Investigation of In-Cylinder Soot Formation and Oxidation during Transient Engine Operation

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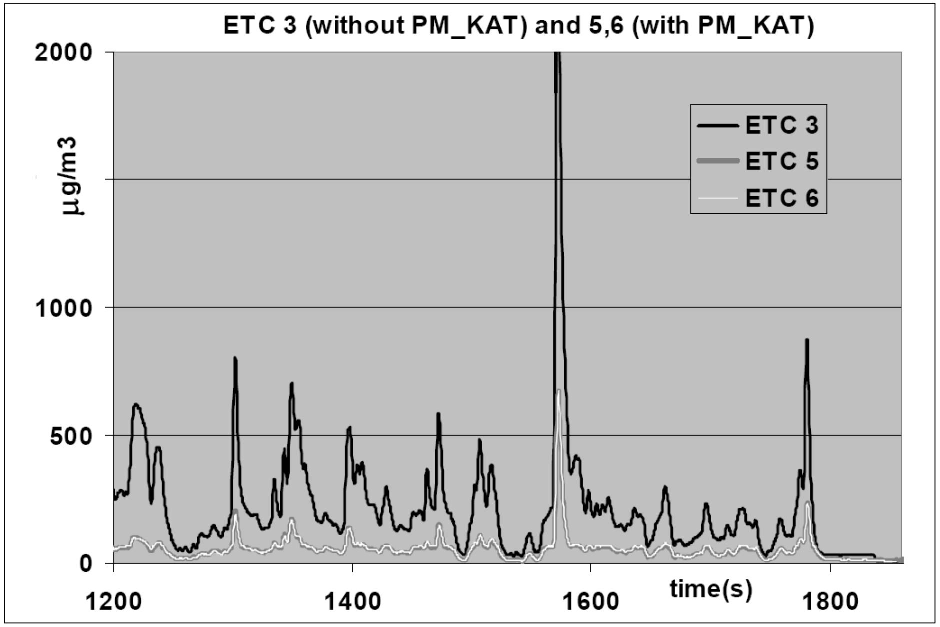
INTRODUCTION



Source: Schindler et al, 2004-01-0968

- **Soot emissions measured using an AVL Micro Soot Sensor during ETC cycle**
- **Significant challenge to total emissions are „transients“**

- **Cycle specific characterization is necessary to understand processes**
- **Existing soot instrumentation is neither cylinder nor cycle specific**
- **11th ETH Conference – correlation of exhaust stream and in-cylinder measurements**
- **12th ETH Conference – Exhaust stream measurement of transient soot emissions**
- **Today: Combination of these two works to consider transient, in-cylinder processes**

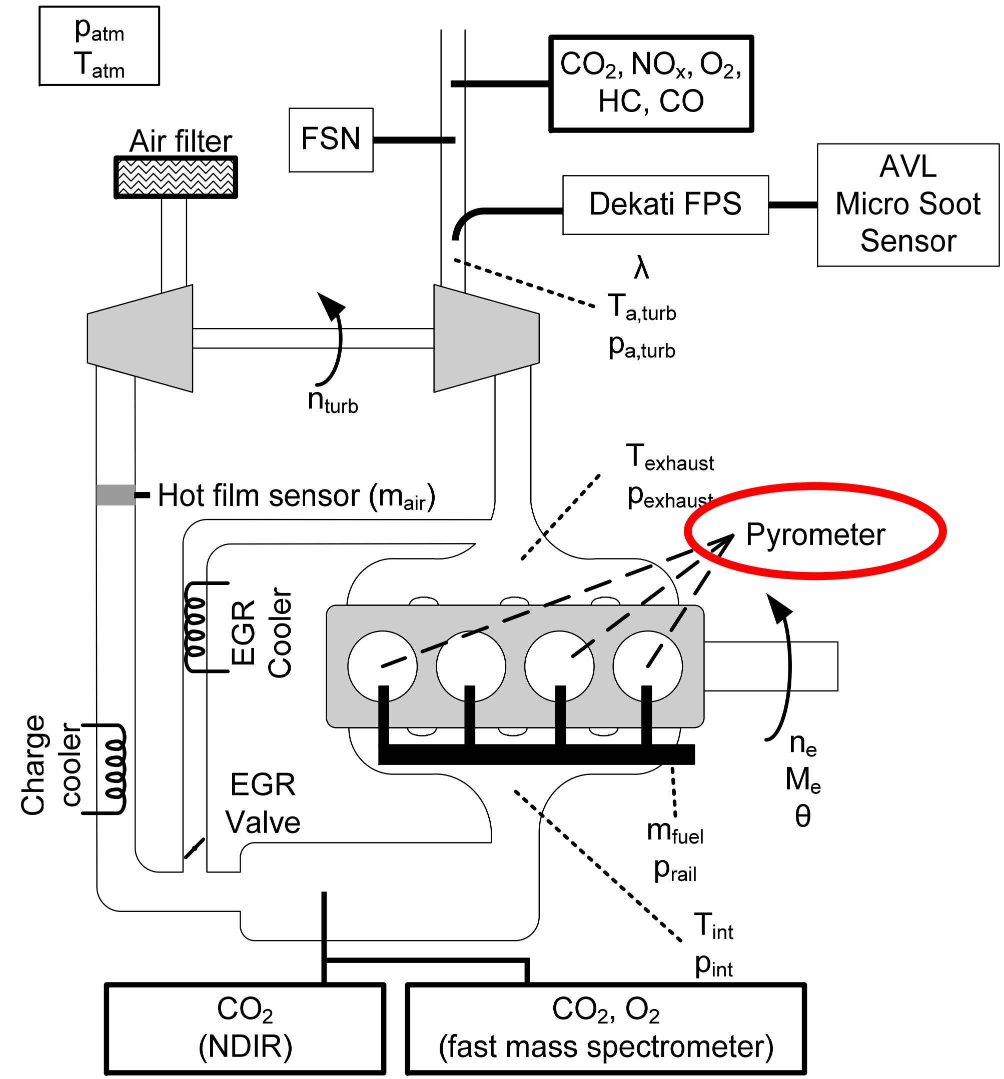
OUTLINE

- Testbench and instrumentation
- Overview of in-cylinder pyrometry
- Overview of exhaust stream measurements
- Detailed analysis of in-cylinder measurements and observed phenomena

