

Experimental Investigations of a DISI Engine in Transient Operation with Regard to Particle and Gaseous Engine-out Emissions

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ABSTRACT

The investigation of transient engine operation plays a key role of the future challenges for individual mobility in terms of real driving emissions (RDE). A fundamental investigation of the transient engine operation requires the simultaneous application of measurement technologies for an integrated study of mixture formation, combustion process and emission formation. The major prerequisite is the combustion cycle and crank angle resolved analysis of the process for at least several individual consecutive combustion cycles during transient operation.

The investigations are performed with a multi cylinder DISI engine at an Engine-in-the-Loop test bench, able to operate the engine in driving cycles as well as within target profiles (e.g. speed and torque profiles). The research project describes the methodology of analyzing elementary transient operational phases, (e.g. different variants of load steps). The aim is to visualize the detailed influences of engine parameters on individual consecutive combustion cycles during transient operation.

For the integrated analysis, several state of the art measurement technologies like fast response emission analyzers (HC, CO, CO₂ and NO) and fast particle emission analyzer (number and size distribution) are supplemented by the simultaneous use of optical diagnostic methods. For this reason a high-speed camera setup is used to visualize the fuel injection process as well as the resulting soot luminosity of the following combustion during transient operation. At the same time a special fiber optical spark plug is used to characterize the local lambda value at the spark plug as an indicator for the mixture homogenization and for the evaluation of the in-cylinder conditions prior to spark timing.

KEYWORDS: Transient engine operation, load step, particle emissions, gaseous engine-out emissions, optical diagnostics, combustion chamber local lambda value, differential quotient of lambda value

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INTRODUCTION

No general terminology is provided to give a distinct definition of transient operation but several interpretations are used to deal with it.

One possible approach to classify the transient operation is to consider the temporal influences of engine parameters and their impact on the engine process. This is the basic approach for the classification described in Figure 1 [1]. This means that four different orders of transient operation are to be distinguished. The first

transient order is the four-stroke engine process itself. Due to the fact of the open process control (gas exchange) and the cyclic irregularity, even the steady-state operation of an engine in this terminology is a transient process. The second order process describes all influences given by the request of engine's parameter changes requested by the driver. This exemplarily contains the demand for vehicle acceleration which induces a load-step of the internal combustion engine. Changes in engine speed due to gear shifting or deceleration are also elements of second order processes. Thus the second order is describing what is usually known as the transient processes of driving cycles.

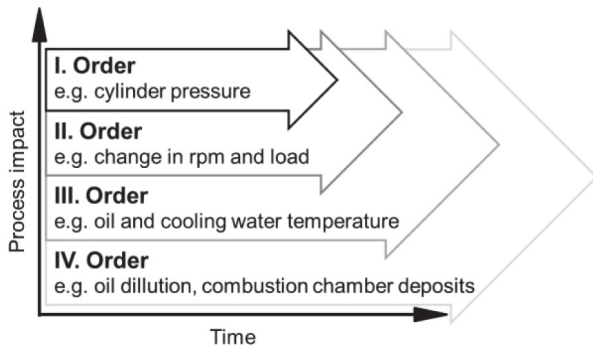


Figure 1. Classification of transient engine operation [1]

The higher transient orders superimpose all lower transient orders. For example, the third order describes the engine's temperature developments, such as surface temperature of the combustion chamber, cooling water or oil circuit temperature. The development of the third order is finally a result of changes within the lower transient orders. Fourth order impacts refer to long-term changes in engine operation e.g. due to oil dilution or injector tip fouling.

The terminology in Figure 1 is suitable to classify the impact and the temporary development of engine processes. This criterion describes the results of an engine with fixed hard- and software setups. The second necessary description to deal with the term transient operation classifies the possible strategies to influence transient operation. Four different strategies have to be considered (see Figure 2).

