Particulate matter sensor for on board diagnosis (OBD) of diesel particulate filters (DPF)

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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.

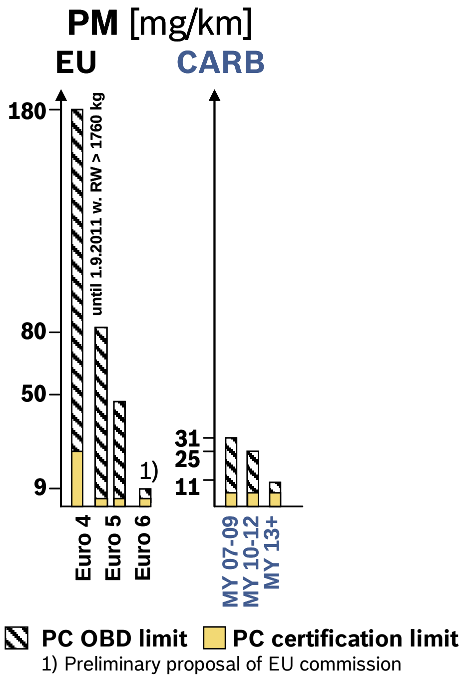

Figure 1: DPF-monitoring-limits according to OBD-legislation (CARB/EU).

Figure 2: Image of Bosch PM sensor with sensor control unit (bottom) and typical application in an exhaust aftertreatment system (top).

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.

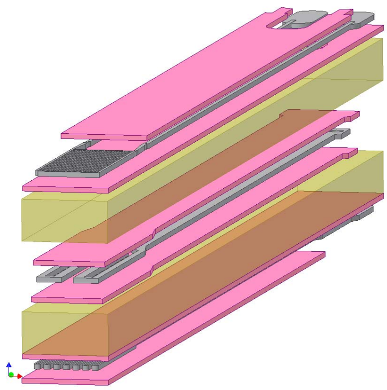

Figure 3: Exploded view of a resistive sensor element with inter-digital electrode (top), heater (centre) and temperature sensor (bottom).

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).

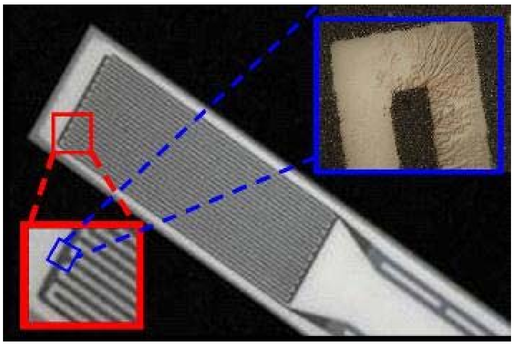

Figure 4: Top-view of the inter-digital electrode including a magnified image of the soot deposit between electrodes.

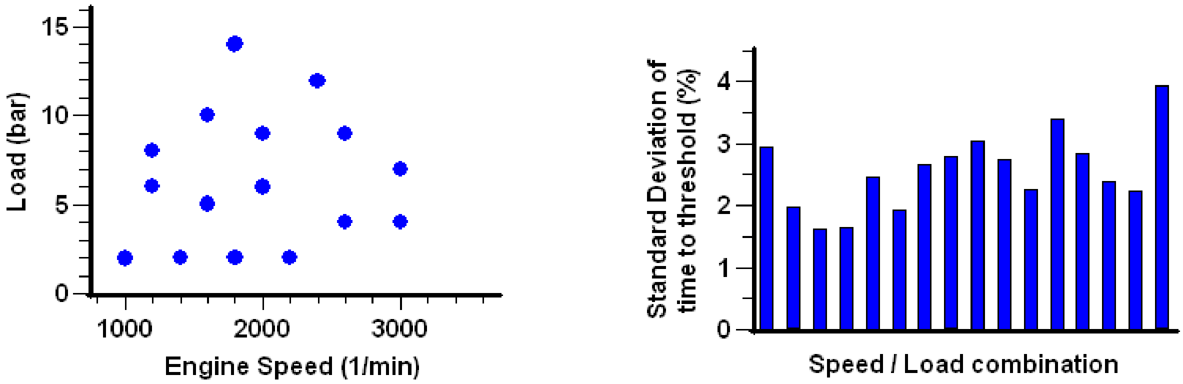

Figure 5: Repeatability (right) of Bosch PM sensor as measured at a selection of speed / load combinations (left) within the engine map of a 4-cyl. / 2.2l common rail engine with DPF.

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).

