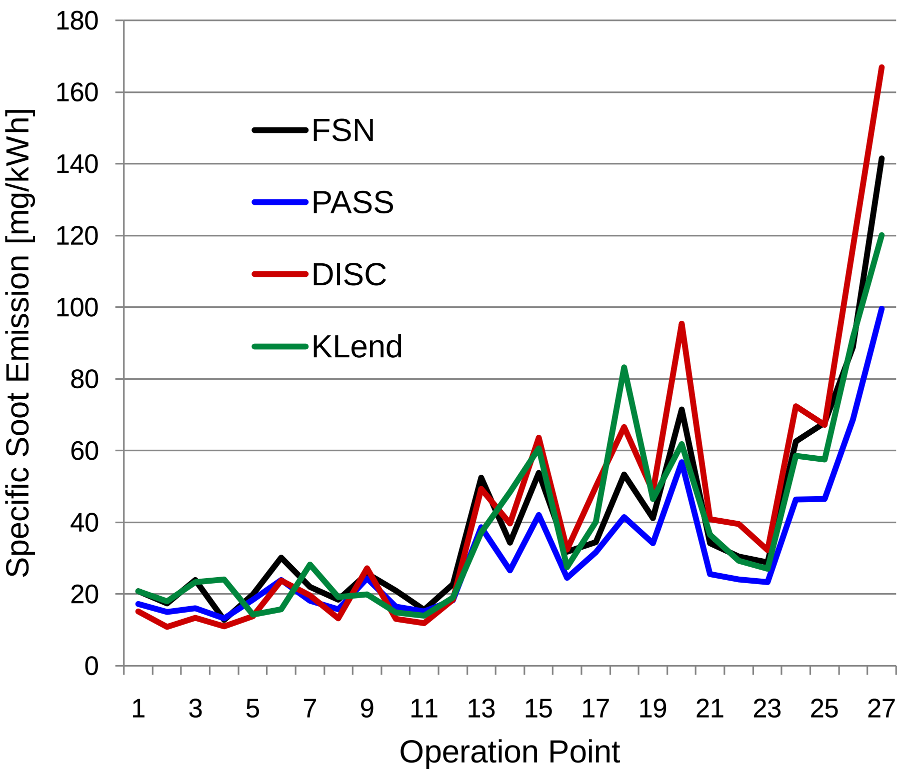
Steady State Observations (2/3)

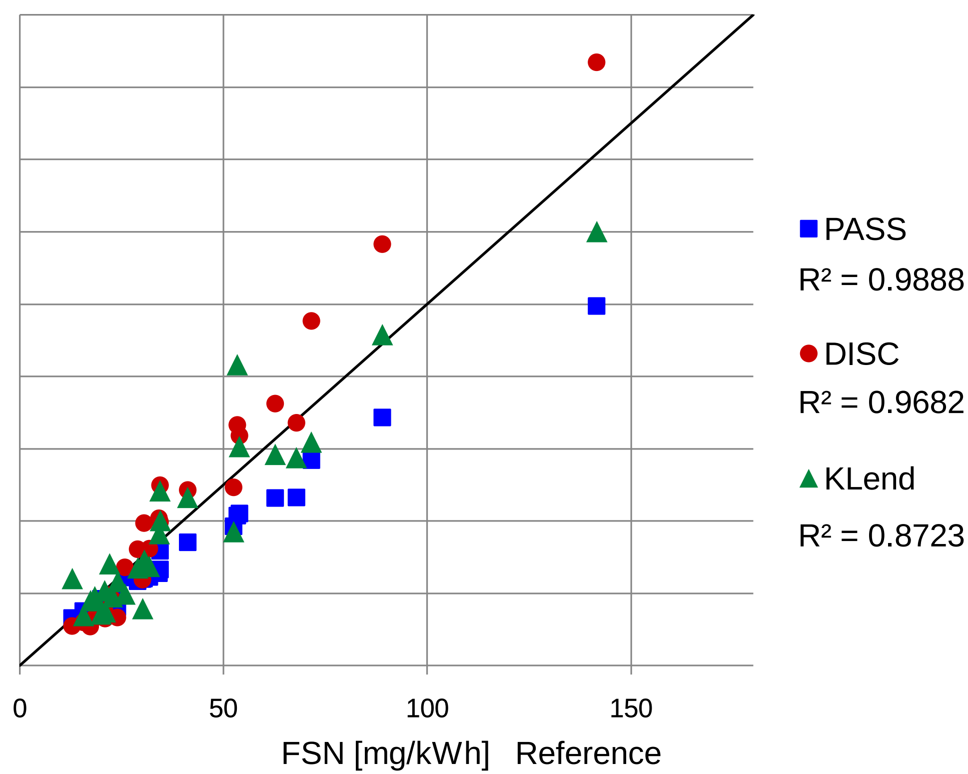
- **27 Operation Points @ 900, 1200 and 1440 rpm**
- **Around 50% Load,**
- **Changes in rail pressure, SOI and numbers of injections**