TESTBENCH AND INSTRUMENTATION

OM611

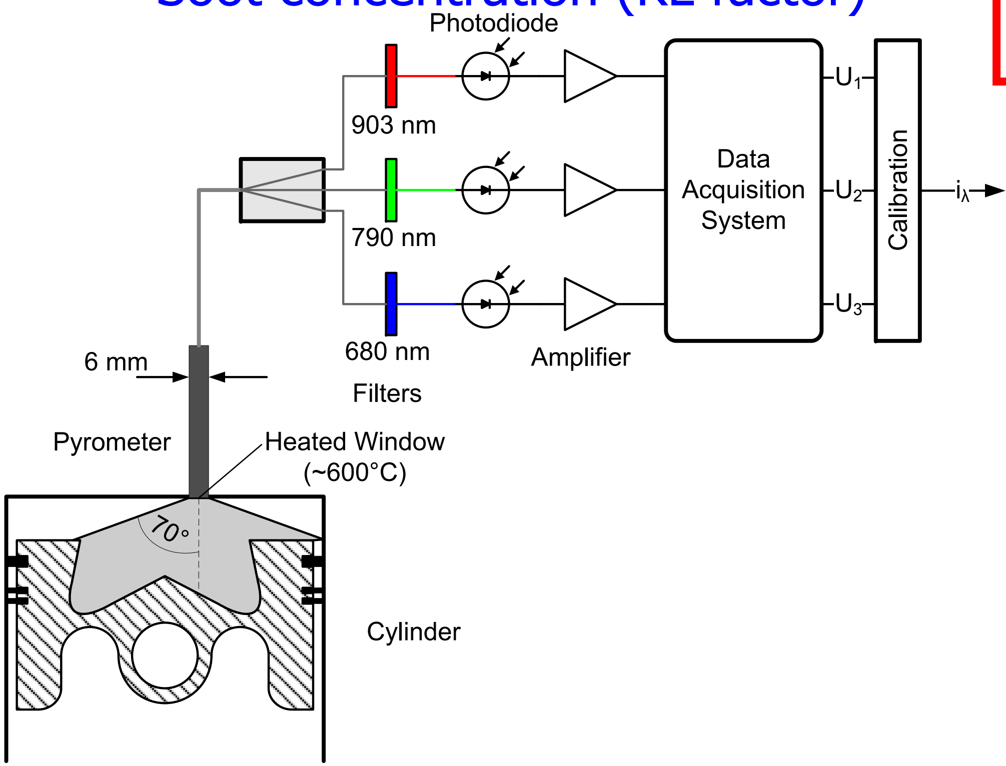
- **Passenger car, common rail engine:**
  - DaimlerChrysler OM611
  - VTG, EGR, $p_{inj,max}$~1350 bar
- **Exhaust stream soot emissions:**
  - Dekati Fine Particle Sampler
  - AVL Micro Soot Sensor
- **Transient characterization of instrumentation (Δt, τ)**
- **Pyrometers mounted in cylinders 1,3 and 4 provide:**
  - Soot concentration
  - Soot temperature



SOOT MEASUREMENT

IN-CYLINDER PYROMETRY

- **Multi-color pyrometry considers light intensity to determine in-cylinder:**
  - Soot cloud temperature
  - Soot concentration (KL factor)
- **Considers only hot** ("glowing") **soot**
- **Limited to soot within field of view**



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

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

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

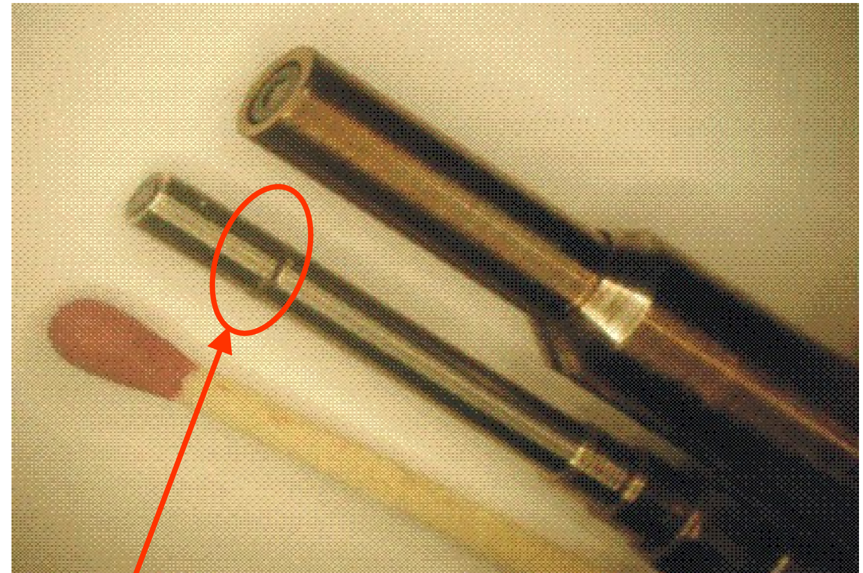
$$KL\Big|_{\lambda_1}=KL\Big|_{\lambda_2}=KL\Big|_{\lambda_3}$$