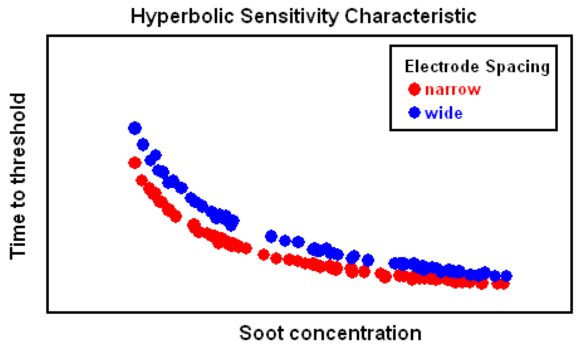

Figure 6: Hyperbolic relationship between soot concentration and time to threshold of the sensor signal as measured on a 4-cyl. / 2.2l common rail engine equipped with DPF and variable bypass.

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.

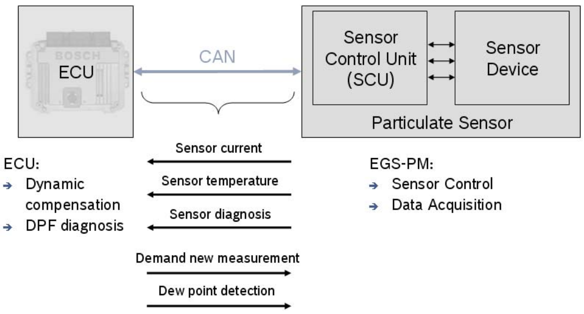

Figure 7: DPF OBD by means of EGS-PM - system view.

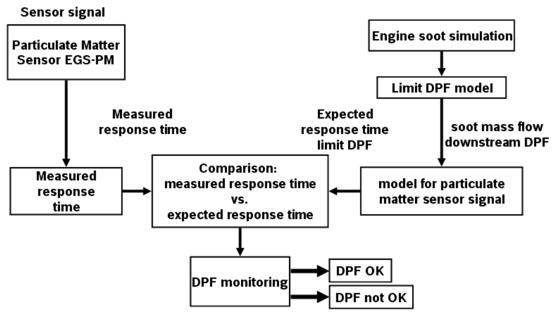

Figure 8: DPF OBD monitoring concept based on EGS-PM sensor signal.

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

[1] California Code of Regulations, Title 13, section 1968.2, Malfunction and Diagnostic System Requirements for 2004 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles and Engines (OBD II)

[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)

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Zürich, August 3rd 2010

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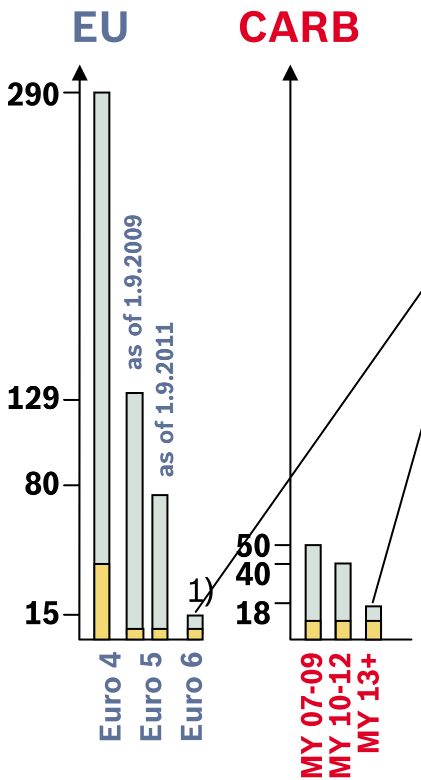
Legislation

PM [mg/mi]



OBD limits   emission standards

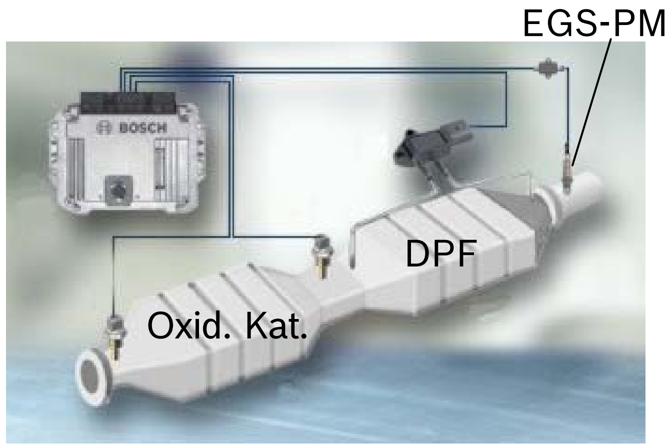
1) preliminary Commission-proposal

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)



