

## **SOOT SENSOR FOR DIESEL EMISSION ONBOARD CONTROL SYSTEMS**

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**ABSTRACT** - During the last few years the market share of vehicles with diesel engines has steadily increased. The reasons for this are the excellent features of this engine, especially its outstanding torque qualities and high efficiency. The development of the diesel engine is increasingly being affected by the stricter emission regulations for limited pollutants. The particulate and NO<sub>x</sub>-emissions in particular are to be reduced drastically within the next few years. A survey of state-of-the-art exhaust aftertreatment systems reveals high demand for further development and optimization. The main problem is reliable evaluation of these systems' functionality under all operation conditions, their secondary emissions, long term stability and maintenance intervals. The EU Commission is urging development of modern emission control technology and of the appropriate sensor technology to enable complete OBD monitoring of such exhaust aftertreatment systems. Many ambitious national and EU projects are being launched to create new exhaust pollutant sensors for the automotive industry that could help establish a multibillion euro market in emission control systems by 2010. The sensors will also help Europe to meet its CO<sub>2</sub> obligations under the Kyoto Protocol. The major innovation in these projects is to create particulate sensors for the next generation of diesel exhaust emission control systems. Such a soot sensor, named Spark Discharge Soot Sensor (SDSS), has been developed by Hamburg University of Applied Sciences since 1998, (1). In principle the SDSS is designed as a combination of conventional spark and glow plugs. In this paper the construction, development and implementation of the SDSS is presented and commented upon. The SDSS was tested on many diesel engines and the measurement results of steady and unsteady tests are presented and analyzed in detail.

### **TECHNICAL PAPER\***

The intensive further development of the diesel engine in recent years has led to significant advances in terms of increased performance and reduced emissions. However, given that even modern EURO 4-certified diesel engines still generate considerably more carcinogenic emissions - especially soot particles - than conventional petrol engines, intensive efforts are being made to reduce these emissions. Future limits, e.g. EURO 5 and 6, will be achieved through a targeted combination of engine-based measures and efficient exhaust aftertreatment. Measuring these drastically reduced emission values, especially the particle concentrations, represents a major technical challenge. Established measurement techniques such as opacimeters and smoke meters are no longer suitable for such tasks in all cases. For instance, if an efficient particle filter system is used, the filter smoke numbers (FSN) are nearly always

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negligible and opacity is strongly influenced by other emissions (e.g. by  $\text{NO}_2$ ), meaning that such low particle concentrations are almost impossible to register.

In order to provide continuous monitoring of a particle filter system it is necessary to install a device behind the particle filter which is capable of recognising and signalling a functional fault in the filter and the resulting increase in the particle emissions (on-board diagnostic system OBD, on-board measurement system OBM). This problem combined with the lack of suitable techniques for monitoring environmentally damaging particulate emissions provided the initial idea for this project.

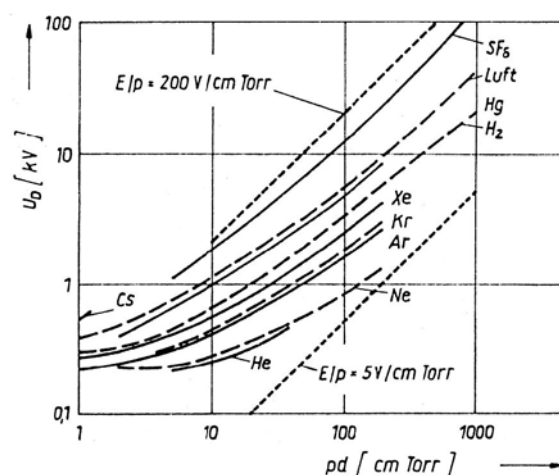
At present, monitoring and gauging the loading degree of a diesel particulate filter (DPF) is determined from the loss of pressure across the filter. However, if the filter element is no longer airtight due to a crack, the pressure difference across the filter is no longer suitable for the diagnosis. An extra sensor is required to detect this defect properly. Besides the so-called soot sensor for checking the DPF, a further sensor could be used before the DPF or the exhaust gas turbo charger which, similar to the lambda sensor of the 3-way catalytic converter, regulates the soot emissions in a closed loop. This would provide an effective and economical control system for limiting soot emissions.

The present paper presents the "Spark Discharge Soot Sensor" (SDSS) and its current state of development. The work to date has served both to overhaul and develop the functional method of the sensor, and also to explore possible areas of use within the exhaust system, i.e. behind the DPF.

#### PRINCIPLE BEHIND THE SPARK DISCHARGE SOOT SENSOR (SDSS)

The minimum spark discharge voltage in gases depends primarily on the electrode gap and the status of the gases, including their temperature, pressure, speed, moisture content and soot particle concentration. In a steady and particle-free gas environment containing a homogenous electric field between the electrodes, these dependencies are as shown in figure 1. These curves are also known as "Paschen" curves.