Hottel and Broughton. **Ind. Eng. Chem.**, 1932. **4**(2)

3 COLOR PYROMETRY

IMPLEMENTED SENSOR

- **System initially developed by LAV[1]; later in conjunction with Kistler AG and Sensoptic[2]**
- **Uses 3 wavelengths for redundancy (T, KL cross-verification)**
- **Wide field of view (140°) considers "most" of the cylinder**
- **Window heated to ~600°C to prevent contamination and provide long-term signal stability**
- **Very small size permits use in production engines (glowplug adapter, for eg.)**



d_{Sensor} = 4mm

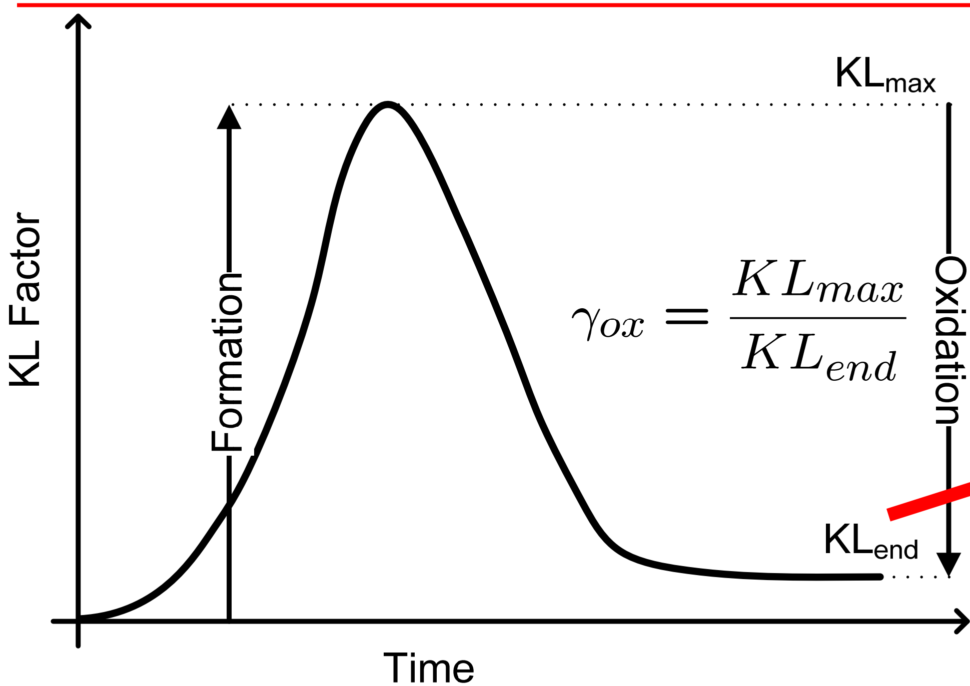
KISTLER
measure. analyze. innovate.

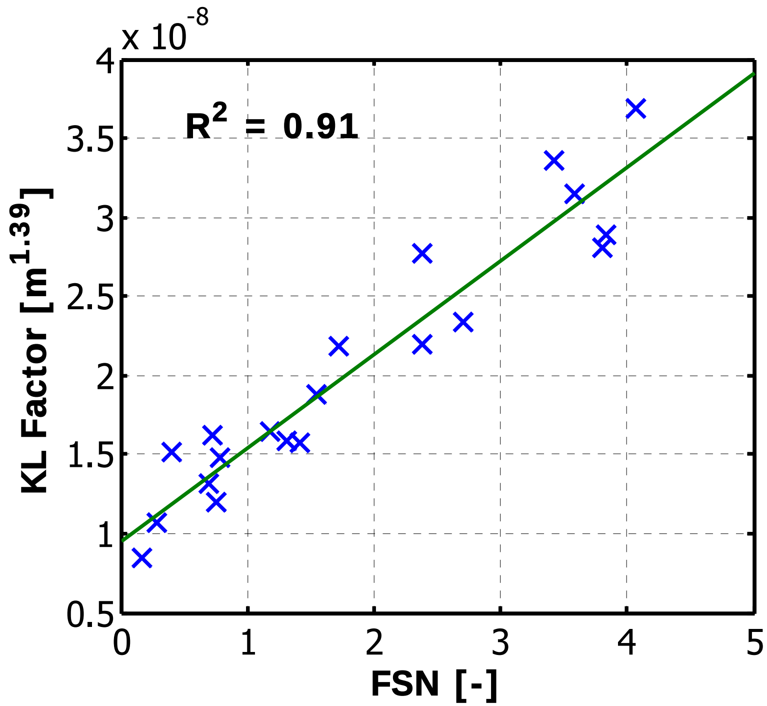
SENSOPTIC

[1] R. Schubiger *et al*. **MTZ**, 2002. **5**(63):342-353
[2] S. Kunte *et al*. **KTI Technical Report**, 2005.

