Development and Validation of a Virtual Soot Sensor

Extended Summary

The pollutant emissions from diesel engines must be further reduced, because of their impact on health and environment. This reduction of the legislative emission limits has lead to an increased complexity of the ECU calibration process and to expensive aftertreatment methods in order to fulfil the legislative limits as well. Integrating feedback of the Particulate Matter (PM) and NO_x emissions into the engine management could make fulfilment of legislation easier and reduce the complexity of the necessary calibration process.

Due to the fact that production type PM sensors for raw emission will not be available, or will be exceedingly expensive in the near future, a virtual soot sensor (VSS) has been developed, which provides estimates for the PM without any additional information from a PM measurement. The VSS provides predictions for the PM in real-time (cycle resolved). Its inputs are ECU variables and characteristic values of the heat release rate which are obtained on-line from in-cylinder pressure measurement. The structure of the VSS has been derived from optical kL-measurement data, i.e. from representative, crank angle resolved evolutions of the in-cylinder PM (3-color pyrometry).The kL-evoultion has only been used in the developing phase of the VSS. Once developed, the information of the in-cylinder representative soot trace is not available anymore. The model is structured into three consecutive phases which represent the in-cylinder PM evolution and is calibrated with measurements of the exhaust PM concentration of a standard engine operating map only. The three phases correspond to an initial phase of dominating formation of PM, a phase of formation and oxidation in balance, and a phase of dominating oxidation. The oxidation dominating term uses an exponential function for soot reduction. The argument depends from a reaction kinetic term, a turbulence term and a load term represent the oxidation rate. The duration of the oxidation is represented in a characteristic time scale, depending from the heat release rate characteristics. For steady state experiments, the VSS shows an excellent correlation with the exhaust gas PM concentration that has been measured with a photo-acoustic soot sensor (PASS) (see Figure 1). In addition a reasonable ratio between soot formation and soot oxidation is reproduced (Figure 2). Furthermore, the VSS is able to predict transient PM emissions with a sufficient precision (Figure 3). The performance of the control structure (separately developed in [1]) with integrated VSS is demonstrated on various driving cycles. These results demonstrate the potential of virtual sensors in the context of advance control strategies and offer opportunities to expand this non-integrating, cylinder-pressure-based approach to other pollutants (primarily NO_x) as well.

[1] Tschanz, F.; Amstutz, A.; Onder, C. & Guzzella, L. Feedback Control of Particulate Matter and Nitrogen Oxide Emissions in Diesel Engines *Submitted to Control Engineering Practice*, **2012**

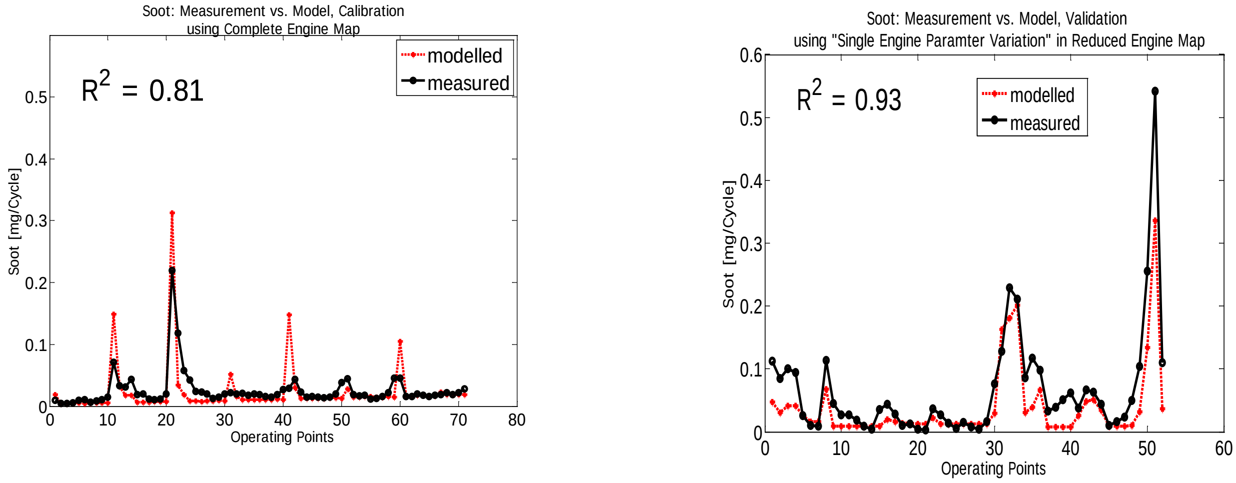

Figure 1: Steady state calibration (left) and validation (right) of the virtual soot sensor.

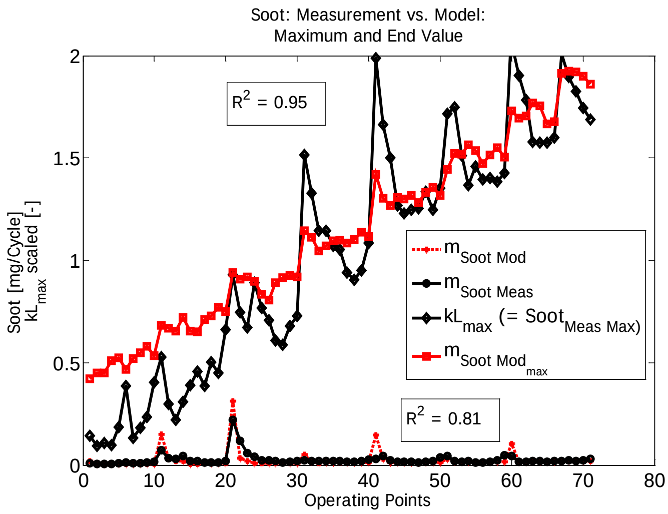

Figure 2: Steady state calibration of the VSS with the maximum modeled soot mass vs. the maximum kL value.