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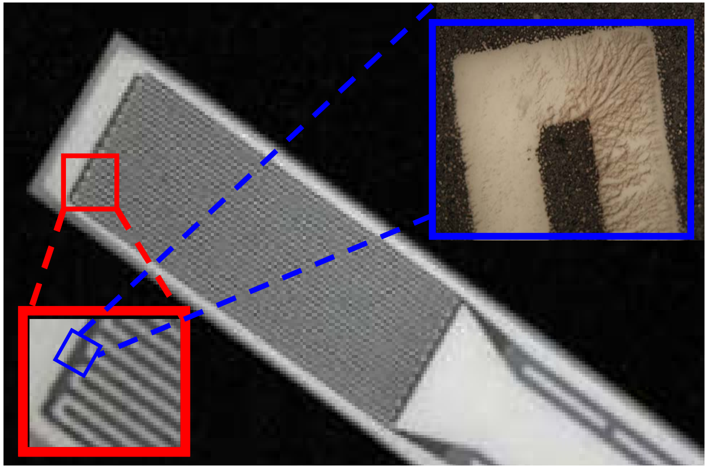
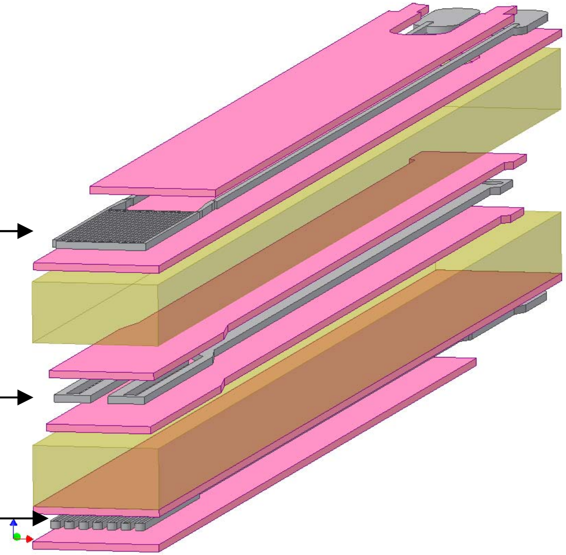
Resistive soot sensor: Overview



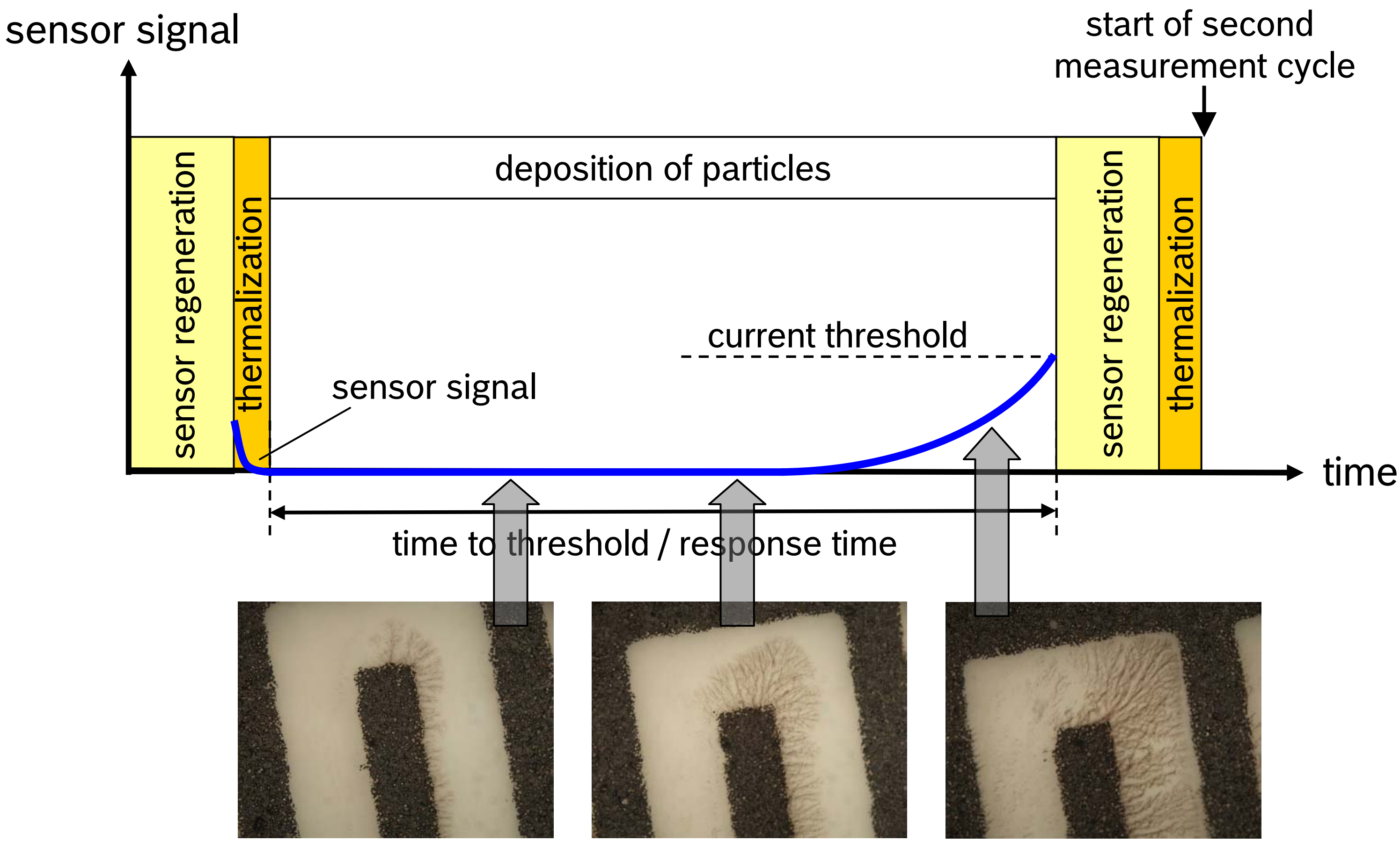
electrode structure
on ceramic substrate