3 COLOR PYROMETRY

USEFUL PARAMETERS





- **KL_{end} – correlates with exhaust stream measurements** (R^2 ~0.8…0.9)

➔ **Cycle resolved engine out soot emissions**

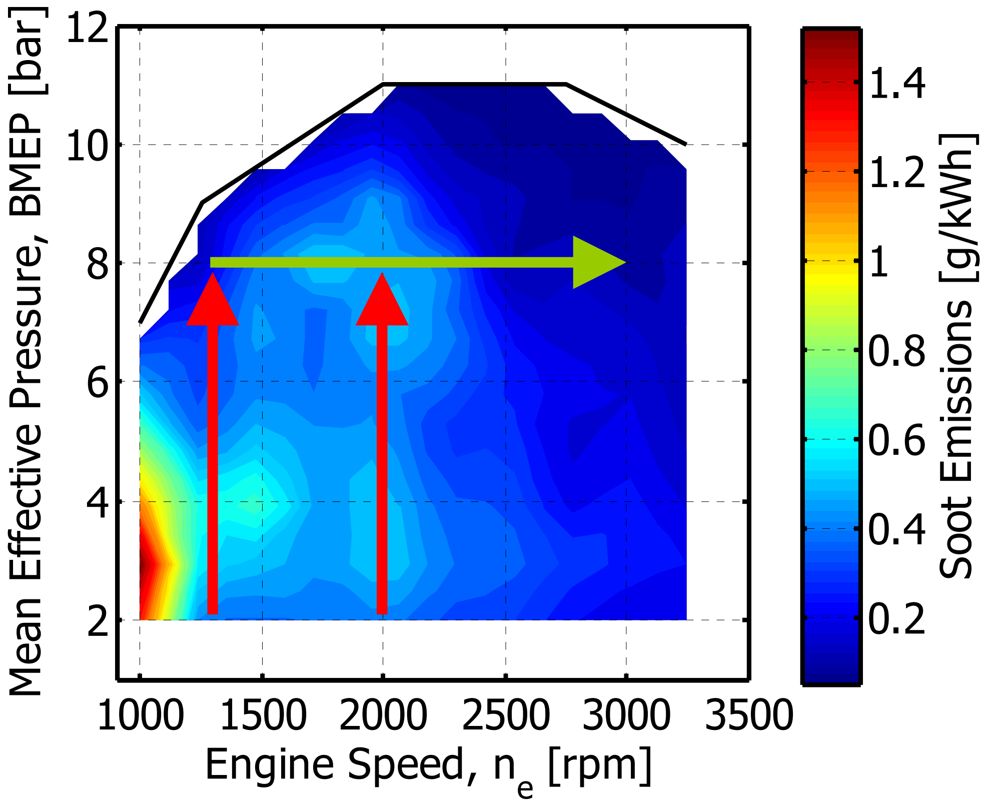
- **KL_{max} – measure of soot formation**
- **γ_{ox} – measure of soot oxidation**

➔ **Relative characterization of formation and oxidation processes**

Kirchen *et al*. **Proc. Stuttgart Symposium**, 2008. **2**:129-145

TRANSIENT MEASUREMENTS

CONSIDERED TRANSIENTS



- **Acceleration** (speed increase)
  - No notable change over steady-state
- **Tip-in** (load increase)
  - 1250 and 2000 rpm
  - Δt=0.5…5 s

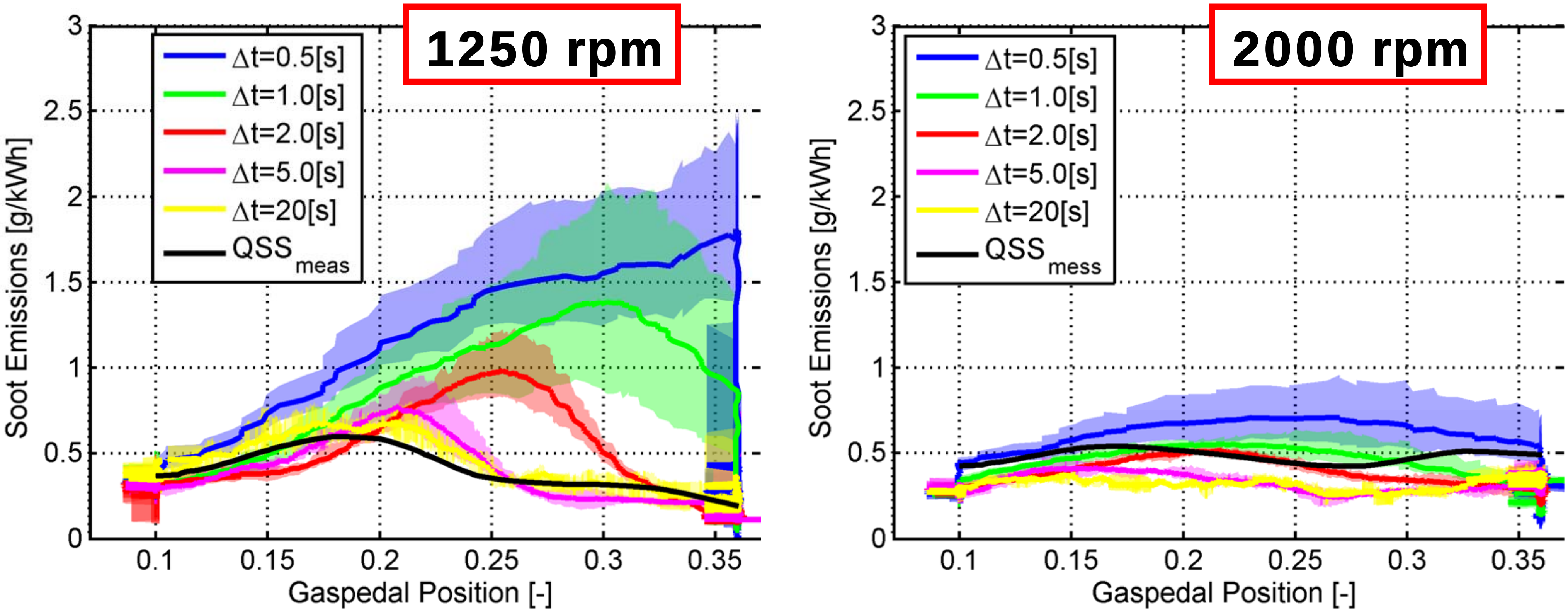
$$QSS = f(n, p_{me})$$

- **Transient and steady-state emissions compared using a Quasi Steady State (QSS) approximation**[1]

