Measurement of the Instantaneous In-Cylinder Soot Temperature and Concentration in a Multi-Cylinder Engine

Patrick Kirchen
Stefan Walther
Peter Obrecht
Konstantinos Boulouchos

Aerothermochemistry and Combustion Systems Laboratory ETH Zürich

Dieter Karst
Claudio Cavalloni

Kistler Instruments AG

Sensoptic

OVERVIEW

GOALS: **Correlation between in-cylinder and engine-out soot emissions**

Characterize cylinder and cycle specific soot emissions in a multi - cylinder engine

- **Overview of instrumentation and measurements**
- **Selection and evaluation of a suitable correlation between FSN and Pyrometry**
- **Use of the correlation to investigate cycle to cycle soot emission variations**
- **Investigation of soot formation and oxidation processes**

INTRODUCTION

SOOT INSTRUMENTATION

GOALS: Correlation between in-cylinder and engine-out soot emissions

Characterize cylinder and cycle specific soot emissions in a multi - cylinder engine

FSN

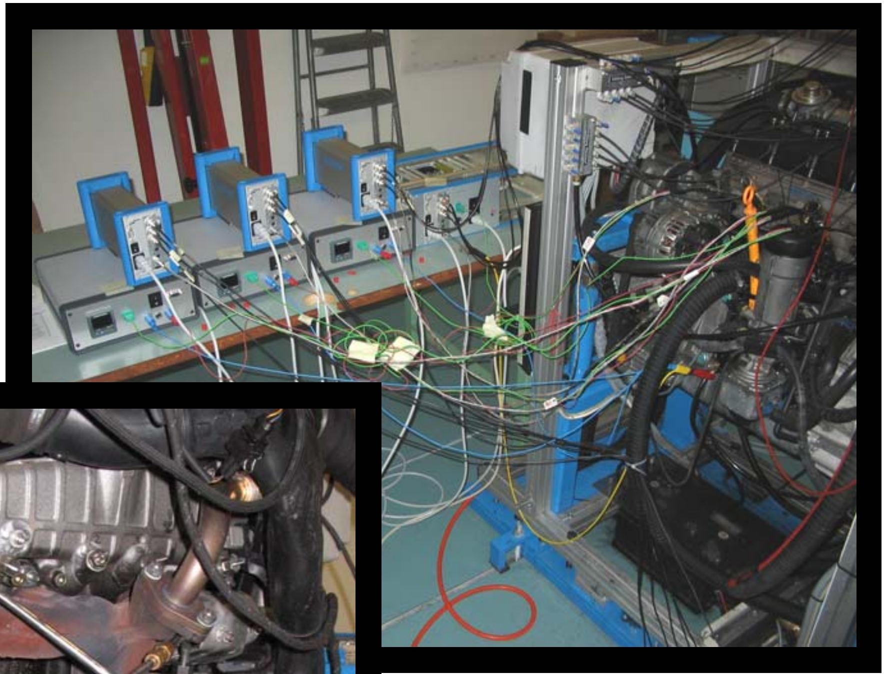
- Measurement of the steady-state, engine-out soot emissions (in exhaust system)
- Extracted exhaust is drawn through filter paper – paper blackening is measured
- A measure of all particulate components

Pyrometry

- In-cylinder measurement of soot formation and oxidation processes
- Light radiated from soot is used to determine:
  - Soot temperature
  - KL-Factor (~ soot concentration)
- Considers only hot (glowing) soot

MEASUREMENTS TESTBENCH / INSTRUMENTATION

- **VW TDI, 4 cyl. (Kistler)**
- **Soot instrumentation**
  - In-cylinder 3 color pyrometry (KL-factor)
  - Exhaust mounted AVL 415S (FSN)
- **Additional parameters**
  - Cylinder pressure (cylinders 1, 2, 4)
  - Intake air pressure (1 Sensor)
  - Air mass flow rate (venturi)
  - Exhaust CO_2 concentration for λ

