

Soot Emission Measurements and Validation of a Mean Value Soot Model for Common-Rail Diesel Engines during Transient Operation

Patrick Kirchen, Peter Obrecht and Konstantinos Boulouchos
ETH Zurich

Copyright © 2009 SAE International

ABSTRACT

Measurements of the soot emissions and engine operating parameters from a diesel engine during transient operation were used to investigate the influence of transient operation on the soot emissions, as well as to validate a realtime mean value soot model (MVSM, [1]) for transient operation. To maximize the temporal resolution of the soot emission and engine parameter measurements (in particular EGR), fast instruments were used and their dynamic responses characterized and corrected. During tip-in transients, an increase in the soot emissions was observed due to a short term oxygen deficit compared to steady-state operation. No significant difference was seen between steady-state and transient operation for acceleration transients. When the MVSM was provided with inputs of sufficient temporal resolution, it was capable of reproducing the qualitative and, in part, quantitative soot emission trends. The intake charge temperature at intake valve closing was identified as an important parameter, as its consideration as a model input significantly improved the MVSM performance and it correlated with experimentally observed soot emission phenomena. The absolute influences of this temperature are not yet fully understood and are the subject of future research.

INTRODUCTION

Soot emissions from diesel engines are well known to have negative influences on human health [2–6] and the global climate [7, 8]. In light of this, the regulations governing the emission of particles from diesel engines are becoming ever more stringent. The soot emissions measured during the transient phases of the regulated driving cycles, have a substantial impact on the total cycle emissions (see [9] or [10], for example) and must thus be considered.

It is therefore desirable to operate the diesel engine with a minimum of particle and NO_x emissions. In [11] this was done using a control oriented model for NO_x and the measured relative air fuel ratio λ as a surrogate for a soot sensor or a suitable control oriented model, as neither were available (see [12], for example). In [1], a phenomenological, mean-value soot model (MVSM) suitable for realtime calculations was developed and validated for steady state operation on two engines with a total of three fuels.

In this work, transient soot measurements are used for the further development and validation of the MVSM to consider transient operation of diesel engines. The experimental methodology utilized for the transient measurements is presented, as is an analysis of the engine operating parameters and soot emission to elucidate the influences of transient operation on the soot emissions. Thus, the goals of this work can be summarized as 1) to experimentally investigate the influence of transient engine operation on soot emissions; and 2) to evaluate the ability of a Mean Values Soot Model (MVSM) [1] to calculate the soot emissions during transient engine operation.

TRANSIENT SOOT EMISSIONS From the measurement of vehicle soot emissions during driving cycles such as the New European Driving Cycle (NEDC), it has been seen that the soot emitted during transient operation has a substantial influence on the total emission over the entire cycle. To gain a detailed understanding of the soot emissions during transient engine operation, soot instrumentation capable of measuring the soot emissions with a high temporal resolution is necessary. Commercially available instruments capable of transient exhaust stream measurements are based on the differential mobility spectrometer [13], cascade impactor principle [14] [15], photoacoustic soot sensor (PASS) [16], and light extinction [17]

principles. The latter two provide the mass concentration of the soot, while the former three can also be used to obtain size information.

In [18], a Dekati Mass Monitor (cascade impactor operating principle) was used to measure the soot mass during tip-in transients of different durations. The change in the soot emissions due to the transient operation was characterized using a Quasi Steady State (QSS) approximation, with which the steady state soot emissions are estimated based on the measured engine speed and load during the transient. In general, faster transients resulted in short term spikes in the NO_x and soot emissions. The increase in NO_x emissions was attributed to an instantaneous increase in the fueling rate, coupled with a slower increase in air quantity resulting in higher in-cylinder temperatures, thereby accelerating the NO_x formation. Similarly, the soot emissions are increased due to an oxygen deficit caused by the turbo-lag and slow closing of the exhaust gas recirculation (EGR) valve. The influence of the slow EGR valve closing was also noted in [19], where a considerable decrease in the transient soot emissions was noted when the EGR valve was maintained in a closed position throughout the duration of the transient. In [18] it was also noted that as the injection pressure is rapidly increased while the charge pressure is only slowly increased, a deeper spray penetration and increased wall impingement will result, leading to increased particle emissions.

[20] used a two-color pyrometer to measure the in-cylinder soot concentration in a diesel engine operating under transient conditions. By using a representative "soot concentration weighting function" it was possible to characterize the cycle-specific soot emissions during tip-in transients. Again, an increase in the exhaust-stream soot emissions was seen and attributed to the slow response of the turbocharger and EGR valve. Furthermore, it was found that the increase in the soot emissions was fundamentally caused by poor oxidation, characterized by a strong signal after the end of injection.