[1]Hagena *et al*. **SAE** 2006-01-1151, 2006

TRANSIENT SOOT MEASUREMENTS

TIP-IN

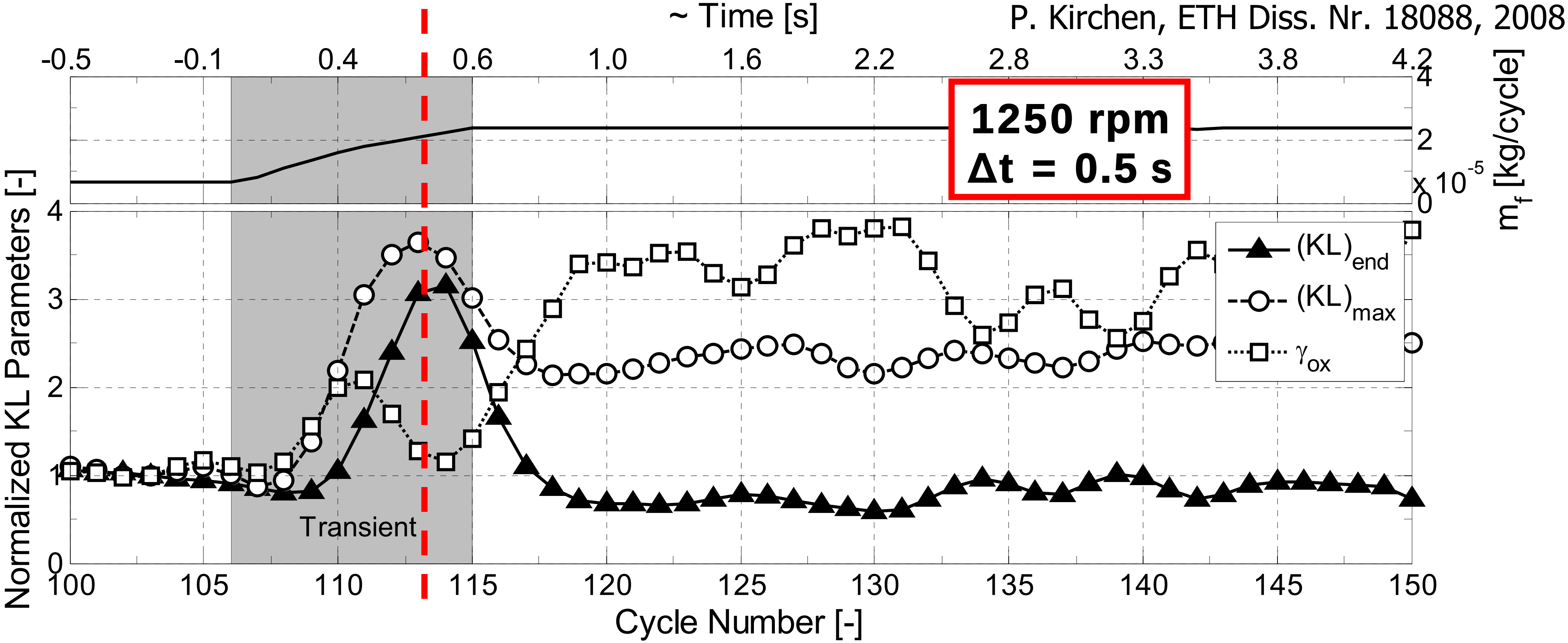


- **Transient soot emissions generally higher than steady-state (QSS)**
- **Faster transients result in much higher emissions**
- **Transient soot emissions lower than at 1250 rpm**
- **Only the fastest transient results in increased soot emissions**

Kirchen and Boulouchos. **SAE**, 2009. **2009-01-1904**

IN-CYLINDER PYROMETRY

TIP-IN TRANSIENT (1250 rpm)



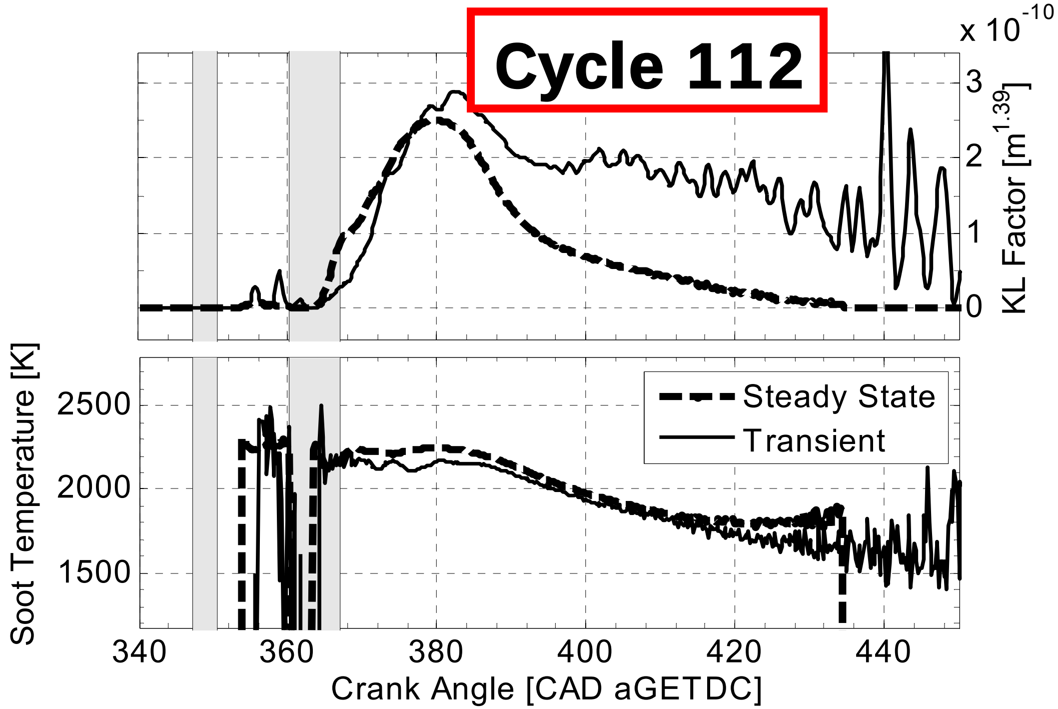
- **Comparison of normalized KL parameters during transient**
- **Increase in fuel quantity -> increase in KL_{max}**
- **Corresponding increase in oxidation (γ_{ox}) lags behind**