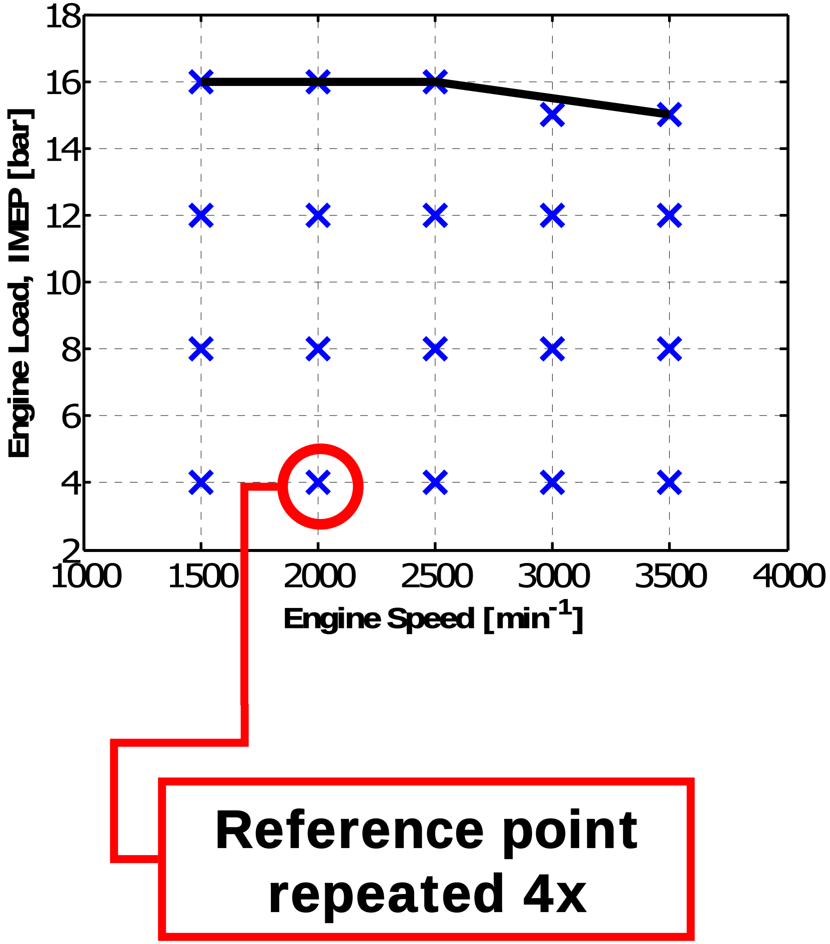


MEASUREMENTS

OPERATING POINTS

- **20 steady state operating points from the entire map**
- **Wide soot emission range:**

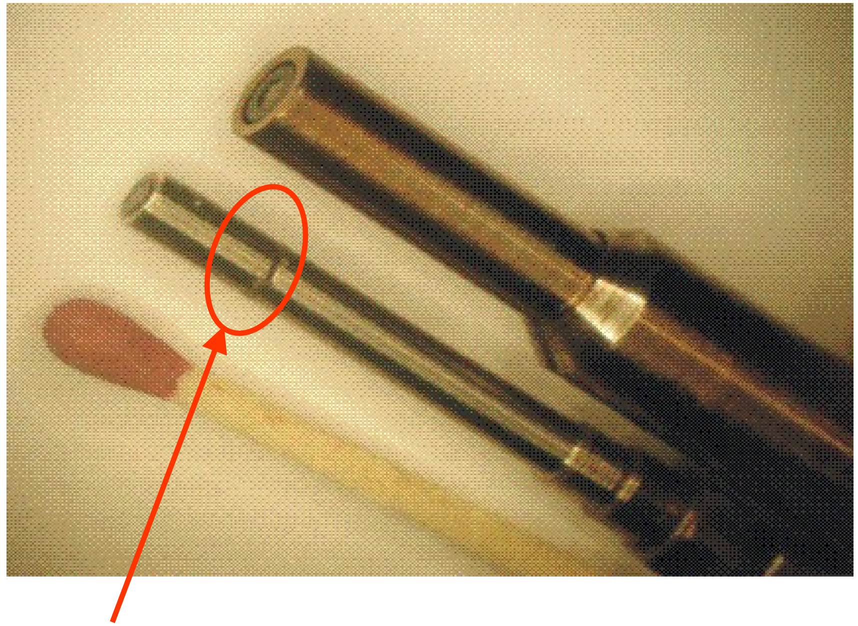
  FSN = 0.4 ... 4.1
- **Reference point**
- **Cylinders 1, 2, 4 with 3 color pyrometry und cylinder pressure**



3 COLOR PYROMETRY

IMPLEMENTED SENSOR

- **System developed by:**
  - Kistler AG
  - LAV (ETH Zürich)
  - Sensoptic
- **Uses 3 wavelengths for redundancy**
- **Window heated to 600°C to prevent contamination**
- **Small size permits use in production engines (glowplug adapter, for eg.)**



d_{Sensor} = 3mm

KISTLER
measure. analyze. innovate.