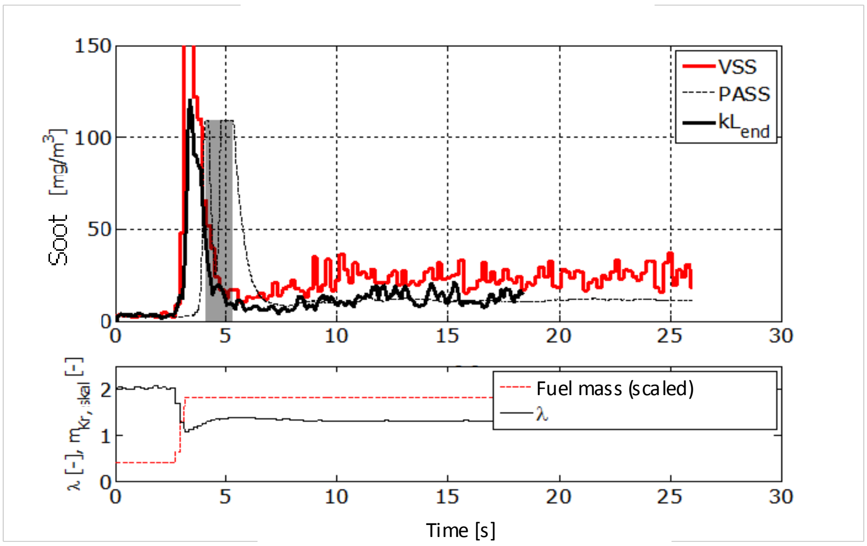

Figure 3: Load transient at 1300 rpm, 2.5 – 12 bar mean effective pressure within 0.5 s.

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Development of a Virtual Soot Sensor for Internal Combustion Engine Applications
26.06.2012

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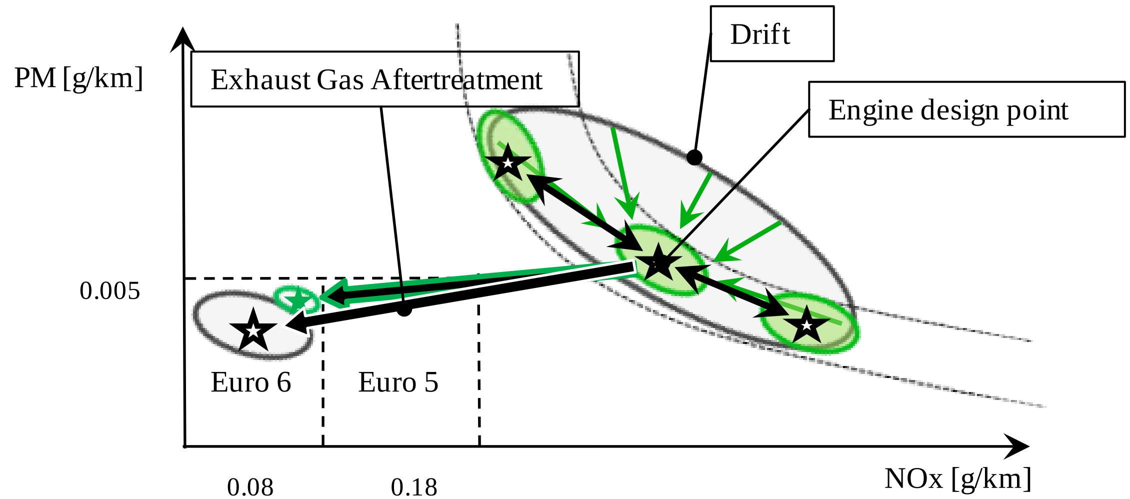
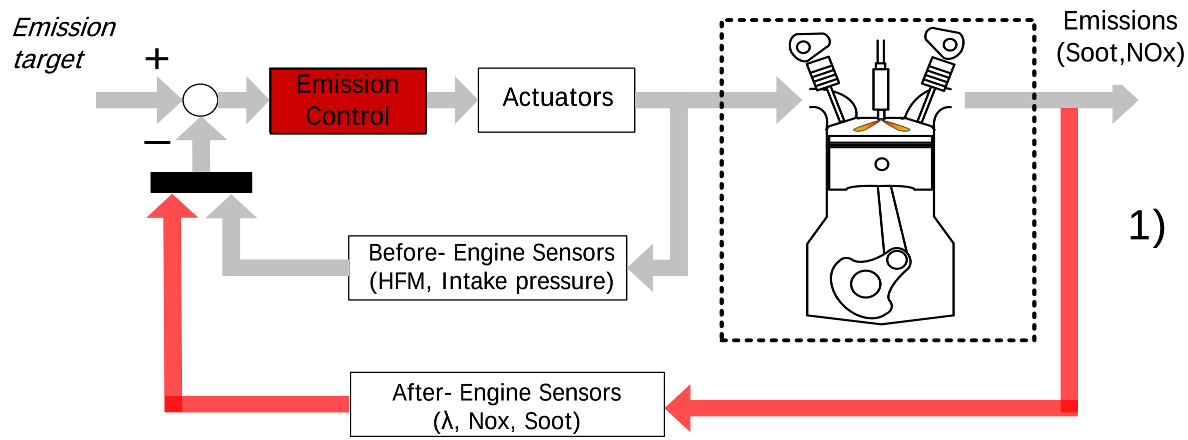
Outline