EXPERIMENTAL METHODOLOGY

Measurements of the exhaust stream soot emission and engine operating parameters were used in this work for the validation of the MVSM, as well as to understand the influences of the engine operation on the soot emissions. Outlined below is an overview of the test apparatus, the methodology for the soot emission and EGR rate measurement during transient engine operation, the characterization of the dynamics of the instrumentation and a description of the considered engine transients.

ENGINE TESTBENCH The measurements were carried out on a DaimlerChrysler OM611 common rail diesel engine equipped with a variable turbine geometry tur-

Parameter	DC OM611
Number of cylinders	4
Swept volume	2.15 [l]
Compression ratio	19:1 [-]
Stroke	88.4 [mm]
Bore	88 [mm]
Number of valves	4
Engine control	EDC 15
Aspiration	VTG
EGR	High pressure, cooled
Max. injection pressure	1350 [bar]
Soot instrumentation	AVL Micro Soot Sensor

Table 1: Comparison of main specifications of the engine used for transient measurements

bocharger and high pressure EGR system [21, 22] coupled to an asynchronous dynamometer. The general specifications of the engine can be found in table 1, while a detailed description of the testbench can be found in [11]. Figure 1 shows the non-ECU instrumentation, and serves as a reference for the discussion below.

EXHAUST STREAM SOOT MEASUREMENT The exhaust stream soot (elementary carbon) mass concentration was measured using an AVL Micro Soot Sensor MSS (AVL 483) [16] and Dekati Fine Particle Sampler (FPS4000) partial flow dilution system, as shown in figure 1. Due to its response time of less than 1 s, the AVL MSS is suitable for characterization of the soot emissions during transients. So that the raw soot concentration in the exhaust stream can be determined from the diluted concentration measured by the MSS, the dilution ratio is provided from the FPS4000 software with a temporal resolution of 1 Hz.

The soot concentration measured during the transients was temporally corrected through consideration of the gas transport Δt and response times τ of the soot measurement train. This was accomplished in a similar fashion to [23, 24], with the exception that a first order response of the instruments was considered, rather than a second order. This was done to avoid additional differentiations of the measured signals, which requires considerable filtering of the raw signal. The final soot concentration signal $[EC]_{act}$ is obtained using:

$$[EC]_{act} = [\ddot{EC}]_{meas} \cdot \tau_{fps} \cdot \tau_{mss} + \dots \\ \dots [\dot{EC}]_{meas} \cdot (\tau_{fps} + \tau_{mss}) + [EC]_{meas} \quad (1)$$

where $[\ddot{EC}]_{meas}$ and $[\dot{EC}]_{meas}$ are the second and first time derivatives of the measured elementary carbon concentration signals from the MSS and τ_{fps} and τ_{mss} are the effective response times of the FPS and MSS, respectively. The delay and response time parameters given in table 2 were empirically determined such that a step