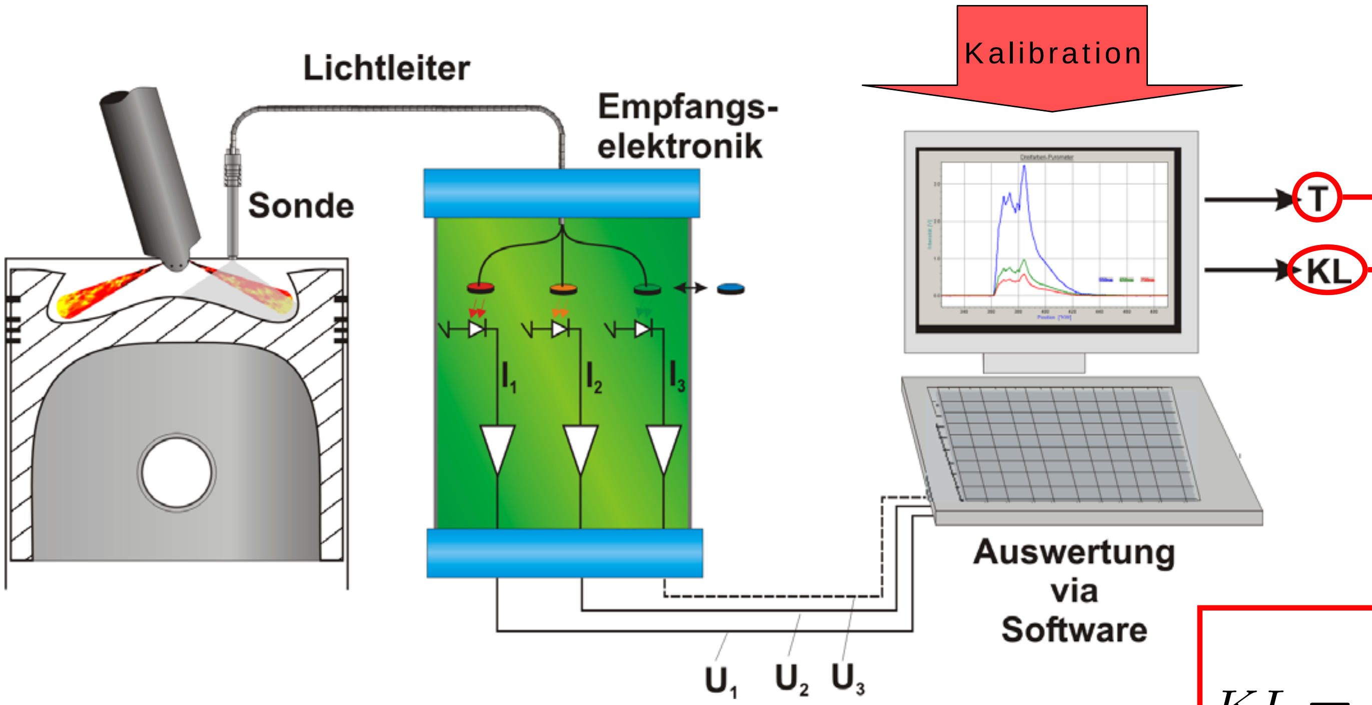
SENSOPTIC

3 COLOR PYROMETRY

OVERVIEW

$$\left[1-\left(\frac{\dfrac{C_2}{e^{\frac{C_2}{\lambda_1 T}}-1}}{\dfrac{C_2}{e^{\frac{C_2}{\lambda_1 T_{s,1}}}-1}}\right)\right]^{\lambda_1^{1.39}} = \left[1-\left(\frac{\dfrac{C_2}{e^{\frac{C_2}{\lambda_2 T}}-1}}{\dfrac{C_2}{e^{\frac{C_2}{\lambda_1 T_{s,2}}}-1}}\right)\right]^{\lambda_2^{1.39}}$$

$$T\big|_{\lambda_1,\lambda_2} = T\big|_{\lambda_1,\lambda_3} = T\big|_{\lambda_2,\lambda_3}$$

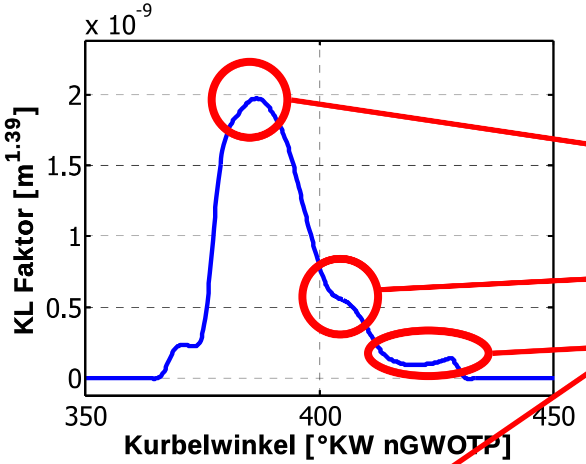


$$KL\big|_{\lambda_1} = KL\big|_{\lambda_2} = KL\big|_{\lambda_3}$$

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

KL-FACTOR

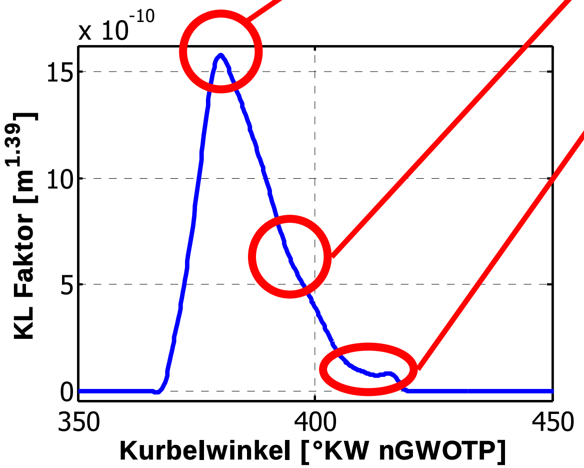
TYPICAL FEATURES



Characteristics of the KL-factor that can potentially be correlated to FSN

- Maximum KL-factor value
- 1st plateau
- 2nd plateau (KL_{end})

