Measurement and Analysis of Soot Emissions During Transient Operation of a Common Rail Passenger Car Diesel Engine

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Introduction

It is well known that the emissions during transient engine operation have a substantial contribution to the total cycle soot emissions from diesel engines. It is therefore desirable to understand the mechanisms which are responsible for the increases in soot emissions seen during transient engine operation. To this end, the soot emissions as well as the engine operating parameters during representative transients were measured on an engine test-bench and compared with their corresponding steady state values.

Experimental Apparatus and Methodology

The steady-state and transient soot emissions from a representative common-rail diesel engine were measured along with the operating parameters of the engine. The four-cylinder engine (DC OM611) was equipped with a variable geometry turbine turbocharger, a cooled EGR system, and a common-rail injection system with a maximum injection pressure of 1350 bar. With the exception of the engine speed and gas pedal position, all engine operating parameters were controlled using the production engine control unit. All investigations were carried out using standard diesel fuel with less then 10 ppm sulfur. The soot concentration was measured in the exhaust stream using a Dekati Fine Particle Sampler (FPS) and AVL Micro Soot Sensor (MSS). The behavior of both of these systems during transient operation was considered by correcting for the gas transport times as well as the response time of the instruments themselves.

As it is well known that re-circulated exhaust gases have a strong impact on the soot emissions, a means of determining the EGR rate during transient engine operation was necessary. The EGR rate was determined based on the intake and exhaust gas stream CO_2 concentrations, whereby it was necessary to measure the CO_2 concentrations with a high temporal resolution. The exhaust stream CO_2 concentration was calculated based on the oxygen concentration measured using a standard lambda-sensor and knowledge of the combustion stoichiometry. The intake stream CO_2 concentration was measured using a fast mass spectrometer (V&F airsense.net). The dynamic response of the instruments used for the EGR rate determination was also characterized and corrected.

The transient soot emissions were measured during tip-in (increase in load at a constant engine speed) and acceleration (engine speed increase at a constant engine load) transients. The tip-in transients were carried out over several representative durations ranging from 0.5…5 s at two engine speeds, while the durations of the acceleration transients were determined using a vehicle model. Each of the transient measurements were repeated five times so that the reproducibility of the measurements could be determined.

So that the transient soot emissions could be quantified compared to their steady-state values, a quasi-steady-state (QSS) approximation was used [1]. The QSS provides an estimate of a steady state parameter based on the measured transient engine speed and load. For example the corresponding steady state soot emissions at any time during a transient can be determined by interpolation from the steady state soot emissions map based on the measured engine speed and load. Naturally this process can be repeated for other parameters such as the EGR rate, and not just the soot emissions.

Measured Soot Emissions during Transient Operation

The measured soot emissions during the tip-in and acceleration transients were compared to their corresponding steady-state values (QSS). No noticeable difference between the transient and steady-state soot emissions was observed during the acceleration transients, while a considerable increase was seen during the tip-in transients, particularly at 1250 rpm. In general, the fastest transients resulted in the highest soot emissions. Furthermore, as the transient duration is decreased, the variability of the soot emissions from one measurement to the next is increased, with considerable variations for fastest transients (±35%).

Detailed Analysis: Tip-in Transients

To understand the cause of the increased soot emissions during the tip-in transients, it is necessary to briefly consider the fundamentals of soot formation in diesel engines. It has been shown that the soot formation can be well described using an equivalence ratio – temperature map [2], by which the normalized soot yield is described as a function of the two aforementioned parameters. The temperature and oxygen concentration themselves are strongly influenced the combustion process itself, as well as by engine operating parameters such as the EGR rate, the air/fuel ratio, and the intake temperature. In general, an increase in the in-cylinder temperature results in increased soot emissions, due to a higher soot formation rate. If the temperature is further increased, the soot emissions will once again decrease due to higher oxidation rates. A decrease in the oxygen availability (lower λ) will always result in an increase in the soot emissions caused by an enhanced soot formation and inhibited soot oxidation.

As a basis for the following analysis, the relative oxygen/fuel concentration λ_{O_2} and the effective charge temperature at Intake Valve Closing (IVC) were determined for each of the transients. The relative oxygen/fuel concentration is a measure of the oxygen mass relative to its stoichiometric mass and is influenced by both the inducted fresh air, as well as the excess oxygen available in the re-circulated exhaust gases. The mean charge temperature at IVC was estimated using the ideal gas law and an engine specific correction function, which accounts for the influence of engine operating parameters such as the intake charge pressure, the EGR rate, the EGR temperature, and the engine speed.

When λ_{O_2} during transient engine operation is compared to its steady-state values, a short term oxygen deficit is seen during the transient engine operation. This oxygen deficit is attributed to a rapid increase in the fuel quantity coupled with a slow increase in the intake charge pressure and slow reduction in the EGR rate, caused by the slow responses of the turbocharger and EGR valve, respectively. At the lower engine speed λ_{O_2} drops to a minimum value of ~1.4, while at 2000 rpm the minimum value is only ~1.8. It should be noted that these are global values and that as they approach unity, the soot yield increases rapidly.

When the mean charge temperatures at IVC during the transient operation are compared to their steady-state values, a reduction in the temperature after the transient is seen. This temperature reduction is more predominant at the higher engine speed and can also be seen to correspond to a reduction in the soot emissions after the transient. This phenomena is also expected from consideration of the temperature – equivalence ratio map, as previously mentioned. Additionally, this temperature provides an indication of the overall thermodynamic state during the combustion and soot formation and oxidation processes. It plays a strong role on processes such as the fuel evaporation, the ignition delay, the premixed combustion fraction and the soot formation and oxidation rates themselves.

References

1. Hagena, J.R., Z.S. Filipi, and D.N. Assanis, *Transient Diesel Emissions: Analysis of Engine Operation During a Tip-In.* SAE 2006-01-1151, 2006.
2. Akihama, K., et al., *Mechanism of the Smokeless Rich Diesel Combustion by Reducing Temperature.* SAE paper 2001-01-0655, 2001.

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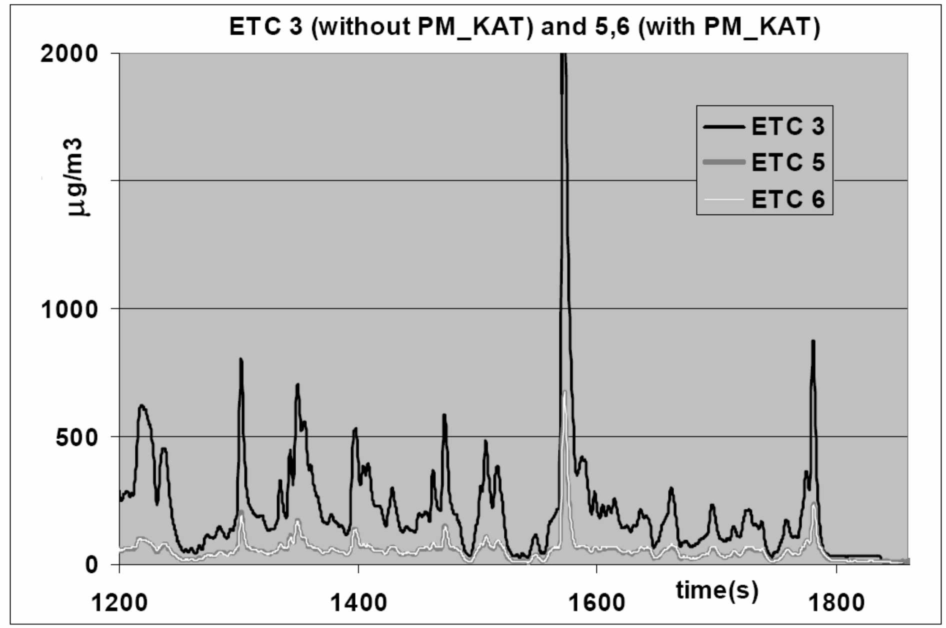
OVERVIEW