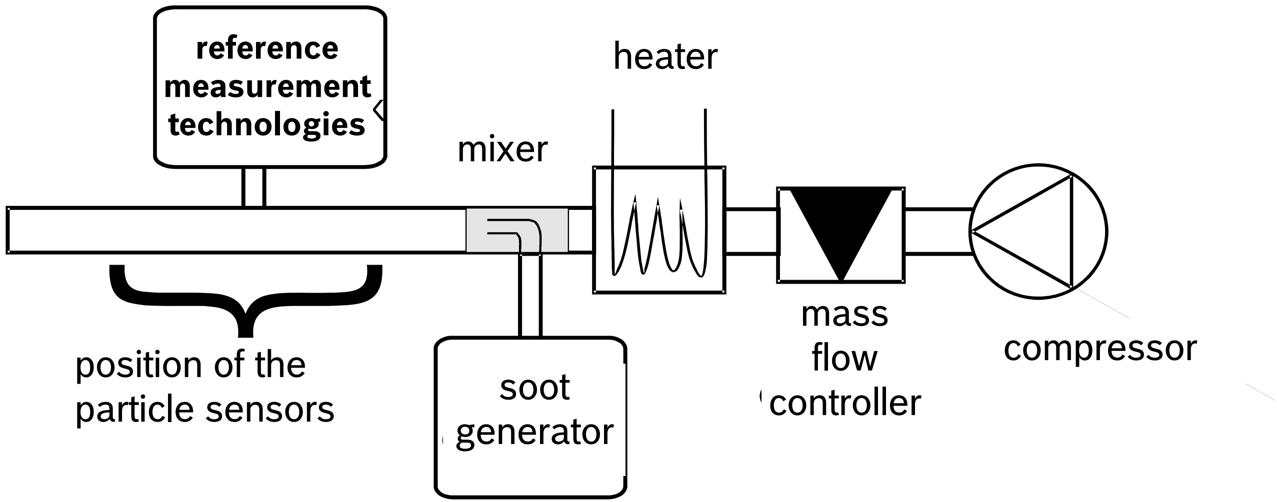
Schematic drawing of the sensing element