$$\sum_{i=1,2,4} KL\Big|_{Cyl.i}$$

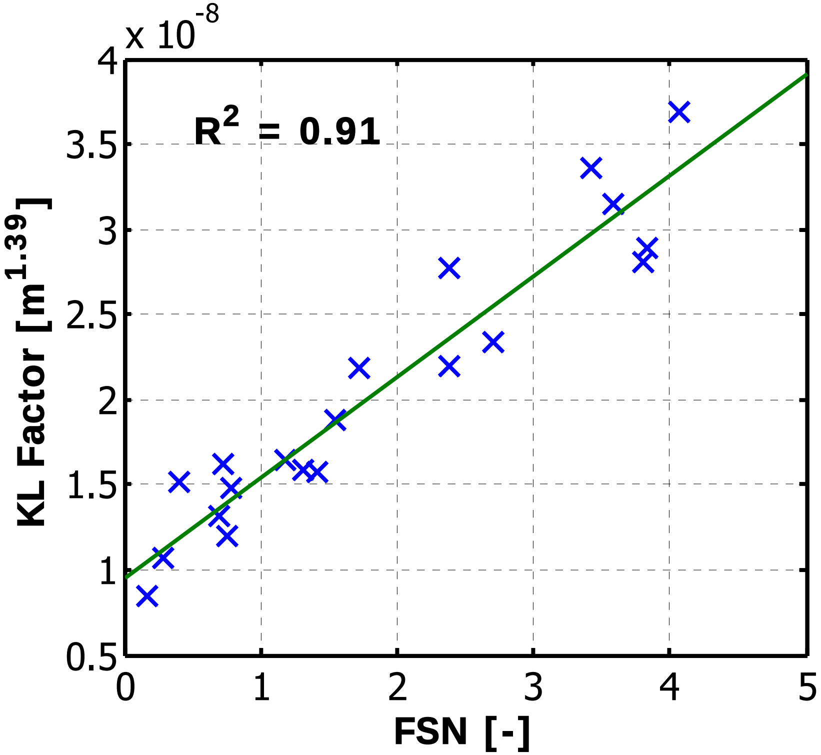


CORRELATION OF KL VALUES WITH FSN OVER ALL POINTS

R^2	Cyl. 1	Cyl. 2	Cyl. 4	All Cyl.
1. Plateau	0.79	0.80	0.91	0.84
2. Plateau	0.87	0.88	0.89	0.91

KL-FSN CORRELATION

- Maximum KL-Factor value – no correlation with FSN
- Investigation of the correlation between 1st and 2nd plateau and FSN
- Correlations using cylinder specific and summed KL factor values
- Best correlation with the summed KL factors from all cylinders



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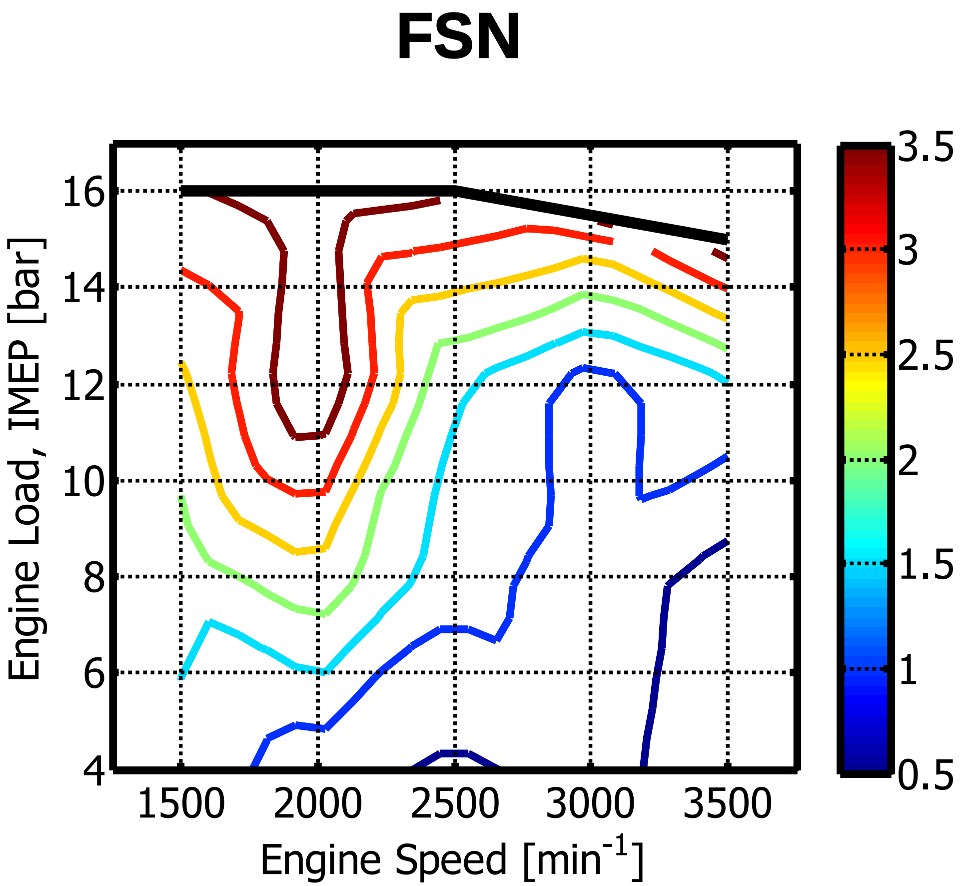
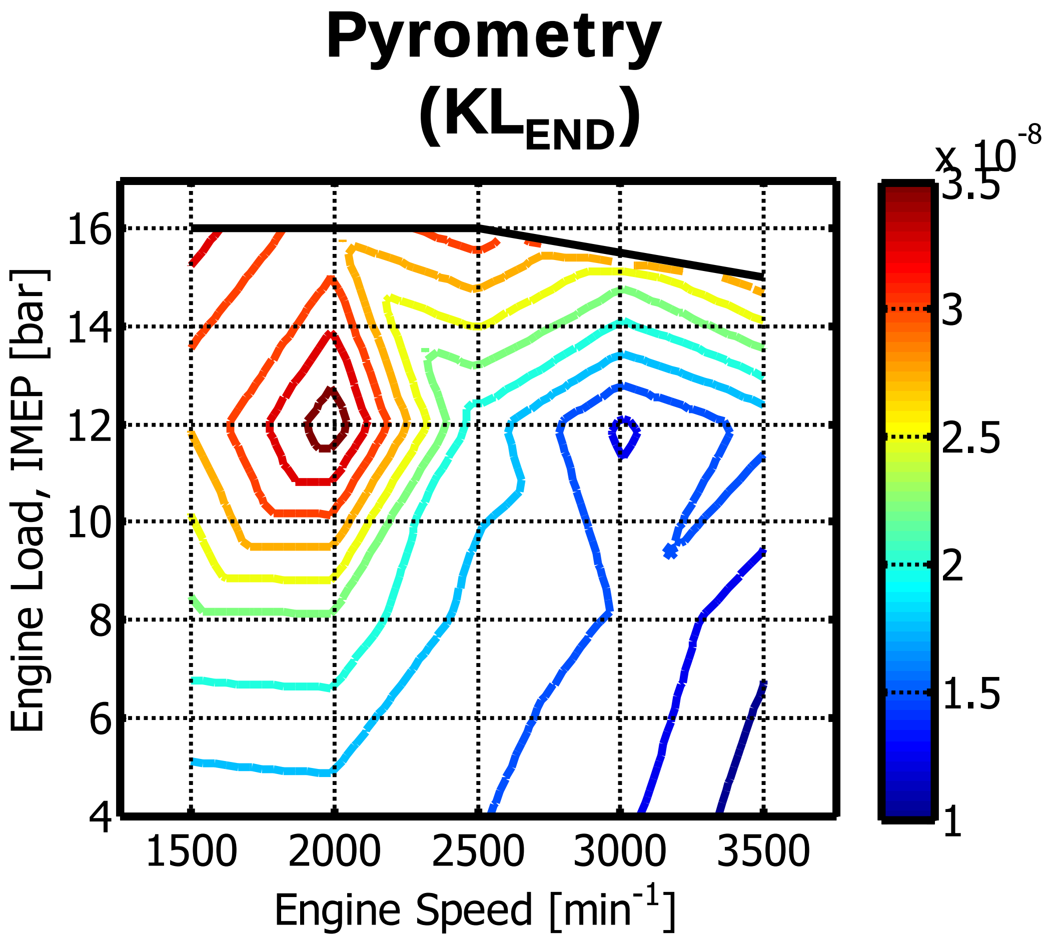
$$\sum_{i=1,2,4} KL\Big|_{Cyl.i}$$