Figure 1: Paschen curves for static spark discharge in gases. Key: d electrode gap, p gas pressure, E electric field strength,  $U_D$  high voltage between the electrodes



Experiments have proven that soot, i.e. carbon, particles between the electrodes and/or deposited on the cathode facilitate the release of electrons by the electrical field. The required voltage for an electrical discharge falls by up to 70% as a result. It was also discovered that this influences the stability of the voltage at which an electrical discharge occurs. For instance, in a soot-free atmosphere, i.e. in pure air, the distribution range for the spark voltage

was  $\pm 22\%$ . In the presence of soot this range was reduced to  $\pm 4\%$ , even in the case of very low soot concentrations.

The measurement method (1) of the SDSS is based on determining the minimum level of the electrical spark voltage in the exhaust gas at which a spark occurs between two electrodes. To do this, the sensor control unit charges a spark coil with a specified level of energy. The spark coil is then discharged across a spark gap in the exhaust gas stream. By means of an implemented spark detection facility one determines whether the energy available is sufficient to create a spark. This information is forwarded to the control unit where it is processed. If the energy was sufficient, the energy for charging the coil in the next measurement cycle can be reduced; otherwise it is increased. This process is continually repeated at frequencies of up to 200 Hz. The measured value thus centres on the energy level which is actually required, despite the static fluctuations in the sparking.

In order to obtain dependence between the minimum sparking voltage and the soot concentration we need to determine the influence of the other parameters, i.e. the cross influences. Besides the minimum level of sparking voltage, all parameters which exert a significant cross influence such as temperature, mass flow rate, air-fuel ratio etc. need to be acquired during the measurement. These parameters are required anyway for engine management, meaning that no additional sensors need be built into the exhaust system for this measurement.

## CONSTRUCTION OF THE SENSOR AND ITS USE IN THE EXHAUST GAS SYSTEM

The SDSS is basically a combination of a spark plug and a glow plug (2), (3). The ceramic insulator (see figure 2) needs to be heated in the exhaust pipe to prevent soot deposits and uncontrolled discharges between the centre electrode and the exhaust pipe (earth).

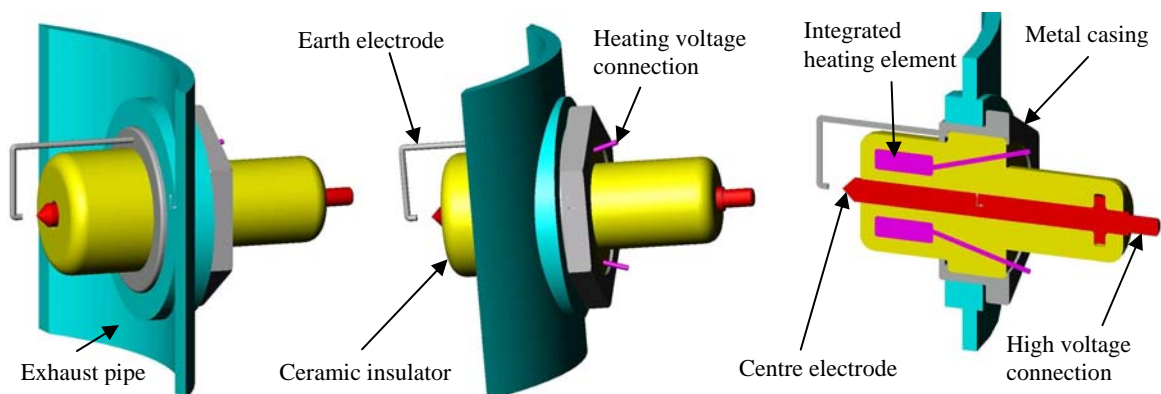


Figure 2: Design principle of the SDSS with integrated heating element.

The demands on the ceramic of the insulators are very high as these have to demonstrate sufficient breakdown resistance and good chemical strength at relatively high temperatures of approx. 500 to 600°C in the hot exhaust gases. Integration of the heating element in the ceramic insulator was deemed to be too costly for the production of the SDSS prototypes. For this reason a number of variations for combining the ceramic insulator and heating element were designed and tested; in all cases the insulator was made from at least two bonded ceramic parts. All the different variations were deployed in the full stream of the exhaust gas system.

In the first sensor variations cores of conventional spark plugs were used. To ensure burn-off of the soot residues deposited on the ceramic insulator, a heating element made of platinum wire integrated in a ceramic cup was also fitted. This design is referred to here as variation S072 (see Figure 3). It also differs from the other variations in its use of a flat earth electrode to increase the sensor sensitivity. A number of these prototypes were subjected to intensive testing; some of the measured results and the related evaluation and analysis are presented below.

