INTRODUCTION

To meet current emission legislation standards in the EU and US modern diesel vehicles are commonly equipped with a trap for particulate matter, so called diesel particulate filter (DPF). While the required in-use monitoring (OBD) of the functional DPF efficiency can be provided by evaluating the pressure difference over the filter for current OBD-limits, it proves very difficult to meet the tightened regulations of upcoming CARB and EU legislation [1,2] with this oblique method. This calls for direct measurement of the particulate matter emissions with a novel sensor that provides sufficient accuracy and sensitivity as well as the ruggedness necessary for stable lifetime operation under exhaust-gas conditions.

PARTICULATE MATTER SENSOR

Based on well-proven multi-layer technology Bosch has developed a ceramic exhaust-gas sensor for particulate matter (EGS-PM) which is shown in figures 2-4. On the sensing surface a DC voltage is applied to two inter-digital electrodes (IDE), on which soot particles are deposited from the exhaust gas during operation. The characteristic drop of resistance due to formation of electrically conductive soot paths between the electrodes can be used to determine the soot emission. An integrated heater and temperature sensor allow for controlled regeneration of the sensing element by oxidation of the deposited soot at elevated temperatures.
SENSOR PERFORMANCE ON ARTIFICIAL SOOT AND ENGINE TEST BENCH

To evaluate the sensor performance and study different influences on the sensor signal the EGS-PM was operated both on a new soot particle test bench with an ethene burner and in the exhaust gas of a 4-cylinder, 2.2 litre engine with a common rail injection system and Euro4 application. The engine test bench was furthermore equipped with a variable bypass around the DPF to simulate variations of the filter efficiency as expected from DPF defects. On both test-benches the sensor shows excellent signal repeatability of 3-8% for 2 sigma (see figure 5).

By selecting engine operating points with similar exhaust gas parameters but different engine-out soot emissions and additionally varying the filter efficiency as described above it was possible to determine the sensor response characteristic over a wide range of particle concentrations. Figure 6 shows the typical inverse relationship between time-to-threshold and soot concentration which allows for improved discrimination of filter efficiencies at low emission levels. Furthermore the improvement in response-time by reduction of electrode-spacing is clearly visible.

SYSTEM INTEGRATION

For reliable measurement of the small currents involved and ease of integration into vehicle projects the sensor comes equipped with a sensor control unit as shown in Figure 2. This SCU handles operation of all sensor components as well as data acquisition. Data is transferred to and from the engine control unit (ECU) via CAN-bus thereby allowing plug-and-play operation without the need for dedicated circuits within the ECU (Figure 7).
DPF OBD CONCEPT

While emission limits set by legislation are defined with respect to specified driving cycles, engine-out emission can vary significantly for in-field driving due to driver behaviour and different engine load conditions. To overcome those influences we have developed an DPF OBD concept, shown in figure 8, that compares the measured EGS-PM response-time with a model based predicted response-time. The latter uses the simulated soot mass flow of the engine as well as other exhaust gas parameters and takes a limit DPF model into account to predict sensor behaviour downstream DPF.

**Figure 7:** DPF OBD by means of EGS-PM - system view.

**Figure 8:** DPF OBD monitoring concept based on EGS-PM sensor signal.

SUMMARY / CONCLUSION

A concept of a resistive soot sensor was presented which consists of an inter-digital electrode for soot detection and an integrated heater and temperature-sensing element for controlled regeneration of the sensor.

The natural hyperbolic characteristic of sensor response time vs. particle concentration was shown as well as excellent repeatability of 3-8 % (2 sigma) in measurements both on an ethene burner lab test bench and over a wide operating range of a 4-cylinder / 2.2l common rail engine.

Ease of integration into existing vehicle projects due to the associated sensor control unit with CAN interface was outlined as well as an DPF OBD concept that allows for in-field diagnosis.

REFERENCES


[2] Official Journal of the European Union; Communication on the application and future development of Community legislation concerning vehicle emissions from light-duty vehicles and access to repair and maintenance information (Euro 5 and 6); (2008/C 182/08)
Particulate matter sensor for on-board diagnosis (OBD) of diesel particulate filters

14th ETH Conference on Combustion Generated Nanoparticles
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Exhaust Gas Sensor for Particulate Matter (EGS-PM)

Legislation

PM [mg/mi]

<table>
<thead>
<tr>
<th>EU</th>
<th>CARB</th>
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<tr>
<td>290</td>
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Legislation

- CARB-legislation for DPF-OBD (OBDII Nov. 9, 2007)
- EOBD: preliminary Commission proposal (September 2007, PM and PN limit)

Requirements

- Δp-based diagnostics not sufficient for OBDII requirements MY2013
- EGS-PM necessary to fulfill OBDII legislation for PC/HD application (>MY2013)
Resistive soot sensor: Overview