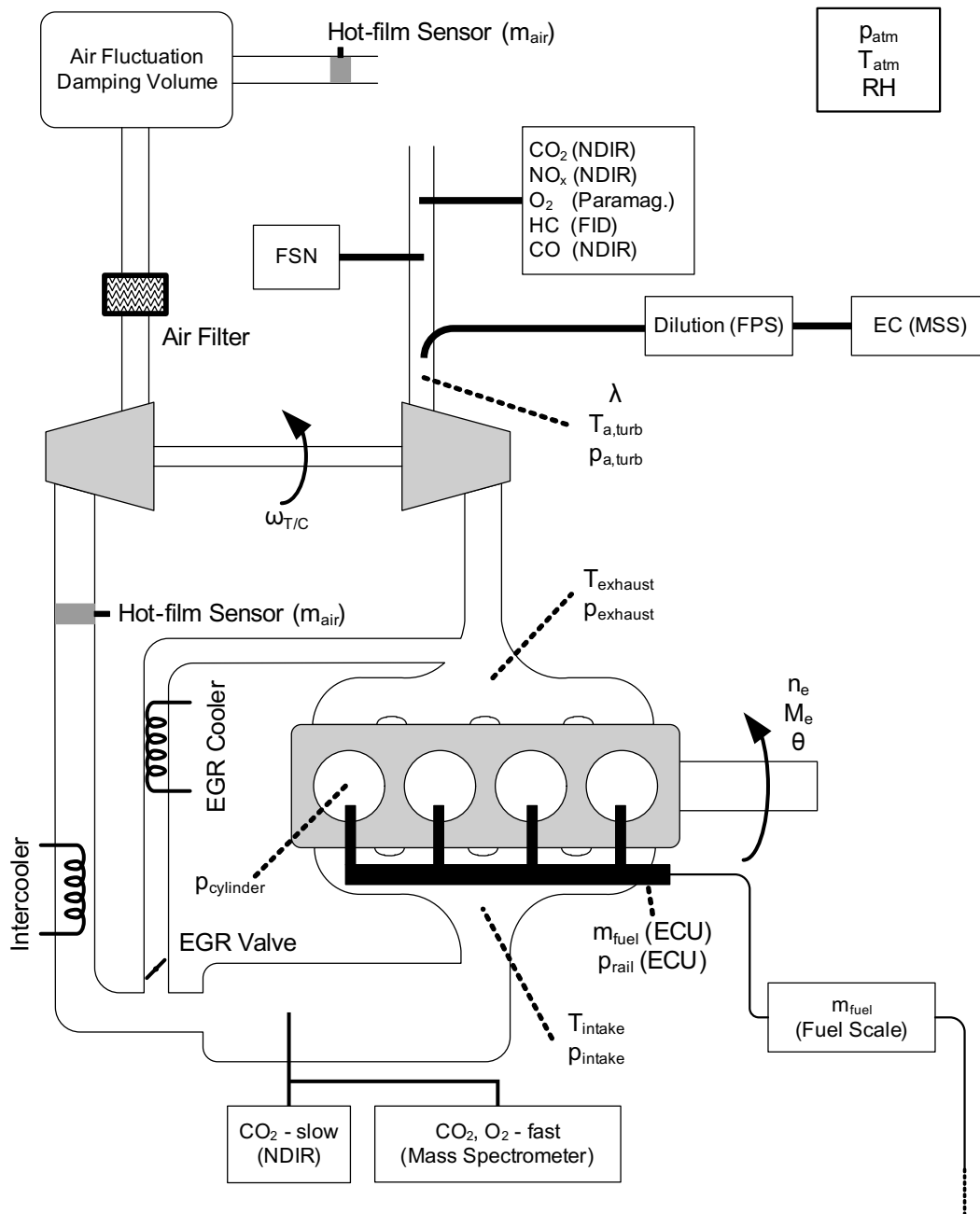


Figure 1: OM611 testbench and relevant instrumentation

τ_{fps}	0.3 s
τ_{mss}	0.5 s
Δt_{fps}	1.5 s
Δt_{mss}	0.4 s
$\Delta t_{fps-mss}$	0.6 s

Table 2: Response (τ) and gas transport (Δt) times of the soot measurement train (see equation 1)

change in soot concentration, generated by a three-way valve positioned at various locations in the soot measurement train, was adequately reproduced. It should be noted that the response times represent not the actual re-

sponse time of the instrument itself but rather an effective time scale, including the response time of the instrument and any gas mixing ("smearing" of the concentration signal).

EGR MEASUREMENT The fraction of recirculated exhaust gases (EGR) in the fresh mixture was determined through consideration of the CO_2 concentrations in the exhaust and intake streams. During steady state operation, two NDIR analyzers (Fisher-Rosemount Binos 1001) were used. However, due to their slow response and long gas transport times, an alternative method with a better temporal resolution was used for transient measurements.

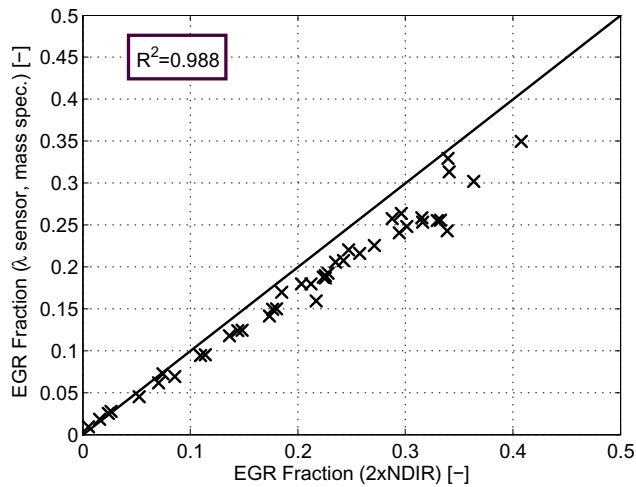


Figure 2: Comparison of the two methods for EGR rate determination. Steady state operation.