1. Introduction
2. Instrumentation
3. Definition of transient
4. Soot emission measurements
5. Analysis (EGR, λ, temperature,…)
6. Conclusions

INTRODUCTION

- **Particle emissions during transient operation have a substantial contribution to cycle emissions**
- **Investigate influences of transient engine operation on soot emissions**
- **Characterize soot emissions and engine operating parameters (EGR, λ, T, ...)**

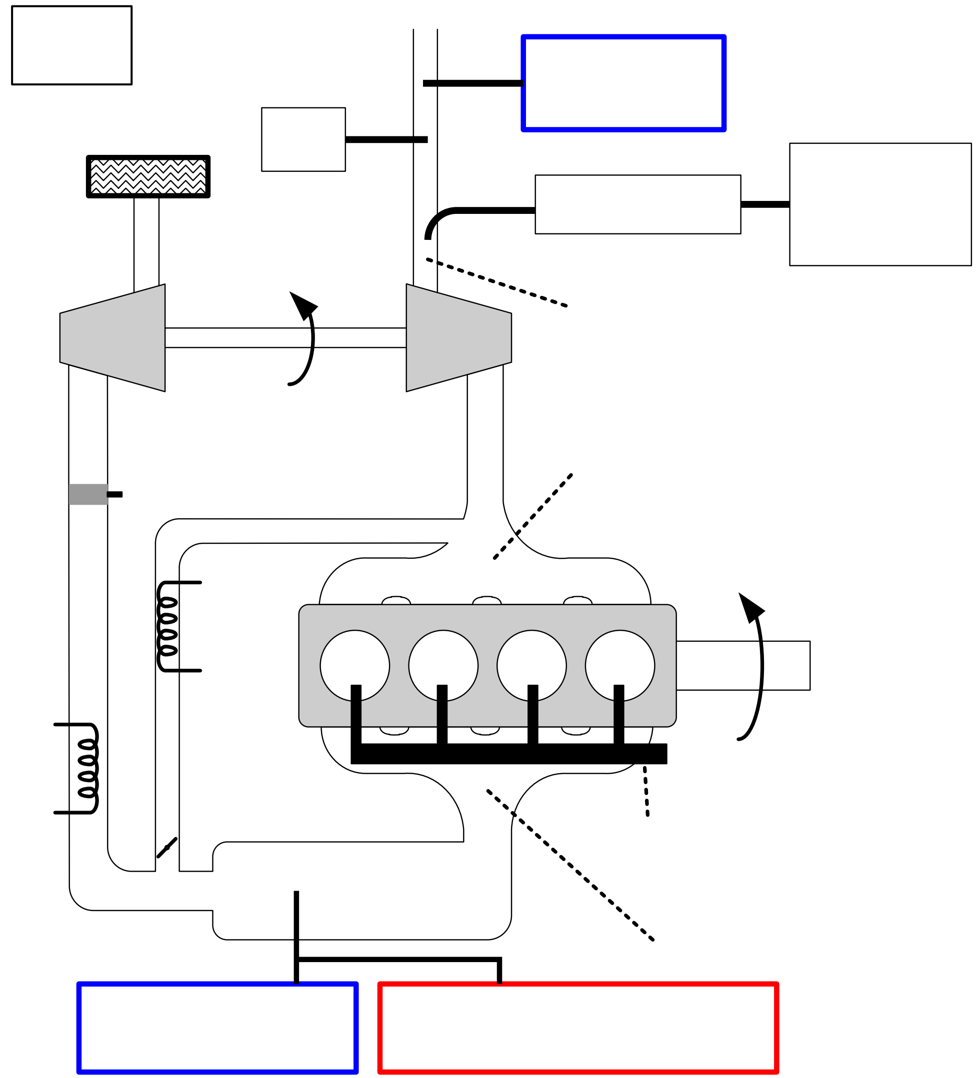


Source: Schindler et al, 2004

Soot emissions measured using an AVL Micro Soot Sensor during ETC cycle

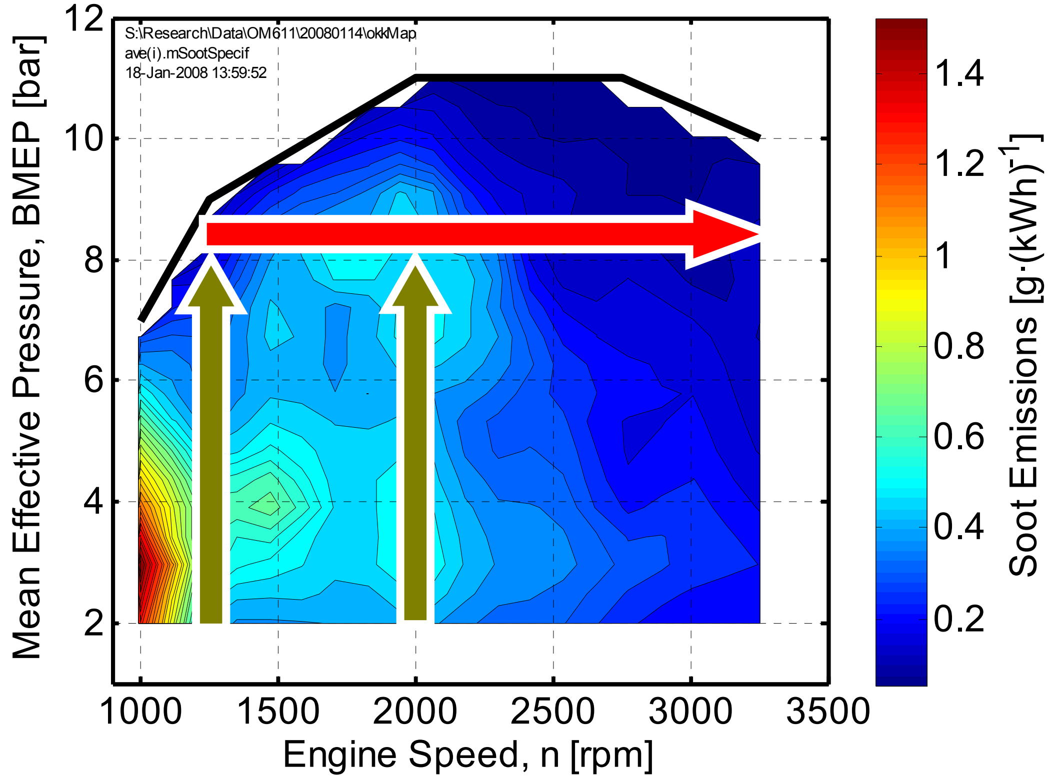
TESTBENCH AND INSTRUMENTATION

- **Passenger car common rail engine:**
  - DaimlerChrysler OM611
  - VTG, EGR, $p_{inj,max}$~1350 bar
  - Standard diesel
- **Soot emissions:**
  - Dekati Fine Particle Sampler
  - AVL Micro Soot Sensor
- **Injection / air path parameters taken from ECU**
- **EGR Rate:**
  - Intake CO_2 concentration: fast mass spectrometer
  - Exhaust CO_2 concentration: estimated from λ-sensor
- **Transient characterization of instrumentation**



INVESTIGATED TRANSIENTS

- **Want to reproduce "typical" engine transients of engine testbench**
- **Consider two types of transients:**
  - Acceleration (engine speed change)
    - BMEP = 8 bar
    - Δt = 3, 20 s (1st and 3rd gear)
  - Tip-in (load change)
    - 1250 rpm, 2000 rpm
    - Δt = 0.5, 1.0, 2.0, 5.0 s

