
# SOOT SENSOR FOR EMISSION ONBOARD CONTROL SYSTEMS

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**Emissions Legislation**

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- Sequential Measuring with Delphi PM Sensor
- Continuous Measuring with SDSS

**Principle Behind SDSS**

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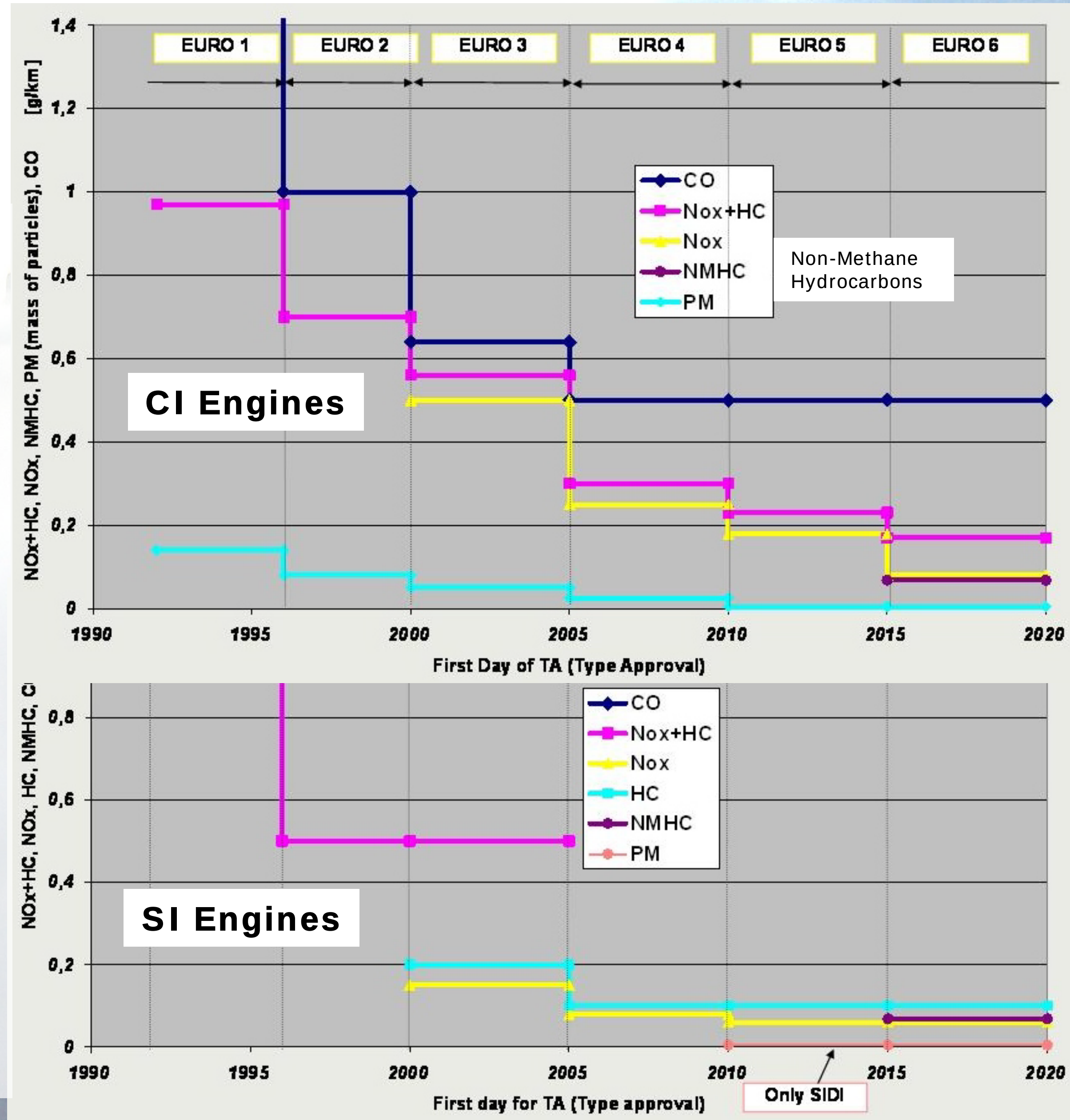
- Blower Test Bed with Artificial Engine Soot
- SI MPI Engine Test Bed

**Conclusion and Outlook**

# ENGINE EMISSIONS LEGISLATION EVOLUTION

**Standard Measured**

- Future standards and legislations for the **soot emission** (**PM**) and the **particle counting** (**PC**) requirements have need of new measurement technologies of soot concentration at **CI** and **SI** engines.

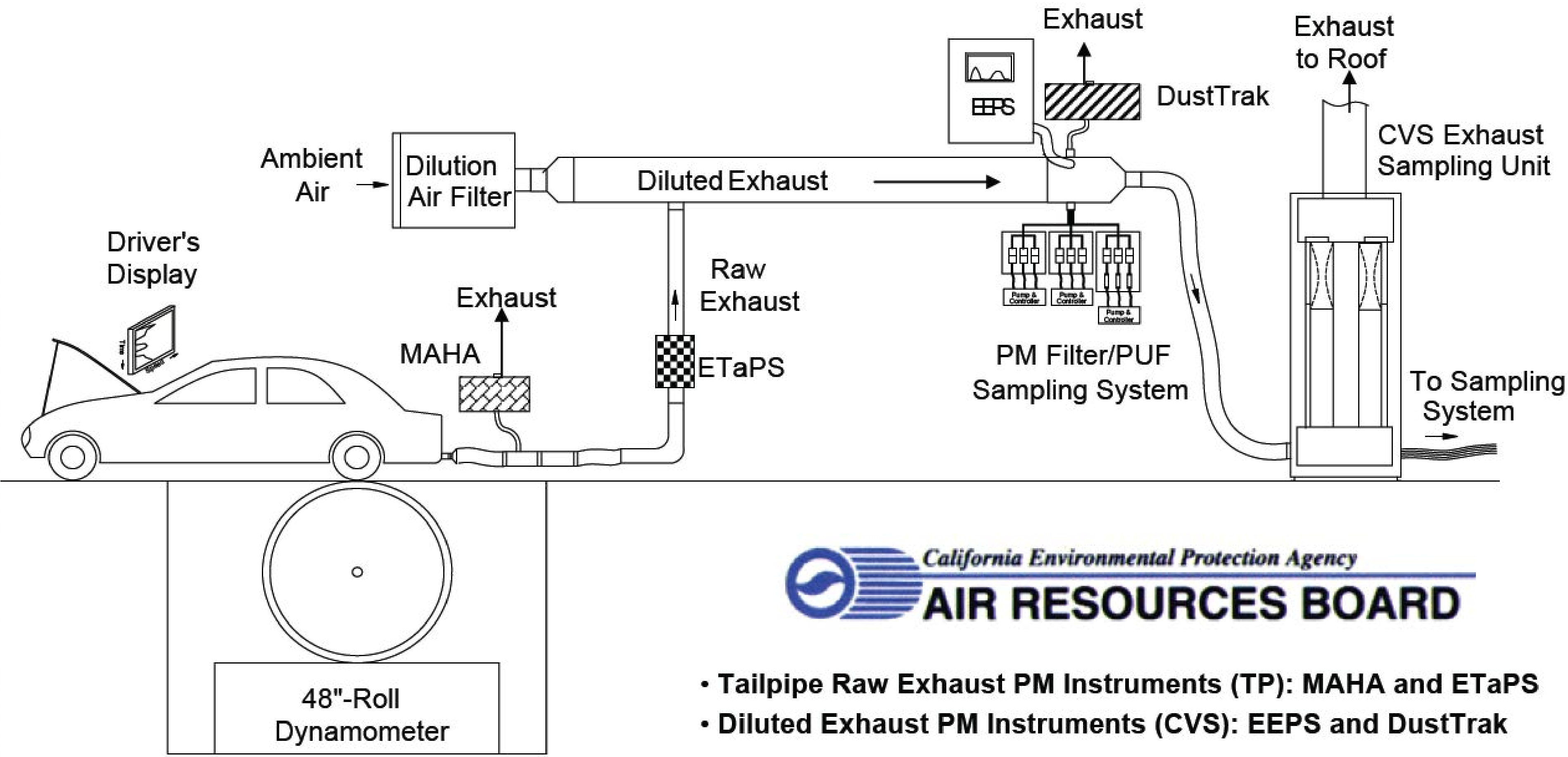



**OBD Soot Sensors**

- For monitoring and gauging the loading degree of DPF
- **To control the soot emissions in closed loop.**

# STANDARD REAL-TIME PM MEASURES

## LAB TEST SETUP




California Environmental Protection Agency
AIR RESOURCES BOARD

- **Tailpipe Raw Exhaust PM Instruments (TP): MAHA and ETaPS**
- **Diluted Exhaust PM Instruments (CVS): EEPS and DustTrak**

Source:

EVALUATION OF HIGH PM EMITTING **LIGHT DUTY GASOLINE** VEHICLES AND POTENTIAL REPAIR BENEFITS: PRELIMINARY RESULTS
19th CRC ON-ROAD VEHICLE EMISSIONS WORKSHOP, March, 2009 San Diego, California