The intake CO_2 concentration was measured using a fast mass spectrometer (V&F Airsense.net) and the exhaust stream CO_2 concentration was estimated based on the measured relative air fuel ratio λ . The mole fraction of the recirculated exhaust gases in the intake stream is then:

$$X_{EGR} = \frac{n_{ex,int} \cdot A}{\lambda \alpha_{st} \cdot 4.76 + n_{ex,int} \cdot A} \quad (2)$$

$$A = n'_C + n'_H + \lambda \alpha_{st} \cdot 3.76 + (\lambda - 1) \alpha_{st}$$

where $n_{ex,int}$ is the number of moles of exhaust gas in the intake stream per mole of injected fuel, α_{st} is the stoichiometric number of moles of oxygen per mole of fuel and:

$$n'_C = X_c \cdot \frac{M_f}{M_C} \quad (3)$$

$$n'_H = X_H \cdot \frac{M_f}{M_H} \quad (4)$$

where M_f , M_C , and M_H are the molar masses of the fuel¹, carbon and hydrogen, respectively. The number of moles of exhaust in the intake stream can be determined using:

$$n_{ex,int} = \frac{X_{\text{CO}_2,int} \cdot \lambda \alpha_{st} \cdot 4.76}{1 - X_{\text{CO}_2,int} \cdot (n'_C + n'_H + \lambda \alpha_{st} \cdot 3.76 + (\lambda - 1) \alpha_{st})} \quad (5)$$

where the mole fraction of CO_2 in the intake $X_{\text{CO}_2,int}$ is measured directly by the mass spectrometer.

Shown in figure 2 is an operating point specific comparison of the EGR fractions measured using the two different methods (i.e. 2 NDIRs; and λ -sensor and mass spectrometer) during steady state operation. A good agreement between the two methods can be seen, indicating that the mass spectrometer and λ -sensor can be used to measure the EGR rate during steady-state operation. Thus,

¹The molar mass of the fuel is assumed to be 170 g/mol [25]

it is assumed that this method is also valid for transient measurements, given that the dynamic response of the sensors and gas transport times are accounted for.

CONSIDERED TRANSIENTS Acceleration and tip-in transients were investigated in this investigation, as they were considered to be of relevance for soot emissions and still representative of driving cycle transients and are defined as follows:

Acceleration During an acceleration transient, the engine speed is linearly increased while the engine load is held constant. The duration of an acceleration transient is defined by the dynamics of the vehicle.

Tip-in During a tip-in transient, the engine load (gas pedal position) is linearly increased while the engine speed is held constant. The duration of the tip-in transient can be arbitrarily defined but is usually considered to be in the region of 0 to 10 s [18].

The acceleration durations were determined through the consideration of the vehicle dynamics described using:

$$\frac{du_v}{dt} = \frac{-\frac{1}{2}C_d\rho_a A - C_r m_v g + M_e R_{trans,i} R_{diff} r_w}{m_v} \quad (6)$$

$$\omega(t) = \frac{30u_v(t) R_{diff} R_{trans,i}}{\pi r_w m_v} \quad (7)$$

where u_v is the vehicle speed, m_v is the mass of the vehicle, C_d is the aerodynamic drag coefficient, A is the frontal surface area of the vehicle, C_r is the rolling resistance coefficient, ω is the engine speed, $R_{trans,i}$ and R_{diff} are the transmission ratios of the i^{th} gear and the differential respectively, and r_w is the radius of the wheel. From this model the duration for an acceleration from 1250 rpm to 3000 rpm at $BMEP = 8$ bar were determined and are listed in table 3.

It should be noted that real-world transients include simultaneous changes of engine speed and load. This investigation considers the parameters separately so that their individual influences on the soot emissions can be identified.

To maximize the repeatability of the measurements, the engine was conditioned prior to the transient measurements. This included running the engine at a reference point (3000 rpm, 8 bar $BMEP$) until the exhaust temperature was stable [26], followed by five repetitions of the fastest acceleration transient to dislodge any additional soot deposits in the exhaust system. After the preconditioning program, each transient was measured five times so that the variability in the measurements could be determined.

	Engine Speed [rpm]	<i>BMEP</i> [bar]	Transient duration [s]
Acceleration	1250→3000	8	2.29 (1 st gear)
	1250→3000	8	7.60 (2 nd gear)
	1250→3000	8	21.9 (3 rd gear)
Tip-In	1250	2→8	0.5, 1.0, 2.0, 5.0
	2000	2→8	0.5, 1.0, 2.0, 5.0

Table 3: Specifications of the investigated acceleration and tip-in transients.