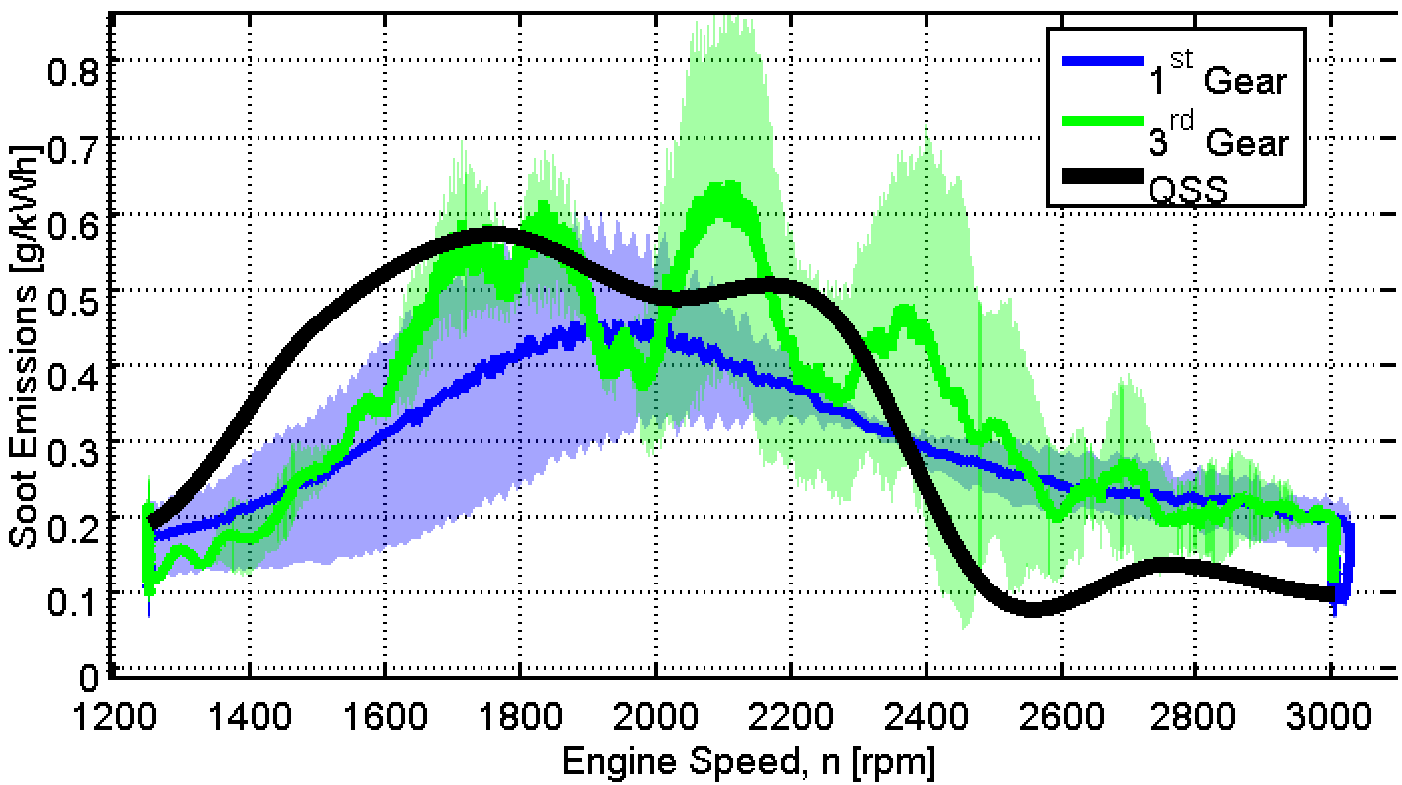


$$PM = f\left(n, p_{me}\right)$$

- **Compare with steady state using Quasi-Steady-State (QSS) approximation**
  (see also Hagena et al (2006))

TRANSIENT SOOT MEASUREMENTS ACCELERATION

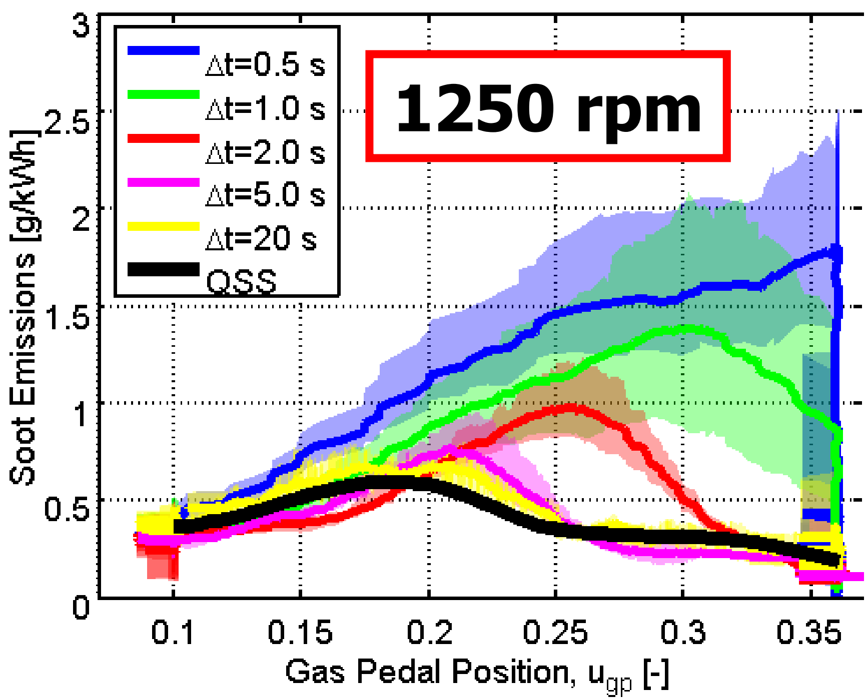
- **No significant difference noted between steady-state and transient operation – will not further discussed**
- **Considerable variation in measured emissions**