- **Motivation**
- **Soot model used for VSS**
- **Test facility**
- **Results**
- **Conclusions**

Motivation

- **Emission Control**
  - ✓Eliminiation of drift (due to aging)
  - ✓Direct Calibration
  - ✓Optimum exhaust raw emission for optimum aftertreatment
- **Sensor for PM does not exist**
  - ➢„real time-capable“ virtual soot sensor is required





1) Tschanz, F.; Amstutz, A.; Onder, C. & Guzzella, L.
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Concept of the Virtual Soot Sensor (VSS)

Reference Exhaust Soot Measurement

PASS

(Photo-acoustic Soot Sensor)

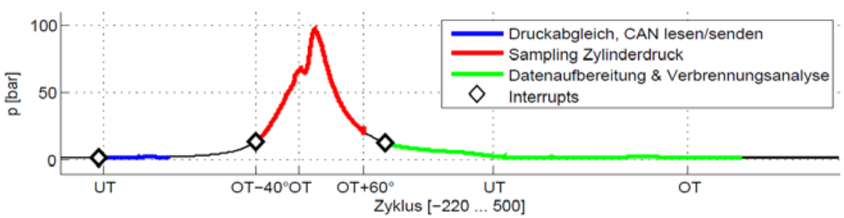
Online Combustion Analysis /

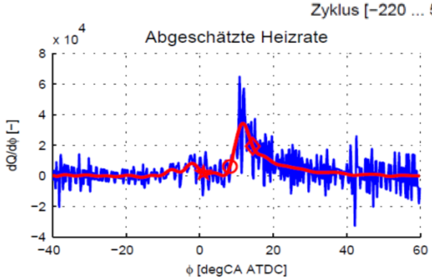
Heat release rate according to

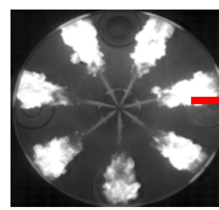
Hohenberg (1st law approach)

Representative soot evolution /

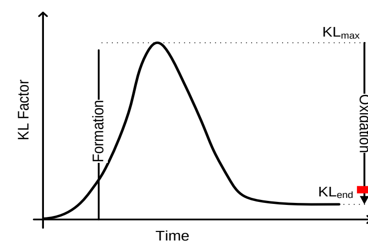
Multi-Colour-Pyrometer

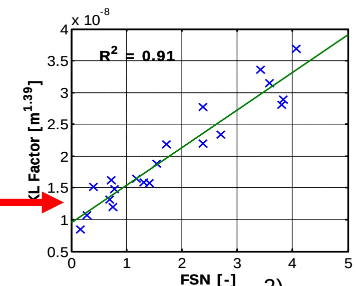






1)





2)

Soot intensity (kL-Factor) as representative Soot concentration inside the combustion chamber

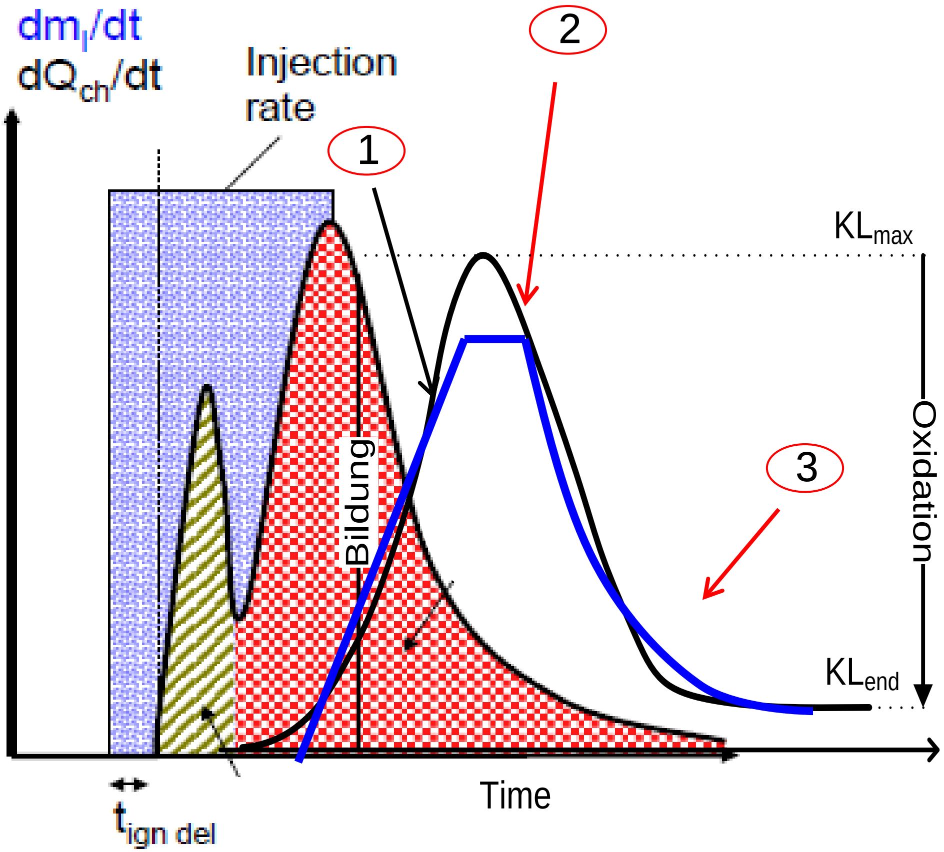
Virtual Soot Sensor

VSS

1) Schneider, B. *Experimentelle Untersuchungen zur Spraystruktur in transienten, verdampfenden und nicht verdampfenden Brennstoffstrahlen unter Hochdruck*, in Diss. ETH No. 15005. 2003.