- 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

Schematic view of sensor signal over time



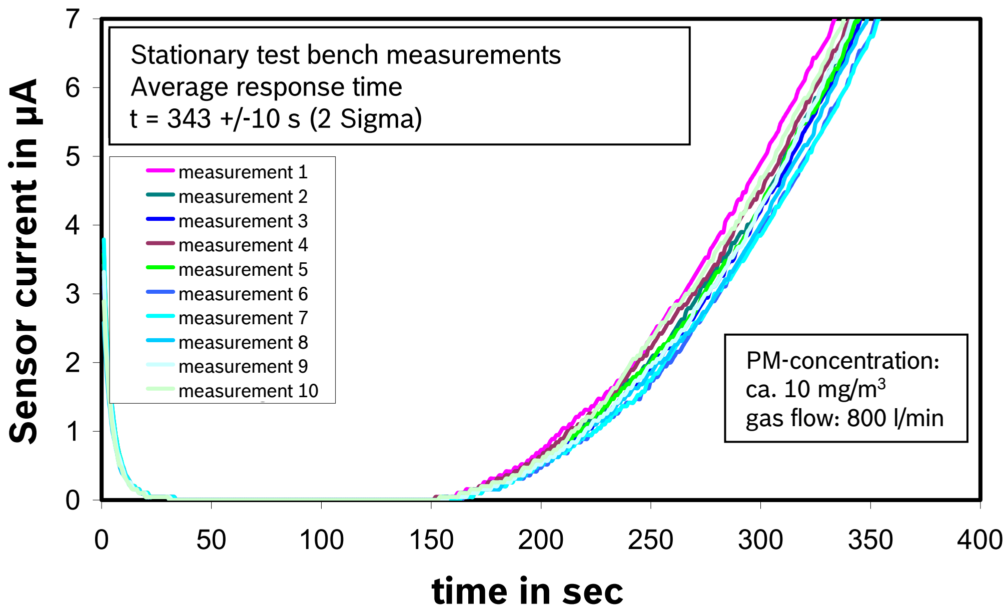
Schematic setup of the artificial soot particle test bench



- 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

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)



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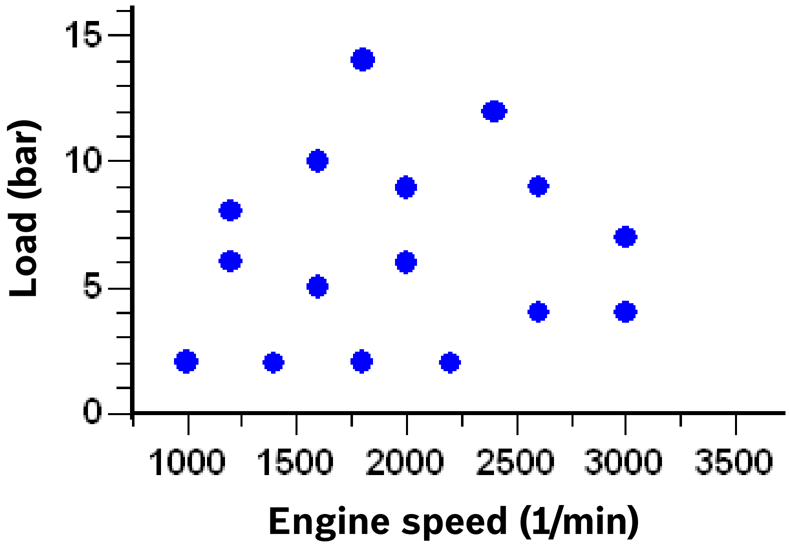
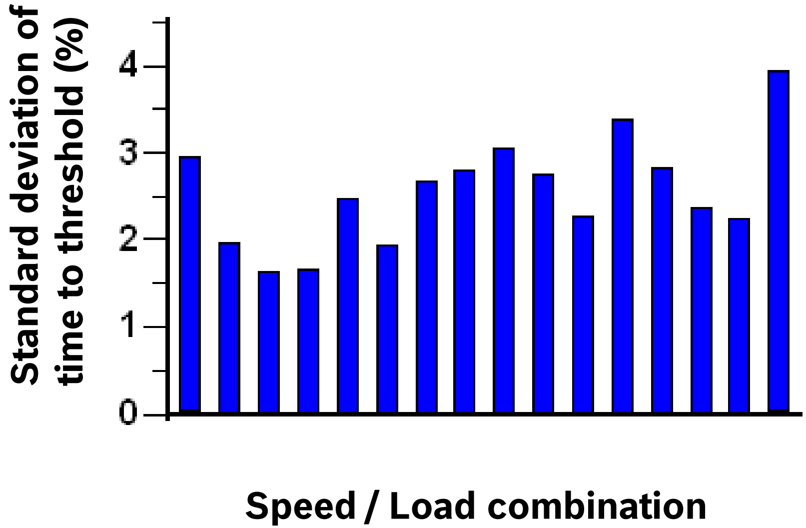
Repeatability – steady-state engine operation