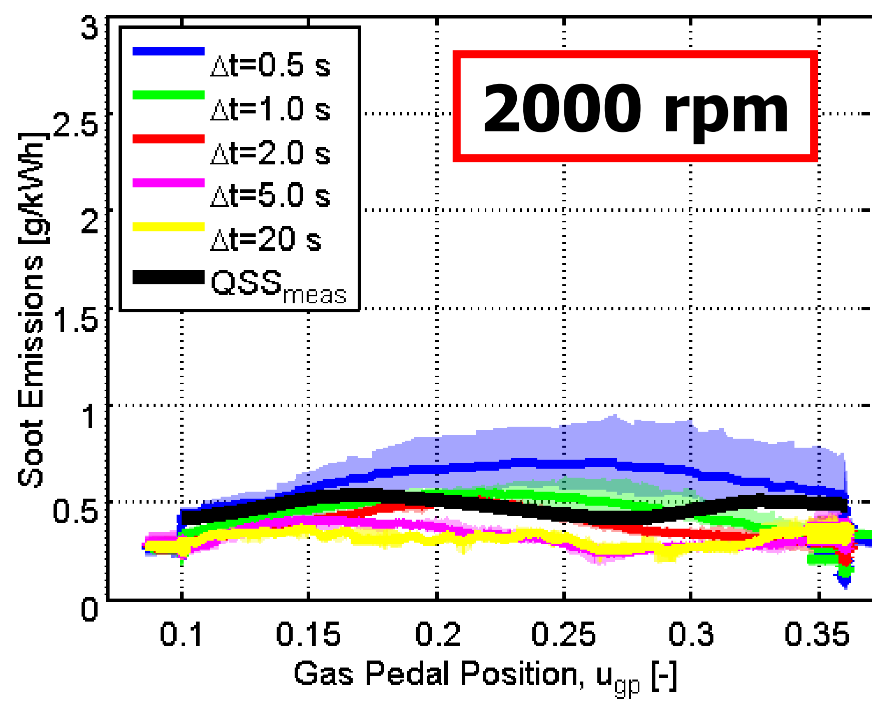


TRANSIENT SOOT EMISSIONS

TIP-IN

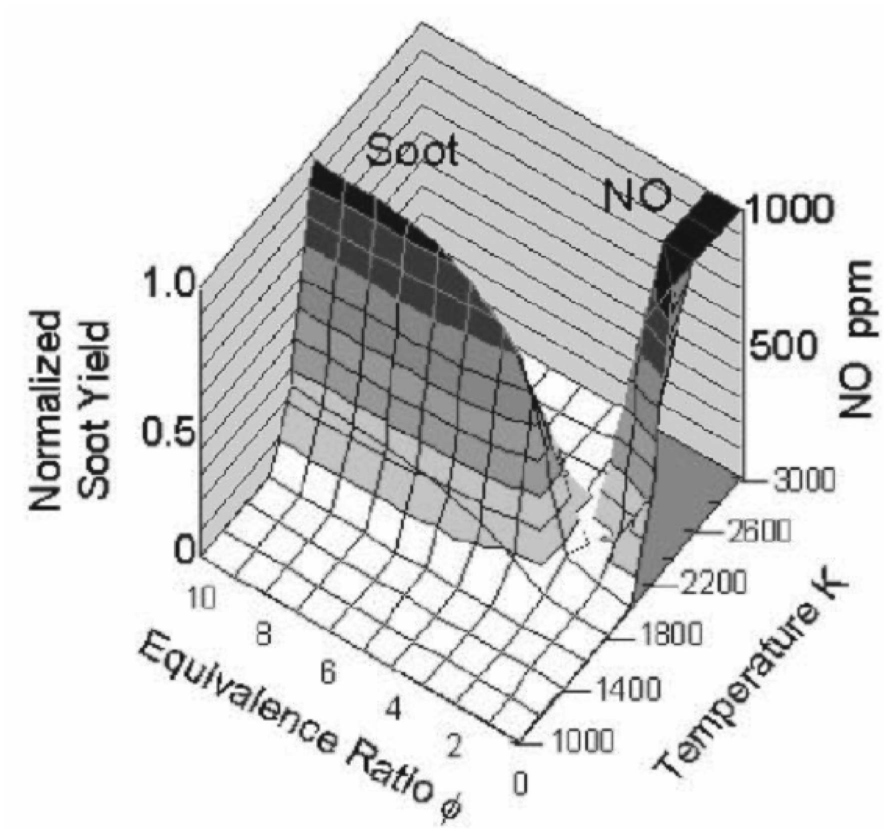
- Transient soot emissions increase with decreasing transient duration
- Large variability in measurements
- Peak soot emissions are lower at higher engine speed
- Why do we see increased soot emissions?





ANALYSIS

- **Oxygen concentration includes effects of EGR and p_{ivc}**
- **Global temperature influences**
  - Combustion process (ignition delay, fuel evaporation, premixed fraction)
  - Soot formation and oxidation
- **Soot emissions are influenced by many parameters:**
  - EGR Rate
  - Air/Fuel Ratio (λ)
  - Intake temperature
  - Injection pressure
  - Injection timing
  - …

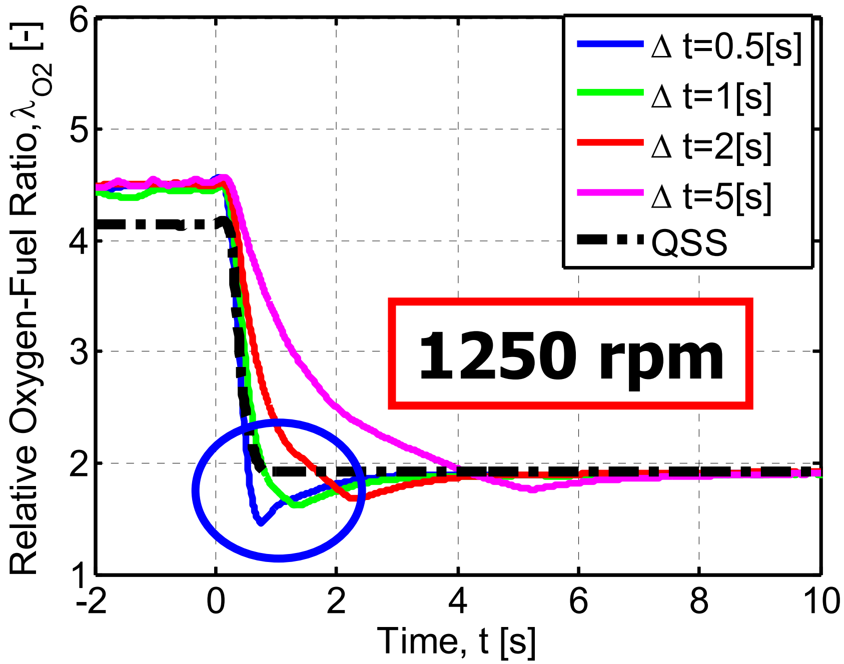


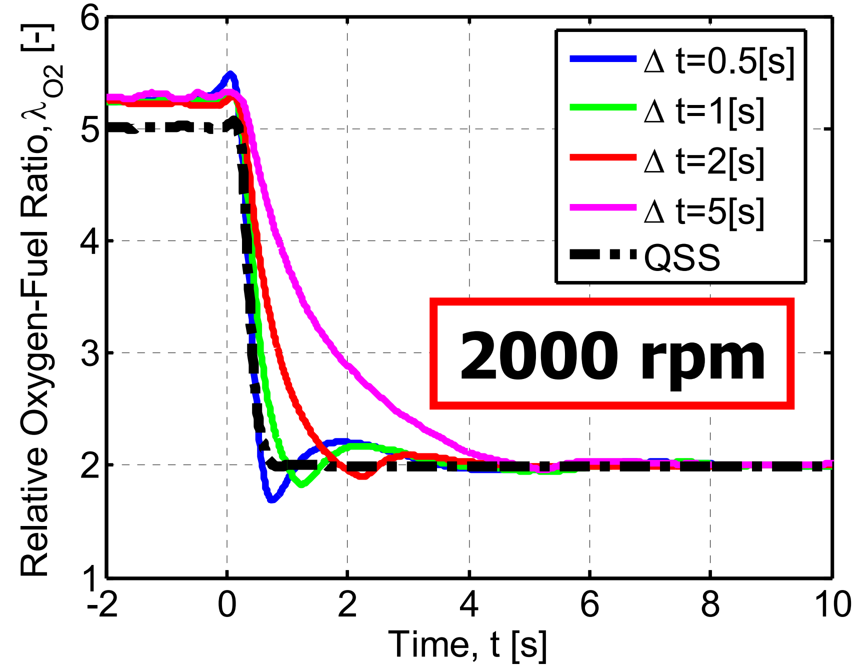
Akihama (2001)

O_2 CONCENTRATION DURING TRANSIENTS

- **Consider combined effect of EGR and p_{int} on oxygen concentration**
- **Short term oxygen deficit results due to transient**
  - λ_{min}~1.4 (1250 rpm)
  - λ_{min}~1.8 (2000 rpm)

$$\lambda_{O_2} = \frac{\left(m_{O_2}(EGR, fresh) \big/ m_{fuel} \right)_{actual}}{\left(m_{O_2} \big/ m_{fuel} \right)_{stoich}}$$