2) Kirchen, P., *Steady-State and Transient Diesel Soot Emissions: Developement of a Mean Value Soot Model and Exhaust-Stream and In-Cylinder Measurements*, in Diss. ETH No. 18088. 2008.

Model - Concept



Parts:

1 •Soot formation
-f($dQ_{B_{diff}}/d\varphi$, p, T)

2 •Equilibrium: formation, oxidation

3 •Soot Oxidation
Exponential decrease, f(conc. O_2, T and turbulence)

Model - Equations

- **Formation**

$$m_{Soot,\,form} = b_1 \cdot m_{fuel,diff}^{\;b_2}$$

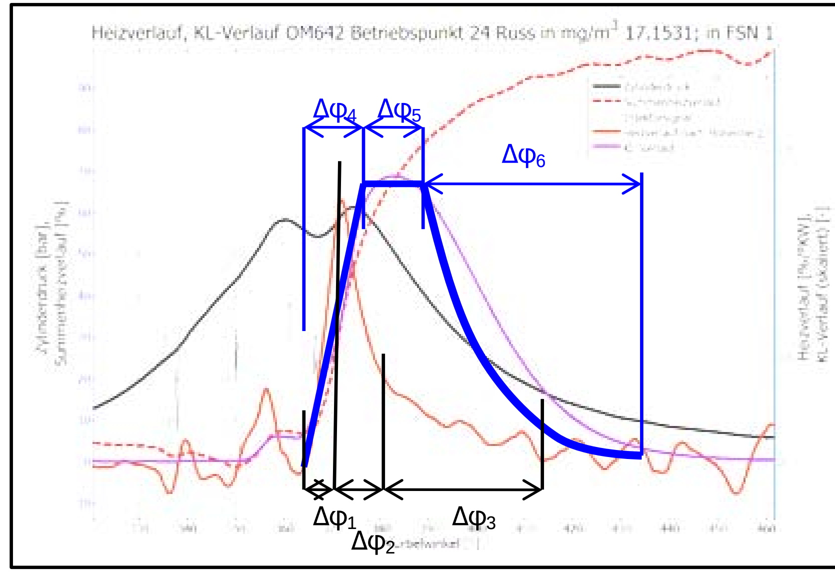
- **Equilibrium**

$$m_{Soot,eq.} = m_{Soot,\,form} \cdot \left(1 + 0 \cdot \overbrace{\left(\frac{\Delta\varphi_2}{\varphi_{ref}}\right)}^{\Delta\varphi_5}\right)$$

- **Oxidation**

$$m_{Soot,end} = m_{Soot,eq.} \cdot \left(0.01 + \exp\left(-B \cdot \overbrace{\frac{b_{12} \cdot \Delta\varphi_3}{\varphi_{ref}}}^{\Delta\varphi_6}\right)\right)$$

$$rpm_{ref} = 2000 \cdot \min^{-1}$$
$$T_{ref} = 1600K$$
$$p_{rail,ref} = 1000bar$$
$$\varphi_{ref} = 1°CA$$
$$IPS = 0 = closed$$



Total nr of parameter to optimize: 12

$$B = \left(\frac{T_{ox}}{T_{ref}}\right)^{b3} \cdot \left(1 + b_4 \cdot EGR_{stoich}\right)^{-b5} \cdot \left(\frac{b_6 \cdot \lambda}{2}\right)^{b7} \cdot \left(\frac{p_{rail}}{p_{rail,ref}}\right)^{b8} \cdot \left(1/\sin\left(IPS\right) \cdot 5\right)^{b9} \cdot \left(\frac{rpm}{rpm_{ref}}\right)^{b10} \cdot m_{fuel}^{\;b11}$$