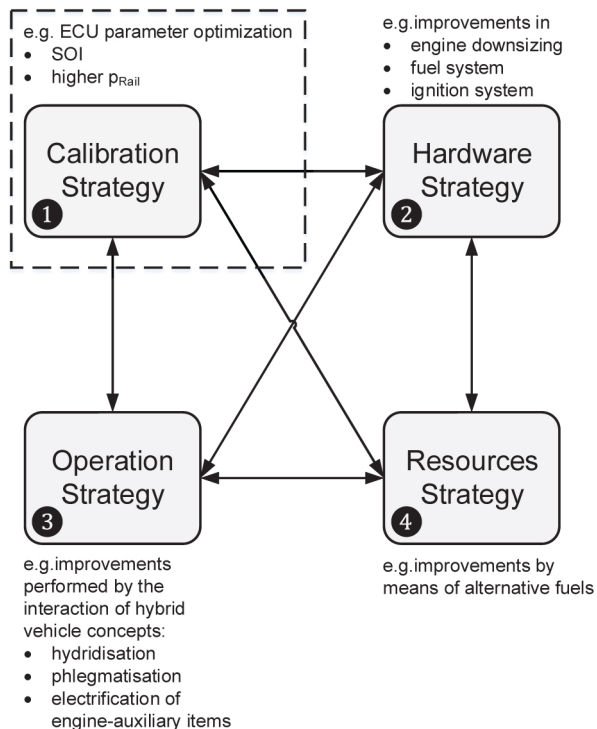


Figure 2. Strategies to improve transient engine operation

The first one describes all possibilities gained from a modified ECU setup and is therefore called ECU calibration strategy. In the context of a DISI engine this relates to changes of process parameters e.g. SOI and is discussed in the results section of this paper. The second one concerns the variations and improvements caused by changes in the hardware setup. These two strategies have strong interrelationships. For example, the opportunities of different engine calibration parameters are restricted to the used engine hardware components. In the case of a DISI engine, the injection system used and its application is limiting the injection calibration as well. The third and fourth strategies follow the potential of an advanced engine operation strategy and the enhancements given by alternative fuels (resources strategy). The engine operation strategy has a great potential considering the possibilities to operate the engine in another manner, e.g. within a hybrid electric vehicle. One possible solution is the phlegmatisation of the engine during emission critical driving maneuvers. The potential to reduce particle number concentrations during a load step for a gasoline engine in a hybrid concept is discussed in [2]. Different strategies to shape the engine torque development within the very first second of a load step have shown that the particle number concentrations can be reduced by more than 50%. The lower torque within this short term torque shaping was compensated by the virtually simulated electrified powertrain on the Engine-in-the-Loop test bed. The results have been performed with a constant calibration setup and show the potential of an unchanged ECU setup within this strategy. The resources strategy takes into account to use another energy resource such as alternative fuels or designer fuels with better emission related properties (e.g. less aromatics) [3,4,5].

MOTIVATION

The motivation for this technical paper is to demonstrate the potential of analyzing transient engine operation up to combustion cycle and crank angle resolved resolution. For this reason the simultaneous application of fast response emission analyzers and optical measurement systems is used. Previous results of entire test runs have shown that acceleration phases have a great potential for improvements of engine-out emissions, different load step variations have been investigated in context of

- gaseous engine-out emissions
- particle emissions
- mixture formation processes

related to the question:

- *How do individual combustion cycles possibly influence the emissions results of an entire test run?*

REQUIREMENTS FOR ENGINE TESTING IN TRANSIENT OPERATION

In contrast to steady-state engine operation, the transient operation requires a measurement setup which allows to consistently investigate the engine related sub-processes: gas exchange, combustion process and the emissions formation/reduction. For this

reason the used test bed setup should be able to analyze the processes with highest temporal resolution (up to crank angle resolution) for hundreds of consecutive combustion cycles. Additionally it is important that a synchronization of the measurement equipment in the millisecond range is ensured.

EXPERIMENTAL SETUP

Following the idea to transfer maneuvers of real world driving cycle into a laboratory environment, a customized EiL setup is applied. The EiL test bed ensures reliable investigations with highest reproducibility and repeatability. The multi-cylinder engine used, is characterized by the technical data shown in [Table 1](#).