FSN and KL COMPARISON

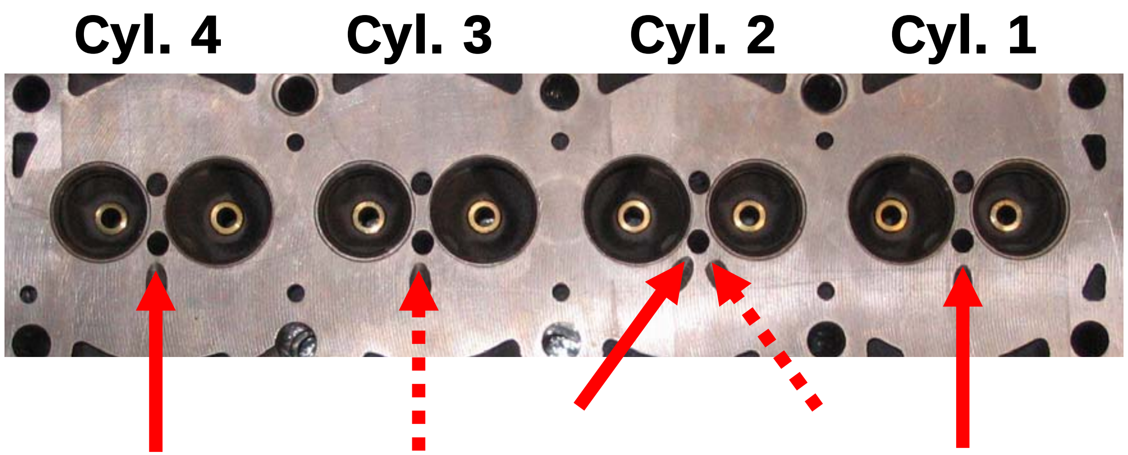


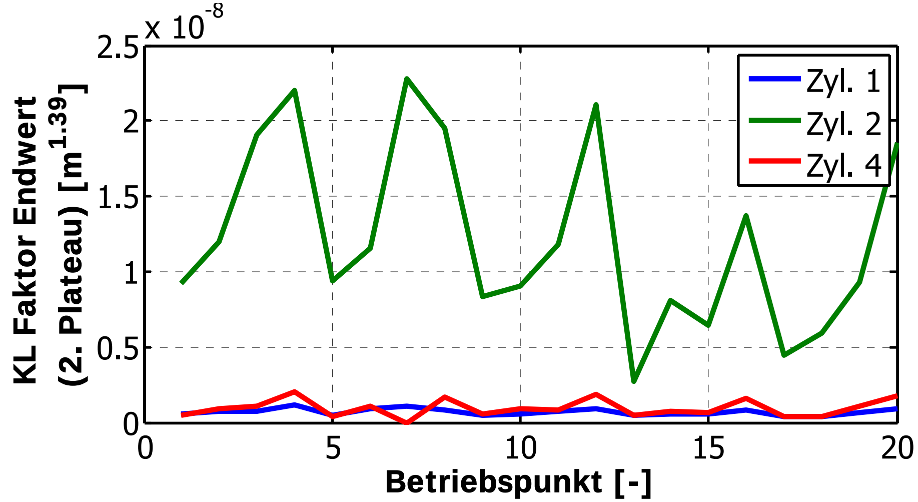


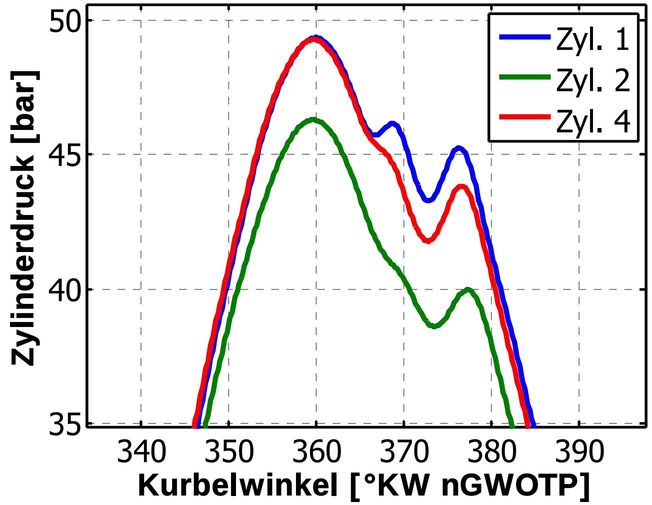
- **Time averaged, engine-out soot emissions**
- **Qualitative soot emission tendencies are reproduced by both methods**