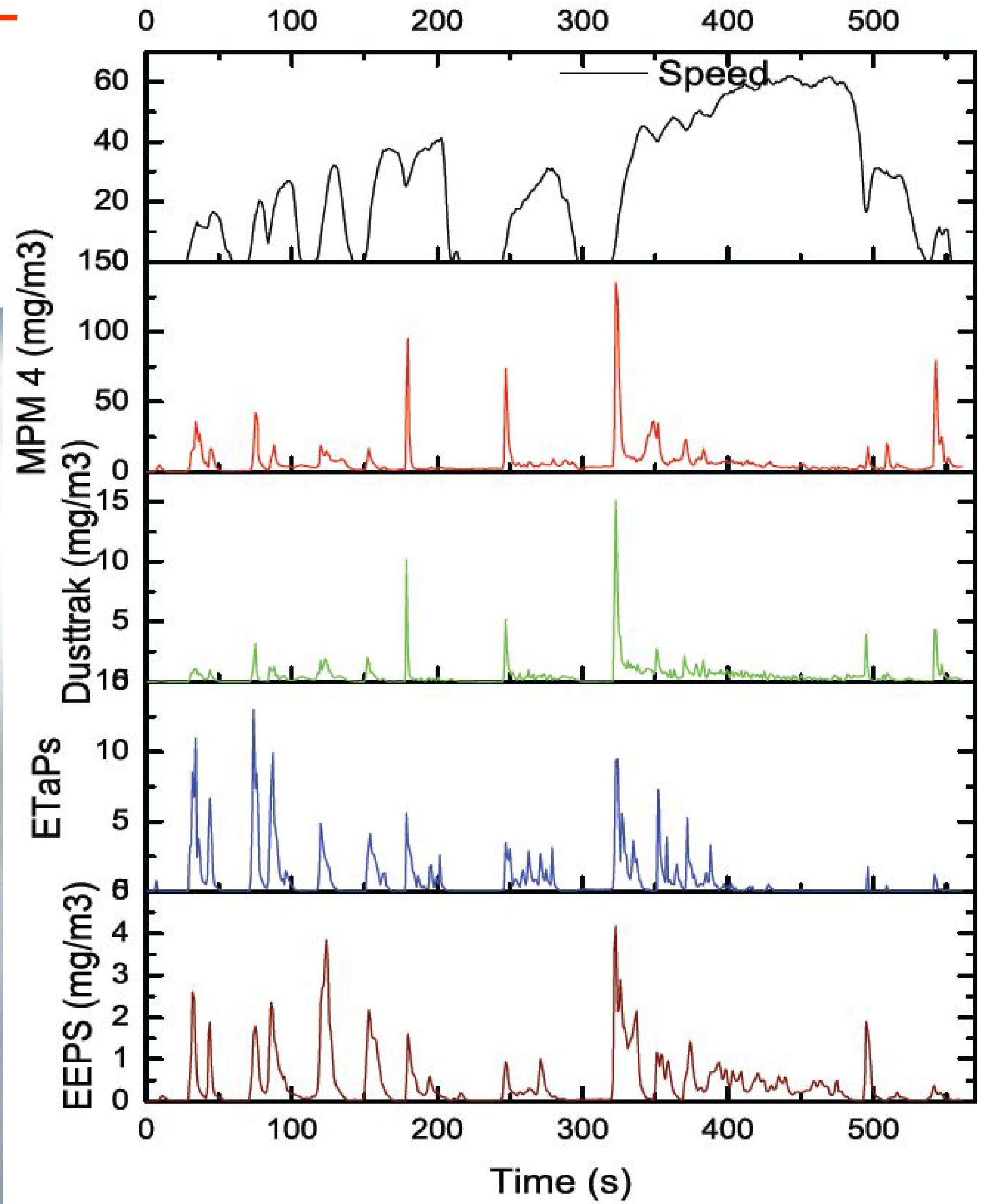
# *STANDARD REAL-TIME PM MEASURES*

## Used Instruments

- **Tailpipe Raw Exhaust** PM Instruments (**TP**):
  - MPM4 (MAHA) and ETaPS
- **Diluted Exhaust** PM Instruments (**CVS**):
  - EEPS and DustTrak

## Conclusion

- Each instrument measures soot concentration slightly different, i.e. they are sensitive to different soot components
- Even the SI (homogeneous mixture formation) and not only SIDI engines emit **relative much soot**



# STANDARD MEASURED APROVED / PROPOSED LEGISLATION

Source: Delphi

## Heavy-Duty

**Euro VI engine emissions (Reg EC No: 595/2009 and (EU) No 582/2011)**
Scope: M1, M2, N1, N2 with RM > 2,610 kg
Application dates: TA 31DEC12 FR 31DEC13

| | CO | THC | NMHC | CH4 | NOx [1] | $NH_3$ | PM Mass | PM [2] Number |
|---|---|---|---|---|---|---|---|---|
| | mg/kWh | | | | | ppm | mg/kWh | #/kWh |
| WHSC (C.I.) | 1,500 | 130 | | | 400 | 10 | 10 | $8.0 \times 10^{11}$ |
| WHTC (C.I.) | 4,000 | 160 | | | 460 | 10 | 10 | $6.0 \times 10^{11}$ |
| WHTC (P.I.) | 4,000 | | 160 | 500 | 460 | 10 | 10 | [3] |

C.I. Compression Ignition P.I. Positive Ignition

1) Admissible level of $NO_2$ may be defined later
2) Measurement procedure to be introduced by 31Dec12
3) Particle number limit shall be introduced by 31Dec12

WHSC, WHTC see pages 6-7

## Passenger Cars and Light-Duty

**Vehicle Scope:** M1 and M2, N1 and N2 vehicles as defined in Directive 70/156/EC with reference mass ≤ 2,610 kg
Extension possible at the manufacturer's request to M1, M2, N1, N2 with reference mass ≤ 2,840 kg

### EURO 5 & 6 SPARK IGNITION EMISSION LIMITS

| Emissions | Unit | PC M[1], LDT N1 CL 1 | | | | LDT N1 Cl 2 | | | | LDT N1 Cl 3, N2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6- 2 | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6- 2 | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6-2 |
| THC | mg/km | 100 | 100 | 100 | 100 | 130 | 130 | 130 | 130 | 160 | 160 | 160 | 160 |
| NMHC | | 68 | 68 | 68 | 68 | 90 | 90 | 90 | 90 | 108 | 108 | 108 | 108 |
| NOx | | 60 | 60 | 60 | 60 | 75 | 75 | 75 | 75 | 82 | 82 | 82 | 82 |
| CO | | 1000 | 1000 | 1000 | 1000 | 1810 | 1810 | 1810 | 1810 | 2270 | 2270 | 2270 | 2270 |
| PM [2] [3] | | 5,0 | 4,5 | 4,5 [2] | 4,5 [2] | 5,0 | 4,5 | 4,5 | 4,5 | 5,0 | 4,5 | 4,5 | 4,5 |
| PN # [3] | Nb/km | - | - | 6,0 * E11 [4] | 6,0 * E11 | - | - | 6,0 * E11 [4] | 6,0 * E11 | - | - | 6,0 * E11 [4] | 6,0 * E11 |

1) No exemption for gasoline Passenger Car 2) Applicable to gasoline DI engines only 3) Test procedure defined in UN Reg 83 Suppl 7
4) Until 3 years after the dates for type approval / 1st registration particle emission limit of 6,0 x E12 may be applied to Euro 6 spark ignition DI vehicles upon request of manufacturer

### EURO 5 & 6 COMPRESSION IGNITION EMISSION LIMITS

| Emissions | Unit | PC M[1], LDT N1 CL 1 | | | LDT N1 Cl 2 | | | LDT N1 Cl 3, N2 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 |
| NOx | mg/km | 180 | 180 | 80 | 235 | 235 | 105 | 280 | 280 | 125 |
| HC+NOx | | 230 | 230 | 170 | 295 | 295 | 195 | 350 | 350 | 215 |
| CO | | 500 | 500 | 500 | 630 | 630 | 630 | 740 | 740 | 740 |
| PM [2] | | 5,0 | 4,5 | 4,5 | 5,0 | 5,0 | 4,5 | 5,0 | 5,0 | 4,5 |
| PN # | Nb/km | - | 6,0 * E11 | 6,0 * E11 | - | 6,0 * E11 | 6,0 * E11 | - | 6,0 * E11 | 6,0 * E11 |

1) Exempted M1 vehicles have to comply with N1Cl3 test I emissions limits - No more exemption for passenger cars from Euro 6
2) Test procedure defined in UN Reg 83 Suppl 7

# STANDARD MEASURED **PM** & **PN** LEGISLATIONS

Source: Delphi

**Heavy-Duty**

**Euro VI engine emissions (Reg EC No: 595/2009 and (EU) No 582/2011)**
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**Passenger Cars and Light-Duty**

**EURO 5 & 6 SPARK IGNITION EMISSION LIMITS**

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6- 2 | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6- 2 | Euro 5a | Euro 5b/b+ | Euro 6-1 | Euro 6-2 |
| THC | mg/km | 100 | 100 | 100 | 100 | 130 | 130 | 130 | 130 | 160 | 160 | 160 | 160 |
| NMHC | | 68 | 68 | 68 | 68 | 90 | 90 | 90 | 90 | 108 | 108 | 108 | 108 |
| NOx | | 60 | 60 | 60 | 60 | 75 | 75 | 75 | 75 | 82 | 82 | 82 | 82 |
| CO | | 1000 | 1000 | 1000 | 1000 | 1810 | 1810 | 1810 | 1810 | 2270 | 2270 | 2270 | 2270 |
| PM [2,3] | | 5,0 | 4,5 | 4,5 [2] | 4,5 [2] | 5,0 | 4,5 | 4,5 | 4,5 | 5,0 | 4,5 | 4,5 | 4,5 |
| PN # [3] | Nb/km | - | - | 6,0 * E11 [4] | 6,0 * E11 | - | - | 6,0 * E11 [4] | 6,0 * E11 | - | - | 6,0 * E11 [4] | 6,0 * E11 |

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**EURO 5 & 6 COMPRESSION IGNITION EMISSION LIMITS**

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|---|---|---|---|---|---|---|---|---|---|---|
| | | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 | Euro 5a | Euro 5b/b+ | Euro 6-1 / 6-2 |
| NOx | mg/km | 180 | 180 | 80 | 235 | 235 | 105 | 280 | 280 | 125 |
| HC+NOx | | 230 | 230 | 170 | 295 | 295 | 195 | 350 | 350 | 215 |
| CO | | 500 | 500 | 500 | 630 | 630 | 630 | 740 | 740 | 740 |
| PM [2] | | 5,0 | 4,5 | 4,5 | 5,0 | 5,0 | 4,5 | 5,0 | 5,0 | 4,5 |
| PN # | Nb/km | - | 6,0 * E11 | 6,0 * E11 | - | 6,0 * E11 | 6,0 * E11 | - | 6,0 * E11 | 6,0 * E11 |

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[2] Test procedure defined in UN Reg 83 Suppl 7

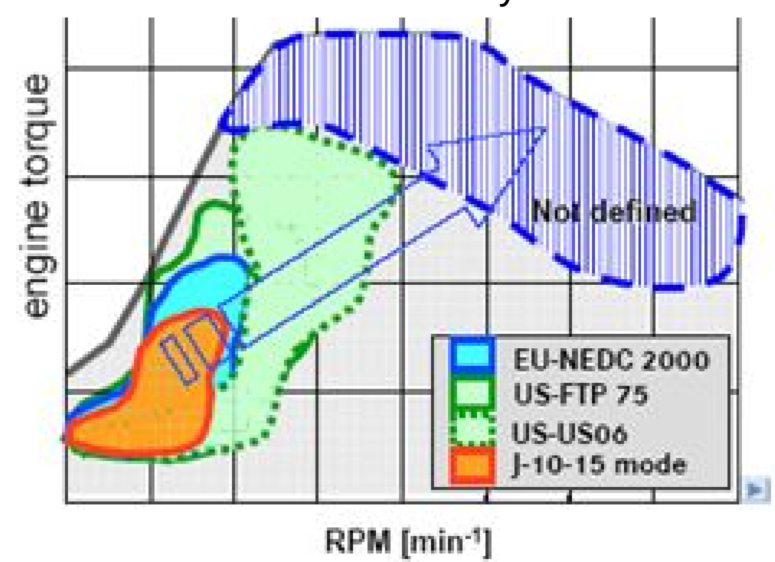
# STANDARD MEASURED AND **OBD** LEGISLATION

| EURO VI | | | |
|---|---|---|---|
| Heavy Duty / CI & PI | | Pass Car & Light Duty / SI (DI) & CI | |
| Phase in 01 Jan 2013 | | Phase in 01 Sep 2014 | |
| Standard measured **10** mg/kWh | **OBD** **40** mg/kWh | Standard measured **4.5** mg/km | **OBD** **25 – 30** mg/km |
| Final 01 Jan 2016 | | Final 01 Sep 2019 | |
| Standard measured **10** mg/kWh | **OBD** **25** mg/kWh | Standard measured **4.5** mg/km | **OBD** **12** mg/km |