reaction kinetics

injection turbulence
charge motion

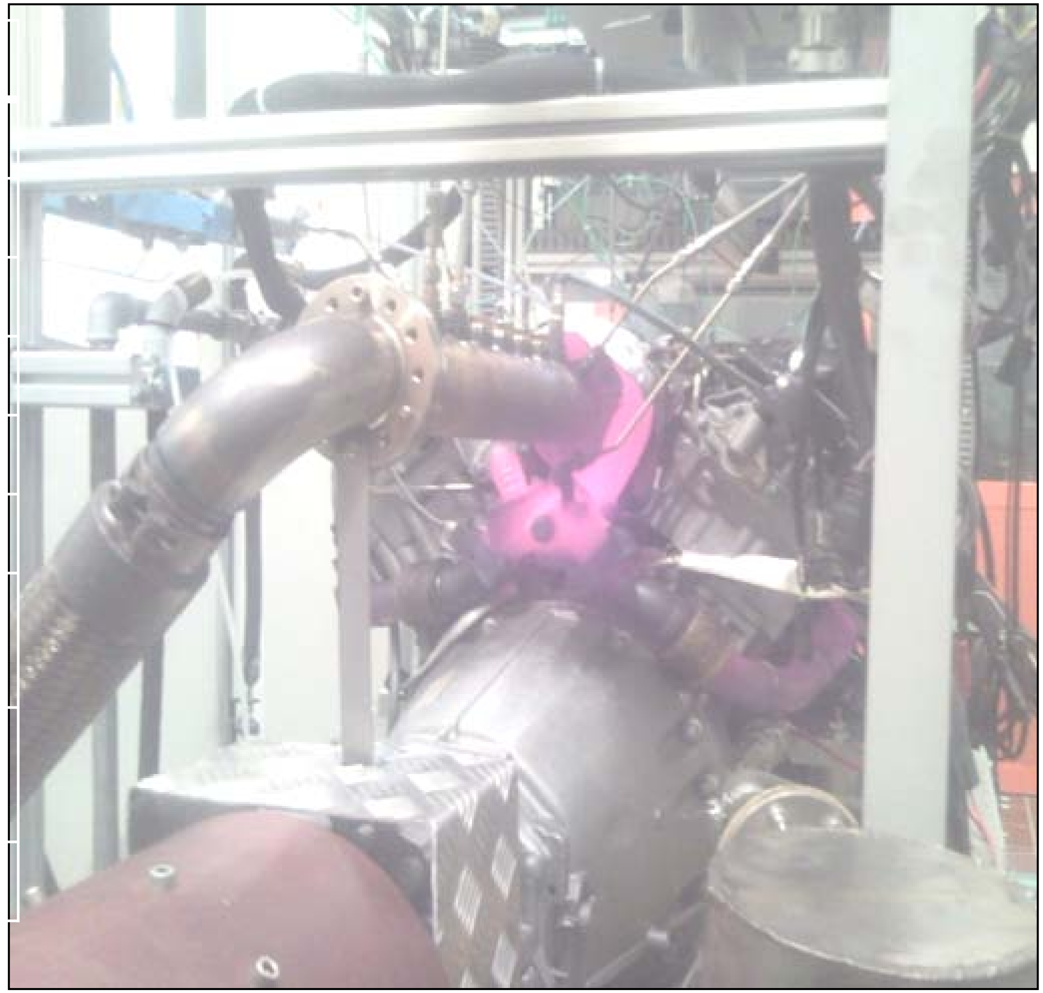
turbulence

load

Test Facility

Daimler OM 642

Displacement volume [l]	3
Cylinder [-]	6 (V-72°)
Valves/ Cylinder [-]	4
Bore [mm]	83
Stroke [mm]	92
Compression ratio [-]	15.5
Power [kW @ 3800 1/min]	165
Max. Torque [Nm @ 1400-3600 1/min]	400 (limited)
Max. injection pressure [bar]	1600



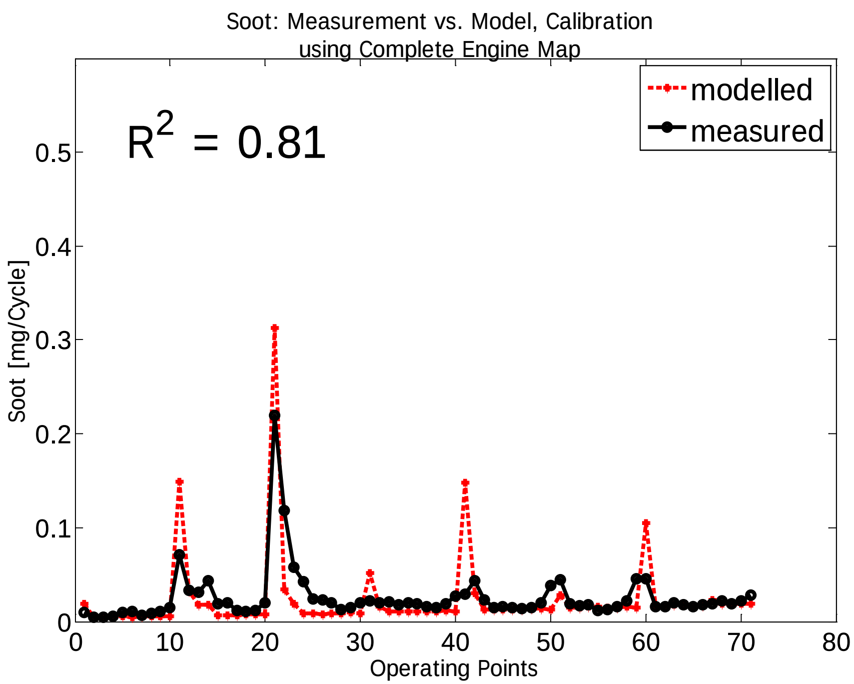
Model - Calibration / Steady State Operation