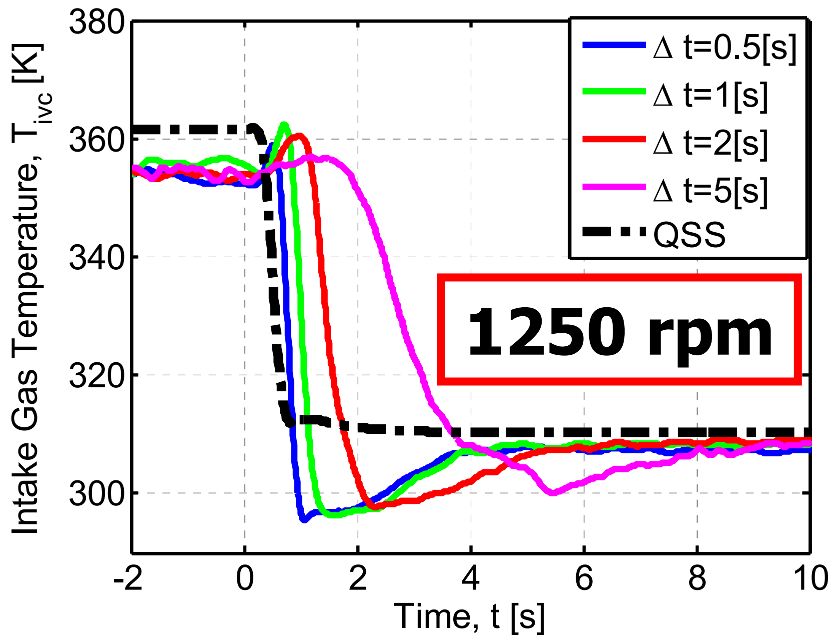


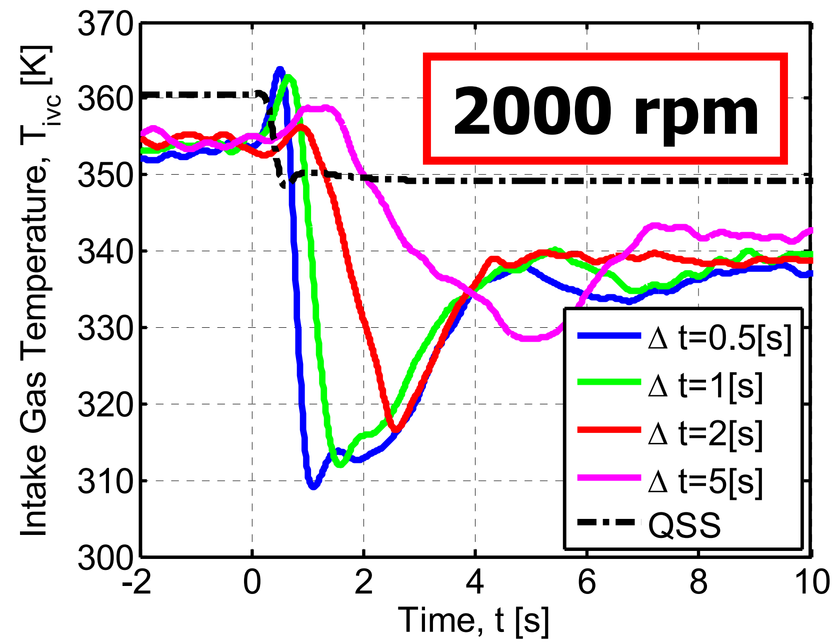
GOBAL TEMPERATURE DURING TRANSIENT

- **Estimate mean charge temperature at intake valve closing**

$$T_{IVC} = \frac{p_{IVC} \cdot V_{IVC}}{R_m \cdot m_{air}\left(1+\frac{EGR}{1+EGR}\right)} \cdot f_{corr}\left(p_{IVC}, EGR, T_{EGR}, n\right)$$

- **Lower temperature seen after transient than during steady state operation (QSS)**

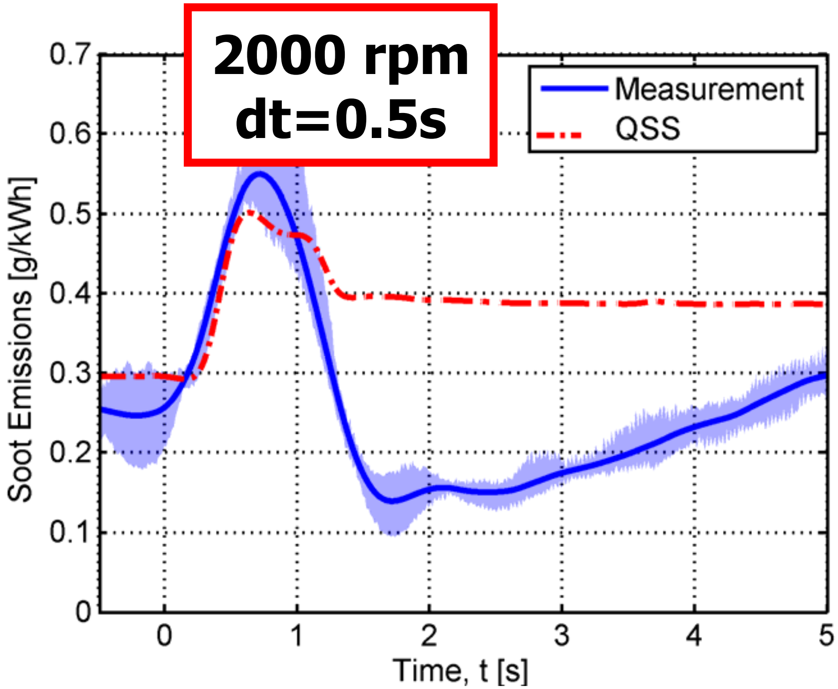


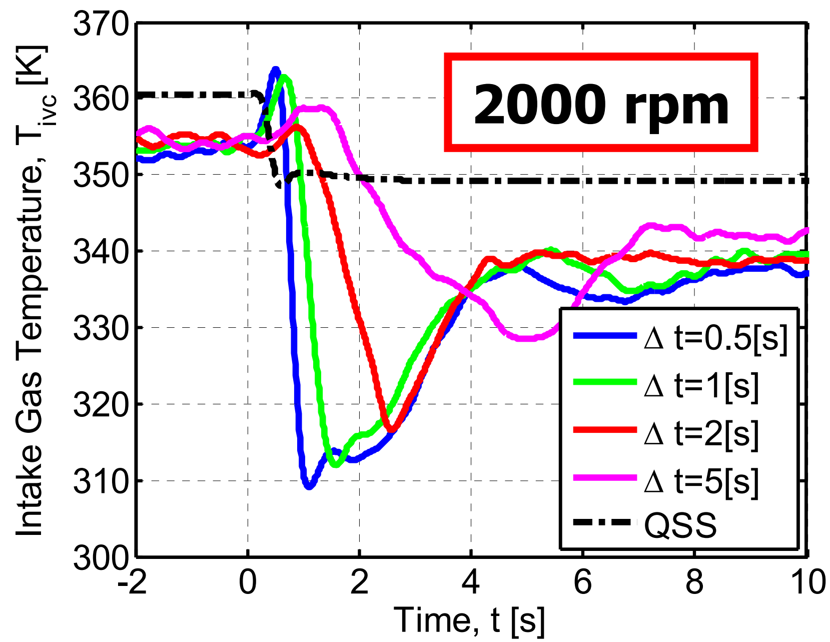


EVIDENCES OF TEMPERATURE INFLUENCE

- **Short term reduction in soot emissions seen immediately after transient**
- **Soot emissions reduction coincides with decreased temperature**

- **Decreased temperature due to:**
  - Lower EGR rate
  - Lower cylinder wall temperatures (probably…)