Table 1. Technical data of the multi-cylinder test engine

Engine Data	Unit	
Type		Gasoline
Cylinder		Six in-line
Displacement (total)	V_H	2979 cc
Max. engine power	P_{max}	225 kW @ 5800 rpm
Max. engine torque	Md_{max}	400 Nm @ 1200 rpm
Compression ratio	ϵ	10.2 : 1
Valve timing		Variable
Charging system		Turbocharger
Fuel		RON98
Fuel injection nozzle		Bosch HDEV 5.2
Combustion mode		Homogeneous
Engine Control		Bosch MEVD 17
Emission certification		Euro V

To ensure a continuous process analysis for at least one individual cylinder, the special measurement technologies are arranged at cylinder six. The injected fuel mass per stroke is measured with a fuel meter (AVL STS PLU 131). For this reason the fuel pipe supplement between the high pressure rail and the fuel injector of cylinder six is separated and the fuel meter is integrated. The measured fuel mass per stroke therefore exclusively refers to cylinder six. By focusing on the analysis of engine-out emissions several exhaust gas supply arrangements are used. For the results presented in this paper the fast response emission analyzers are prepared in a way that one of the two sampling lines is arranged close to the exhaust valves of cylinder six and the second sampling line is placed after the turbocharger. The three fast response systems together (Cambustion NDIR500, CLD500 and HFR500) are able to analyze the CO, CO₂, NO and HC emissions combustion cycle resolved within the investigated engine speed range [6]. The simultaneous application of the different analyzers furthermore allows calculating the combustion cycle resolved emission-based lambda value. For this case it is important that the fast response emission analyzers are supplied with the same exhaust gas composition, otherwise the lambda value is possibly influenced by the fluctuations within the exhaust gas composition when different

sampling pipes and different arrangements are used. For this reason a major sampling pipe is placed at the exhaust port of cylinder six. The entry into the pipe is located very close to the exhaust valves. The advantage of this arrangement is that the emissions measured, belong without restriction to the combustion processes of cylinder six and all analyzers are supplied with the identical exhaust gas composition. In this way the interaction with other cylinders and the uncertainties caused by inhomogeneous exhaust gas composition within the exhaust port is therefore reduced to a minimum.

In addition, the major sampling pipe prepared in the exhaust port of cylinder six is also used for the exhaust gas supply of the particle size spectrometer (Transient Engine Particle Analyzer, Cambustion DMS500 MkII) [7]. The system is capable to measure the particle number concentrations, the particle size, and the size distribution (range 5 nm to 1 µm). With the aim to get highest temporal resolution, the particle spectrometer is operated with the highest possible measurement frequency of 10 Hz. Although it is not sufficient to record cycle-to-cycle changes, it allows identifying and characterizing particle emission peaks within transient operation.

In addition to the fuel measurement system and the emission analyzers, cylinder six is also equipped with optical diagnostics systems. This enables the temporal resolution of measurements up to the crank angle range and supports an identification of local effects inside the combustion chamber. The high-speed camera setup consisting of a CMOS high-speed camera (LaVision, HSS6), a high-speed controller and an endoscope (visible light range, Ø = 8 mm) is used to record the Mie-scattering signal of the injected fuel and the soot luminosity during the combustion process. For the illumination of the injected fuel, the laser beam of a cw-laser ($\lambda = 532$ nm) is coupled by a fiber optic system within a second optical access in the cylinder head. Both, the illumination access and the detection access are adapted in the cylinder head between the intake valves and exhaust valves (in gear box direction).

The previously discussed systems are capable to give information about the results of the combustion process but are limited in their ability to uncover previous developments which may refer to the emergence of emissions. Relating to the aspect of analyzing engine-out emissions of a DISI engine with a variable valve train and a turbocharger as detailed as possible, the information on the combustion chamber lambda value is of particular interest. For this reason a fiber optical spark plug (LaVision ICOS) is applied for crank angle resolved determination of the local lambda value. The measurement principle of the spark plug is based on the property of fuel molecules to absorb light in the infrared wavelength range. A description of the system can be found in the work of Berg et al. [8].

The arrangement of the most important measurement systems at the test bed is schematically visualized in [Figure 3](#).