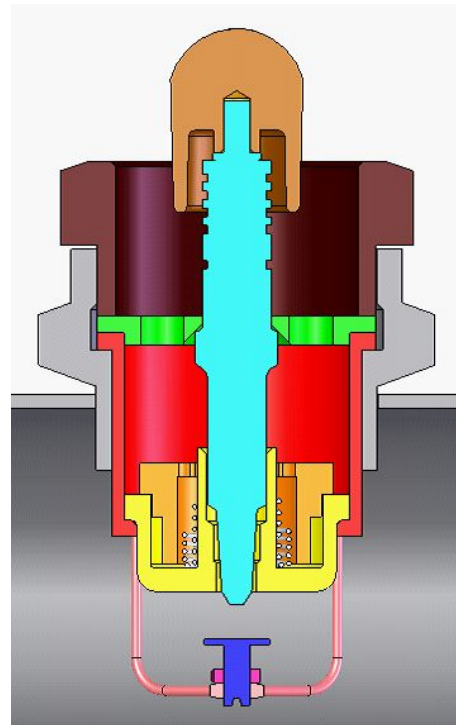
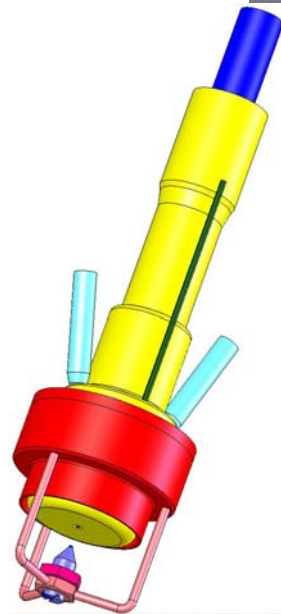


Figure 3: Sensor **S072** with spark plug core, flat earth electrode and heating element made from platinum wire integrated in a ceramic cup

Figure 4: Sensor **S074** (left) and **S075** (right) without spark plug core, with pointed earth electrode, platinum wire heating and thermo element for temperature regulation of the ceramic cup.



The spark plug core was eliminated in **S073** and later variations (see Figure 4). Also, the design of the ceramic cup was adapted to match the dimensions of the heating coil. Here, special attention was placed on reducing the exchanged heat flow between the sensor and exhaust pipe, allowing the amount of heating power required to be reduced.

Tube sections were produced to provide flexible mounting of the sensors; these sections were fitted by means of clamps at the appropriate points in the exhaust gas system. To protect the sensor from excessive thermal exhaust loads it was inserted from the side or from below (see Figure 5).

The DPF was inserted in a bypass (Figure 6). The bypass vane therefore controls the amounts of the filtered and unfiltered exhaust gas mass flow, allowing the soot concentration to be varied within a certain engine operating point.

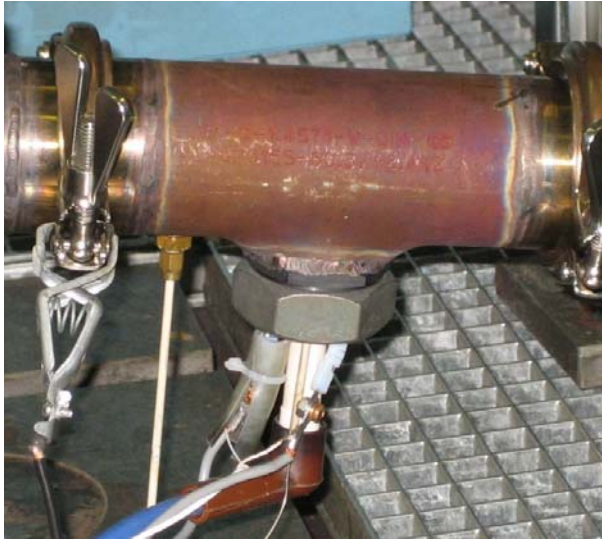


Figure 5: SDSS fitted in exhaust gas system

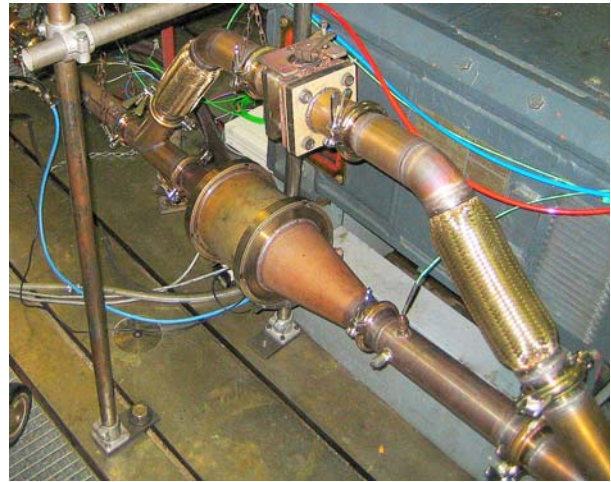


Figure 6: DPF in bypass

#### MEASUREMENT RESULTS<sup>†</sup> OF THE SDSS FOR THE VERSION S072

The following sensor signal processing was used for DPF monitoring:

The reference signal was subtracted from the measured signal to yield the compensated sensor signal. The compensated signal was compared with the opacity, the FSN and the gravimetric measurements.

The reference signal was calculated using the characteristic curves of the cross influence parameters. These characteristic curves were produced on the basis of stationary comparative measurements. The instationarity of the processes has no impact on the monitoring of the DPF, as no (rapid) time-related response is required from the sensor in such a case.