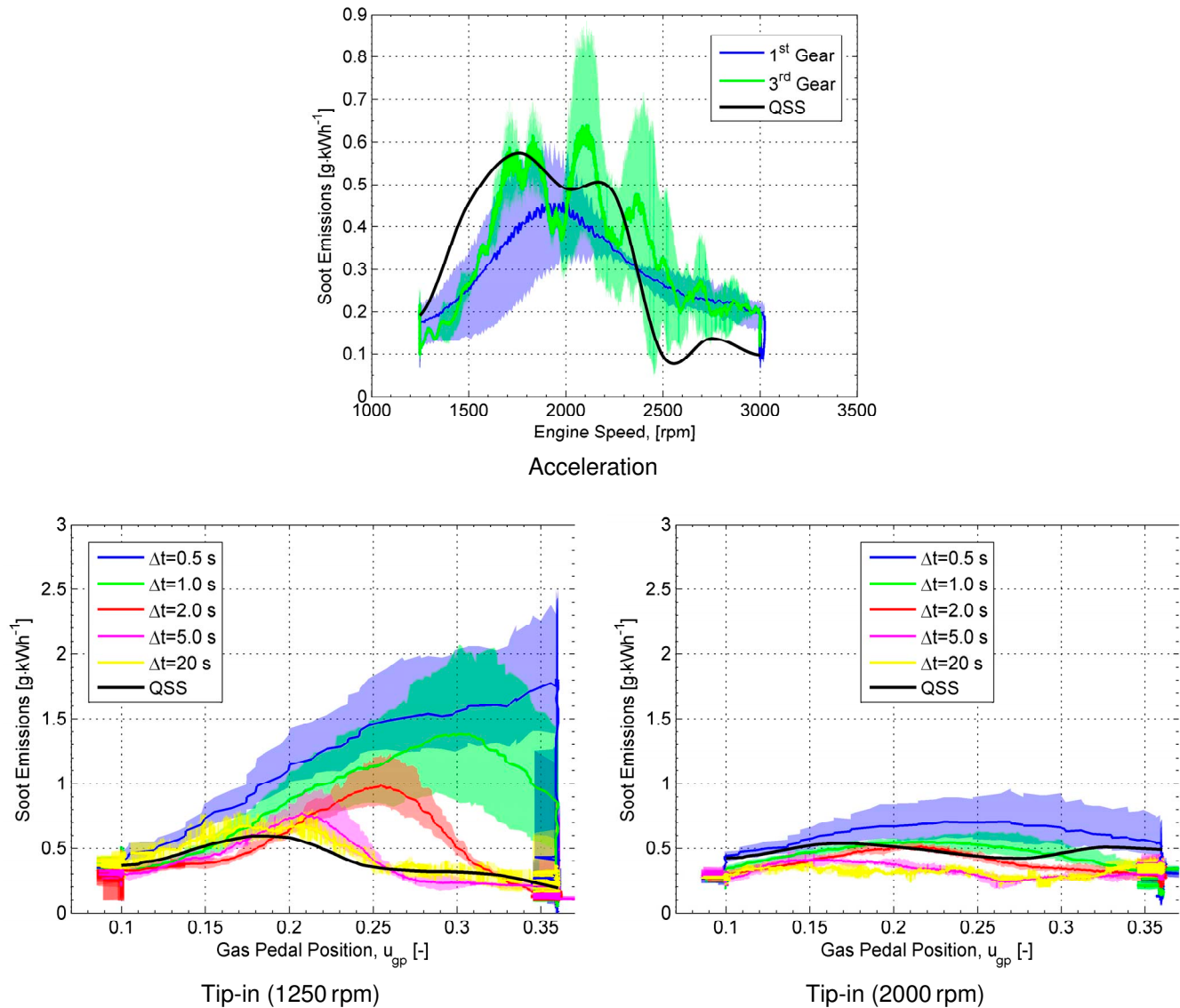


Figure 3: Measured exhaust stream soot emissions during acceleration (top) and tip-in (bottom) transients of different durations. Lines indicate the mean of five measurement repetitions for each transient, while the shaded areas are bounded by the maximum and minimum measured soot emissions.

EXPERIMENTAL RESULTS

The soot emissions and engine parameters measured during transient operation were compared to their respective steady state values determined using a Quasi Steady

State Approximation (QSS), which provides an estimate of the corresponding steady state-value on the basis of the engine speed ω and load *BMEP* during the transient [18], i.e.:

$$QSS = f(\omega, BMEP)$$


Documents
 Document Sharing Hub