a) Calibration using 72 operating points in the „whole“ engine map

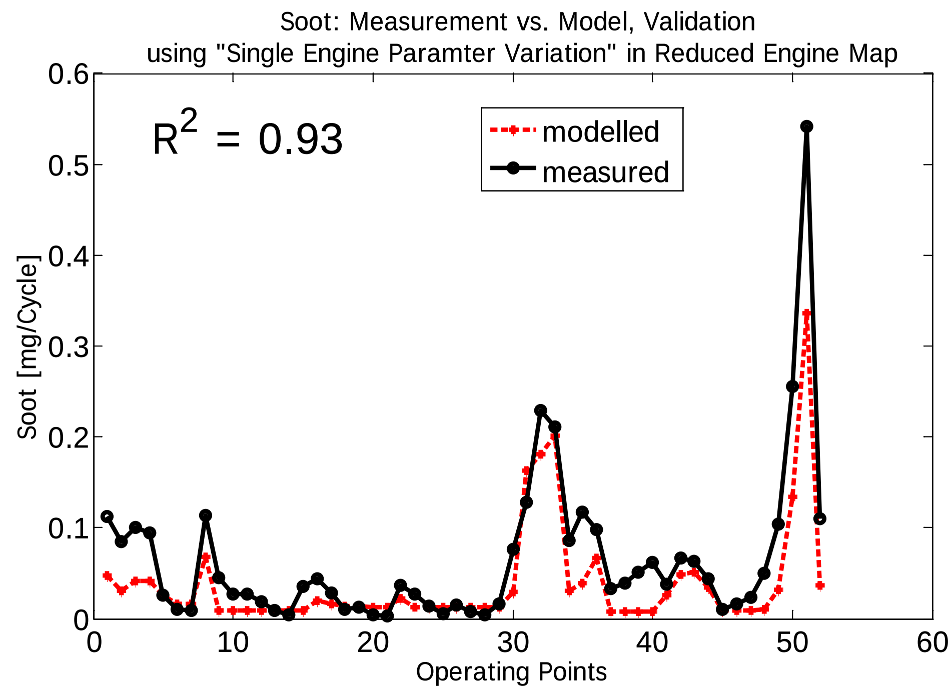
b) Validation at 52 operating points of

- Single-Engine-Parameter-Variation (SOI, EGR, IPS, p_{Rail}, λ)
- in „interessting“ region of engine map (1200 – 2200 rpm, 3-8 bar BMEP)