## OBD Soot Sensors

- For monitoring and gauging the loading degree of DPF
  - **Delphi Sensor** for **Sequential** PM Measuring and for OBD of Particulate Filters
- **To control the soot emissions in closed loop**
  - **SDSS Sensor** for **Continuous** PM Measuring, for OBD of Particulate Filters and for Closed Loop PM Control

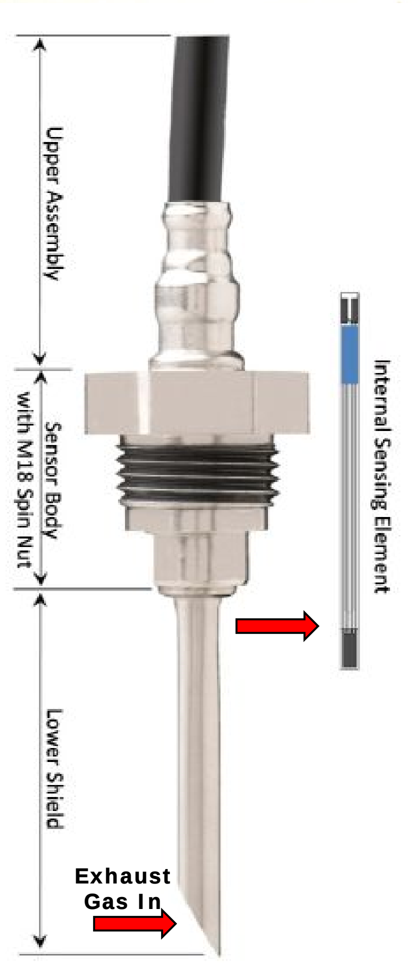
Proposed Future Extensions of Standard Drive Cycles

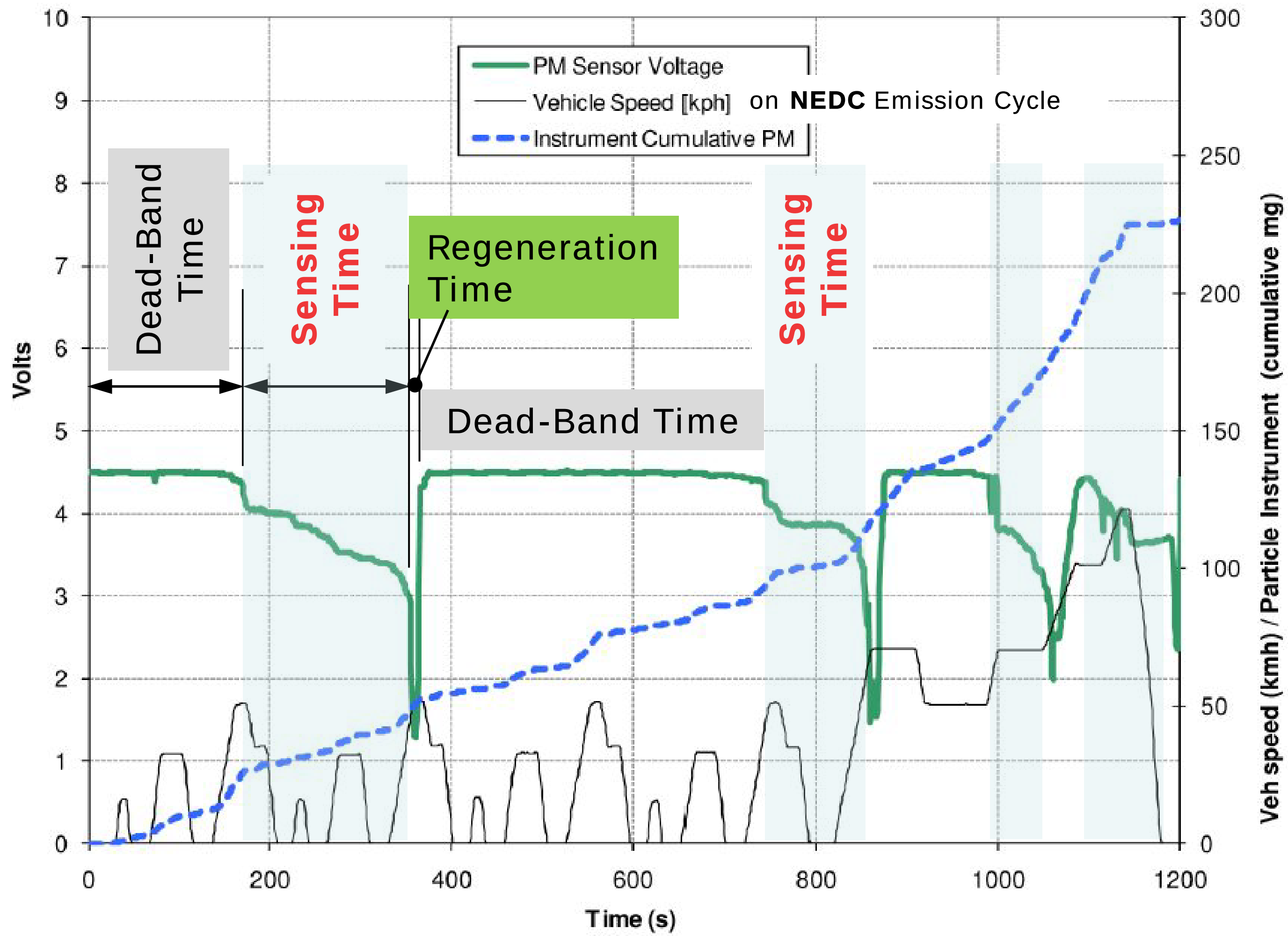


# ***SEQUENTIAL*** *MEASURING* ***OBD*** *SOOT SENSORS*

For monitoring and gauging the loading degree of DPF

- **Delphi Sensor** for **Sequential** PM Measuring and for OBD of Particulate Filters (Source: SAE Paper 2012-01-0372)

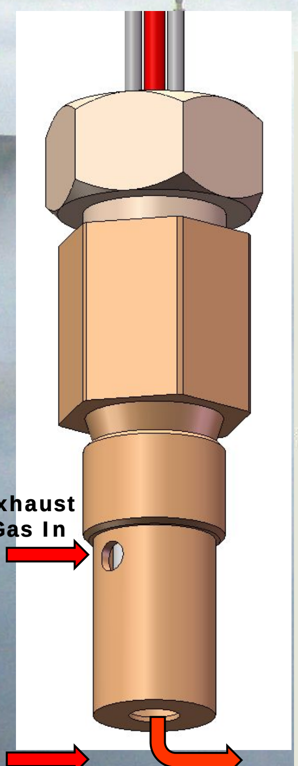


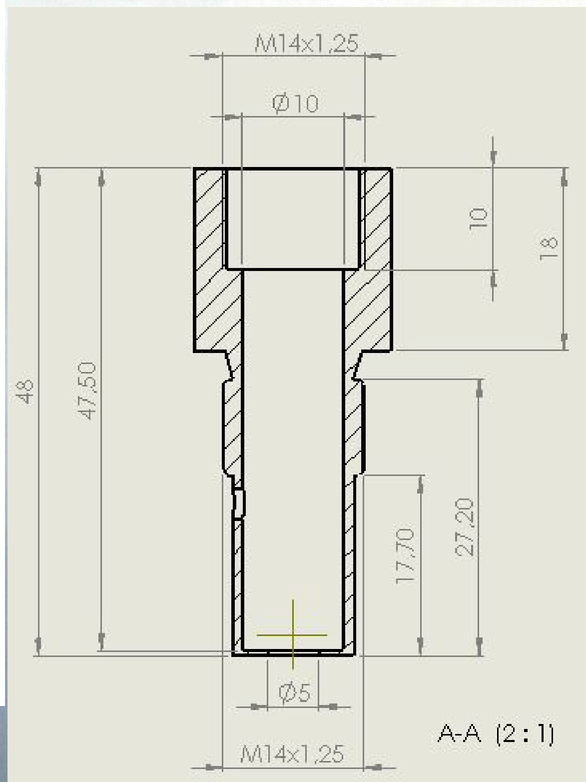



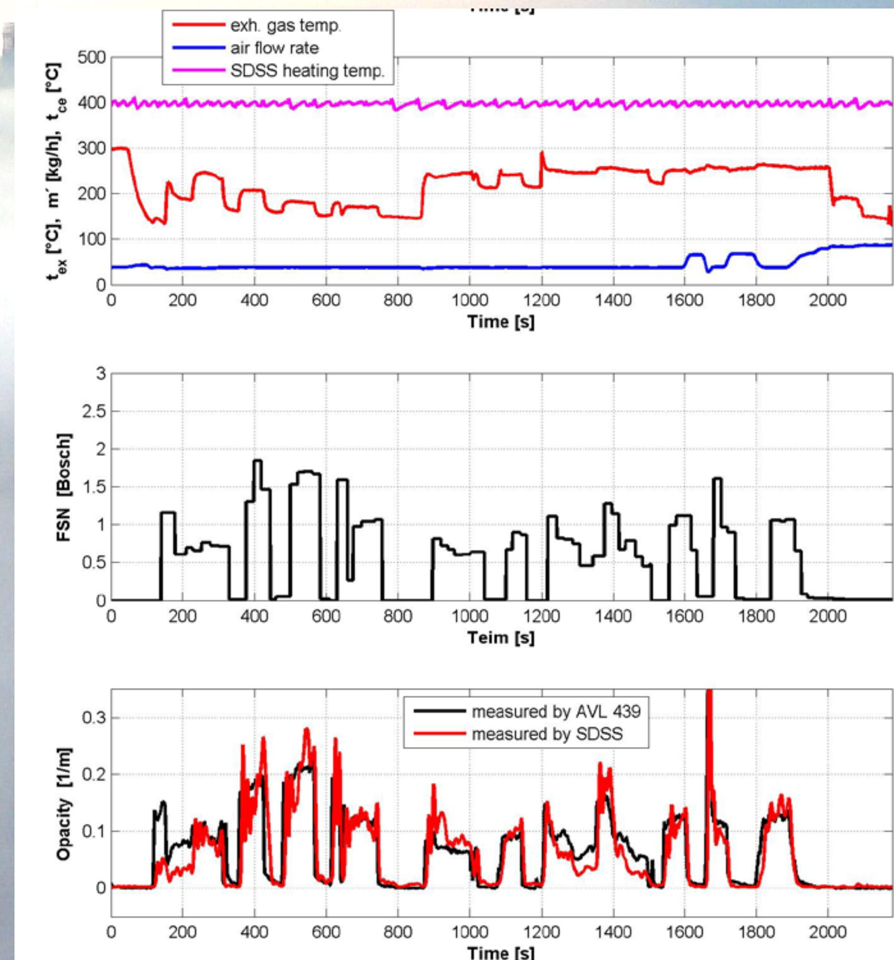
# *CONTINOUS MEASURING OBD SOOT SENSORS*