Steady State Observations (3/3)

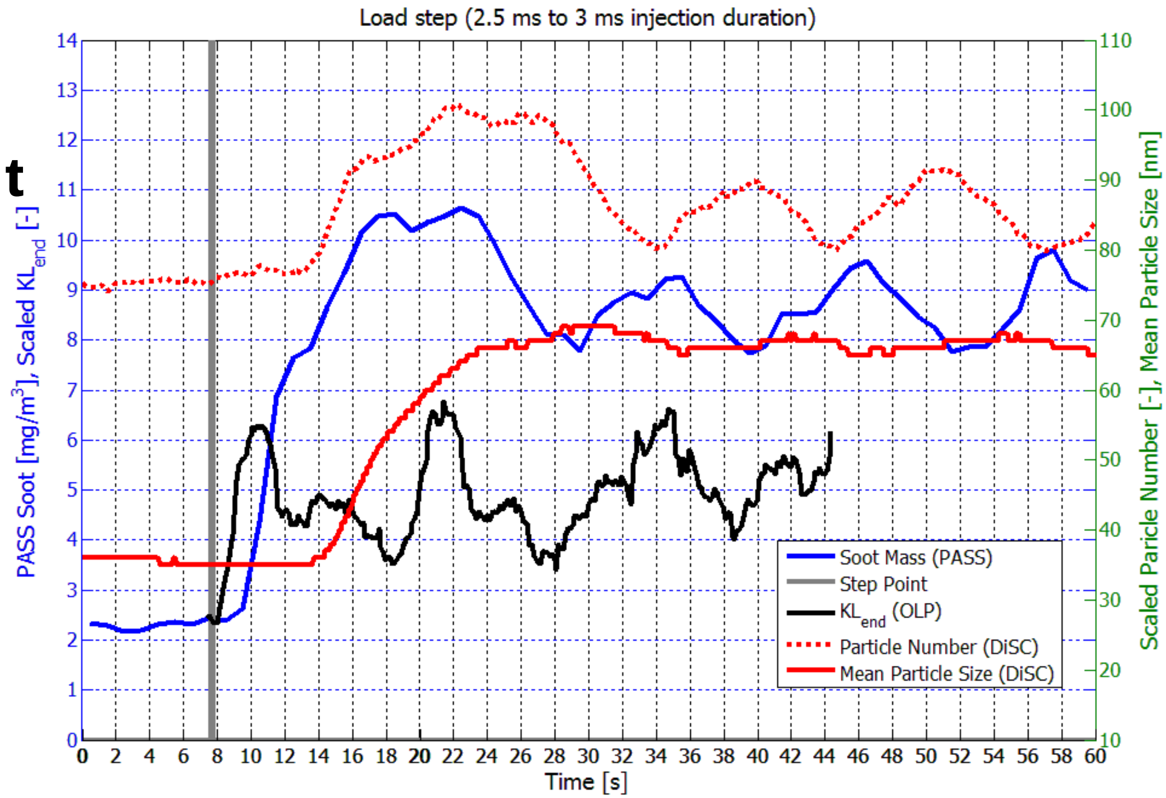
- **Mean size increased with higher exhaust emissions**
- **KL_{end} multiplied with size-dependent factor**