Multiple tests were carried out to determine that the version S072 SDSS only functions correctly with exhaust gas temperatures of below 350°C. For this reason, the sensor signals described above for exhaust temperatures of below 350°C were rated "confident" and their results charted in a bold line.

At high soot concentrations the SDSS tends to become sooted for a certain period, thereby falsifying the measured signal. In order to detect this status a second signal of the sensor (plausibility check) was incorporated which exceeds preset limits (unsooted limits, shown as dotted lines in the charts) in the case of sooting.

In the first sequence of measurements (Figure 7) load and rpm changes without DPF were tested to establish the response time of the sensor. In the second set of measurements (Figure 8), three stationary engine operating points were tested. The bypass vane was also operated with three different opening settings in each case. Gravimetry was also used in this set of tests as a reference.

<sup>†</sup> All the measurements presented below were made at the Automotive Engineering Research Institute (FIF), Dresden University of Applied Sciences (HTW)

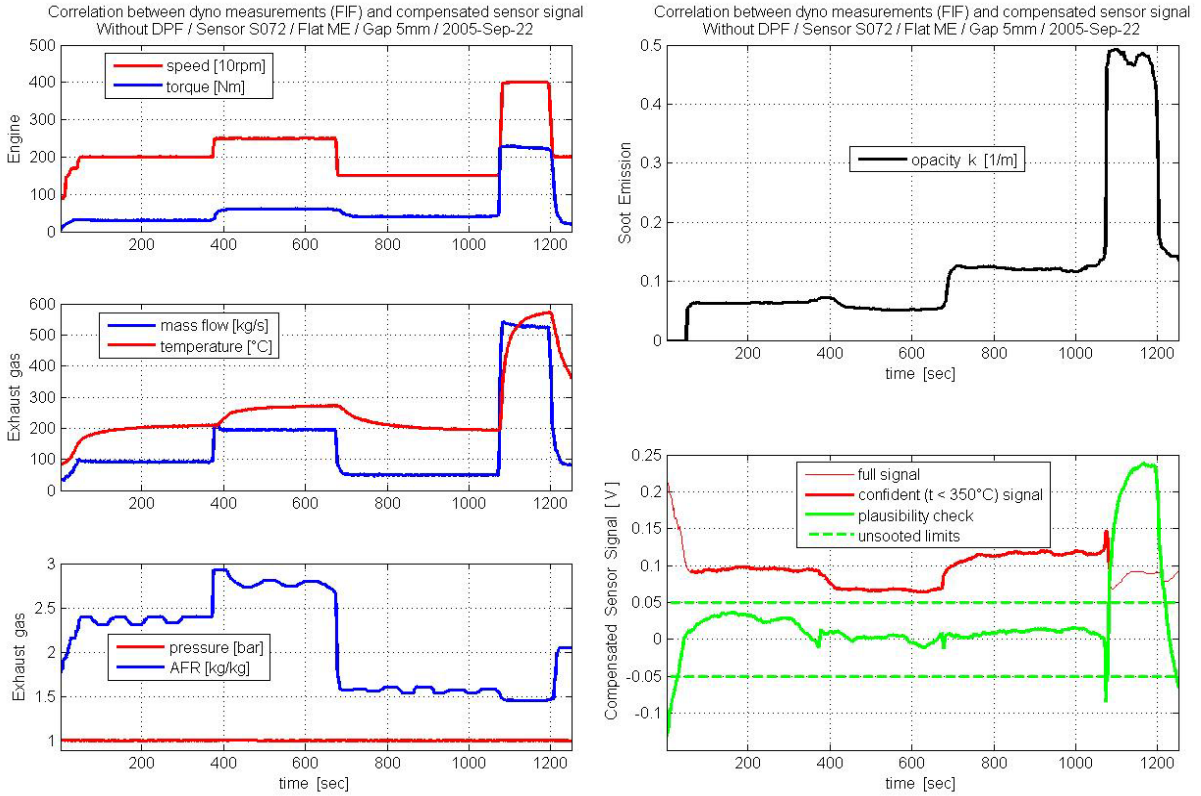


Figure 7: Version S072 of SDSS. Load and rpm changes without DPF

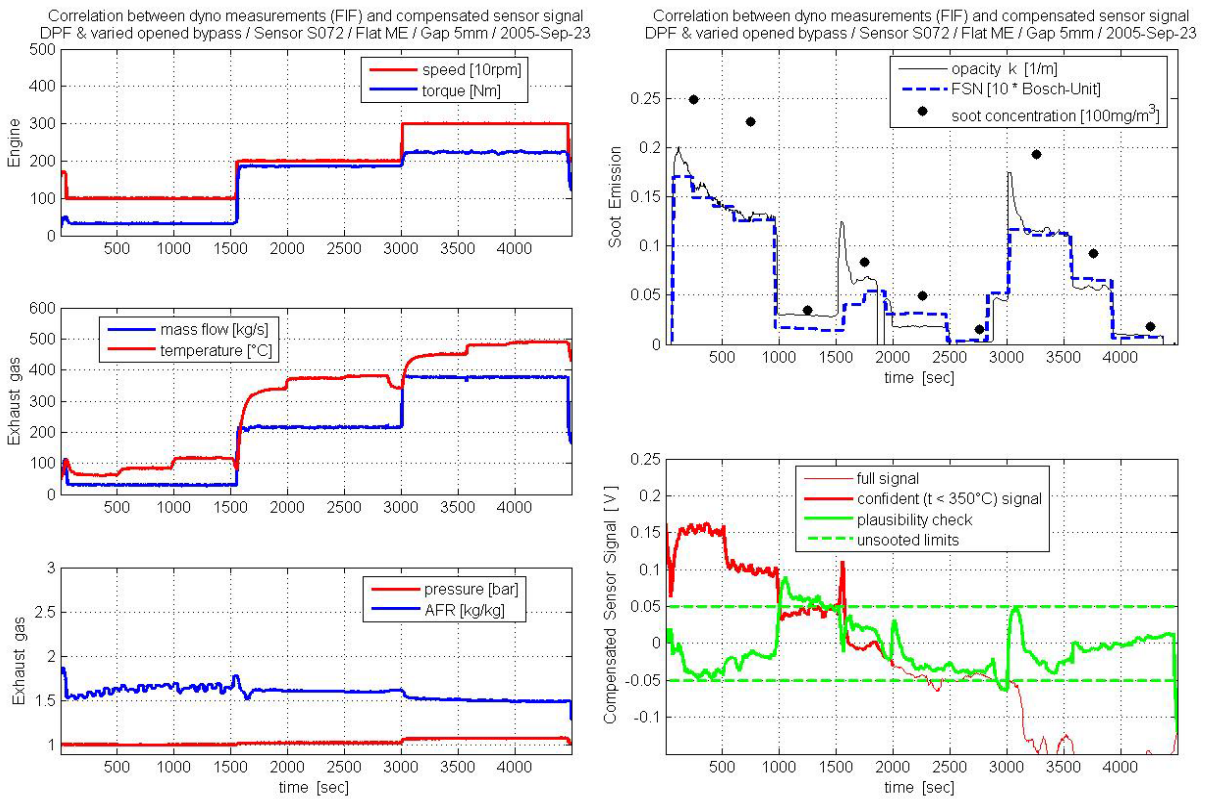


Figure 8: Version S072 of SDSS. Operating points with DPF, variable opening of bypass vane

The following conclusions could be drawn from the analysis of the measured results in figures 7 and 8:

- Version S072 of the SDSS generates a reproducible signal at temperatures of below 350°C. The results show a relatively good correlation to the soot concentration results. However, this dependence - and therefore also its potential for use to monitor a DPF - needs to be studied more closely.
- But if the sensor is sooted, it takes several minutes until the deposited soot film has burned off as a result of its relatively large dimensions. The main measured signal cannot be used during this time.
- Also, the sensor signal is not precise enough in the engine warm-up phase. This is probably due in part to the fact that some exhaust gas parameters for which no characteristic curves have yet been produced change rapidly at the same time.