## To control the soot emissions in closed loop

- **Spark Discharge** Soot Sensor (**SDSS**) for **Continuous** PM Measuring**,** OBD of Particulate Filters and **Closed Loop PM Control**

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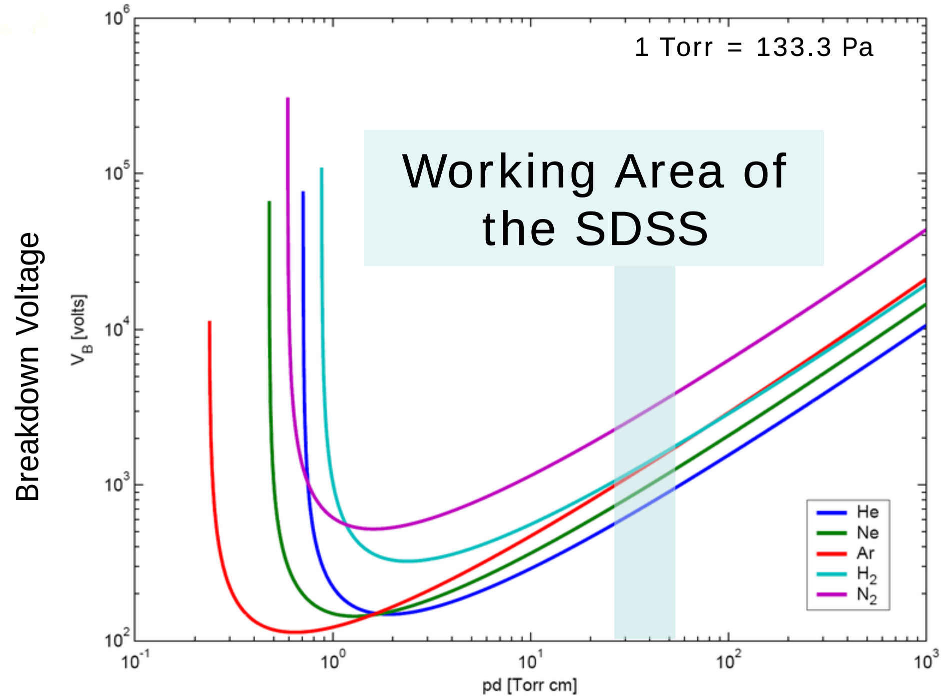
# PRINCIPLE BEHIND SDSS

- The **minimum spark discharge voltage** in gases depends primarily on the **electrode gap** and the state of the gases, including their temperature, pressure, flow 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 the figure.

Paschen Curves
Source: Wikipedia.org




Product of pressure (p) and electrode clearance (d)

- These dependencies are also known as "Paschen" curves and show the dependence of the breakdown voltage (**$U_D$**) of the product between gas pressure (**p**) and electrode clearance (**d**).

# PRINCIPLE BEHIND SDSS

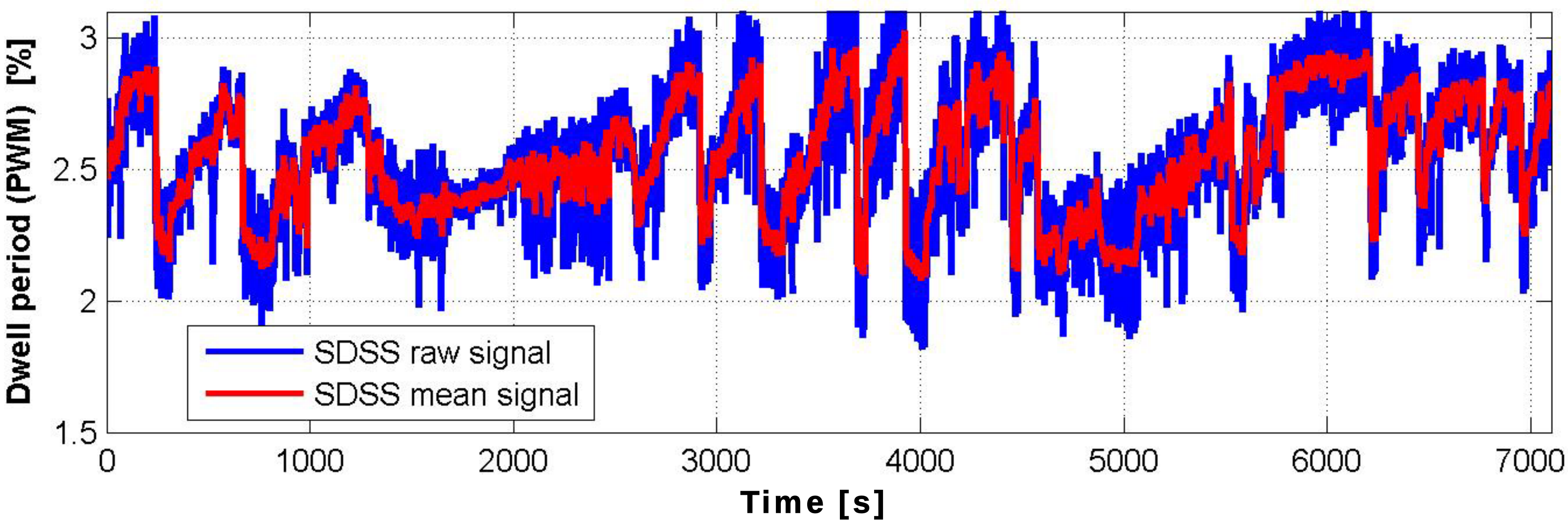
- Experiments have proven that **soot** (i.e. carbon) **particles** between and deposited on the electrodes facilitate the release of electrons by the electrical field. The required voltage for an electrical discharge falls by up to 70% as a result.

- It was also discovered that **soot particles** between and deposited on the electrodes 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 ±22%. In the presence of soot this range was reduced to ±4%, even in the case of very low soot concentrations.

- **The measurement method of the SDSS is based on determining the minimum level of the electrical spark voltage in the exhaust gas at which sparks occurs between two electrodes.**

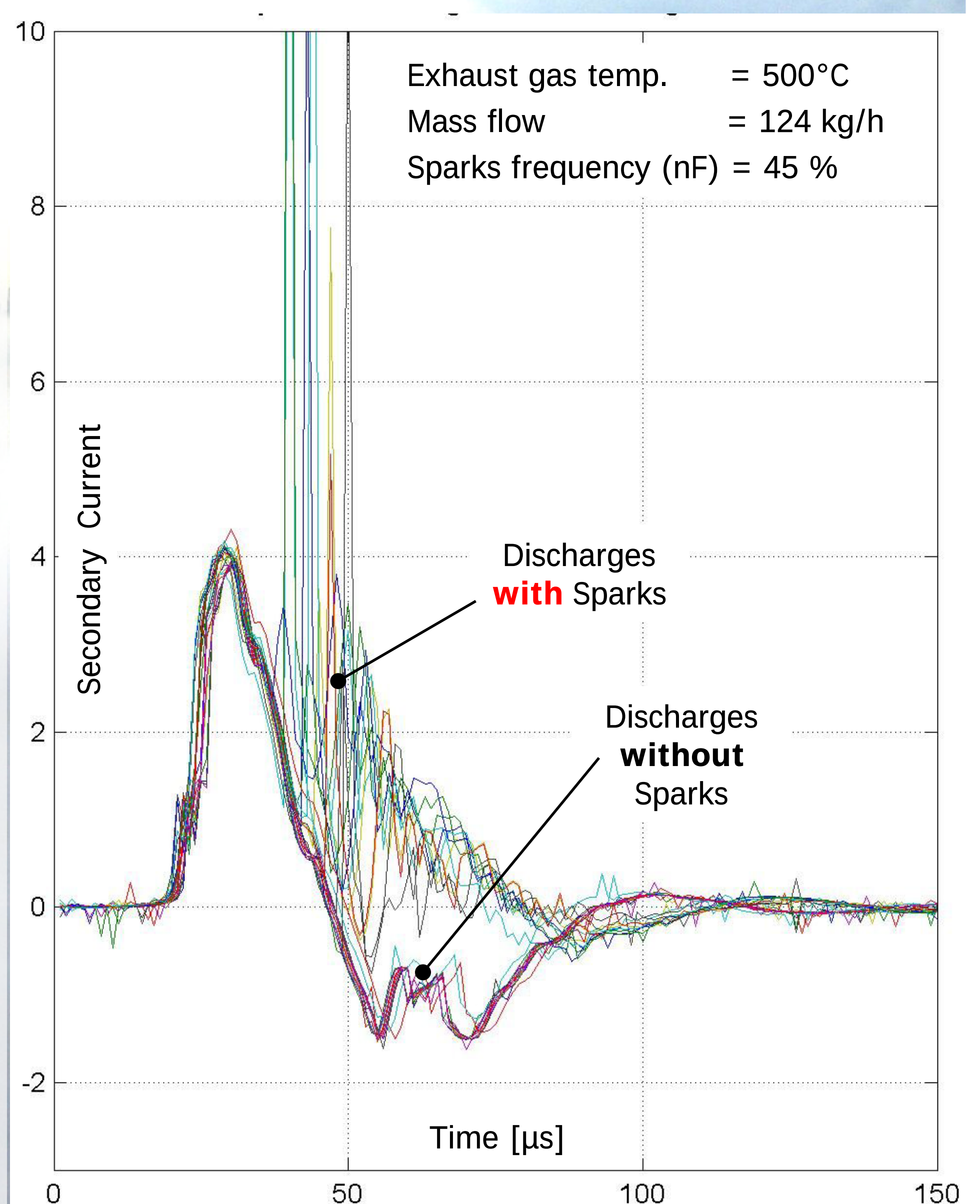
# PRINCIPLE BEHIND SDSS

- For searching the **minimum** electrical spark voltage level, the sensor Electronic Control Unit (**ECU**) charges a spark coil with a variable level of energy by means of **dwell period variation** (**PWM**, see figure).
- The spark coil is then discharged across the **SDSS 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.



