

Soot and NO_x Reduction by Spatially Separated Pilot Injection

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ABSTRACT

To this day, Diesel engines with direct injection are the most efficient internal combustion engines for passenger cars. The major challenge of these engines with a conventional Diesel combustion process is the high level of particulate matter and nitrogen oxide emissions. Diesel engines in passenger cars normally use a pilot injection strategy for NVH reasons, which influences the engine-out soot emissions negatively. The Diesel fuel of the pilot injection is still burning when the main injection takes place, so, liquid components of the main injection interact with the flame of the pilot injection. The time for mixture formation decreases and the combustion takes place under locally very rich conditions which results in high levels of soot formation. For this reason new emission level restrictions cannot be reached without modern exhaust gas aftertreatment systems, which are quite expensive and can have an impact on the gas exchange. So, a reduction of both soot and nitrogen oxide emissions by in-cylinder methods without any penalty to efficiency is favorable. The present paper describes a new injection strategy for Diesel engines. The pilot injection is spatially separated into the combustion chamber. So, the main injection does not interact with a still burning pilot injection flame. First investigations of this new injection strategy have shown a reduction of soot with persisting nitrogen oxide emissions, so, the trade-off between both emission types is optimized. Additionally a significantly improved tolerance of EGR allows further reduction of nitrogen oxide emissions. Soot formation and oxidation process at the new injection strategy is analyzed by 2-color-measurements.

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INTRODUCTION

Fossil fuel resources which are carried out to produce gasoline and diesel fuel are limited. For this reason and with regard to existing CO₂-induced global warming the primary focus in research and development should be directed towards the use of advanced engine technologies with very low fuel consumption and even lower pollutant emissions. The importance of such measures increases when taking into account the rapidly growing individual mobility in countries with high populations like China and India. During the last two decades, dust and particulate emissions have been reduced through a number of different measures. The influence of different particulates in the atmosphere is very complex and different processes concerning climatic phenomena interact strongly with each other. As an important consequence of these very complex atmospheric phenomena, the CO₂ emissions and thus the climate changing potential of fossil fuels should not be discounted. Hence, all measures to further reduce pollutant emissions should be put under the premise of technical solutions with optimal efficiency to expend the lowest possible amount of primary energy [1].

Diesel engines with direct fuel injection remain a very good option for high efficiency propulsion systems in mobile applications for the individual mobility. Increasingly stringent emissions regulations, especially for soot and NO_x emissions, which are primarily due to environmental and health risks, are ambitious challenges for engine manufacturers. Conventional Diesel engines offer high thermal efficiencies and therefore will play a key role for reducing fuel consumption. However, a major drawback of these engines is the relatively high soot and NO_x emission level that result from the direct fuel injection and the following combustion process. The combustion in conventional Diesel engines leads to a very heterogeneous mixture with locally rich, stoichiometric and lean areas. This mixture simultaneously causes soot because of the rich areas and NO_x because of high burning temperature zones (Zeldovich mechanism) in stoichiometric regions. Utilizing conventional methods, both emission components cannot be reduced at the same time which is well known as the soot-NO_x-trade-off [2].