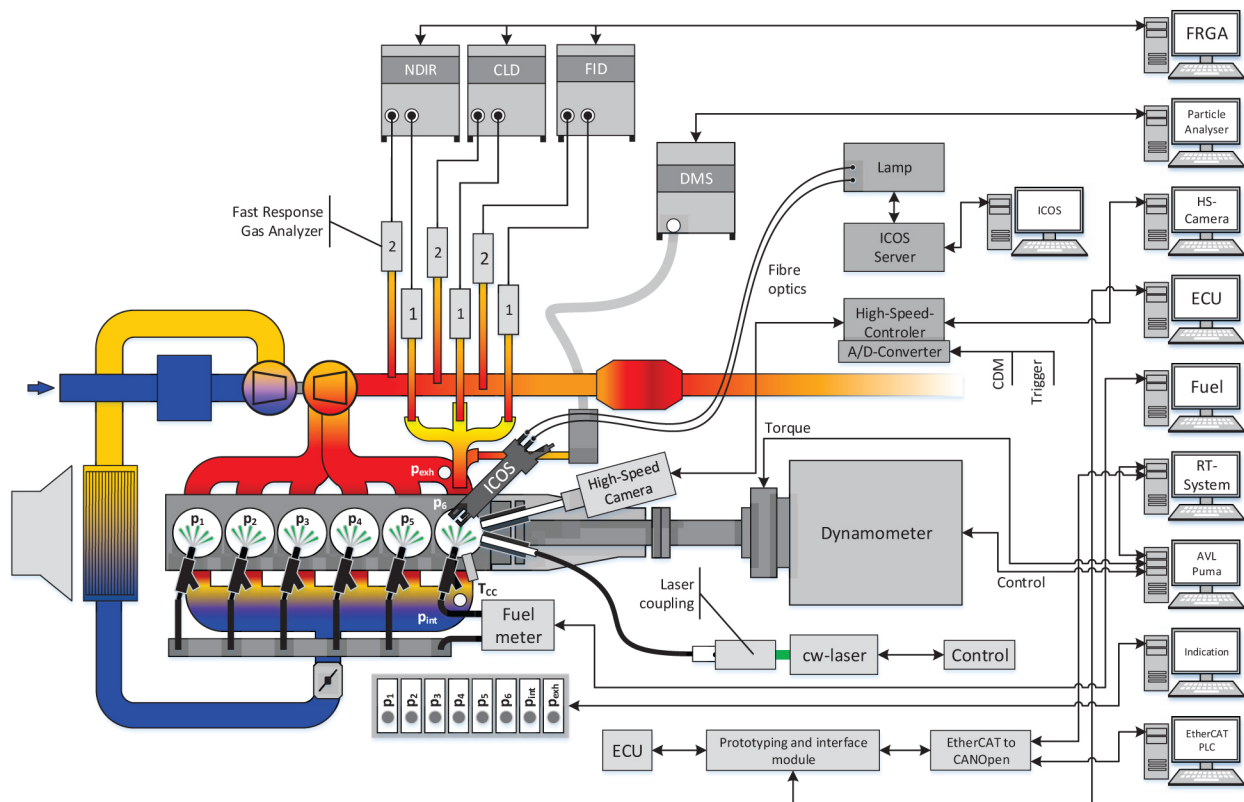


Figure 3. Schematic description of the arrangement of measurement systems at the Engine-in-the-Loop test bed

Investigated Transient Processes

It is well-known that most of the PN emissions in driving cycles apart from engine start and warmup are detected directly at the beginning and during acceleration phases [9,10]. The transfer of a virtual acceleration on the engine test bed goes along with a load step demand. In this case two different conditions prior of a positive load step (acceleration) have to be distinguished: tip-in and load to load condition.

Tip-In

The tip-in is a positive load step beginning in motored operation followed by the demand of a higher engine load with the shortest possible delay. This is an emission critical maneuver due to the previous cooled down conditions of the combustion chamber surfaces during motored operation. In combination with the demand for a high engine load, this means that wall wetting impacts have a strong effect on the occurrence of partially non-premixed combustion areas during the initial combustion cycles after the beginning of fired operation (injection release).