## MEASUREMENT RESULTS OF THE SDSS FOR THE VERSION S075

The following improvements in the design and functioning were achieved in this version:

- In this version the sensor has smaller dimensions and therefore less heating power.
- The changed design has resulted in improved electrical insulation between the high voltage and heating circuits.
- The measured signals are also less susceptible to external disturbances.
- The plausibility signal was improved and mirrored, meaning that it could be used for continuous monitoring of the main signal.
- The temperature limit was extended so that the SDSS works fault-free up to an exhaust gas temperature of 500 °C. No measurements have yet been made above this temperature.

Of the tests carried out, five ESC (European Stationary Cycles) cycles are presented.

Figure 9 shows the results with fully open bypass vane. At this setting, most of the soot particle-charged exhaust gas flows unfiltered past the sensor. The sensor detects the increased soot emission; however is itself sooted as a result of the high soot concentration. The correct status, however, is recognised thanks to the plausibility signal. This indicates that the soot emission was above the FSN = 1 value (Bosch scale) for a longer period. This in turn signifies that, in the event of a DPF diagnosis, the SDSS recognises that the DPF is faulty.

Figure 10 shows the results with the bypass vane almost closed.

Figure 11 shows the results with the bypass vane fully closed. It should be taken into account, however, that a very small exhaust mass flow always flows across the bypass due to incomplete seals.

In a further test the bypass was fully closed using a cover and a damaged DPF used instead of an intact filter. The exhaust gases could flow directly through the middle of the filter as a result (see Figure 13). The results are shown in figure 12.

A comparison of the results of all the tests shows that the signals of the SDSS cannot be clearly distinguished; figures 9 to 12 show that a precise time-related assessment of the soot concentration cannot therefore be made from these results. However, it is clearly apparent that the measured soot concentration and that detected by the sensor are synchronous across the operating points of the engine.