SOOT FORMATION AND OXIDATION PROCESS

In modern Diesel engines with direct fuel injection, the injection process itself is in addition to the main injection often extended to multiple pilot and post injections. The pilot injection is needed for noise reduction due to Diesel knock and an early post injection is applied for better soot oxidation reasons [3]. Usually these part injections are all performed with the same injector which is mounted centrally into the cylinder head. Therefore the fuel of all part injections is injected into the same regions of the combustion chamber. Hence, a strong interaction between the temporally separated part injections and the resulting combustion conditions is evident. With a small amount of fuel injected before the main injection, significant reductions of combustion noise can be achieved when compared to engine operation without pilot injection. The fuel of the pilot injection starts to burn before the main injection takes place and increases the temperature in the combustion chamber. The ignition delay of fuel in Diesel engines with direct injection depends strongly on the temperature in the combustion chamber. With the pre-conditioned combustion chamber the ignition delay for the main injection decreases, so, the premixed part of the combustion decreases as well and the diffusion-controlled part increases. Consequently, the maximum pressure gradient and peak temperatures during the combustion decrease, which leads to decreases in both the engine noise and the formation of nitrogen oxides. Unfortunately, the larger fraction of diffusion-controlled combustion leads to higher soot emissions. This becomes even more apparent with an increasing amount of pre-injected fuel and the accompanying disproportionate increase in the soot emissions. Not only the larger part of diffusion-controlled combustion, but also several other parameters are responsible for the higher soot emissions. Local air-fuel-ratios for the fuel injected during the main injection are reduced due to the already-burned pilot fuel, which both increases the soot formation and decreases the soot oxidation during the combustion. Additionally, a direct contact of injected liquid fuel with the still-burning pilot fuel can take place and lead to an intense soot formation [1]. This leads to poor homogenization of the main injection and therefore to very rich areas which result in high soot emissions. As can be seen in [figure 1](#), soot formation increases very strongly at local relative air-fuel-ratios below 0.5.

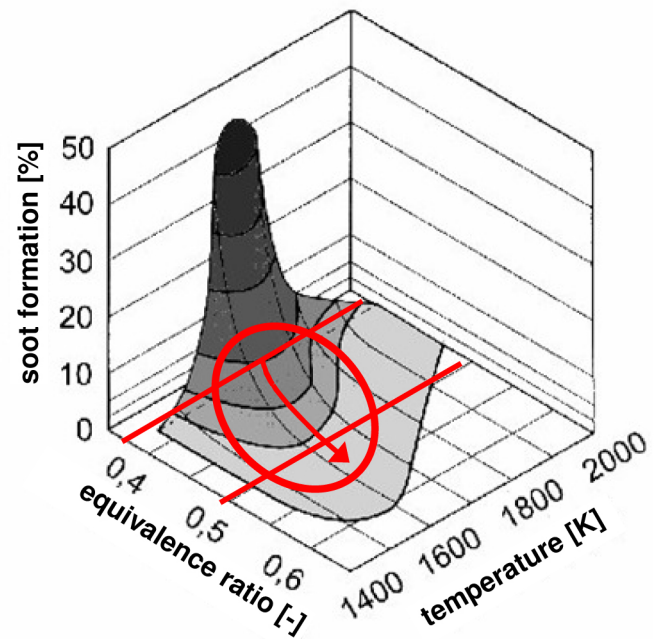


Figure 1. Soot formation dependent on air-fuel-ratio and temperature [8]

The soot concentration in a cylinder is the difference between soot formation and soot oxidation. The progression during combustion is shown in [figure 2](#). The whole progress is divided into a first net soot formation phase, during which the in-cylinder soot concentration increases, and afterwards two net soot oxidation phases with decreasing in-cylinder soot concentration.

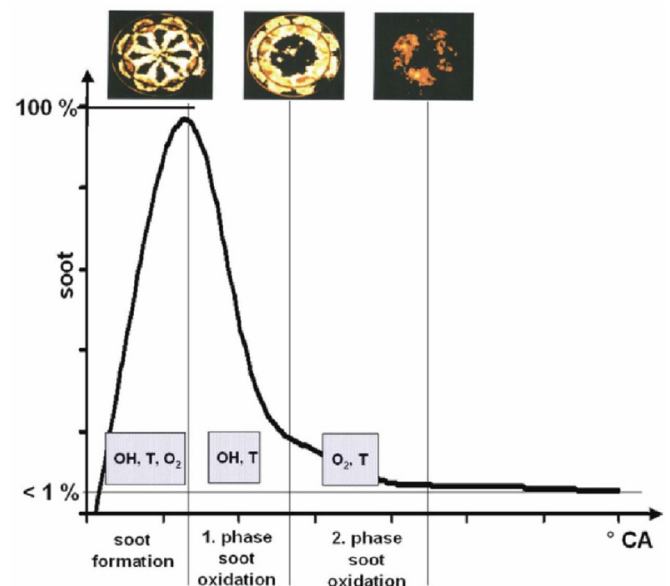


Figure 2. Soot formation and oxidation, [5, 6]