Load-Load

The load step from a comparatively lower load level is not as critical as the tip-in maneuver, due to the higher surface temperature level at the beginning of the load step. Nevertheless, it is also a maneuver with high engine-out emissions. In the work of Köpple et al. [11] it is visualized by using instantaneous surface temperature measurements, that the piston temperature during a direct load step (fuel injected mass reaches steady-state values after ~ 10 combustion cycles) from

IMEP = 0.2 MPa to IMEP = 0.8 MPa (rpm = 2000 = const.) is still rising even 100 seconds after the load step demand. This confirms the superposed orders of transient engine operation discussed and visualized in Figure 1. The optical analysis of the soot luminosity has furthermore shown that a large amount of the injected fuel at the beginning and during the load step is deposited on the piston surface. In combination with the lower temperature level at the piston surface, the fuel isn't totally evaporated prior to spark timing. This finally leads e.g. to a partially strong diffusive combustion at the piston surface (poolfire). With increasing piston temperature in the subsequent combustion cycles this effect becomes less severe. A difference of just 30 K in the piston surface temperature prior to ignition between combustion cycles with significant soot luminosity and the combustion cycles with comparatively lower soot luminosity confirms the sensitivity of this relationship. The results in the work of Köpple et al. [11] also show that the start of injection has a strong impact on the particle number concentration. The earlier the injection, the higher the particle number concentration during the load step is.

EXPERIMENTAL RESULTS

The analysis of real world driving cycles has revealed that the engine speed during the initial combustion cycles of a load step is only slightly changing. For this reason the engine speed is kept constant for all the load step variations. In this way a possible influence of a changing engine speed and related changes in the in-cylinder flow field during the test runs are excluded.

Given the continuously changing conditions from cycle-to-cycle a statistical analysis of combustion cycles in transient operation is challenging. Within this project the test runs of the load step variations are performed as shown in Figure 4. Every test run consists of twelve load steps. At the beginning of the test run, the engine speed is increased to the applied value before a reference load step is performed for engine warmup. The engine is generally forced by external conditioning systems so that the cooling water and engine oil circuit has all the time constant warm conditions ($T = 85^{\circ}\text{C}$). The reference load step is implemented to additionally heat up the exhaust system, ensuring that temperature drifts from test run to test run can be reduced to a minimum. The major part of interest is the analysis of the load steps lettered with one (ls1) to ten (ls10). This is the basis for the analysis of the test runs.

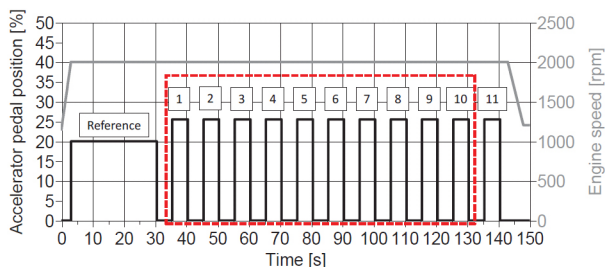


Figure 4. Definition of the test run scheduling

The monitoring of the engine's temperature condition at the beginning of the load step is realized with a modified NiCrNi thermocouple (T_{cc}) placed in the third combustion chamber access (between the two intake valves). The tip of the thermocouple is positioned flush with the wall of the access and therefore assumed to be representative for the temperature of the cylinder head at this individual point. To improve the transient response, the tip of the thermocouple was mechanically recapped, so that the measurement point is exposed to the engine's combustion process. For this reason it is quite difficult to isolate the solely surface temperature development due to the influences caused by the direct contact of the gas. In this context, the signal of the thermocouple is exclusively used to precisely monitor the conditions prior to every load step.

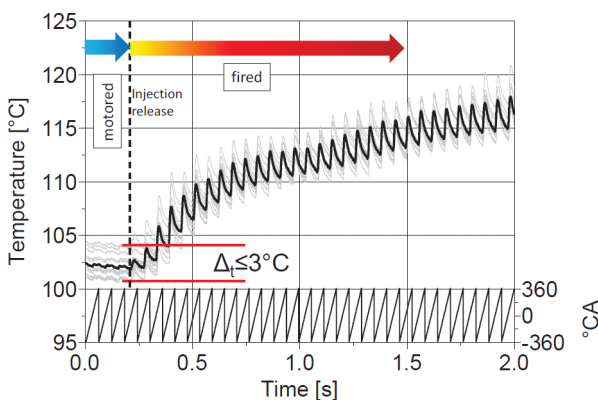


Figure 5. Temperature fluctuations from load step to load step measured with a modified NiCrNi thermocouple at the cylinder head

Figure 5 shows the temperature developments of the ten individual load steps (gray) for 1.75 seconds after injection release. The black graph refers to the averaged data of the temperature. In the very first combustion cycles, the temperature fluctuations are smaller than 3°C from load step to load step.