engine test bench
4-cyl. / 2.2l / CRS





➔ Excellent repeatability throughout wide range of engine map

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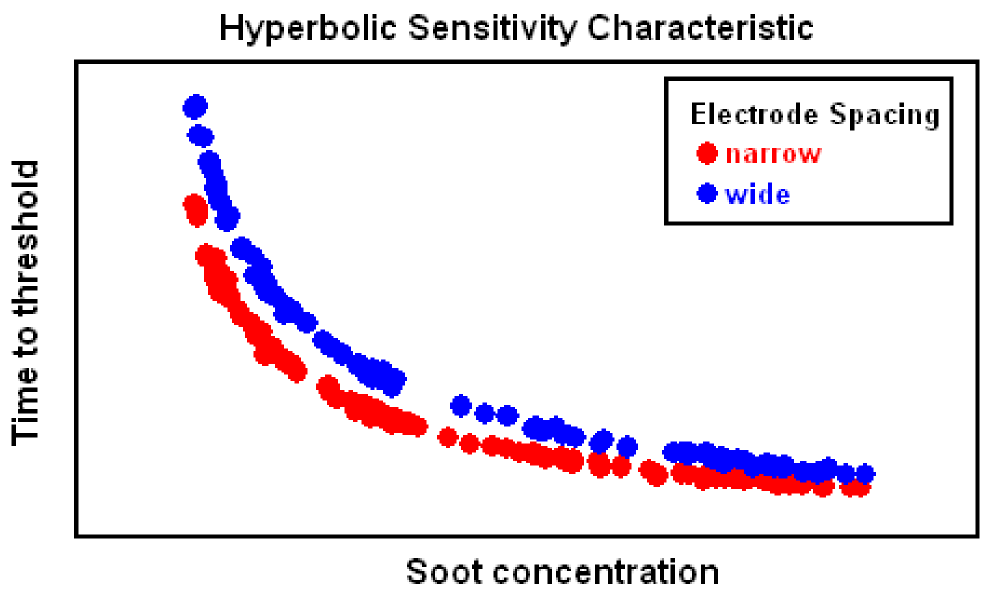
Regeneration interval vs. soot concentration

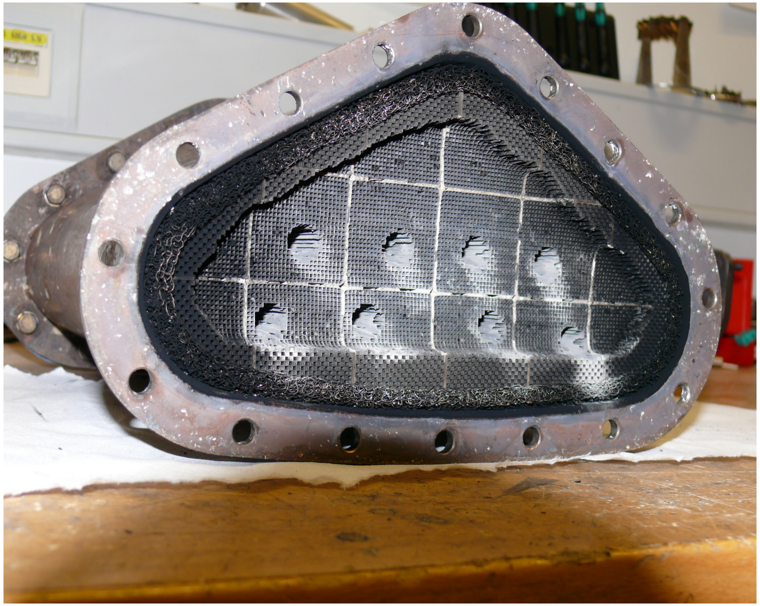


engine test bench
4-cyl. / 2.2l / CRS
adjustable DPF bypass

- "Natural" hyperbolic relationship between time-to-threshold und 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

Setup for the automotive exhaust line measurements

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



- Emission in FTP75 driving cycle:
  PM ≈ 18 - 19 mg/mi

- Measurements done on a chassis dynamometer using a car with a common European calibration setup (6cylinders, engine displacement of 3l)
- Sensor placed 655mm downstream DPF