Additionally, the main influencing parameters for the different phases are shown. During both the soot formation and the second oxidation phases, the oxygen concentration has been shown to be a primary parameter in influencing the final engine-out soot emissions. The small images on the top of the diagram show the soot radiation during the combustion. It can be seen that the soot at the end of combustion is located near the cylinder wall. So, in the center of the combustion chamber there exists an excess of oxygen that cannot be utilized in the soot oxidation phase [7].

ADVANCED SPLIT INJECTION STRATEGY (ASIS)

Modern diesel injection systems often use expensive piezo injectors that are able to produce very precise injection events. Very modern piezo injectors are actuated directly, so, multi-pulse injections with continuous and discontinuous shapes are possible. This is done to reduce pollutant emissions. This study shows another way to avoid pollutant emissions with relatively low-priced solenoid injectors.

The Advanced Split Injection Strategy (ASIS) is a combustion process for Diesel engines with a spatially separated pilot injection. A second injector and its nozzle orifices are directed into the center of the combustion chamber. In this way, the spray jets of the main injection do not reach the flame of the pilot injection, regardless of the delay between the pilot and main injections. In this manner, it is possible to increase local air/fuel-ratios and thus avoid soot formation.

Another advantage of the spatially separated pilot injection is the more complete use of the oxygen in the whole combustion chamber. The main injection of a normal Diesel combustion process occurs in the same region of the combustion chamber as the pilot injection. Consequently, a part of the available oxygen has already been consumed by the pilot injection at the time of the main injection. The spatial separation of the pilot injection better utilizes the oxygen in the combustion chamber so that locally leaner mixtures can be realized than with a conventional injection strategy [9].

In conventional Diesel fuel injectors, the nozzle orifice geometry is adapted to the maximum amount of fuel that has to be injected at full load at a definite injection pressure in one combustion cycle. Therefore, the smaller fuel amounts of the pilot injection are not easy to control with such an injector. The Advanced Split Injection Strategy uses an extra injector for the pilot injection; the nozzle orifices of this injector are well adapted to the smaller injection quantities of the pilot injection.

Previous experimental investigations [10] were devoted to the development and analysis of this new injection strategy. The pilot injector had two fuel jets and was mounted in various positions. Position 3 and 7 (see [figure 3](#)) were determined to be the best positions for minimal soot emissions.

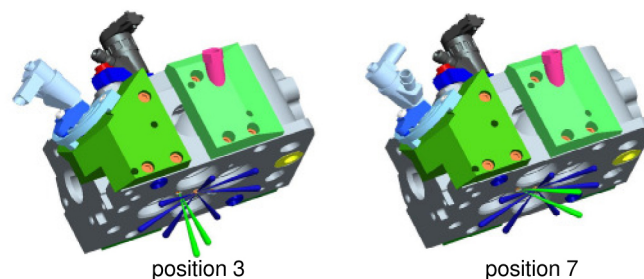


Figure 3. Experimental setup for pilot injection of previous investigations

Additionally, the piston bowl geometry was modified during preliminary numerical investigations. Standard piston bowls for conventional Diesel injection strategies employ omega-shaped bowls, but the new piston geometry includes an additional inner bowl as it can be seen in [figure 4](#). The additional inner bowl gives extra space to make a spatially separated pilot injection possible.