a) Calibration

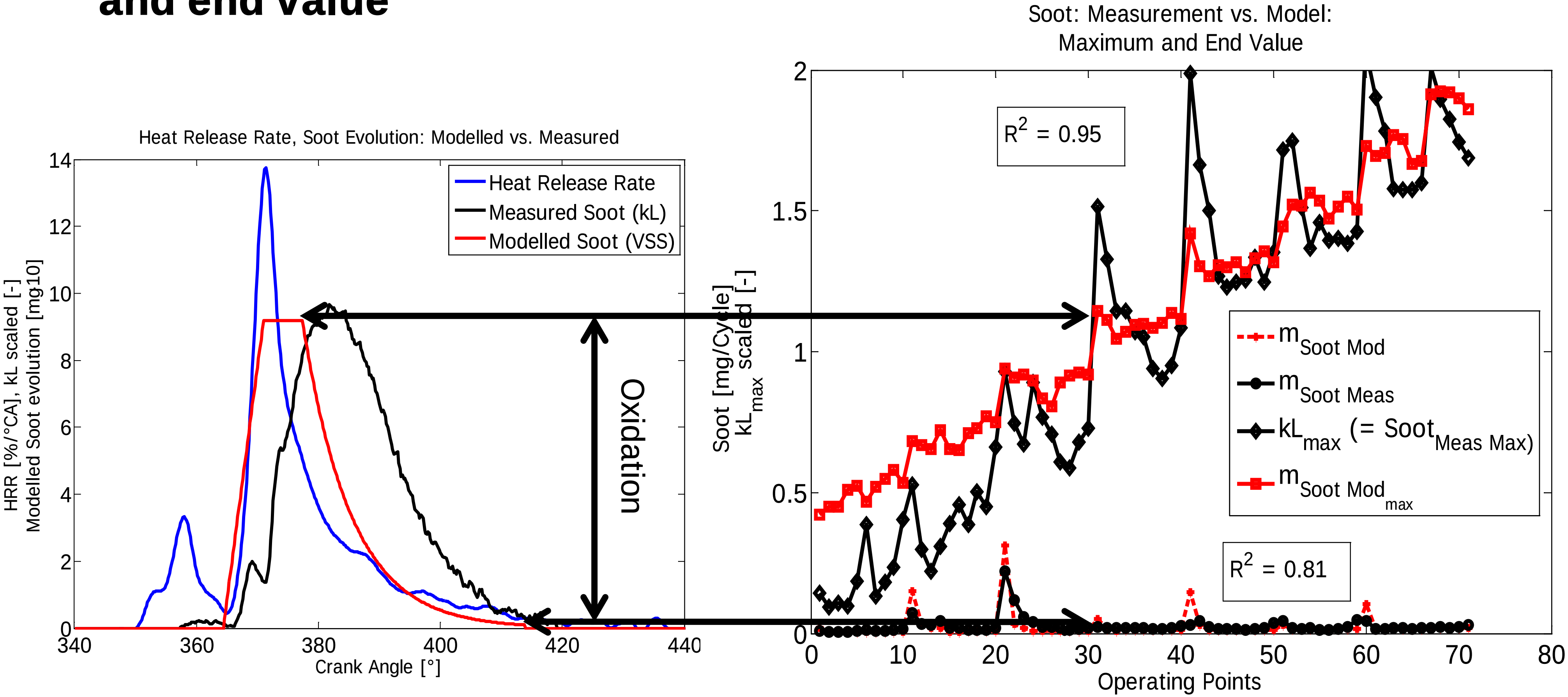


b) Validation



Model - Calibration / Steady State Operation

In-Cylinder soot model behaviour: Maximum soot concentration and end value



Transient Operation: Load Step at 1300 rpm

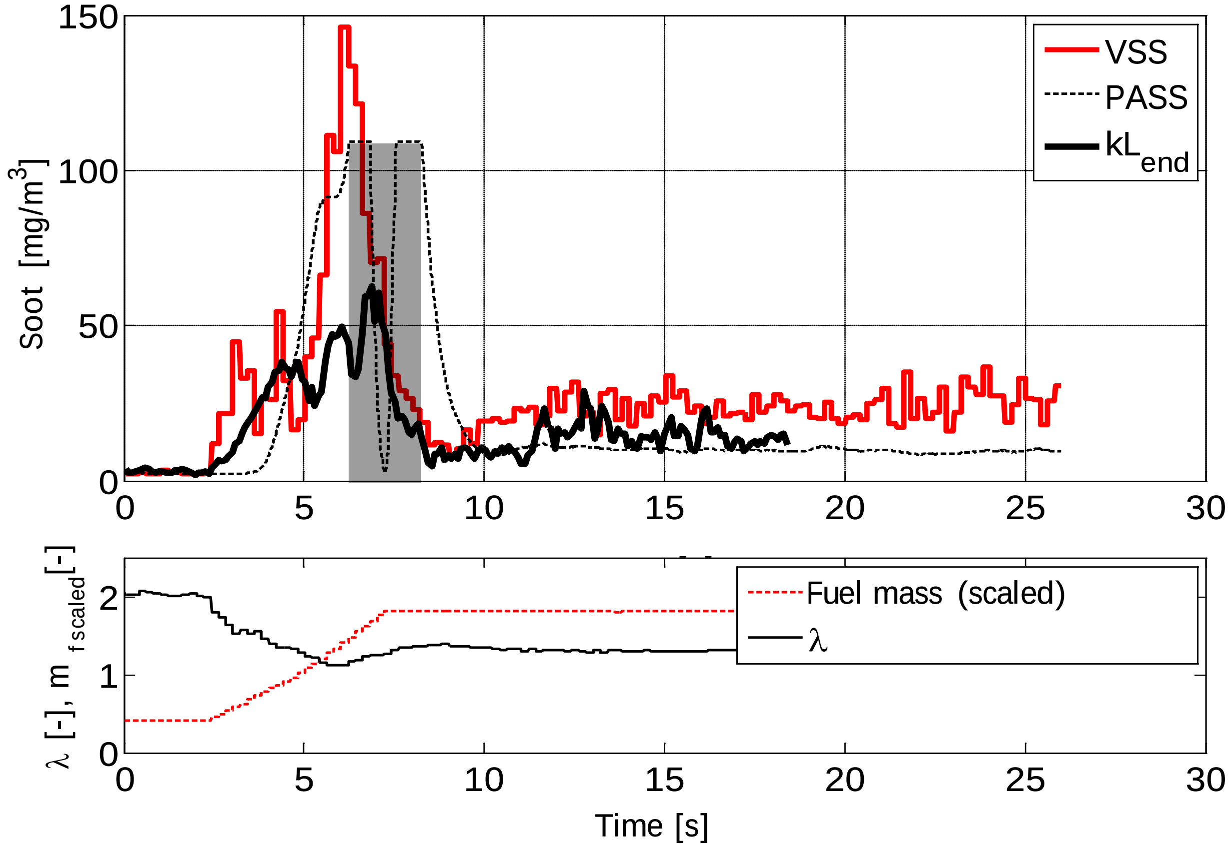
Load step in

0.5 s 1 s 5 s

- Very good agreement between VSS and end value of kL (optical soot signal)

- PASS-Signal with delay in time (due to gas transportation)

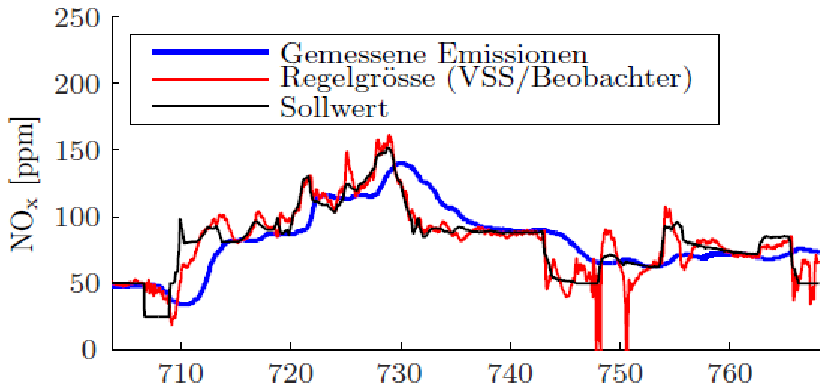
Load step from 60 – 300 Nm with ECU feedforward control only



Integration of VSS into the Feedback Control

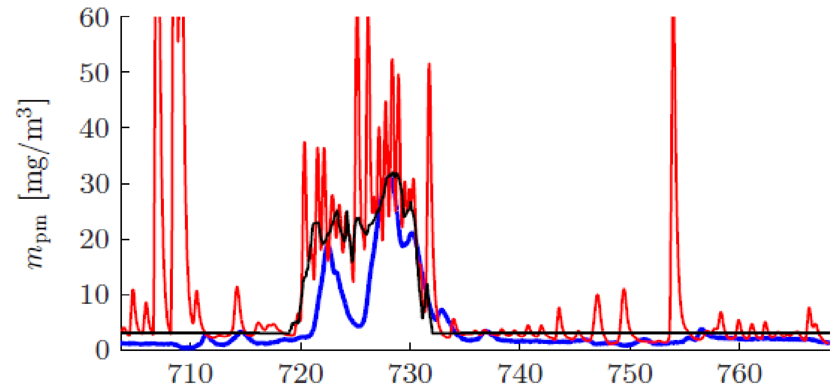
Only VSS used for ECU input (soot feedback), NEDC Part

NOx [ppm]



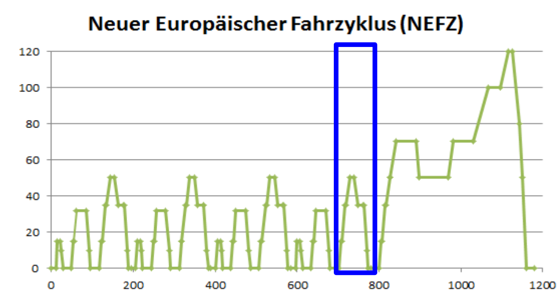
Start of Injection [° CA]

Soot[mg/m³]



1)

Intake Port Shut-off [%]