# PRINCIPLE BEHIND SDSS

- The spark coil is then discharged across the **SDSS 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.
- 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 dwell period values (PWM) centre on the energy level (despite the static fluctuations in the sparking) which is actually required.



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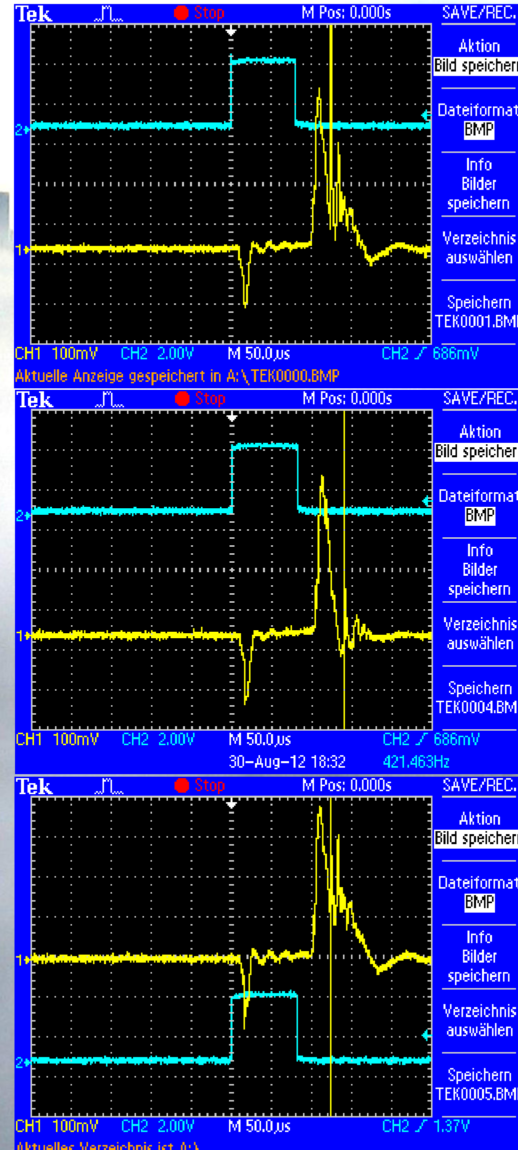
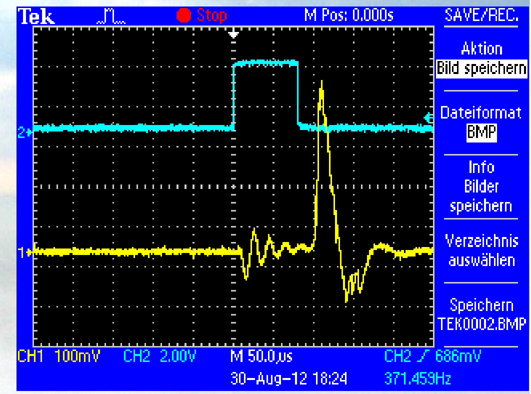
Discharges **with** Sparks




Discharge **without** Spark




Legend:
- Secondary Current (yellow)
- Dwell period (**PWM**) (cyan)

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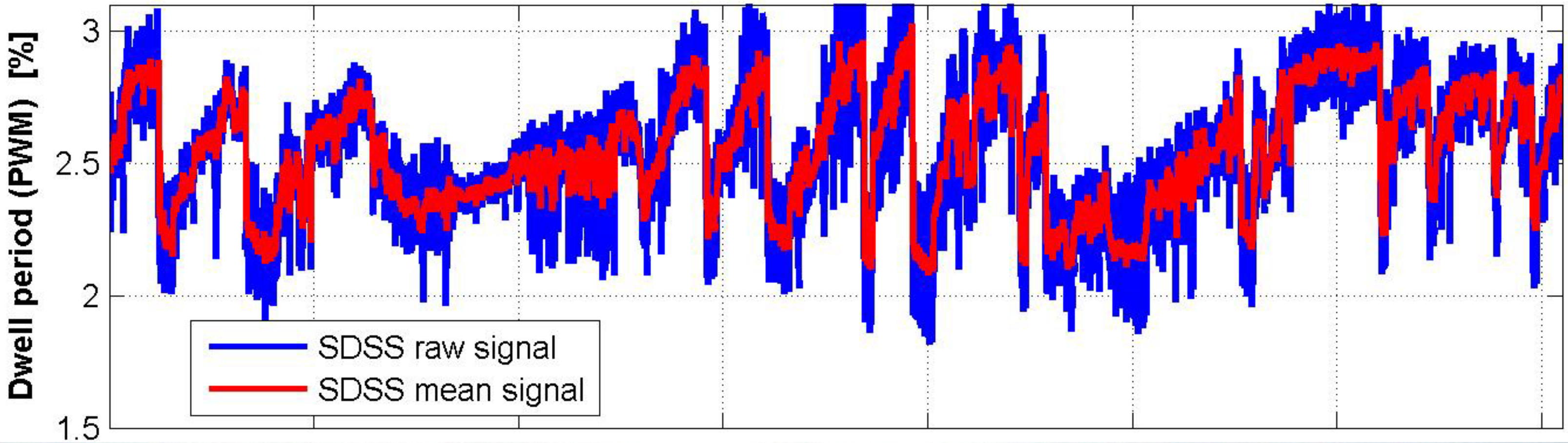
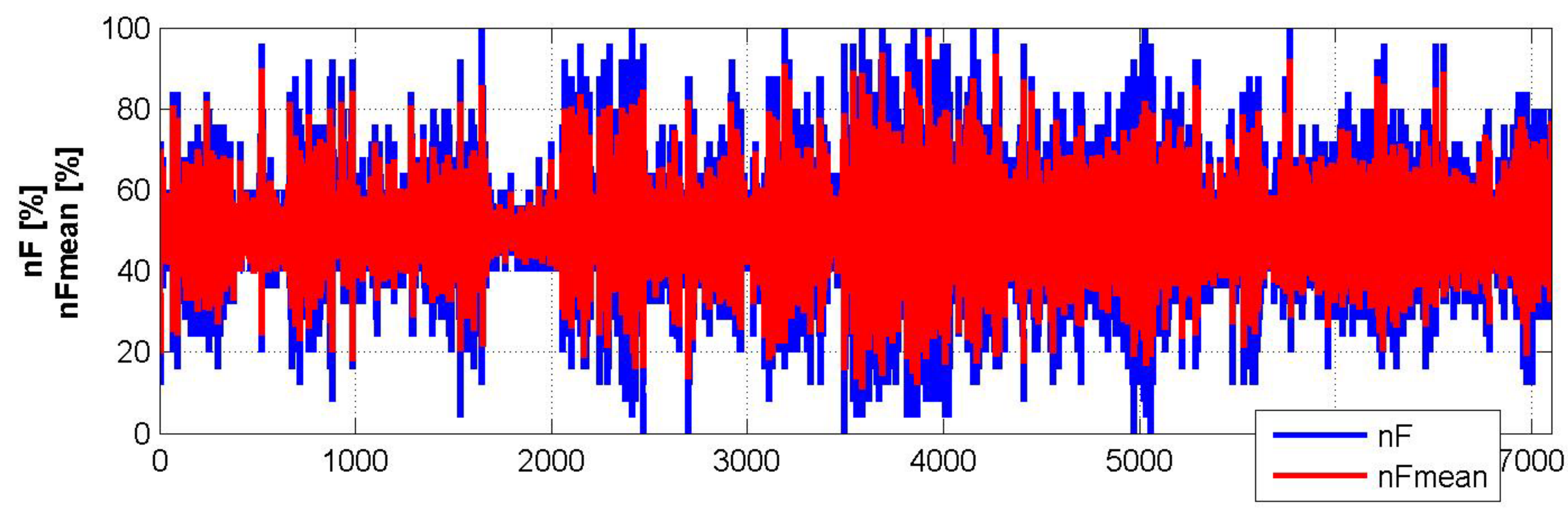
# *PRINCIPLE BEHIND SDSS*




The dwell period (**PWM**) values centre on the energy level (despite the static fluctuations in the sparking) which is actually required for nearly 50% sparks frequency

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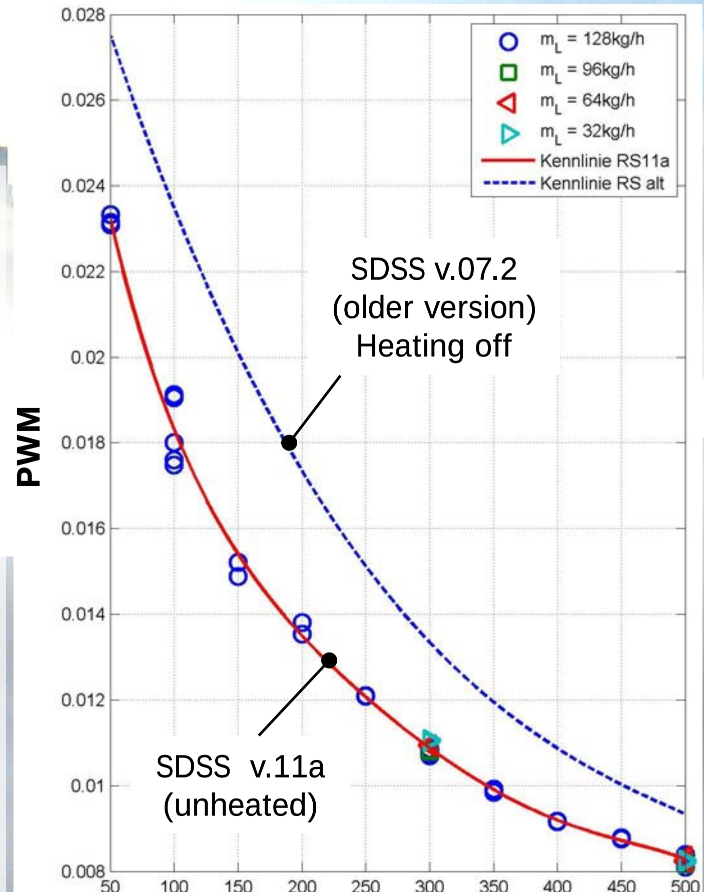
# PRINCIPLE BEHIND SDSS

## CROSS INFLUENCE PARAMETER

- In order to obtain dependence only between minimum sparking voltage (resp. **PWM** level) and soot concentration the influence of the other parameters, i.e. the **cross influences**, need to be known.
- Besides the minimum **PWM** level, all parameters which exert a significant **cross influence** such as temperature (s. figure), mass flow rate, air-fuel ratio, voltage supply etc. need to be acquired during the measurement.