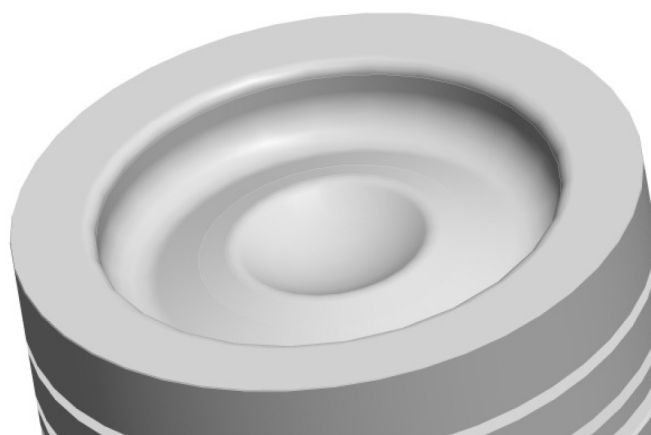


Figure 4. New piston bowl geometry for ASIS

The previous investigations found out that the pilot injector positions 3 and 7 (see [figure 3](#)), which has at least one injection spray jet adjusted into the center of the combustion chamber, are the best for minimal soot emissions. Therefore a new pilot injection geometry was designed. All pilot injection spray jets are now directed into the center of the combustion chamber right into the inner bowl. The number of spray jets is doubled from 2 to 4 to provide a better mixture formation and the nozzle orifice diameters are reduced to 80µm. The given geometry inside the cylinder head placed tight constraints on the positioning of the pilot injector in the cylinder head. So, the only possibility to provide a spatially separated pilot injection without any impact to valve train or intake or exhaust ports was the design depicted in [figure 5](#).

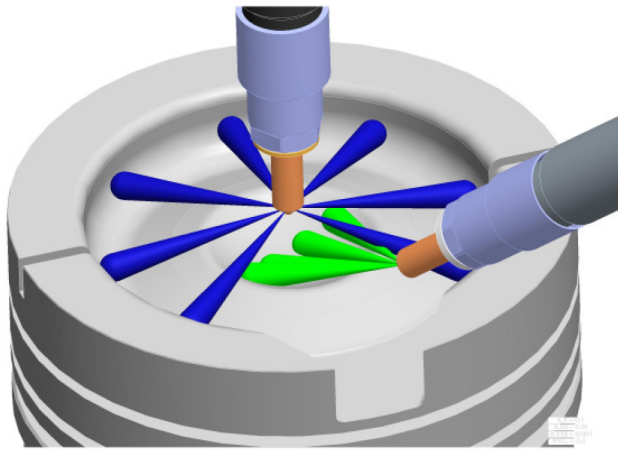


Figure 5. Pilot and main injection with the new ASIS configuration, piston at TDC

As it can be seen, the four pilot injection spray jets are directed into the inner piston bowl to provide a good mixture formation. The piston which stands exactly in TDC has some cut-outs which have been necessary for further optical measurements at this engine. The spray pattern design of the main injector was adjusted to the piston cut-outs, so that the risk of fuel impingement on the cylinder wall is minimized.

Soot emissions of a Diesel engine are normally too high to meet the emission regulation standards, so it is necessary to use a Diesel Particulate Filter (DPF) as part of the exhaust aftertreatment system. A DPF requires regeneration periods, during which additional fuel is injected during a late injection. This increase exhaust temperatures and the soot trapped in the DPF reacts with oxygen. These regeneration periods of the DPF are inefficient and lead to overall higher fuel consumption. With ASIS, it is possible to increase the durations of the intervals between regeneration periods for more efficient operation of a Diesel engine.

NO_x emissions of a conventional Diesel engine are usually too high for legislation restrictions as well as soot emissions. Modern Diesel engines use either selective catalytic reduction of NO_x which is expensive and require maintenance care or a DeNO_x catalytic converter which needs regeneration periods with high fuel consumption. With ASIS a significant increased EGR rate is possible for the same soot emission level. Due to the higher EGR rate compared to Conventional Injection Strategy (CIS) NO_x emissions can be reduced. This increases regeneration periods of a DeNO_x catalytic converter or even makes an exhaust aftertreatment system for NO_x emissions unnecessary.

EXPERIMENTAL SETUP

TEST ENGINE AND HEAD

The test engine is a single cylinder heavy duty engine with direct injection. The cylinder head is an OM457 from Daimler AG, which is large enough for the integration of a

second injector for the spatial separated pilot injection, for an optical access for 2-color-measurements and for the cylinder pressure indication sensor without influencing combustion process. Technical data of this engine can be seen in [table 1](#).