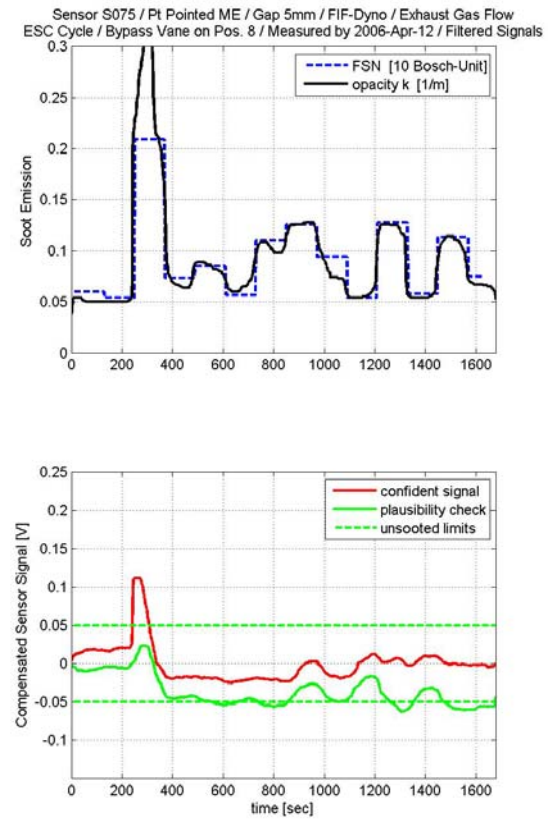
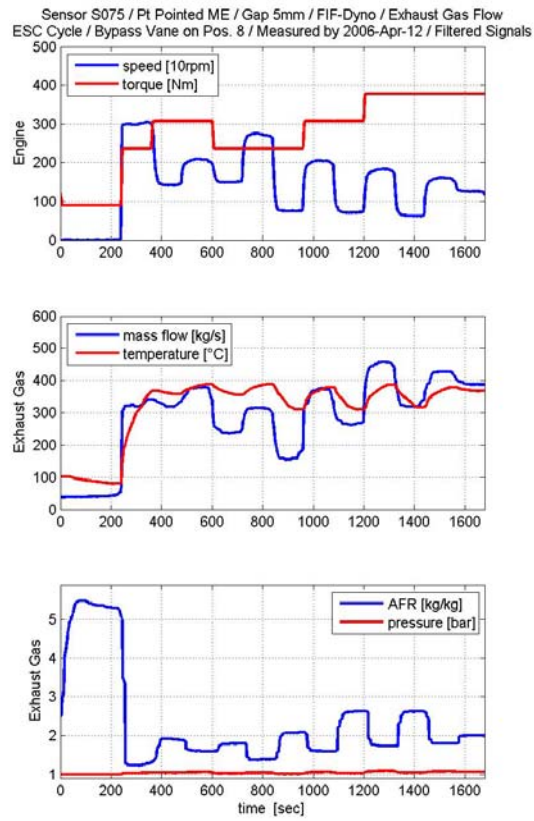


Figure 9: Version S075 of SDSS. ESC cycle with bypass vane fully opened

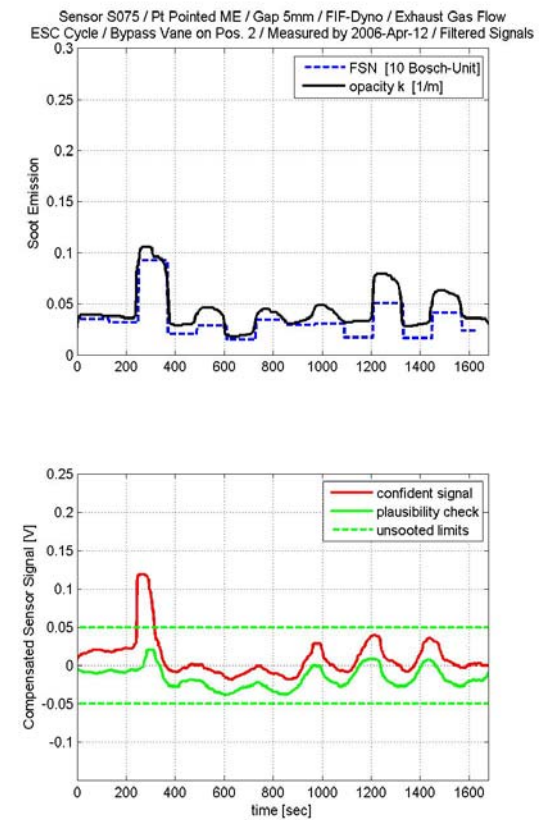
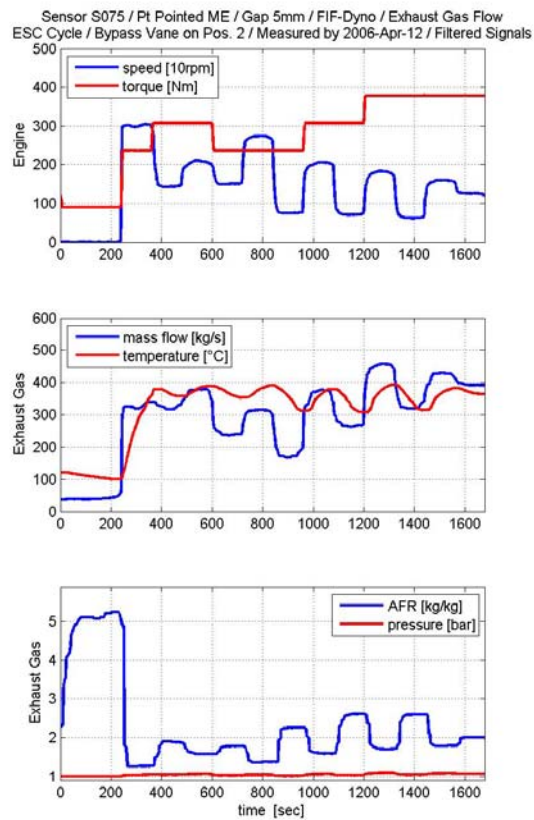