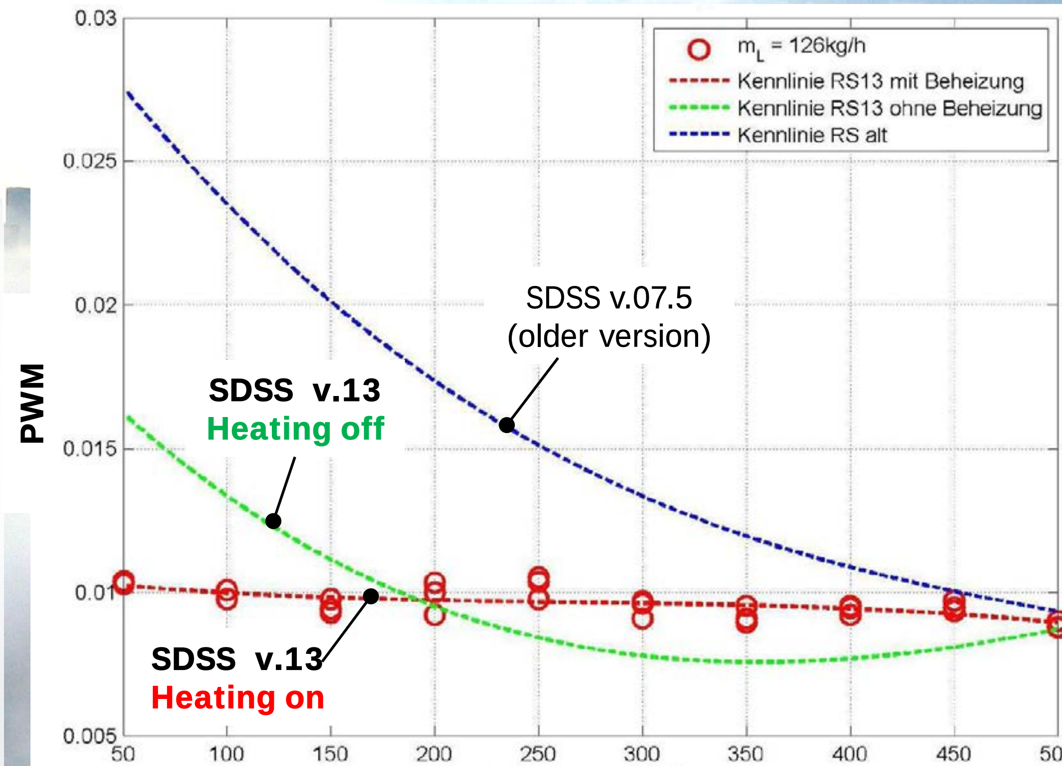

Characteristic lines **PWM, Fluid Temperature** (air) for many flow rates ($m_L$) and two sensor variants

SDSS v.11a

# PRINCIPLE BEHIND SDSS

## CROSS INFLUENCE PARAMETER

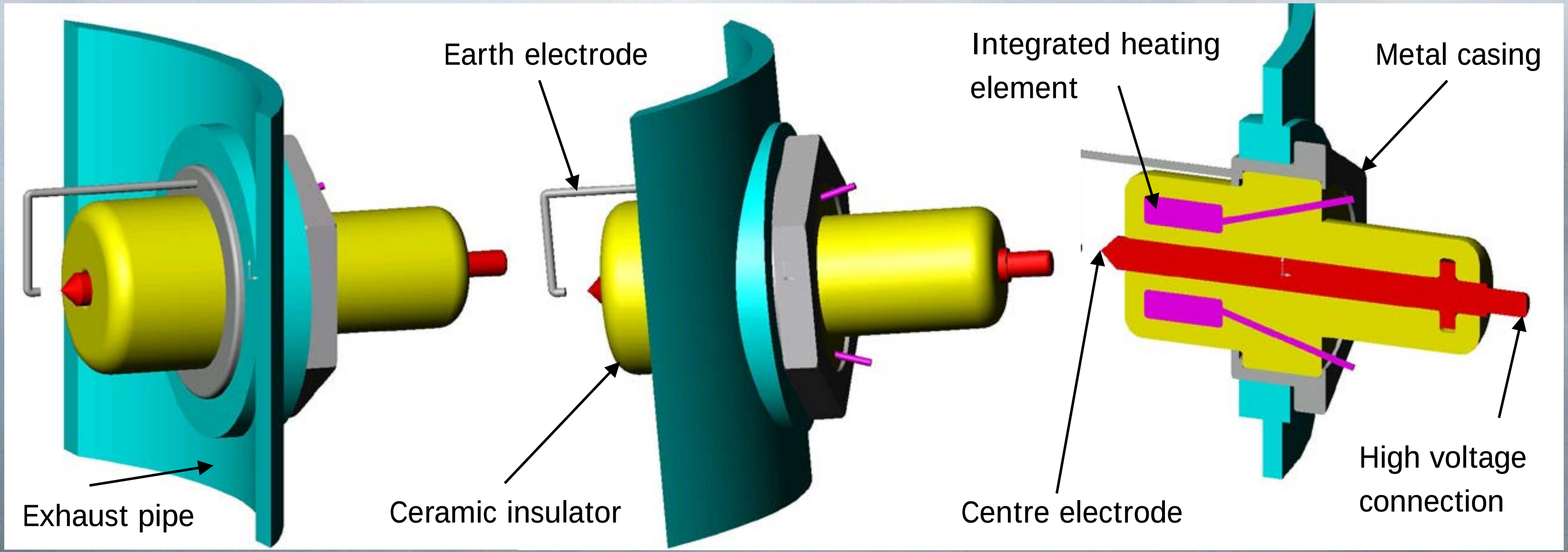
- Besides the minimum **PWM** level, all parameters which exert a significant **cross influence** such as temperature (s. figure), mass flow rate, air-fuel ratio, **voltage supply** etc. need to be acquired during the measurement.
- The **controlled heating** of the **central electrode** reduce the **PWM** dependence from the fluid temperature remarkably.




Characteristic lines **PWM, Fluid Temperature** (air) for some sensor variants

# BASIC DESIGN OF SDSS

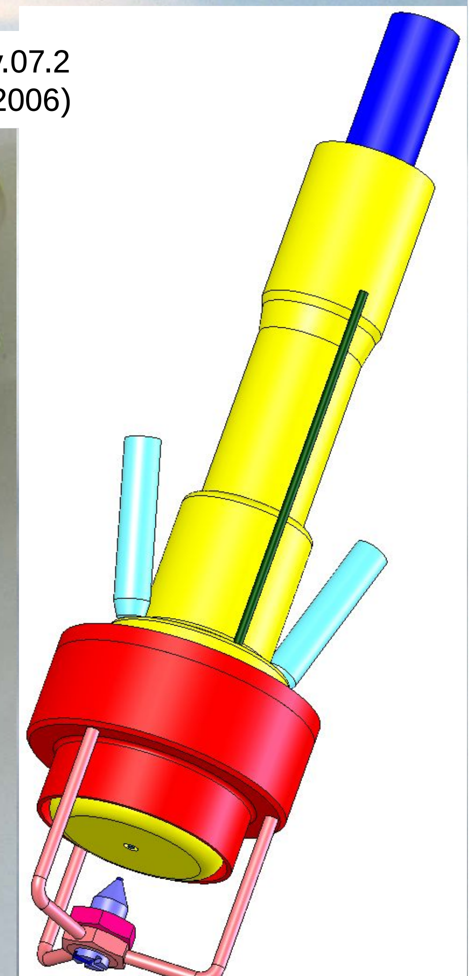
- The sensor is basically a combination of a spark plug and a glow plug.
- The ceramic insulator needs to be heated in the exhaust pipe to prevent soot deposits and uncontrolled discharges between the centre electrode and the exhaust pipe (earth/ground).
- The demands on the ceramic of the insulators are very high, as these have to demonstrate sufficient breakdown resistance and good chemical strength at relatively high temperatures (up to 700°C) in the hot exhaust gases.



# *DESIGN OF OLDER SDSS VARIANTS*

- **In a previous phase**, the integration of the heating element in the ceramic insulator was deemed to be too costly for the production of the sensor prototypes.
- For this reason a number of variants for combining the ceramic insulator and heating element (most made of platinum wire) were designed and tested. In all these cases the insulator was made from at least two bonded ceramic parts.
- In some sensor variants, cores of conventional spark plugs were used.

SDSS v.07.2
(from 2006)

# *DESIGN OF SDSS AND MEASURING EXPERIENCES*

**Conclusions from the analysis of the experience with SDSS v.07.2** (development stadium 2006, see FISITA F2006P241 for details):

- This sensor generates a reproducible signal only at temperatures of below 350°C which show a relatively good correlation to the soot concentration measurements.
- But if the sensor becomes sooted, it takes several minutes until the deposited soot film has burned off as a result of its relatively large dimensions. The sensor 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. However, this dependence and therefore also its potential for use to monitor a DPF was not sufficient.

**Measures for the new SDSS variants**:

- All the variant from **SDSS v.13** have an **integrated heating element** in the ceramic insulator of the central electrode.
- The central electrode diameter is lower as 5 mm for reducing the needed heating power (lower as 35 W).