Table 1. Technical data of the test engine

Displacement	1827 cm ³
Stroke	142 mm
Bore	128 mm
Compression ratio	15.5:1
EGR	0...45%
Boost pressure	2 bar abs. (max.)
Engine Speed	2000 rpm (max.)
Injection pressure	2500 bar (max.)
Coolant / Oil temperature	85°C
Main injector	Bosch CRIN3-18, 7 x 139µm
ASIS pilot injector	Bosch CRI2-18, 4 x 80µm
Fuel	Aral Diesel Ultimate, cetane number 56.5

The fuel is injected by a modern common rail system capable of injection pressures up to 2500 bar. Diesel pressures in this range are necessary when investigating a modern Diesel combustion process. The pilot and main injections are controlled by a Genotec control system. This provides independent, fully flexible control of each fuel injector.

The cylinder head is from an OM457 heavy duty Diesel engine from Daimler AG, which has a bore of 128 mm. The OM457 does not have a bleeder throttle between the outlet valves, so it is possible to place a second injector for the pilot injection for the ASIS injection system. In [figures 6 and 7](#), the modifications to the cylinder head can be seen. The pilot injector is mounted into the head via a sleeve with 40° angle to the bottom plane, so it is possible to realize a spatially separated pilot injection into the middle of the piston bowl. In order to precisely position and hold the injector, additional material has been added to the corner of the head. The bore for the pilot injector has been drilled directly through the standard valve train oil drain, so a new oil drain was mounted into the side of the cylinder head. The cylinder pressure indication is performed with an extra compact cylinder pressure transducer from AVL that is adapted to the constraints of the head design.

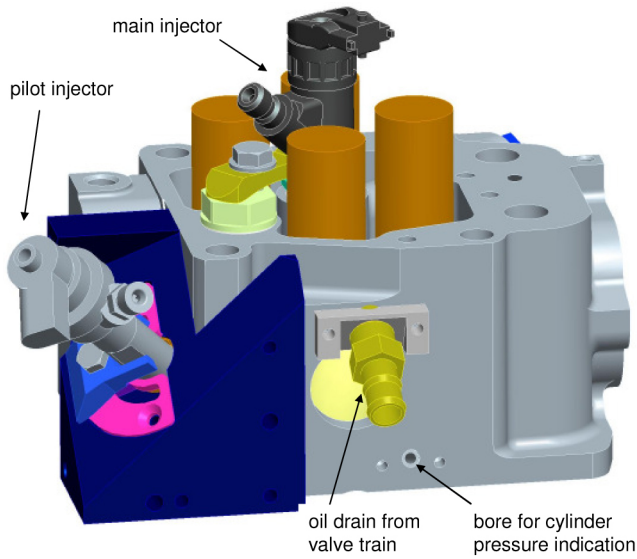


Figure 6. Cylinder head with ASIS pilot injector

For a fundamental investigation of the Advanced Split Injection Strategy it is important to observe the fuel spray of the main injection via a fiber optic for 2-color-measurements. As shown in [figure 7](#) this is realized by a threaded sleeve placed in the opposite side of the cylinder head.

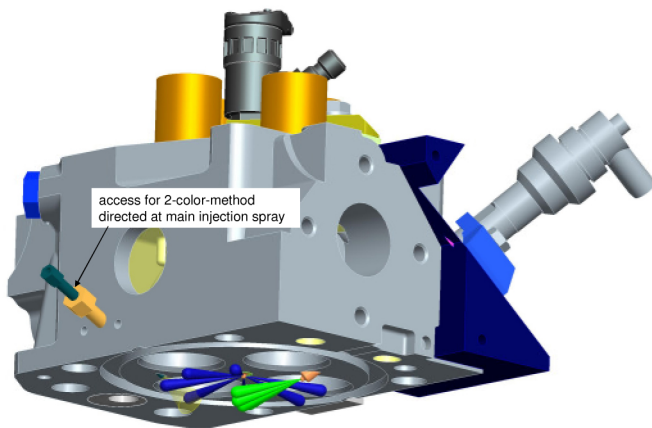


Figure 7. Cylinder head with optical access for 2-color-method

The viewable range of the fiber optic has a complete view of one main injection spray jet in the piston bowl (see [figure 8](#)). So, it is capable of measuring the soot radiation from different injection strategies.