After the test runs, the individual combustion cycles of every load step are sorted consistently. This finally ensures that for every stage of the load step, ten combustion cycles are taken into account. Using the test runs as defined in Figure 4, the influences of different engine speeds as well as an increasing fuel injection pressure is analyzed in combination with different injection timings (SOI=start of injection). In the following Table 2 the variations are described in detail.

Table 2. Test run operating conditions

	Engine speed	P_{Rail}	SOI_{xxx}	Load 1	Load 2 (IMEPn)
No.	[rpm]	[MPa]	$^{\circ}\text{CA b. TDCf}$	[MPa]	[MPa]
1	2000	Map-based (7.5 to 13)	340	mot.	0.6
2			300	mot.	0.6
3			260	mot.	0.6
4			220	mot.	0.6
5		19.5	300	mot.	0.6
6			260	mot.	0.6
7			220	mot.	0.6
8	2500	19.5	300	mot.	0.6
9	3000	19.5	300	mot.	0.6

All the test runs are performed with an accelerator pedal increase of 25.5 % within one millisecond.

Particle Emissions

Influence SoI ↔ Particle Emissions

The effects of a SOI variation for a DISI engine, operated in steady-state conditions, are well known. However, only a few investigations have been published, focusing on the load step situations within the transient operation [12,13]. For this reason the following results focus on the transient part of the load step and are additionally compared to the conditions followed in a steady-state operation.

The results presented in Figure 6 visualize the influence of the injection timing (SOI) on the particle number concentration [$\text{dN}/\text{dlog Dp}/\text{cc}$] for load steps (tip-in) of IMEP = 0.6 MPa. Although the system is placed as close as possible to the exhaust valves of cylinder six, it is obvious that a delay time of approximately 0.4 seconds has to be considered when interpreting the results. Four different injection timings are performed at a constant engine speed of 2000 rpm (test run no. 1 to 4). The earliest injection timing of $340^{\circ}\text{CA b. TDCf}$ (referred to as SOI_{340}) is only of interest for research purposes and has less relevance for series production applications. The SOI_{300} and SOI_{260} represent an usual range for series applications and the fourth variation of SOI_{220} demonstrates the potential and consequences of a comparatively late injection timing. Due to the fact of the cycle-to-cycle

cycle fluctuations in dynamic operation, the data is visualized as an average result of ten consecutive load steps (referred to Figure 4). Focusing on differences between steady-state and transient operation, two time ranges are of particular interest: The first period is the very first second after exhaust gas has entered the particle size spectrometer. This period describes so far the conditions of the highly dynamic transient operation phase (during the load step). Considering differences of the following steady-state operation the second part of interest is defined and discussed as the time range between 2 s to 5 s.

The particle size distribution for SOI_{340} shows that two remarkable particle size regions with comparatively high particle number concentrations are detected: One is found in the smallest diameter region of about 5 nm to 11 nm (see Figure 6 ①) and the second one has a diameter range between 100 nm up to 300 nm (see Figure 6 ②). In contrast to the particle number concentration with later injection timings, SOI_{340} shows only very few differences between the transient part and the steady-state part. The optical investigations have confirmed that this operating point leads to an expected strong piston wetting, resulting in large proportions of diffusive combustion on the piston surface in the late expansion stroke. For this reason it is expected that the PN emissions are mainly caused by this fuel-surface interaction. A detailed look at the total PN emissions revealed that at the beginning a small peak can be detected whereas the PN concentration is slightly decreasing during the steady-state part of the load step profile.