# DESIGN OF NEW SDSS-VARIANTS

- **Measures for the new SDSS variants**:
- All the variant from **SDSS v.13** have an **integrated heating element** in the ceramic insulator of the central electrode.
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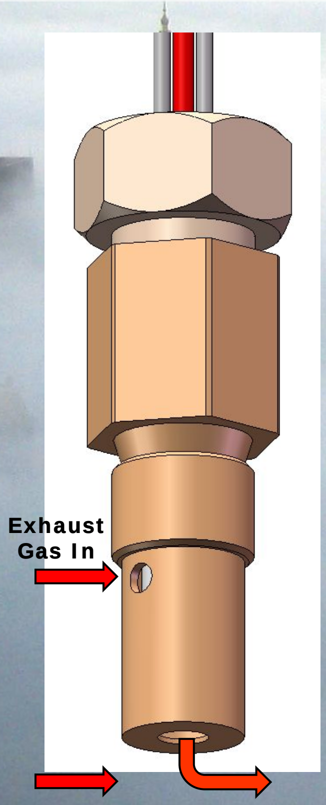


SDSS v.13 after measurements with high soot concentration

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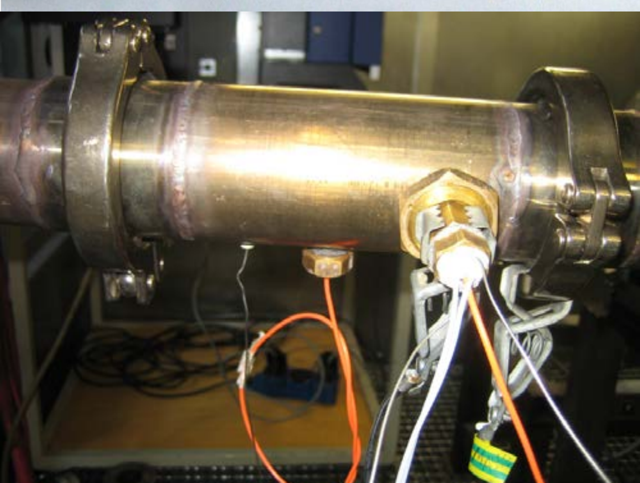
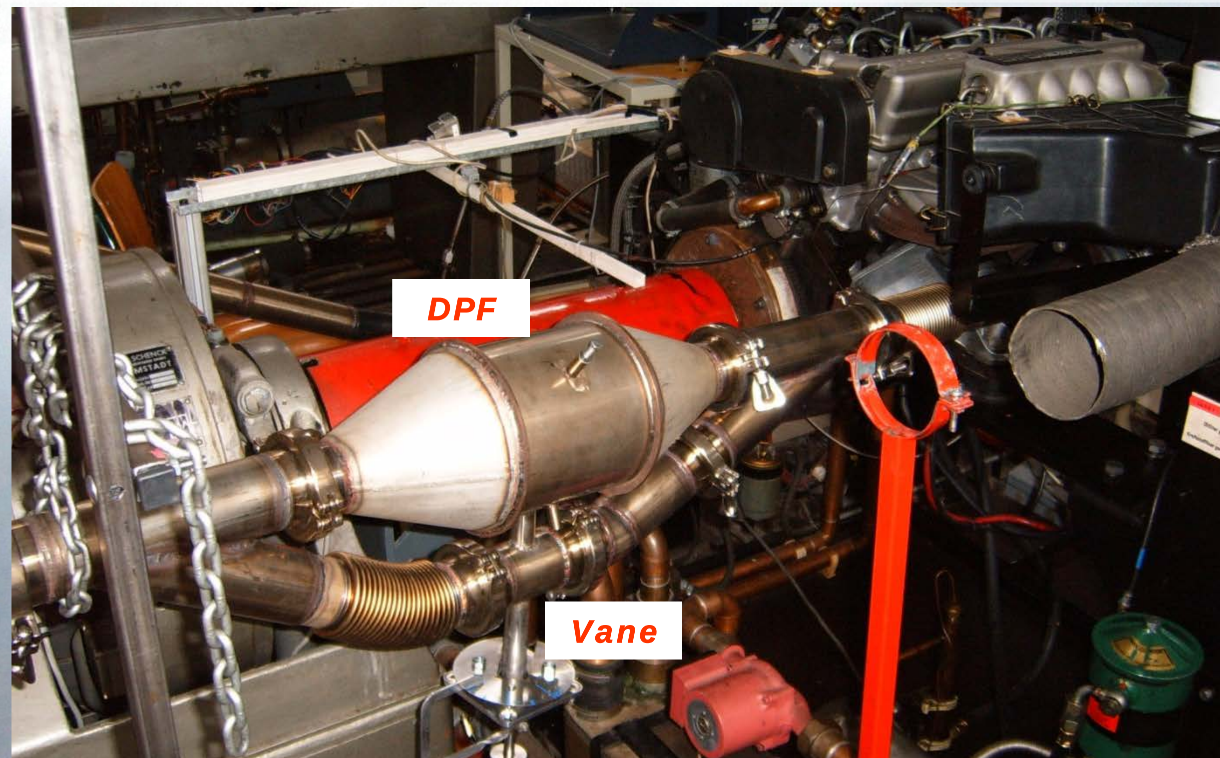
# SDSS IN EXHAUST GAS SYSTEM

- 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.
- Diesel Particulate Filter (DPF) was inserted in a bypass (s. figure). 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.



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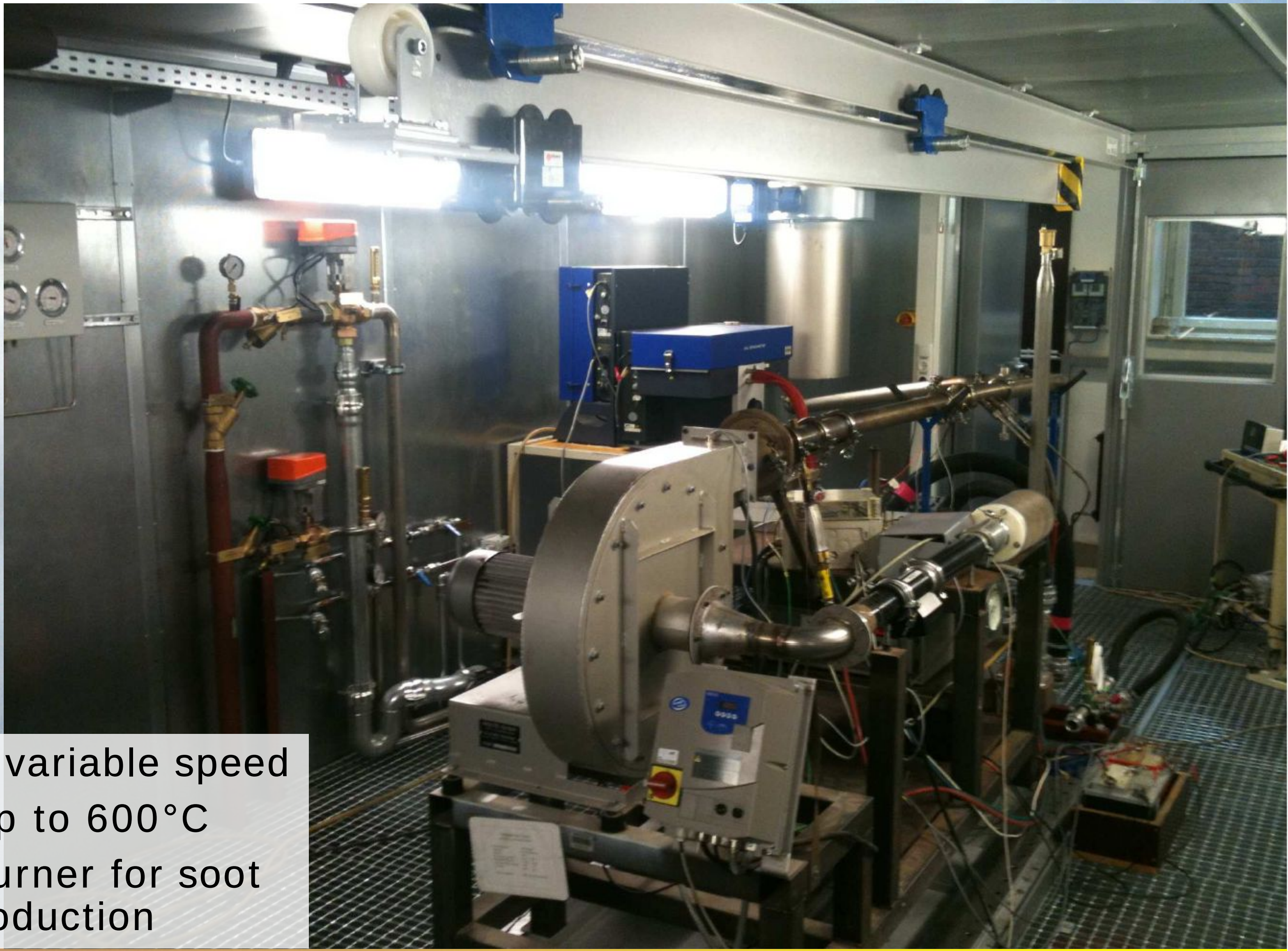
# *MEASUREMENT RESULTS FOR NEW **SDSS** VARIANTS ON **BLOWER** TEST BED AND **SI MPI ENGINE** TEST BED*



- Blower with variable speed
- Air heater up to 600°C
- Acetylene burner for soot emission production