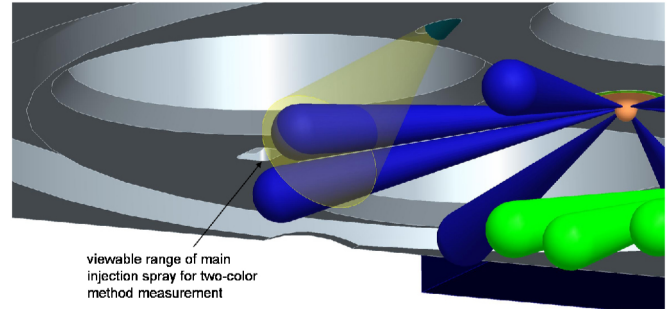
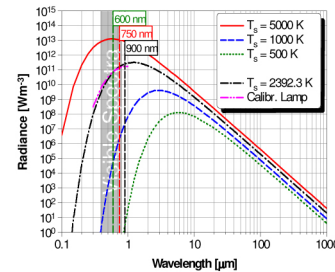


Figure 8. Viewable range for 2-color-method measurements

2-COLOR-MEASUREMENT TECHNIQUE

The two-color method is a pyrometric measuring technique based on the theory of Planck's radiation law. The measured radiation from soot particles in a luminous flame allows the calculation of the soot and/or flame temperature and the soot concentration. Planck's radiation law (see [figure 9](#)) describes the intensity distribution of electromagnetic radiation as a function of the wavelength that is emitted from a black body at a given temperature.



Planck's radiation law:

$$L_{\lambda,s}(T, \lambda) = \frac{c_1}{\pi \lambda^5 [\exp(c_2 / \lambda T) - 1]}$$

real emitter:

$$L_{\lambda}(T, \lambda) = \varepsilon(\lambda) \cdot L_{\lambda,s}(T, \lambda)$$

emission coefficient:

$$\varepsilon(\lambda) = 1 - \exp(-A_e \cdot c \cdot s)$$

Figure 9. Planck's radiation law

With some transformations of these equations at two specific wavelengths, a system of equations with two unknown parameters T (temperature) and c (soot concentration [g/m^3]) can be derived; this is explained in detail in [11]. For the temperature there is an iterative solution (1) and the soot concentration can be calculated directly (2) with the temperature.

$$T = \frac{1}{\frac{1}{T_{s1}} + \frac{\lambda_1}{c_2} \cdot \ln \left[1 - \left[1 - \exp \left(\frac{c_2}{\lambda_2} \left(\frac{1}{T} - \frac{1}{T_{s2}} \right) \right) \right]^{A_{\lambda1}/A_{\lambda2}} \right]} \quad (1)$$

$$c = -\frac{1}{A_{\lambda2}s} \ln \left[1 - \exp \left(\frac{c_2}{\lambda_2} \left(\frac{1}{T} - \frac{1}{T_{s2}} \right) \right) \right] \quad (2)$$

For the calculation of the intensities, some assumptions have to be made regarding, for example, soot particle diameters. So, it is advisable to perform the measurements with three wavelengths and estimate temperatures based on the three resulting wavelength pairs. If all of the assumptions agree within reason with the physical reality, then the calculations with the three wavelength pairs should produce similar results. Otherwise, if the deviation is too large, the values for the assumptions are adjusted until the results converge [11].