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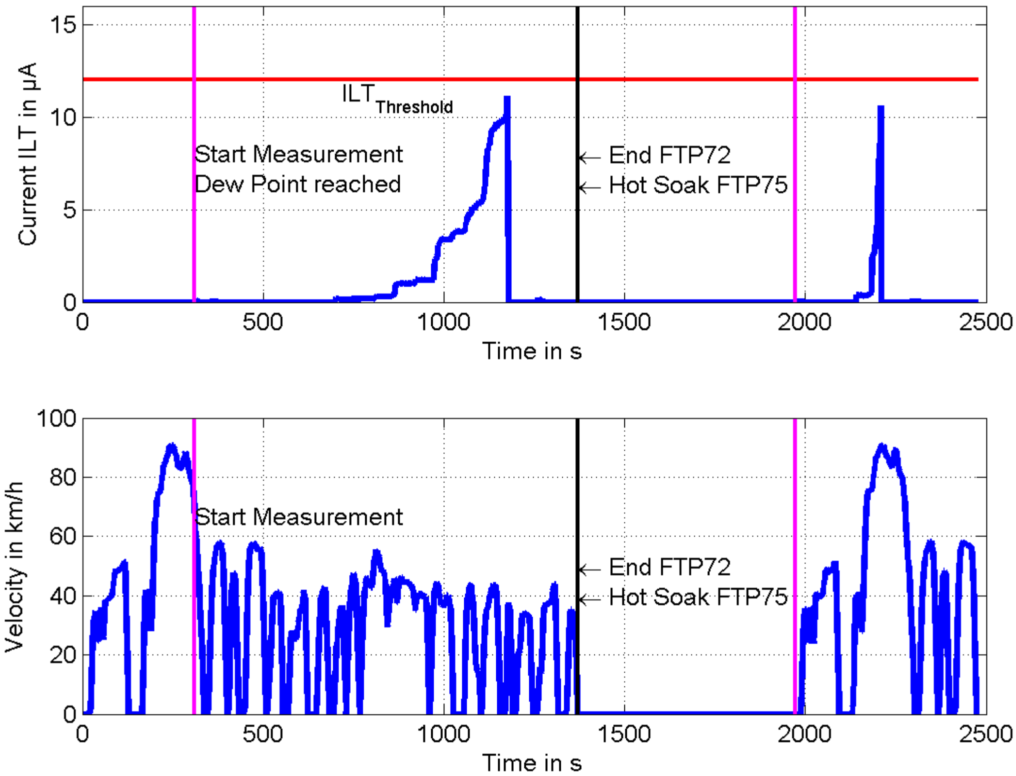
FTP75 Cycle, 3 l Common Rail (DPF 18 mg/mi)