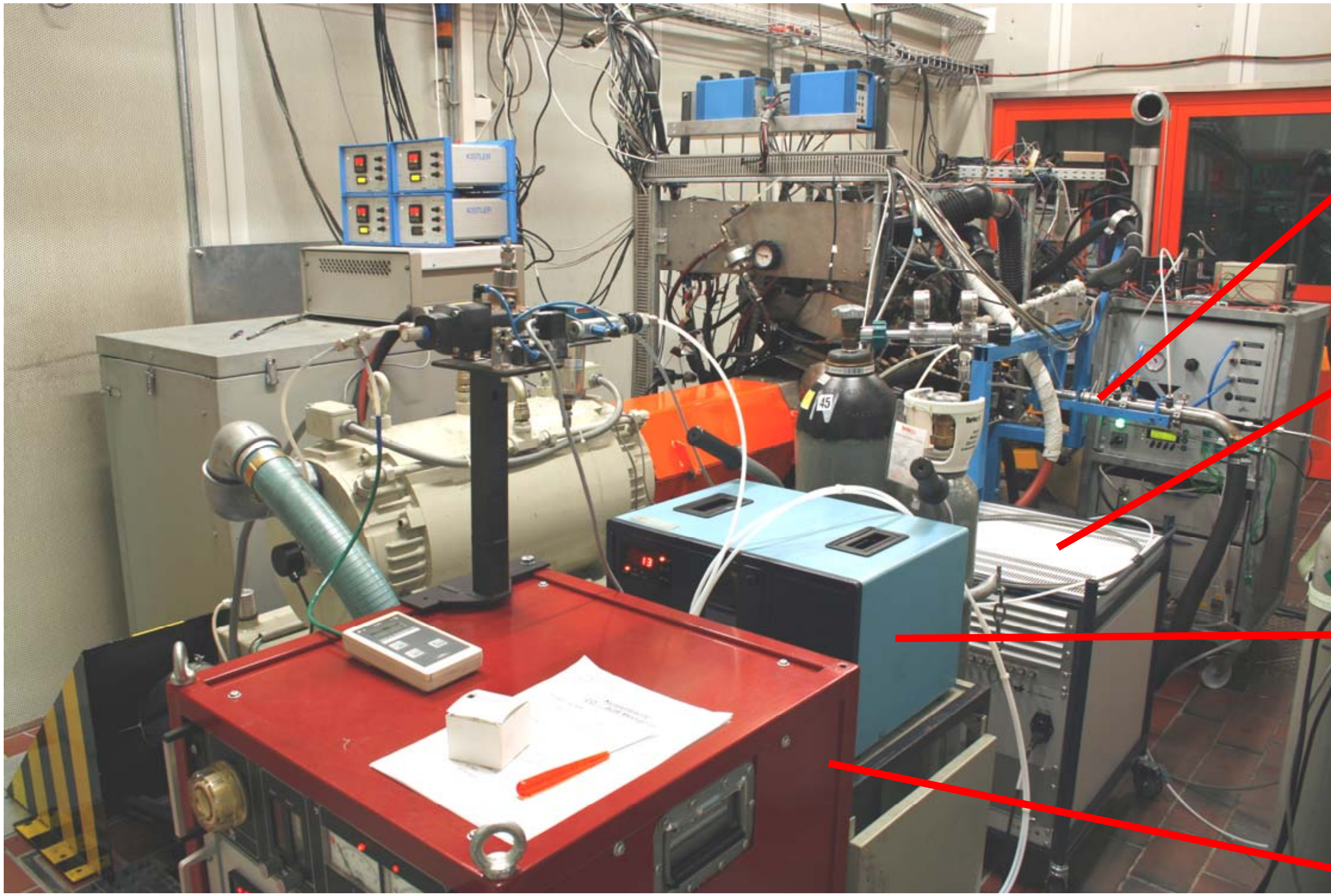
CONCLUSIONS

GOAL: Measurement and analysis of soot emissions during transient engine operation

- **Use a AVL Micro Soot Sensor and Dekati Fine Particle Sampler for soot measurement (correct for gas transport and response times)**
- **Acceleration transients present no substantial change in soot emissions compared to steady state**
- **Tip-in transients cause substantial increase in soot emissions (particularly at low engine speeds) due to an oxygen deficit:**
  - Low charge pressure buildup (low overall charge pressure)
  - Slow reduction in EGR rate
  - Changing thermal boundary conditions (T_{ivc})
- **Global temperature can be used to describe additional soot emission phenomena**

THANK YOU FOR YOUR ATTENTION

TESTBENCH AND INSTRUMENTATION



PASS/FPS
(Soot)

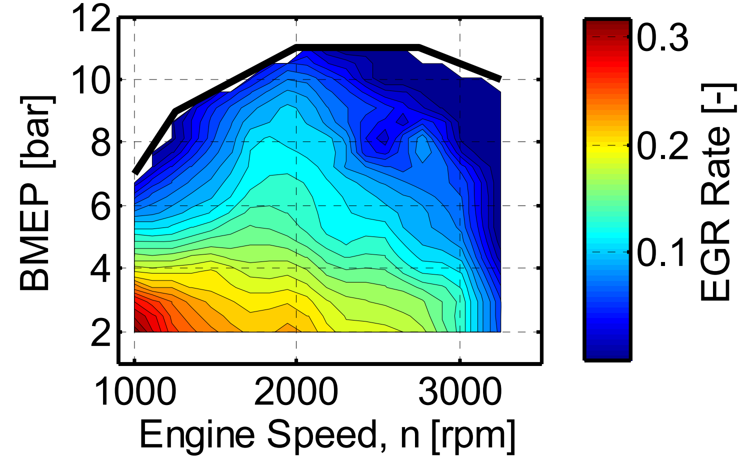
Mass spectrometer
(fast CO_2, O_2)