The measurement setup is shown in the scheme in figure 10. A fiber-optic cable in the cylinder head is directed towards the region of the combustion chamber to be analyzed. The signal is guided through a 3-armed fiber-optic cable into a photodiode module with three interference filters for the wavelengths 600, 750 and 900 nm. The measured output voltages are put through an analysis routine that calculates temperatures and soot concentrations as described in eq. (1) and (2). In addition, the entire system is calibrated with a radiation standard (tungsten lamp) to ensure proper soot temperature and concentration results.

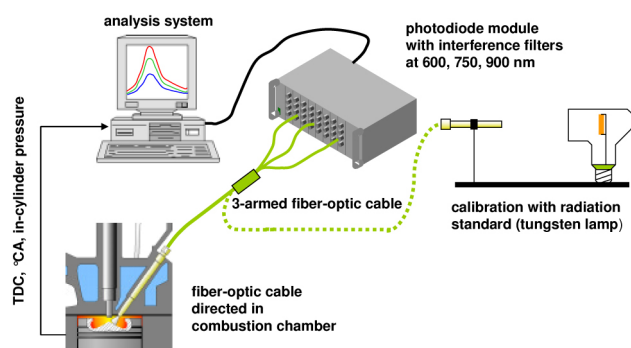


Figure 10. Experimental setup scheme for 2-color-method measurements

RESULTS

The results of the latest investigations with the Advanced Split Injection Strategy (ASIS) focus on basic experiments on one specific operating point at 1300 rpm and 6 bar IMEP, which is about 25% load at medium speed for this engine on the test bench in the Worldwide Harmonized Stationary Cycle (WHSC). The detailed parameters of the investigated operating point can be seen in table 2. The focus had been set to this operating point as the weighting of this operating point in the WHSC is one of the heaviest.

Table 2. Operating point for fundamental investigations in ASIS

Engine speed	1300 rpm
IMEP	6 bar
Boost pressure	1.6 bar
Back pressure	1.6 bar
Equivalence ratio	0.4
EGR rate	15 %
Fuel rail pressure	200 MPa

These elementary investigations refer to various sweeps such as Start of Pilot Injection (SOPI) or EGR which will be presented in the following sections. Afterwards the experimental activities took aim to optimize this operating point on the basis of the fundamental results for both injection strategies, the Conventional Injection Strategy (CIS) with only one injector and the Advanced Split Injection Strategy (ASIS). Furthermore this optimization process was applied to other operating points in the engine map, which are important for the WHSC, as well. The operating points can be seen in figure 11 as well as the stationary operating points for the WHSC. The size of the red bubbles represents the weighting in the WHSC.

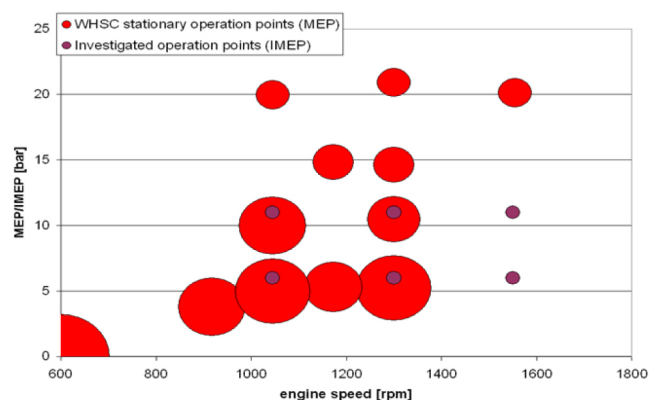


Figure 11. Operating points of WHSC and experimental investigations

For accurate soot emission results, particularly at low emission levels, soot measurements have been performed with an AVL 415S v1.11 smoke meter. Each reported result is the average of three individual measurements; the deviation between the three is very small compared to the mean value.

FUNDAMENTAL PARAMETER SWEEPS AND THEIR INFLUENCES

The first sweeps that are shown in the following subsections are variations in SOI and EGR to determine the behavior of the combustion process and the raw engine-out emissions. The equivalence ratio has been set to 0.37 (without EGR) and fuel rail pressure was operated at 200 MPa for a good mixture and evaporation process of the