Retarding SOI by 40°CA to SOI_{300} leads to a remarkable reduction of particle number concentrations in both, the transient part as well as in the steady-state part of the load step. Looking at the transient part, it is interesting to see, that the initial combustion cycles within the very first half second after injection release, have lower particle number concentrations than the following combustion cycles. A possible explanation for this phenomenon is the aspect that the fuel mass injected is still increasing due to the increasing torque demand from cycle-to-cycle within this initial part of the load step. This goes along with two simultaneous effects: The first one is that the lower injected mass results in less piston wetting compared to conditions at higher engine load with higher injected fuel mass. And furthermore, if less fuel interacts with the piston, the resulting fuel layer on the piston surface is possibly thinner so that the evaporation process could be still fast enough to vapor the fuel on the piston, prior to spark timing. Another helpful aspect in this time period is the lower injection pressure of the map-based application. This leads to a reduced spray penetration length and is therefore an additional feature to reduce piston wetting in the transient part of the load step.

The results of SOI_{260} show that the particle number concentrations in the transient part are further reduced. But after $t = 2$ s the particle number concentrations increase rapidly over a wide particle diameter range. This behavior is related to a change in the control of the variable valve train during this test run.

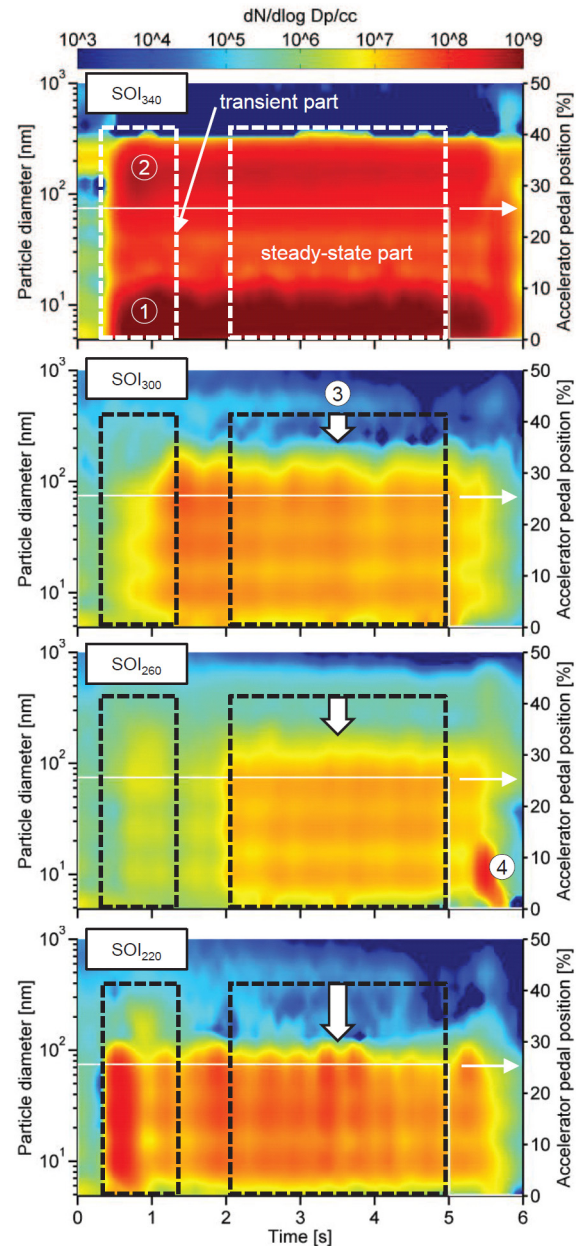


Figure 6. Particle number concentrations as average results of ten load steps at a constant engine speed of 2000 rpm, varied with four different SOI (test run no. 1 - 4)

The result for SOI_{220} shows that, compared to the results with an SOI_{260} and SOI_{300} , the particle number concentrations are increasing in both, the transient part as well as in the steady-state part. In this case two effects have to be considered. A possible explanation is given by the optical indication. Within the transient part, at the beginning of the load step, a spark plug wetting leads to a diffusive flame in this area. In following combustion cycles the spark plug heats up rapidly, so that this effect becomes more and more insignificant. The fluctuations detected in steady-state operation are rather caused by a poor homogenization than by surface wetting effects.