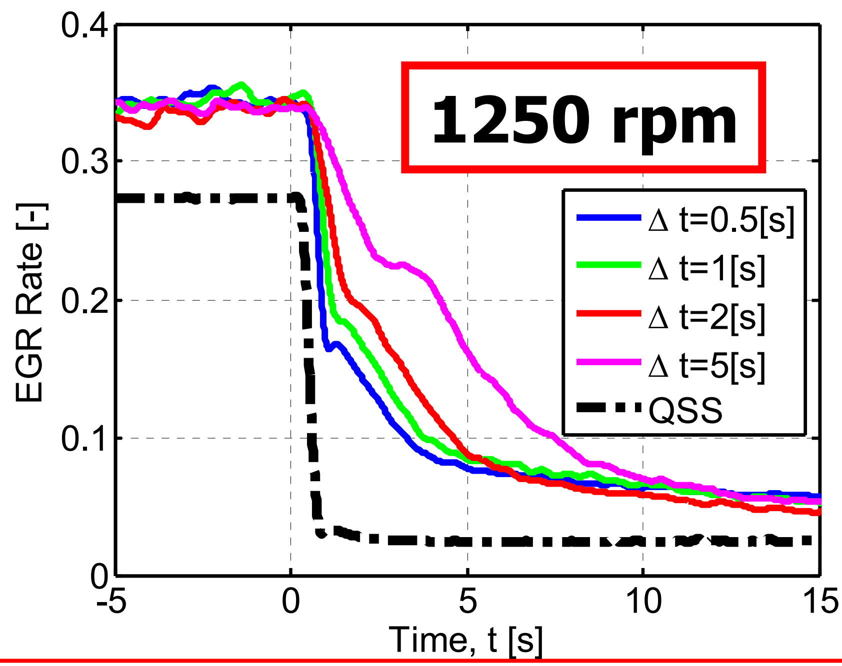
FSN

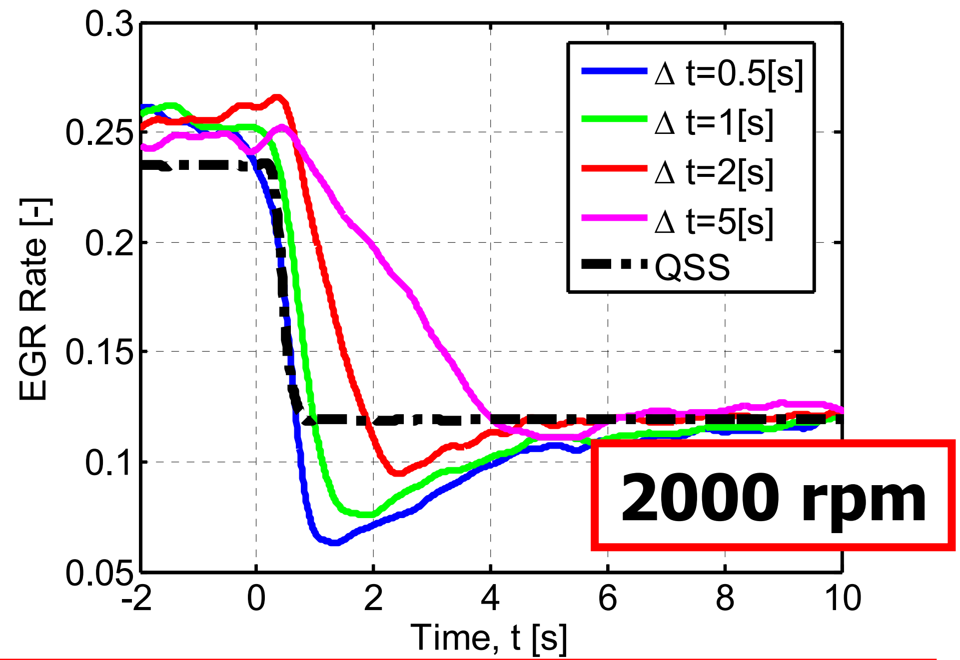
NDIR
(slow CO_2)

EGR RATE DURING TIP-IN TRANSIENTS

- Defined by valve position and intake and exhaust pressure
- Slow decrease at 1250 rpm
- Rapid decrease and undershooting of steady state value at 2000 rpm

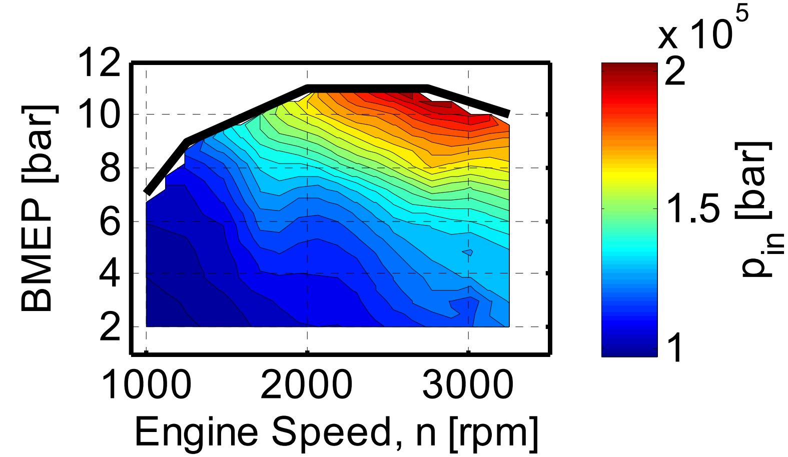




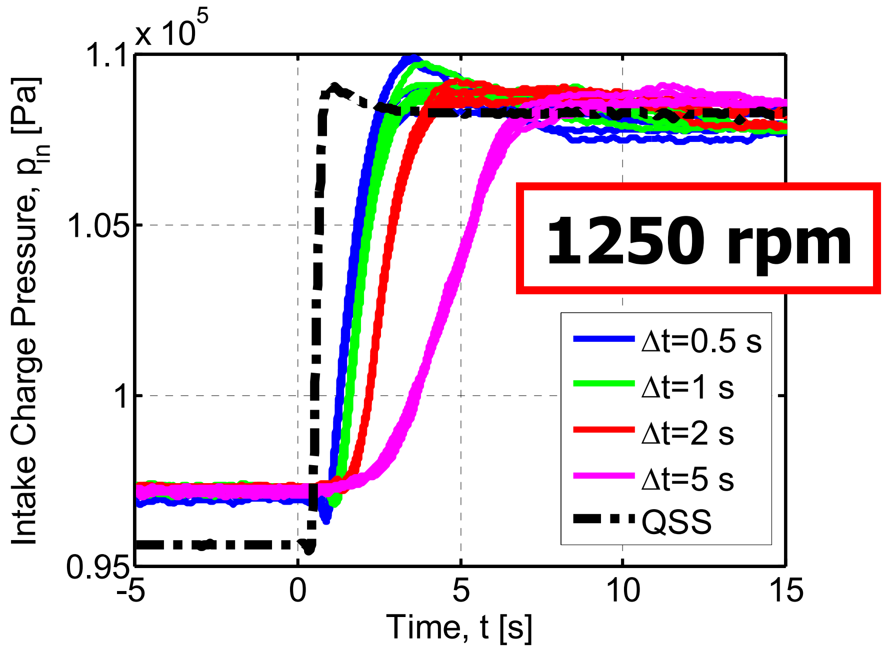


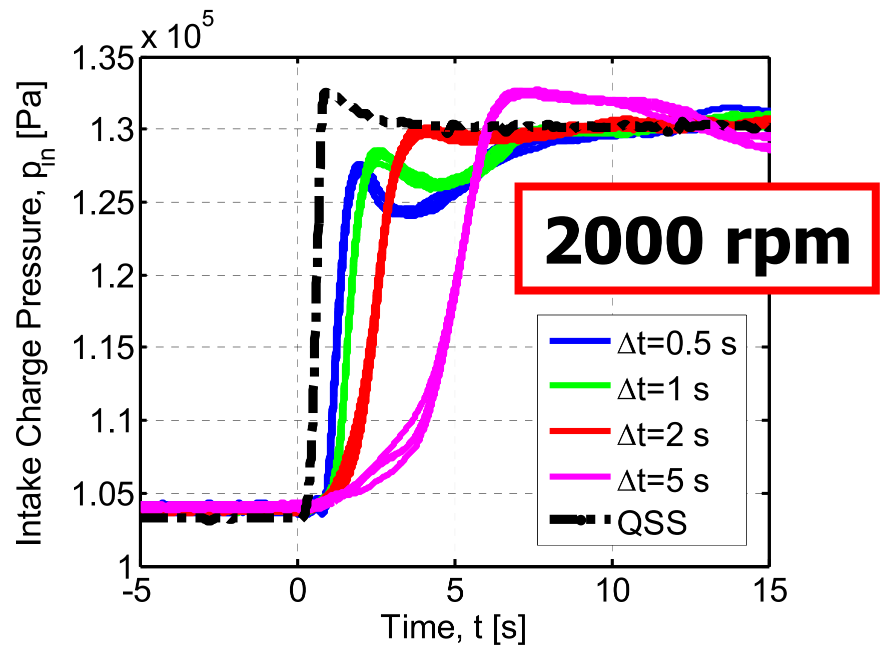
CHARGE PRESSURE DURING TIP-IN TRANSIENTS

- **Charge pressure in general higher at 2000 rpm**
- **Effect of VTG evident at 2000 rpm**