KL_{END} VALUES — CYLINDER SPECIFIC CONSIDERATIONS

- **Cylinder 2:**
  - KL_{end} is an order of magnitude higher than other cylinders
  - Non-perpendicular sensor installation
  - Additional sensor access (lower compression ratio)
- **Combustion and KL-factors in cylinders 1 and 4 are similar**







n=2000 [min^{-1}]; IMEP=4.0 [bar]

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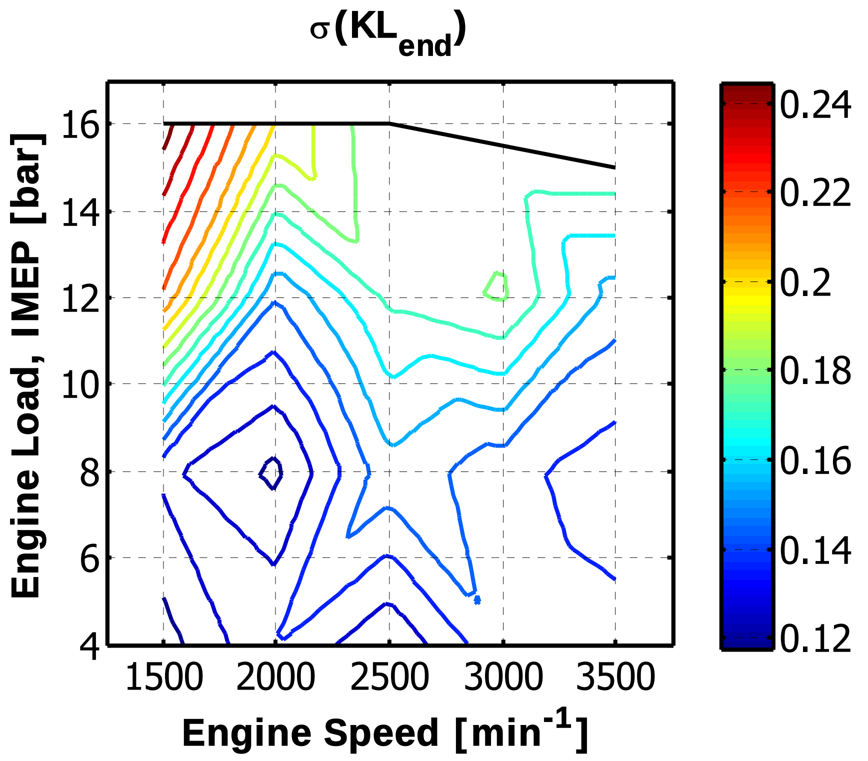
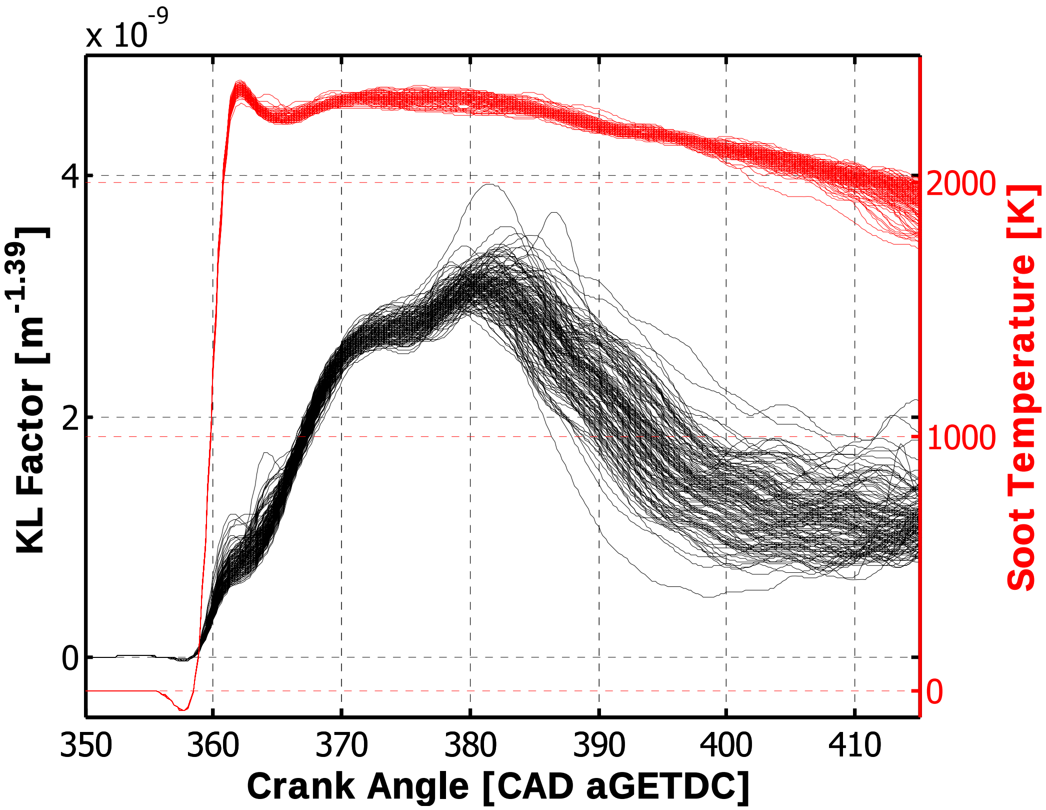
LAV