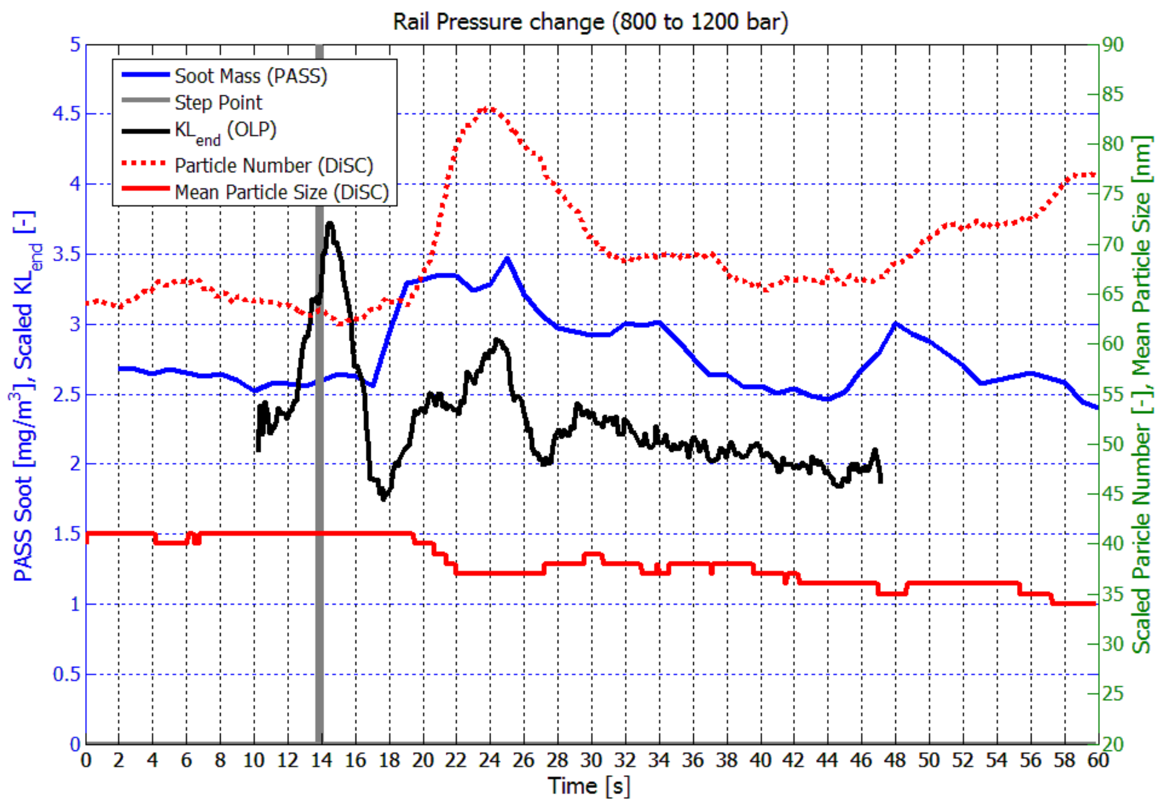
Transient Observations (1/2)

- **Qualitative because of different units**
- **Time delay from different sample positions**
- **KL_{end} smoothed by „Moving average“**
- **„Bumps” are present in every measurement method**



Transient Observations (2/2)

- **Low Soot Emissions**
  (FSN ~ 0.2 - 0.25)
- **Before and after step, same mass in every methode**
- **„Bumps" are present in all measurement methods again**



Conclusions

- **Difficult evaluation of KL_{end}**
- **Good quantitative correlation in steady state and qualitative correlation in transient operation, even at low FSN numbers**
- **The used setup allows an investigation of a dependency between KL_{end} and the particle size**

Outlook

- Further investigations for representative KL-Value at the end of soot oxidation
- Analysis of whole KL-devolution to verify or falsify size dependency
- Applicability (especially OLP) on different engines

Thank you for your attention

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