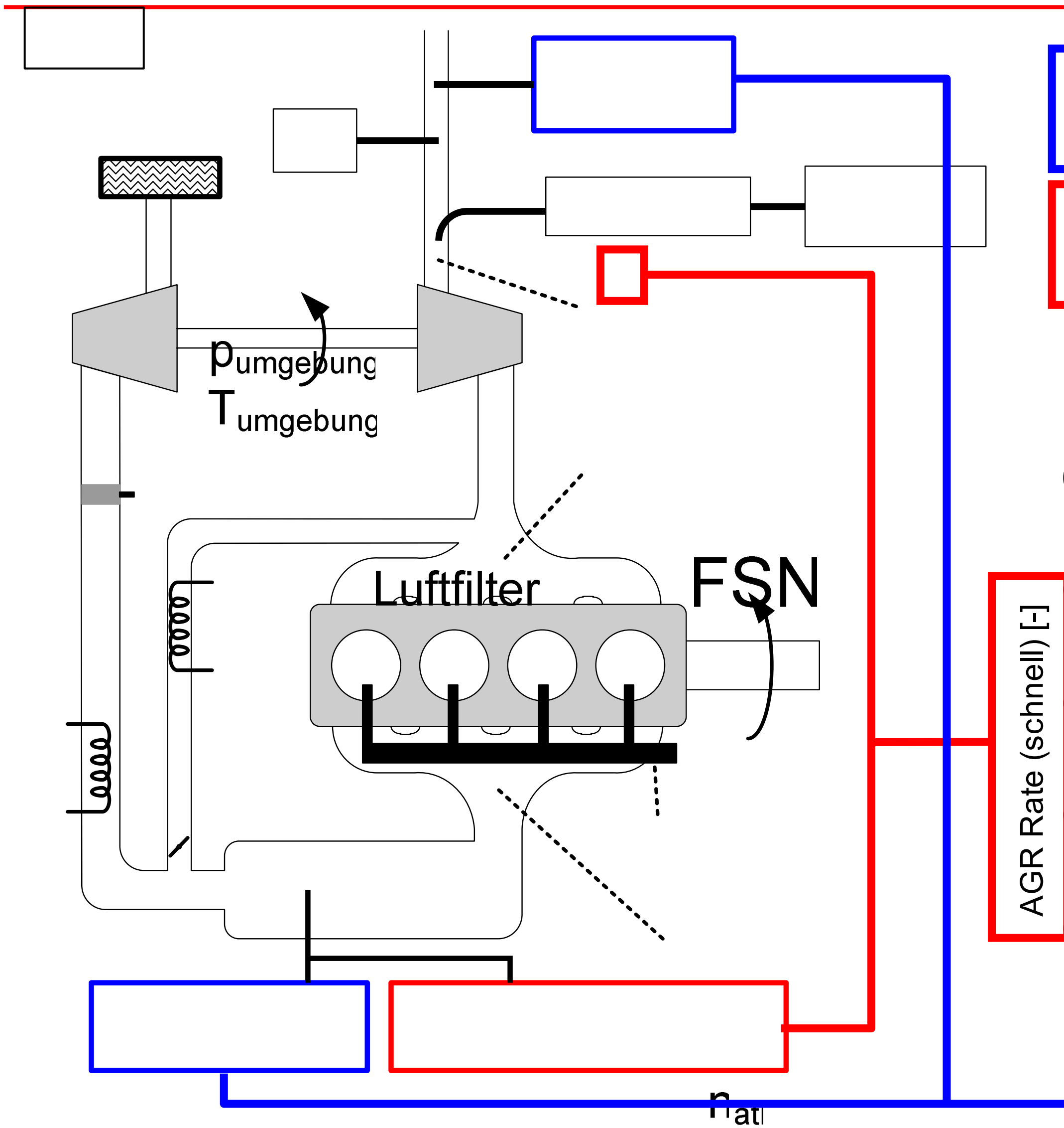


BUT: What is the net effect of EGR and p_{int}?

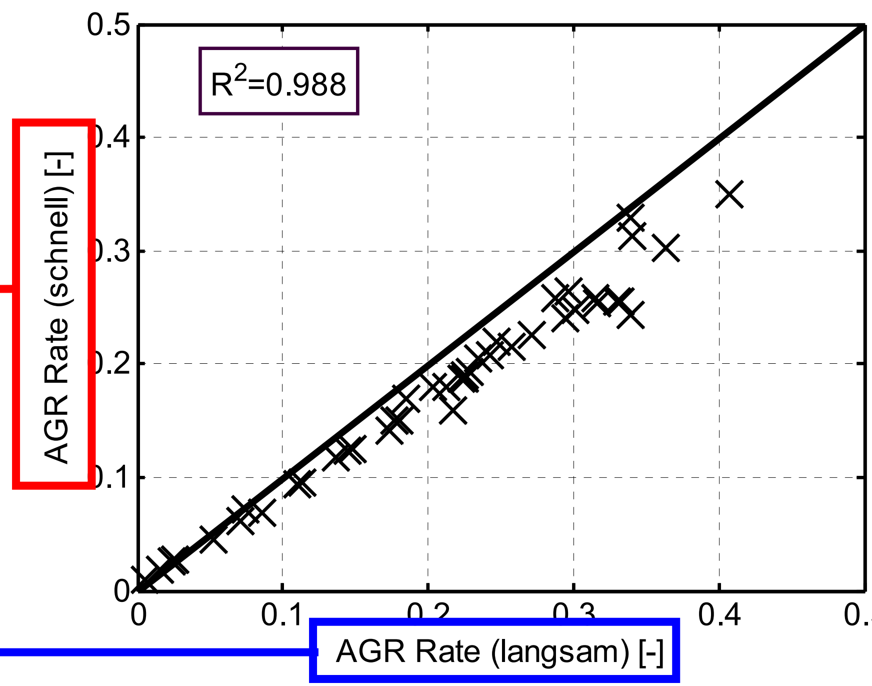




TRANSIENTE AGR – MESSUNG



- **Langsame Messung: 2x NDIR (Einlass und Auslass CO_2)**
- **Schnelle Messung: λ-Sonde und Massenspektrometer (CO_2)**
- **Validierung der schnellen AGR-Messung bei allen stationären Betriebspunkten**



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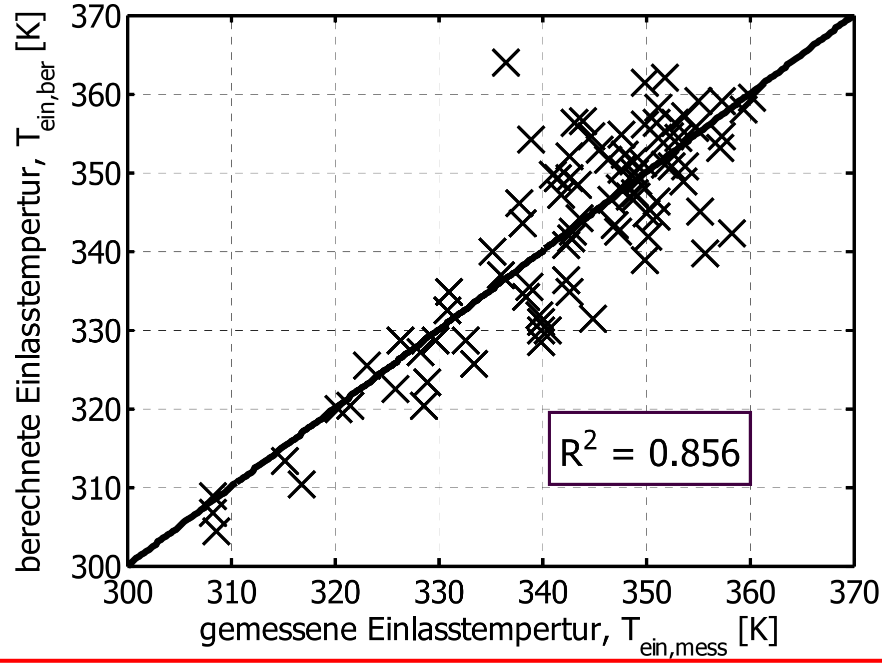
ABSCHÄTZUNG EINLASSTEMPERATUR

- **Abschätzung der Einlasstemperatur aufgrund der idealen Gas-Gleichung und AGR Rate**
- **Empirische Korrektur zur Berücksichtigung Motorbetrieb (gültig für OM611)**

$$T_{ES,ber} = \frac{p_{ES} \cdot V_{ES}}{R_m \cdot m_{Luft} \left(1 + \frac{AGR}{1+AGR}\right)} \cdot f_{Korr}\left(p_{ES}, AGR, T_{AGR}, n\right)$$



- **Ermöglicht die schnelle Beschreibung von Änderungen im thermischen Zustand**
- **Muss wegen träger AGR Temperaturmessung korrigiert werden**

$$T^{*}_{ES,ber} = \zeta \cdot T^{stat}_{ES,ber} + (1-\zeta) T^{trans}_{ES,ber}$$