- ➔ 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

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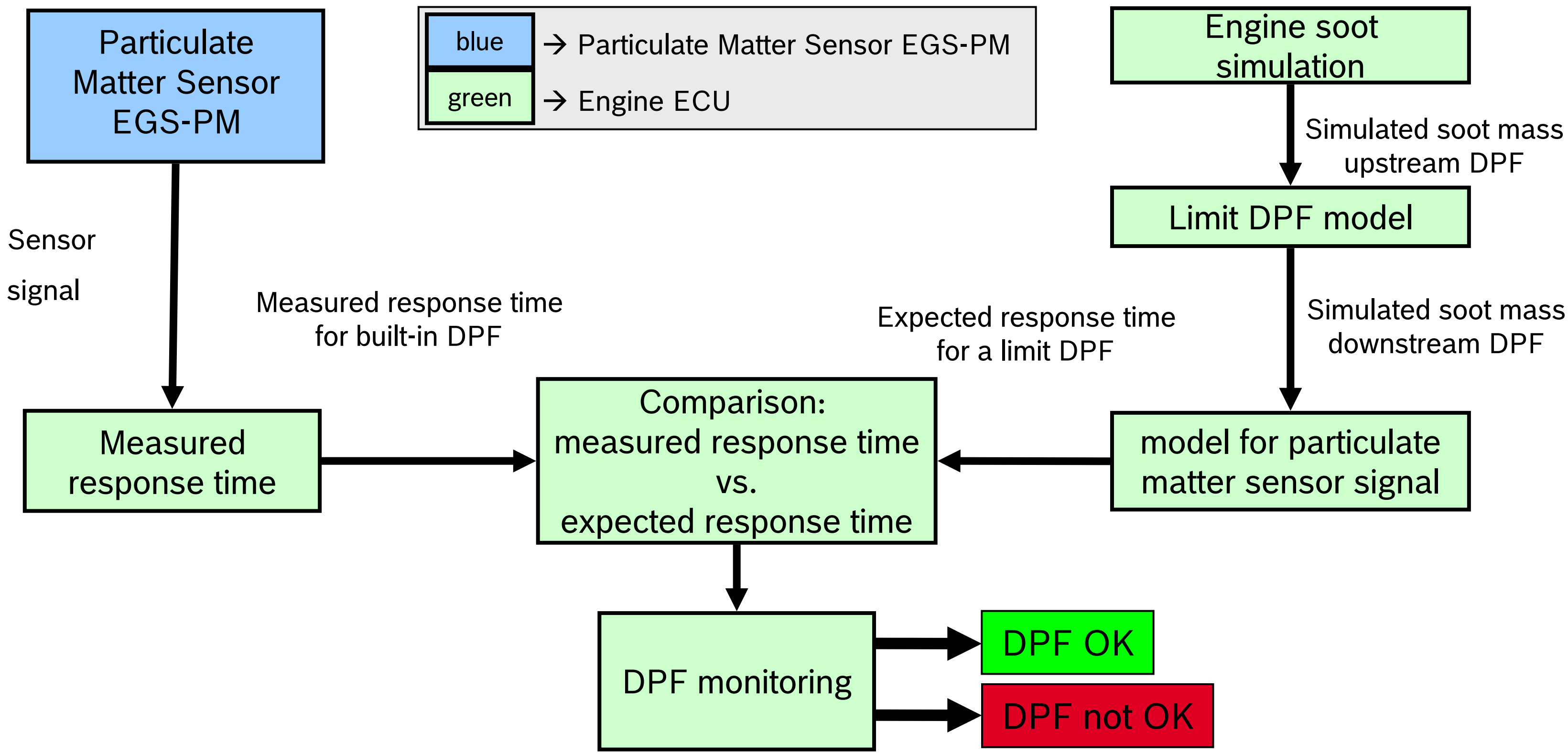
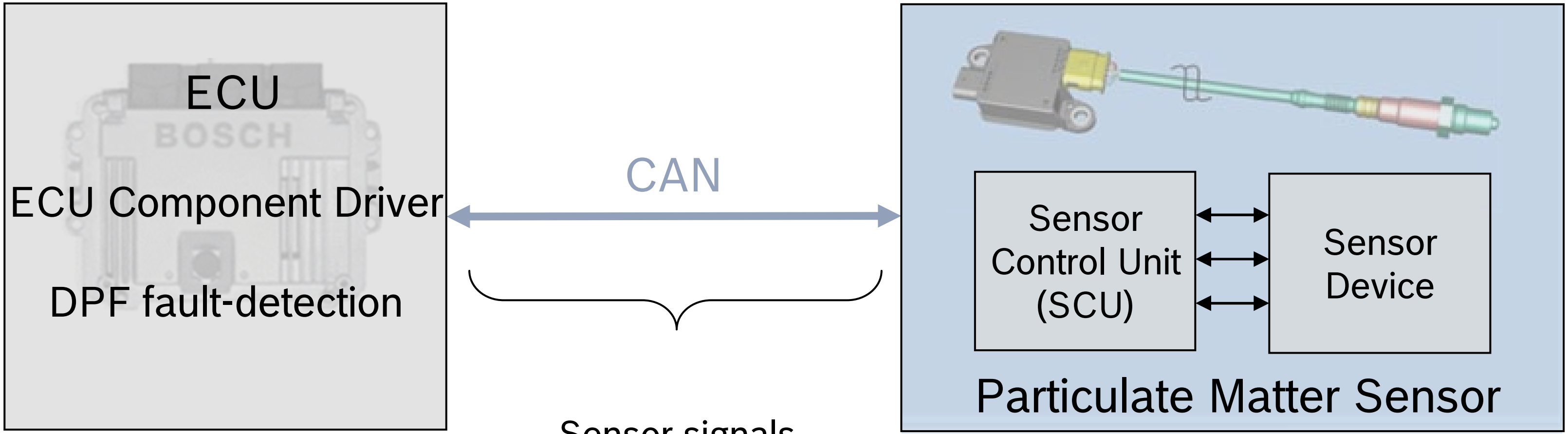
DPF monitoring concept



System view



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

← Sensor signals

← Sensor diagnostics

Demand new measurement →

Dew point detection →

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

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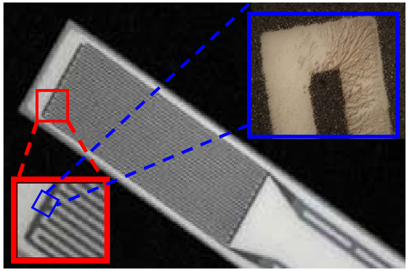
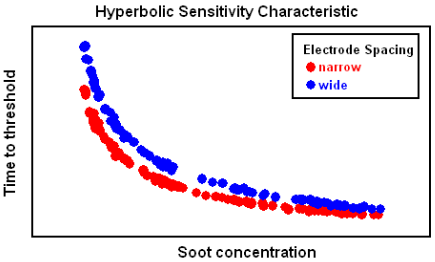
Summary/Conclusions



- 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

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