Figure 10: Version S075 of SDSS. ESC cycle with bypass vane slightly opened



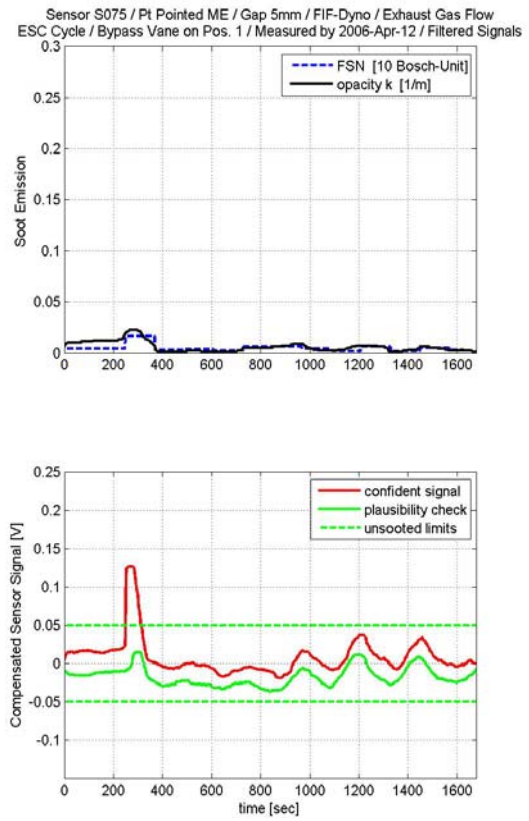
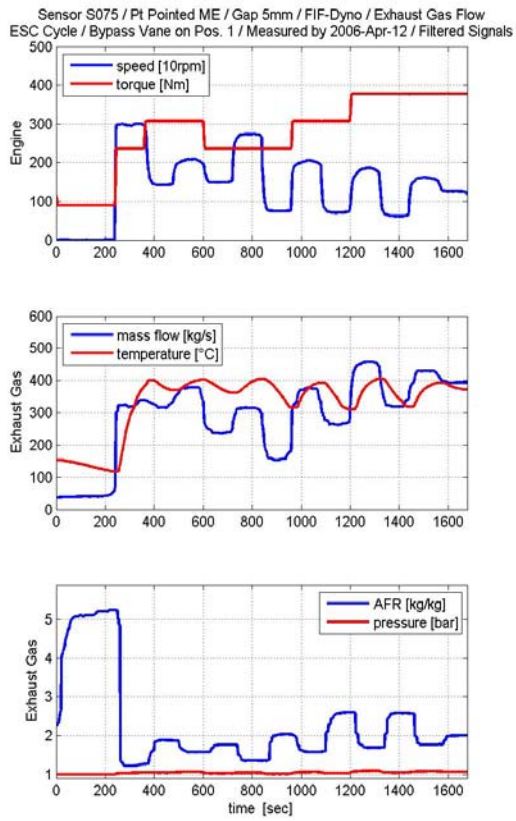