➔ **Poor oxidation leads to increased engine-out emissions (KL_{end})**

- **What causes the poor oxidation?**

PYROMETRY (KL & T)

TRANSIENT vs. STEADY-STATE



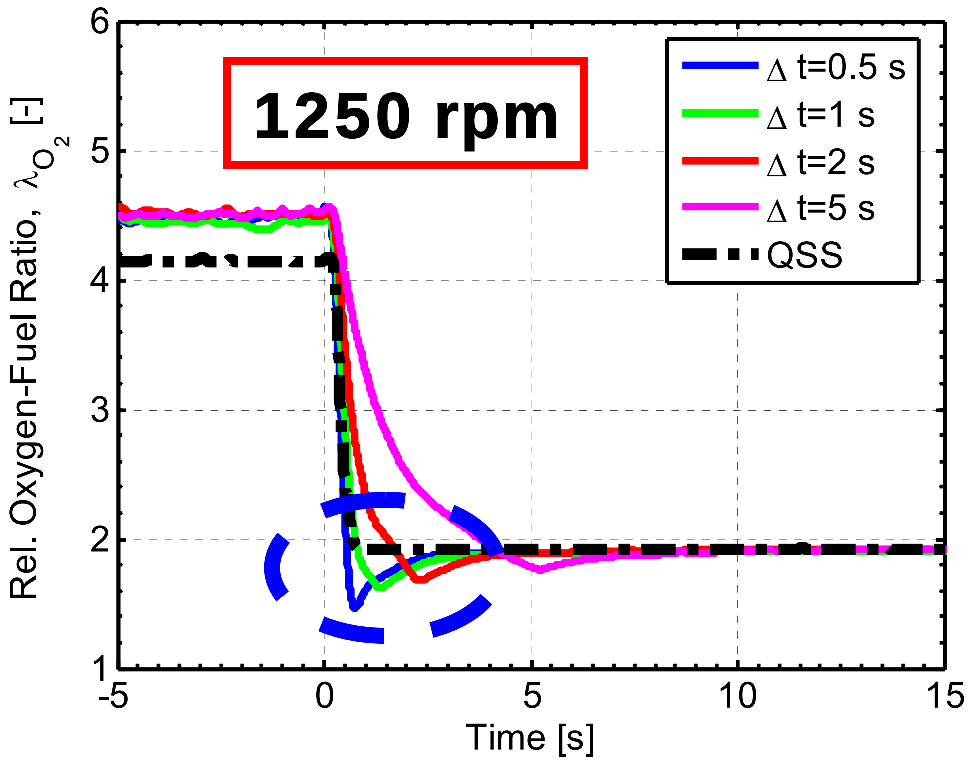
- KL_{max} not strongly influenced by transient operation
- Oxidation considerably slower during transient operation and stops earlier
- No significant differences between steady state and transient soot temperatures

➔ **Oxidation inhibited due to lack of O_2**

P. Kirchen, ETH Diss. Nr. 18088, 2008

OXYGEN AVAILABILITY

TIP-IN TRANSIENT (1250 RPM)