CYCLE TO CYCLE VARIATIONS

- KL history comapred for 144 consecutive operating cycles during steady state operation (n_e = 2500 [min^{-1}], IMEP = 16 [bar])
- Soot formation process ~const.
- Soot oxidation higher variability

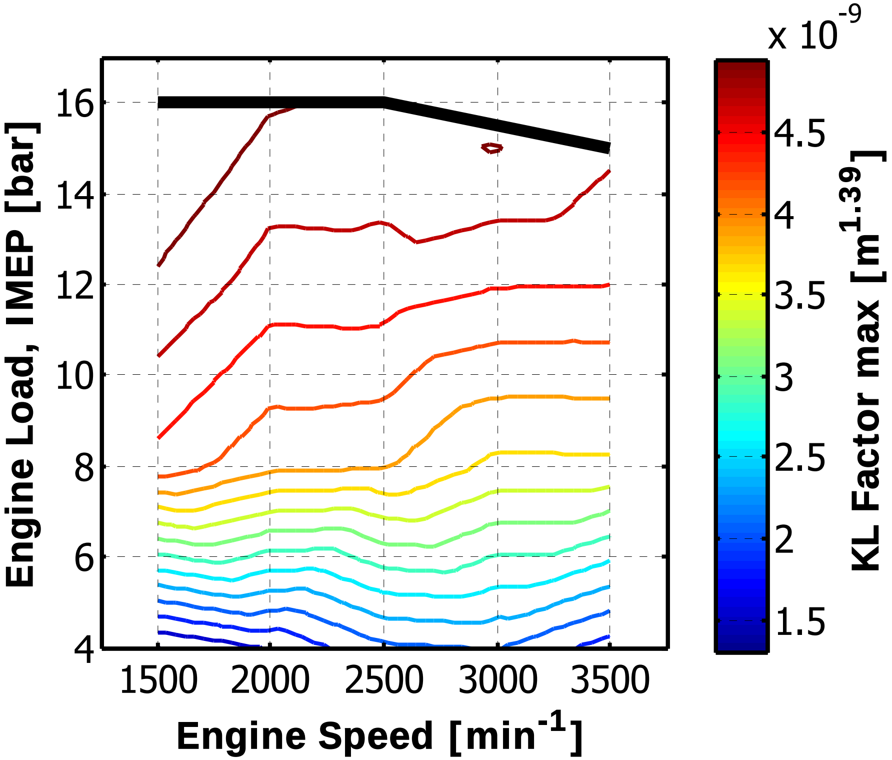


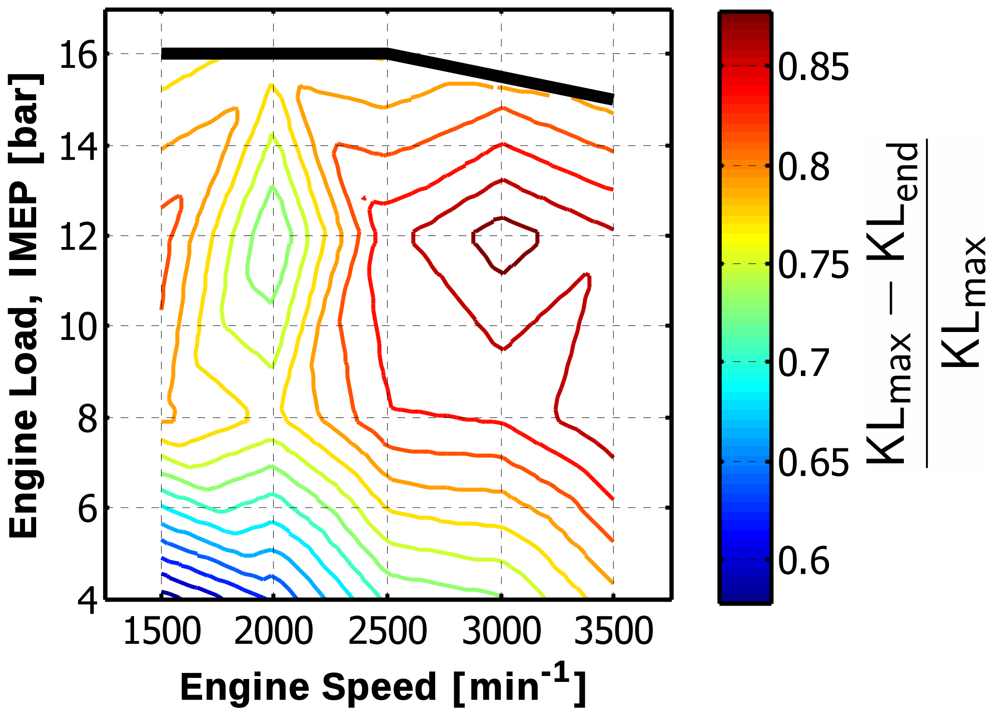


KL_{MAX} AND KL_{END}

SOOT FORMATION AND OXIDATION

- KL_{max} -> maximum soot concentration
- KL_{end} -> soot quantity after oxidation





- More soot formed at higher loads (NOT the same as engine out)
- Oxidized soot fraction strongly influenced by operating point...