Figure 11: Version S075 of SDSS. ESC cycle with bypass vane almost closed

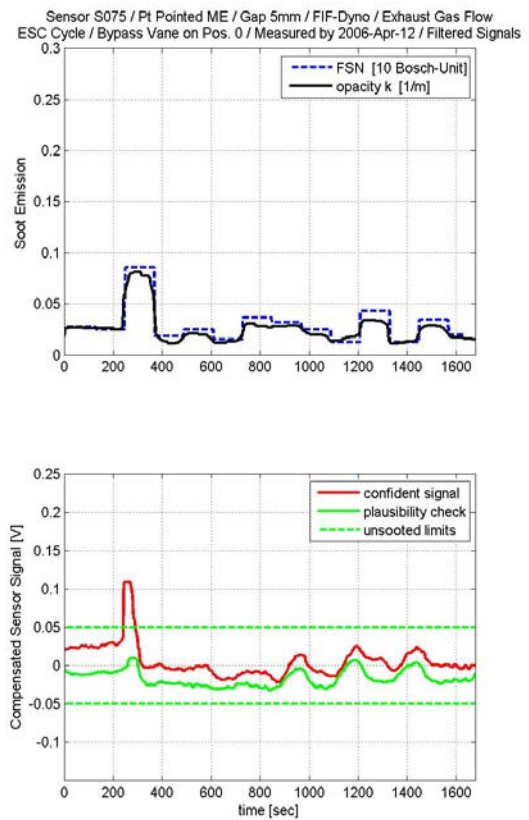
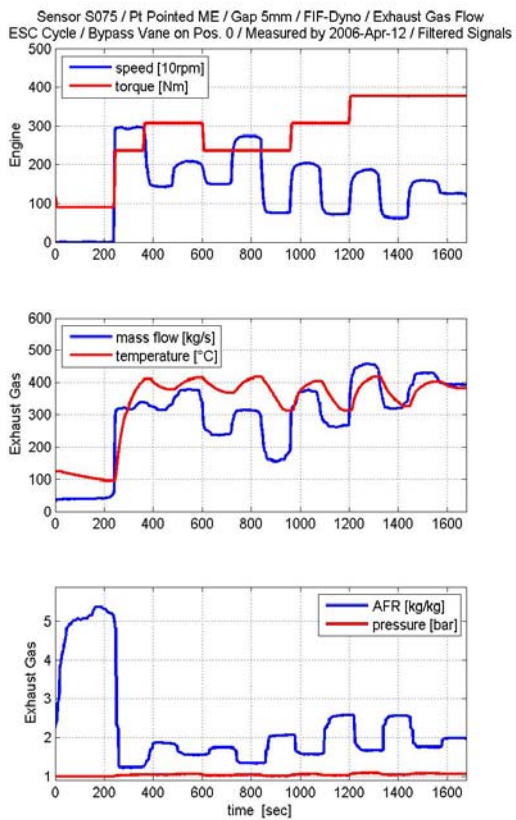


Figure 12: Version S075 of SDSS. ESC cycle with faulty DPF (see Figure 14)

Figure 13: Damaged DPF after use in exhaust gas system. The filter was mechanically manipulated to allow direct passage for the exhaust gases and therefore for the soot particles through the middle of the filter.



If we integrate the SDSS signals and the soot concentrations through the ESC cycle - which is also carried out by the engine management unit for assessment of the DPF status over a certain period - the situation is as shown in figure 14. The curves of the integrated sensor signals are similar to those of the soot concentration. From the results we can deduce that the entire monitoring of the DPF can be effected using a combination of the measured pressure across the DPF and the SDSS signal.

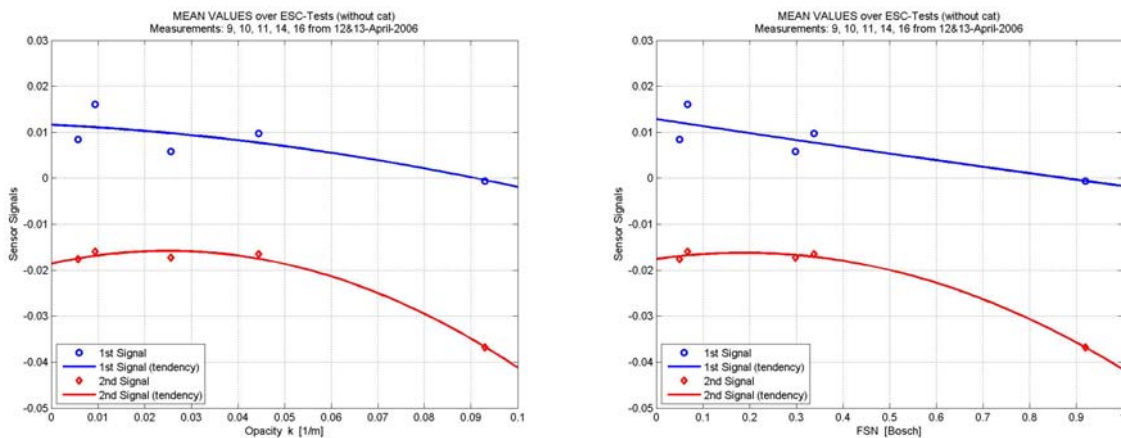


Figure 14: Integral value of SDSS signals with regard to opacity k (left) and FSN (right)

## OUTLOOK

The following steps are planned for the future:

- Further studies are to be carried out on the S075 version of the SDSS.
- The spark detection procedure is to be improved.
- A new version of the sensor is already in preparation and is shortly to be tested and evaluated.
- New materials are to be deployed and tested for the insulation ceramic and the electrodes.
- The cross influence parameters will continue to be determined for all new sensor versions.
- The zero level stability of the sensors is being examined and will be improved if necessary.
- Other methods of processing the signals are currently being developed and tested to enable the use of the SDSS before the DPF and therefore to provide regulation in the soot emission closed loop. The sensor is therefore regarded as a MIMO system and the cross influences are determined by an identification procedure based on various models. The initial results are themselves highly promising and show that the SDSS has a great deal of development potential.
- Industrial partners are being sought with the aim of accelerating these developments and promoting the production of prototypes which are even more compact (possibly with integrated heating).

## REFERENCES

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