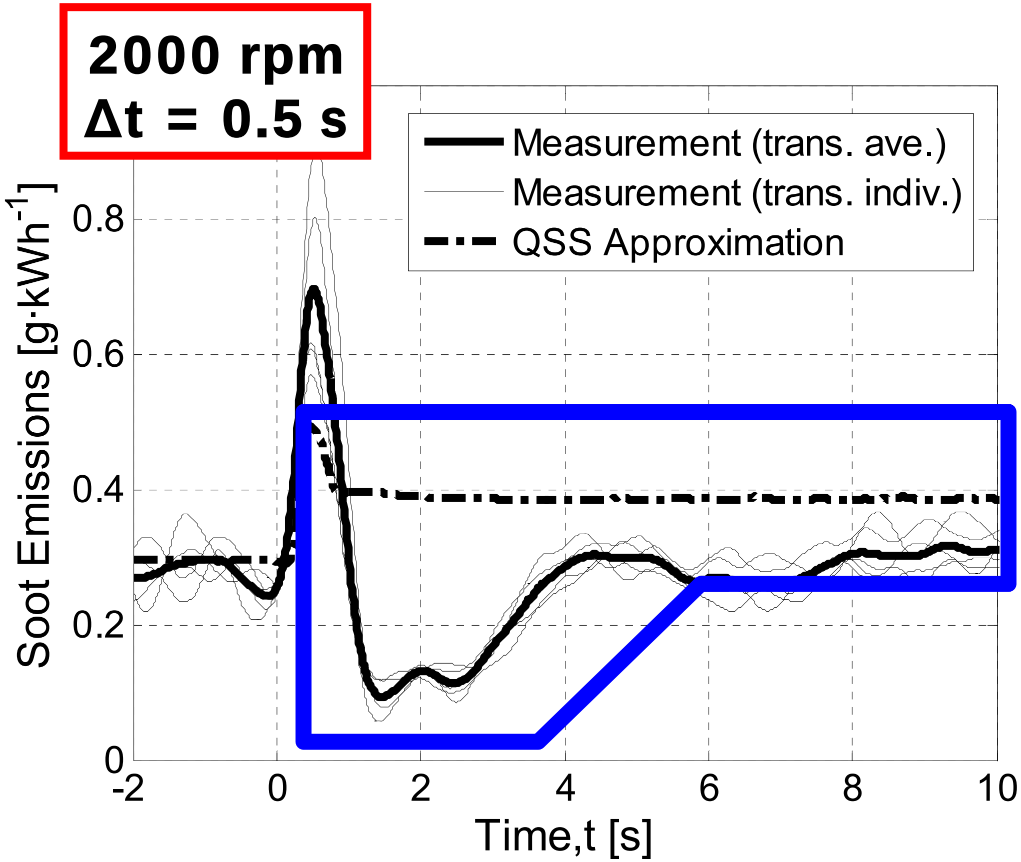


- **Short term oxygen deficit caused by:**
  - Slow EGR valve closing
  - Slow increase in charge pressure
  - Rapid increase in fuel quantity

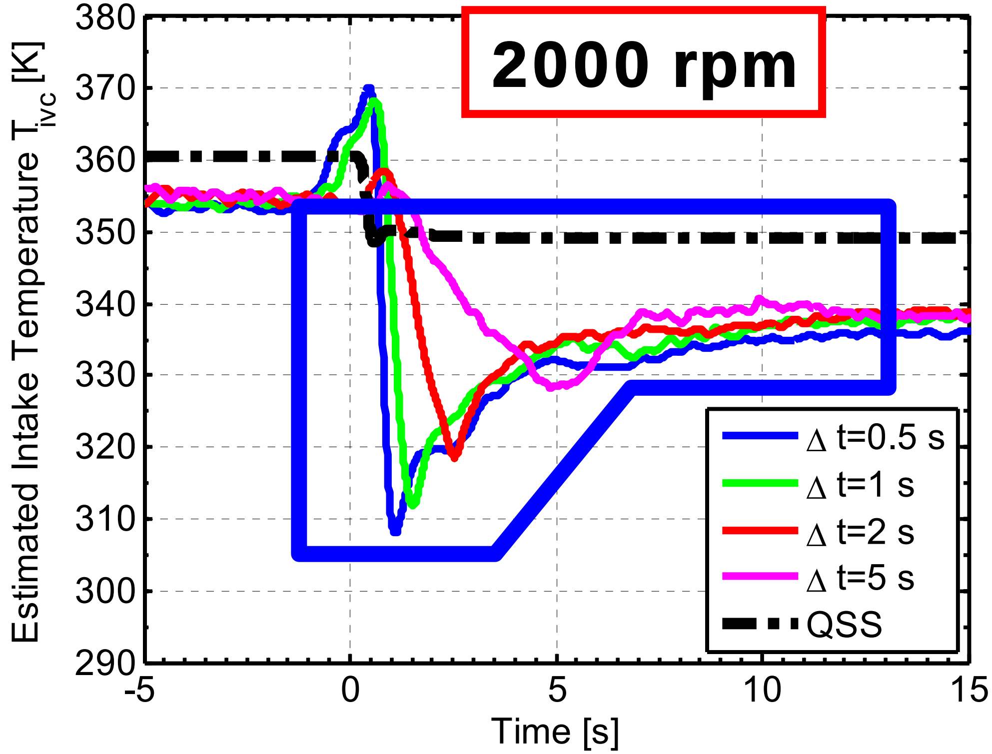
POST-TRANSIENT PHENOMENA

TIP-IN AT 2000 RPM

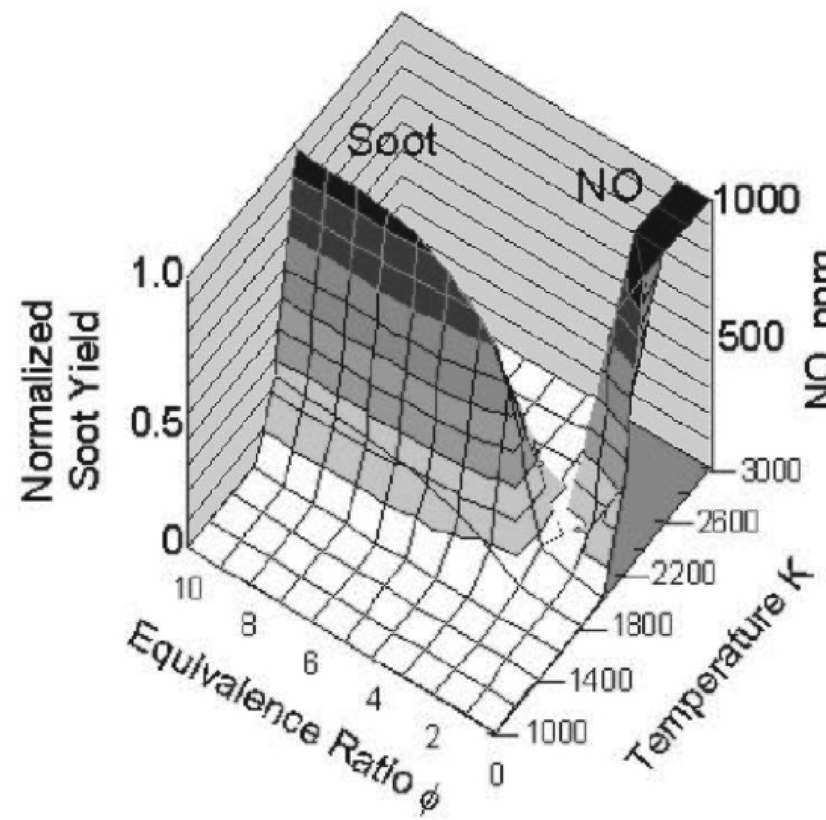
- **After transient:**
  - Transient soot emissions are lower than steady state
  - Only gradually increase and reaproach steady state value (~60s)
- **Phenomena correlates with a gradual increase in intake charge temperature**
- **Mechanism for reduction of engine-out emissions is unclear…**