- Soot particles are deposited from exhaust gas onto sensor surface
- Formation of conductive pathways leads to decreased electrical resistance
- Application of voltage to inter digital electrodes allows measurement of sensor current
- Periodic thermal regeneration by means of integrated heater
Exhaust Gas Sensor for Particulate Matter (EGS-PM)

Schematic view of sensor signal over time

- sensor signal
- deposition of particles
- current threshold
- time to threshold / response time
- start of second measurement cycle
- thermalization

Diesel Systems

GS-S/ENX4-8s | 08/03/2010 | F10_1080 | © Robert Bosch GmbH 2010. All rights reserved, also regarding any disposal, exploitation, reproduction, editing, distribution, as well as in the event of applications for industrial property rights.
Schematic setup of the artificial soot particle test bench

- Ethene burner produces highly reproducible soot concentration with adjustable particle diameter
- Test bench will be calibrated against Micro Soot Sensor and Smokemeter (AVL), particle counter and SMPS
Exhaust Gas Sensor for Particulate Matter (EGS-PM)

Sensor accuracy on artificial soot particle test bench

- Accuracy will be defined based on reproducibility of the sensor signal
  - measured on test bench using burner-generated particulate matter
  - for a variation in soot concentration and gas volume flow
  - excellent signal repeatability: ± 3% (± 2 Sigma)

![Graph showing sensor current over time](image-url)

Stationary test bench measurements
Average response time
\[ t = 343 \pm 10 \text{ s (2 Sigma)} \]

PM-concentration: ca. 10 mg/m³
gas flow: 800 l/min
Exhaust Gas Sensor for Particulate Matter (EGS-PM)

Repeatability – steady-state engine operation

→ Excellent repeatability throughout wide range of engine map
Regeneration interval vs. soot concentration

- “Natural” hyperbolic relationship between time-to-threshold and soot concentration
- Steep slope for small concentrations
  - improved discrimination in the range of small soot concentrations
- Increased sensitivity can be achieved by reduction of electrode spacing

Electrode Spacing
- narrow
- wide

Hyperbolic Sensitivity Characteristic

engine test bench
- 4-cyl. / 2.2l / CRS
- adjustable DPF bypass
Exhaust Gas Sensor for Particulate Matter (EGS-PM)

Setup for the automotive exhaust line measurements

- Symmetrical drilling of DPF at the inflow site and 8 drill-holes

- **Emission in FTP75 driving cycle:**
  \[ \text{PM} \approx 18 - 19 \text{ mg/mi} \]

- Measurements done on a chassis dynamometer using a car with a common European calibration setup (6 cylinders, engine displacement of 3l)
- Sensor placed 655mm downstream DPF
Start of measurement after dew point has been reached

FTP75: DPF defect detection by means of EGS-PM possible
DPF monitoring in the field

Task

- DPF monitoring function is required to work reliably both in OBD certification cycles and in the field
- OBD emission limits are defined with respect to specified driving cycles

Challenge

- Wide variation range of engine-out emissions in conjunction with variable driver behavior (e.g. soot emission in overrun ≃ 0 mg/m³, soot emission during maximum acceleration ≥ 100mg/m³)
- Note: Only relevant for DPF monitoring if DPF partially deteriorated

RB solution

- Decision “DPF OK” / “DPF not OK” based on "filter efficiency"
- Engine-out particulate mass emission-model used for comparison with sensor signal
DPF monitoring concept

- Particulate Matter Sensor EGS-PM
  - Sensor signal
  - Measured response time
- Engine soot simulation
  - Simulated soot mass upstream DPF
  - Simulated soot mass downstream DPF
- Limit DPF model
- Comparison: measured response time vs. expected response time
  - Measured response time for built-in DPF
  - Expected response time for a limit DPF
- Model for particulate matter sensor signal
- DPF monitoring
  - DPF OK
  - DPF not OK
Exhaust Gas Sensor for Particulate Matter (EGS-PM)

System view

ECU Component Driver
- DPF fault-detection

CAN

ECU:
- Signal processing
- DPF diagnostics
- Dew point release

EGS-PM:
- Sensor control
- Data acquisition
- Sensor diagnostics

Sensor Control Unit (SCU)

Sensor Device

Particulate Matter Sensor

Sensor signals

Dew point detection

Sensor diagnostics

Demand new measurement
Summary/Conclusions

- Resistive soot sensor concept: IDE, heater and T-measurement

- Excellent signal repeatability
  - artificial soot particle test bench: ±3% (e.g. @ 10mg/m³, 800l/min)
  - engine test bench: < ±5% (1s) (over wide range of engine map)

- “Natural” hyperbolic relationship between time-to-threshold and soot concentration
  - improved discrimination at low particle concentrations

- Sensor response time sufficient for DPF defect detection
  - FTP72 driving cycle with DPF (18 mg/mi)

- Stand-alone sensor (CAN interface)
  - sensor management, regeneration control, signal processing, verification of sensor signal are controlled by SCU
  - Easy integration of the sensor into existing engine control system

- Layout of concept for an in-field DPF OBD presented