1) FVV, Soot controlled diesel engine, Final report

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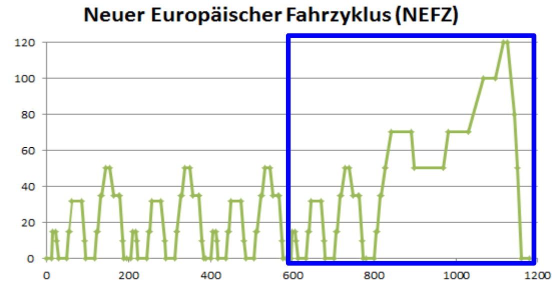
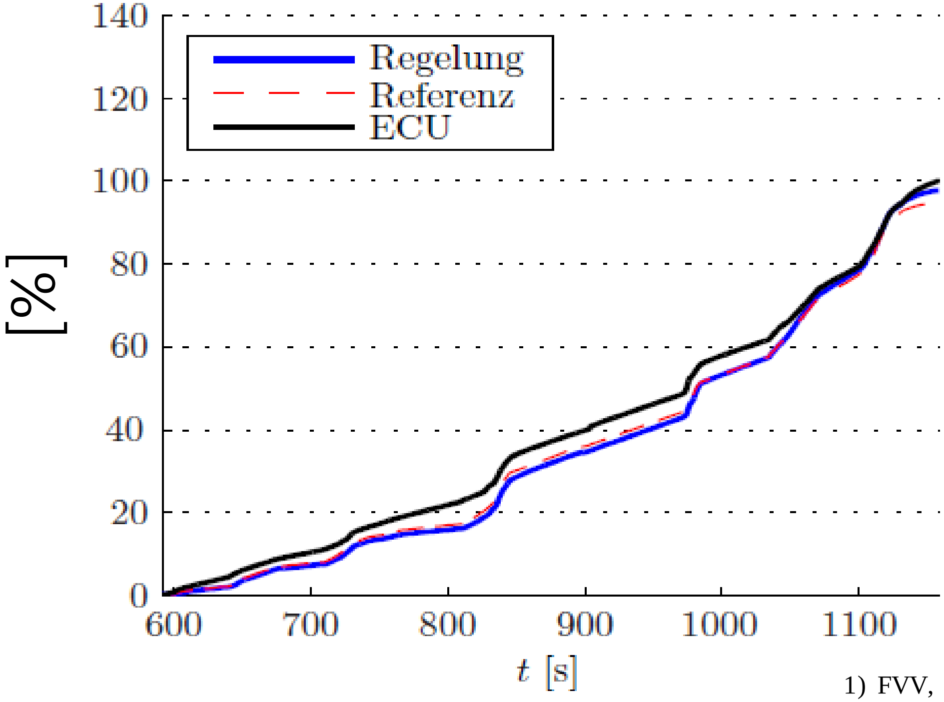
Feedback Control using VSS

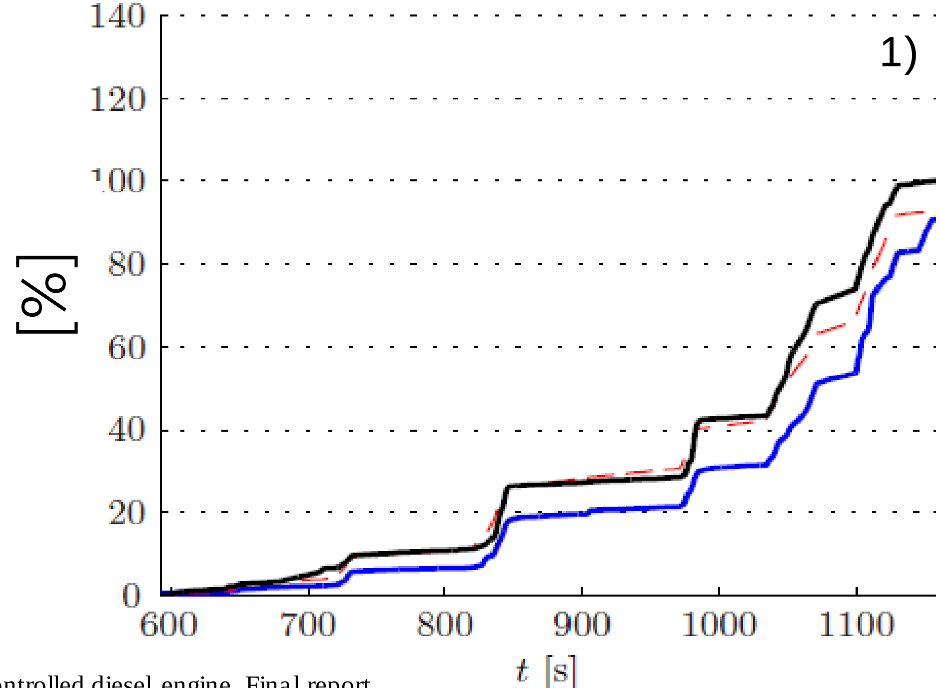
Cumulativ Emissions (NEDC)



NOx (sum)



Soot (sum)



1) FVV, Soot controlled diesel engine, Final report

Summary and Conclusions

- **A virtual Soot Sensor (VSS) has been developed**
  - which delivers satisfactory results in steady state operation
  - which shows an accurate transient behaviour compared to the end value of kL as well as PASS.
  - which is able to provide results „online“ (until ca. 2200 rpm)
  - whose behaviour is suitable for emission feedback control purposes

Acknowledgements:

FVV (Forschungsvereinigung für Verbrennungskraftmaschinen)

BAFU (Swiss Federal Office for the Environment)

Thank you for your attention