T DURING TIP-IN TRANSIENTS



- **Lower temperature after transient, when compared to QSS**
- **Intake charge temperature provides estimate of soot formation temperature**

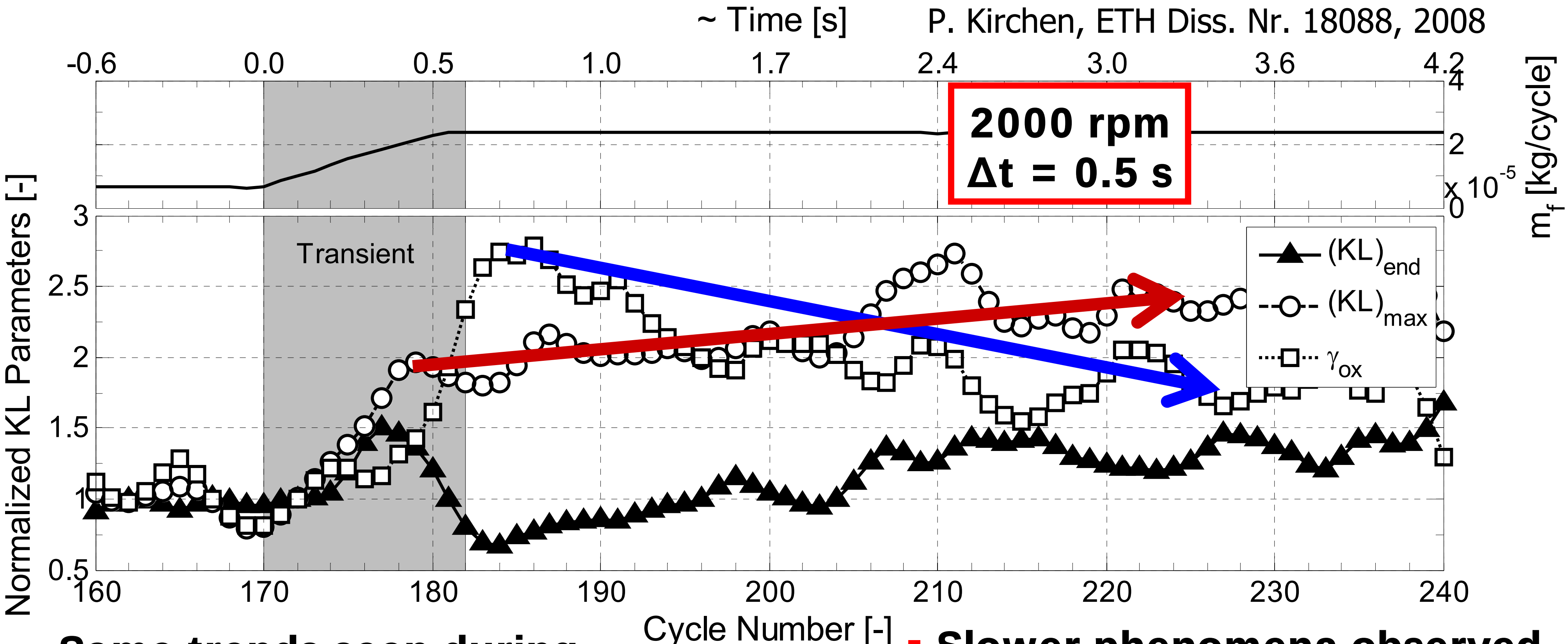


Akihama *et al*. **SAE** 2001-01-0655, 2001

- **Reduction of formation temperature results in lower soot emissions**

IN-CYLINDER PYROMETRY

TIP-IN TRANSIENT (2000 rpm)



- **Same trends seen during transient as at 1250 rpm**
- **Influence of transient less extreme due to higher charge pressure**
- **Slower phenomena observed after transient** (correlates with intake charge temperature)
- **Causality focus of current research…**

CONCLUSIONS

- **Multicolor pyrometry is a powerful tool for the measurements of cylinder and cycle specific, in-cylinder soot concentration and temperature**
- **During tip-in transients:**
  - Soot formation is approximately the same as during steady-state (KL_{max})
  - Soot oxidation is weaker due to an oxygen deficit (γ_{ox})
- **Only 5-10 cycles responsible for high engine out soot emissions**
- **Slow increase in intake charge temperature after transient results in:**
  - Gradual increase in engine-out soot emissions to final steady-state values
  - Gradual increase in KL_{max} to steady state value
- **Precise influence of charge temperature is not yet completely understood ...**

THANK YOU FOR YOUR ATTENTION!!

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