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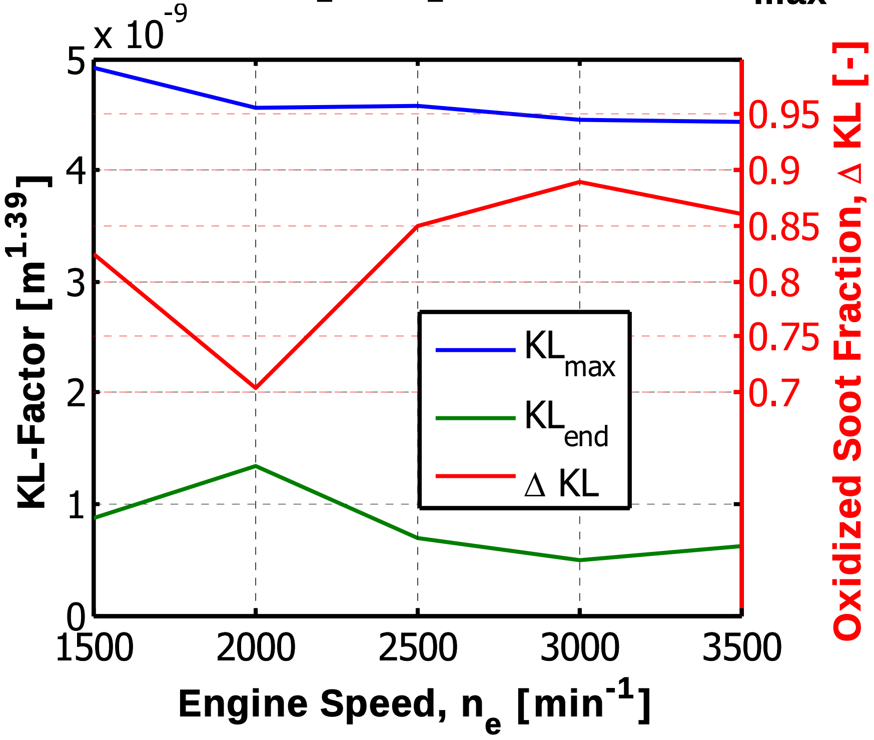
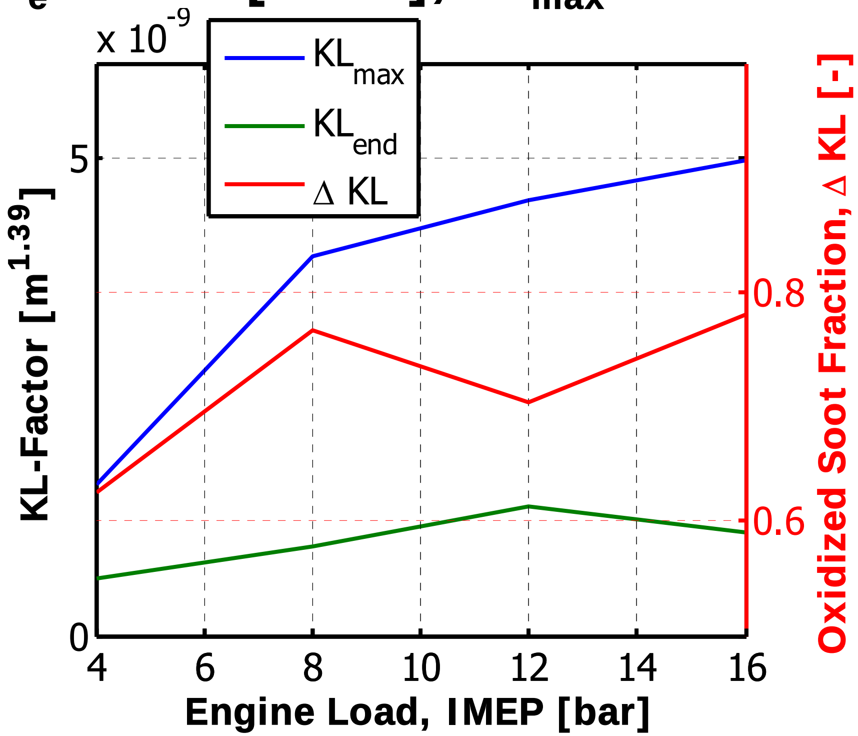
KL_{MAX} AND KL_{END} — LOAD AND SPEED VARIATIONS

- **IMEP = 12 [bar], ~const KL_{max}**



- **n_e=2000 [min^{-1}], KL_{max} increasing**



- **Oxidation influenced by:**
  - Turbulence (n_e, p_{inj})
  - Oxygen concentration (EGR, λ)
  - Temperature
  - Time available for oxidation

CONCLUSIONS / SUMMARY

- **Engine out and in-cylinder soot emissions from a production, multi-cylinder engine were measured using FSN and 3 color pyrometry**
- **The KL_{end} value provides a measure of the cylinder and cycle specific cylinder out soot emissions**
- **FSN correlates well to the sum of the average cylinder specific KL_{end} values**
- **Cylinder out soot emissions are defined by:**
  - Soot formed (~injected fuel quantity)
  - Soot oxidized:
    - Turbulence
    - Oxygen availability
    - Temperature
- **Fluctuations in KL_{end} values during steady state operation are predominantly due to fluctuations in the oxidation process**

THANK YOU FOR YOUR ATTENTION!