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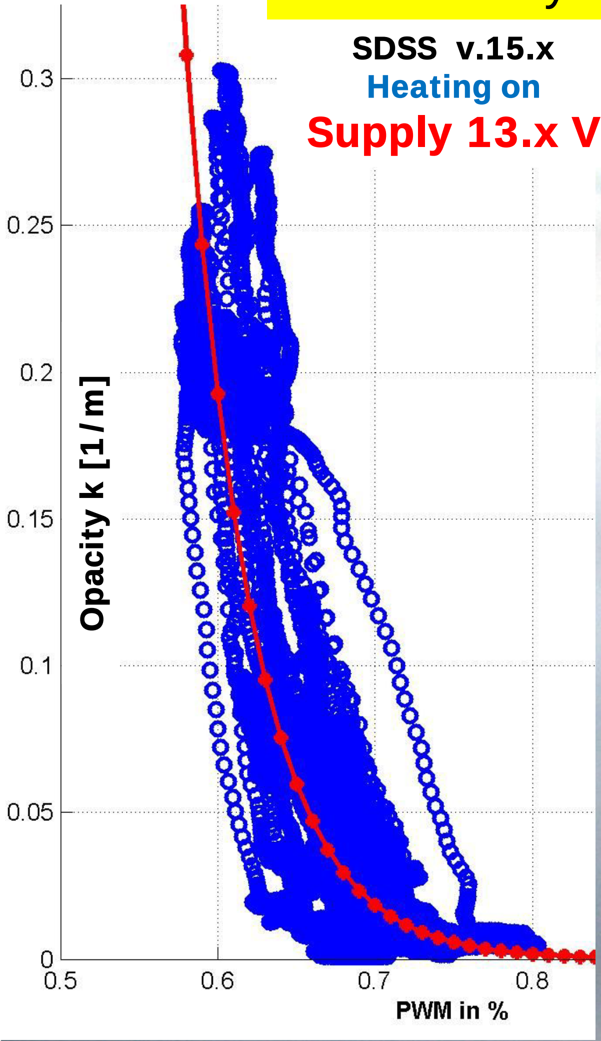
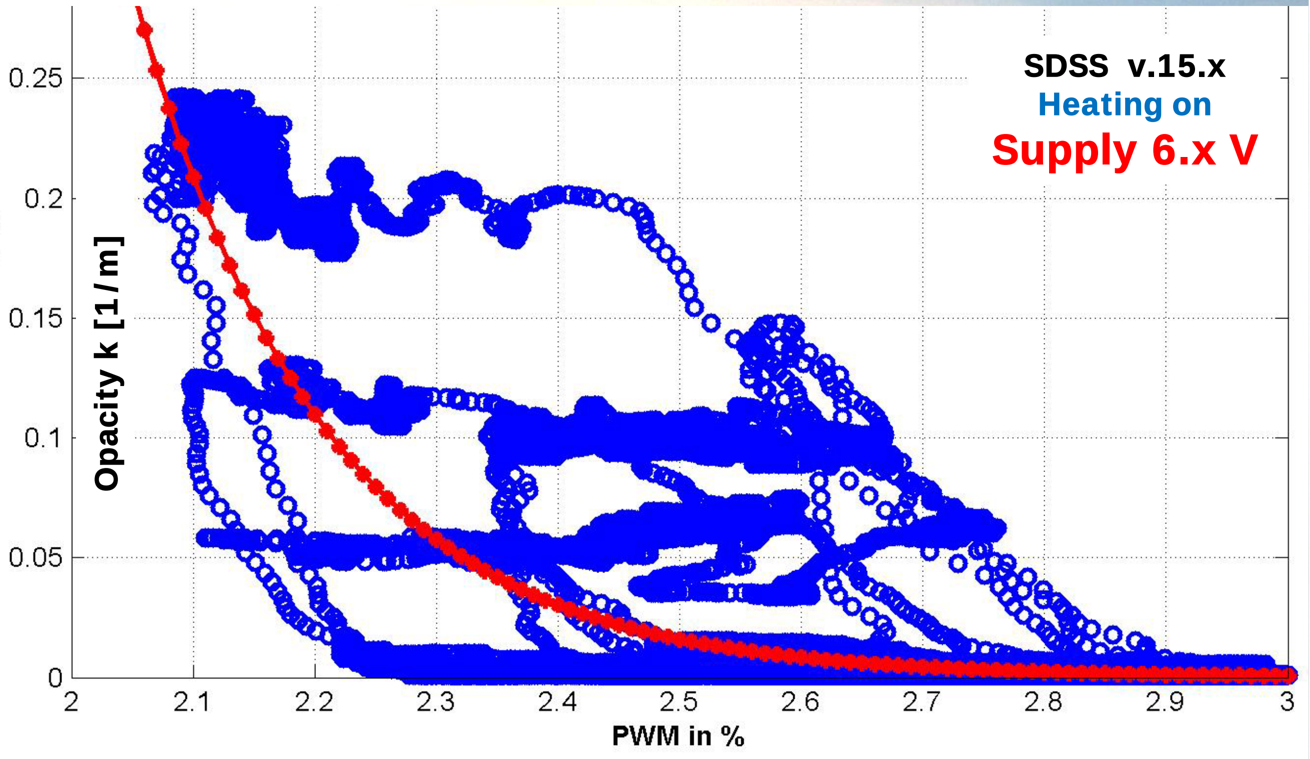
# STEADY CHARACTERISTIC LINES OF NEW SDSS VARIANTS

Without any Correction for other Cross Influence Parameter!




**Steady characteristic lines Opacity k, PWM**
for sensor variants 15.x on Blower Test Bed

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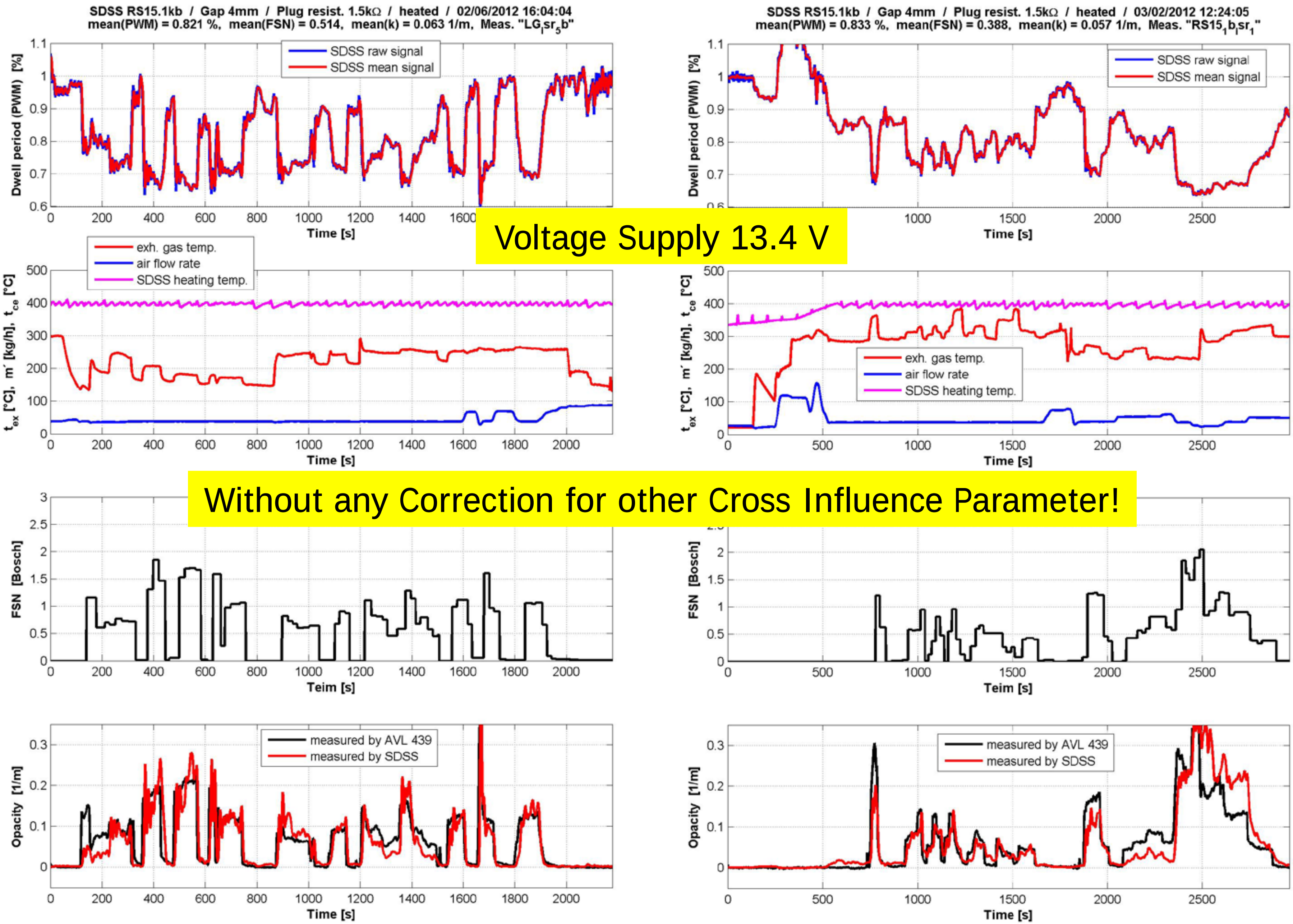
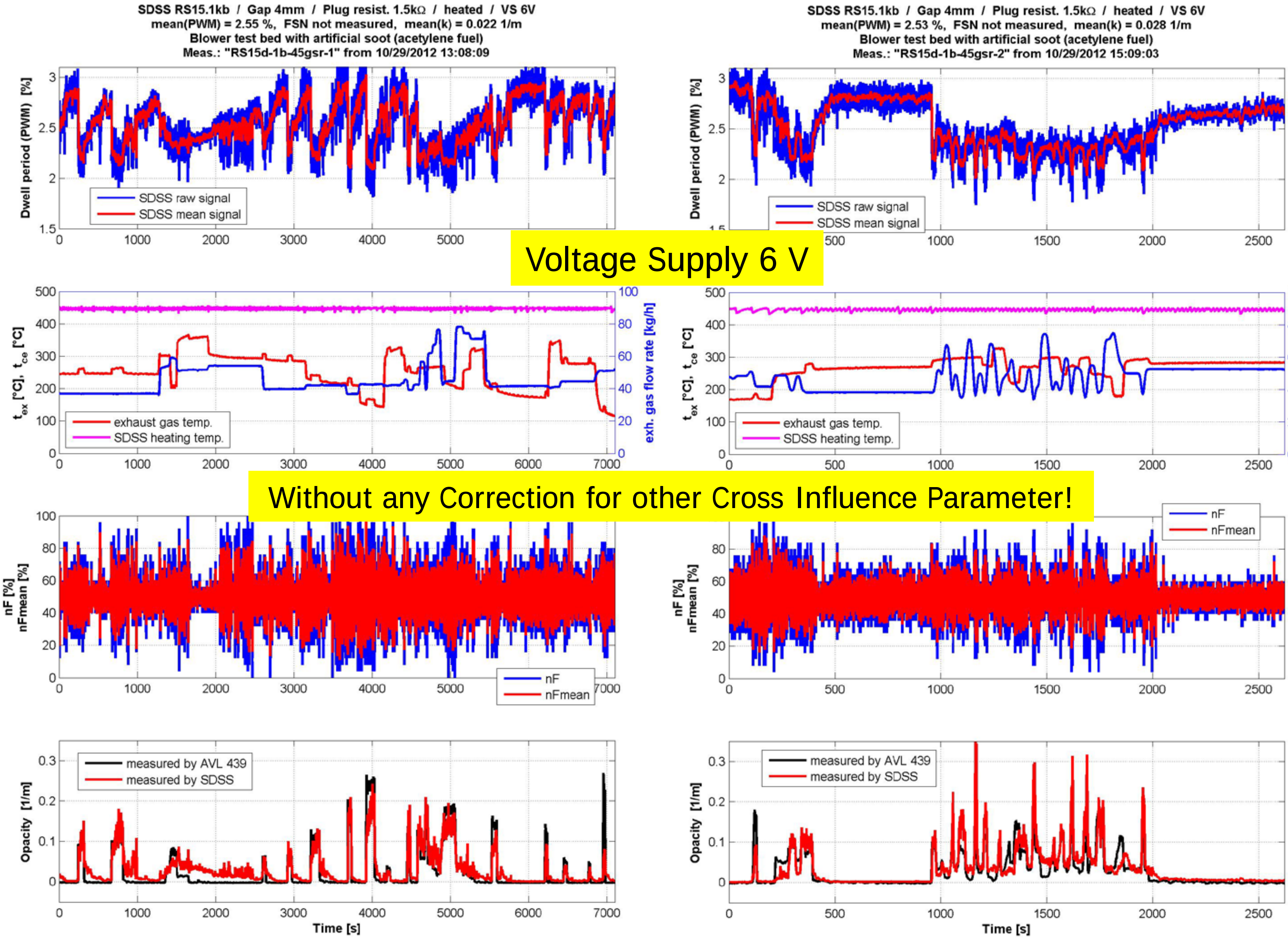
# MEASUREMENT ON ***BLOWER*** TEST BED




Voltage Supply 13.4 V

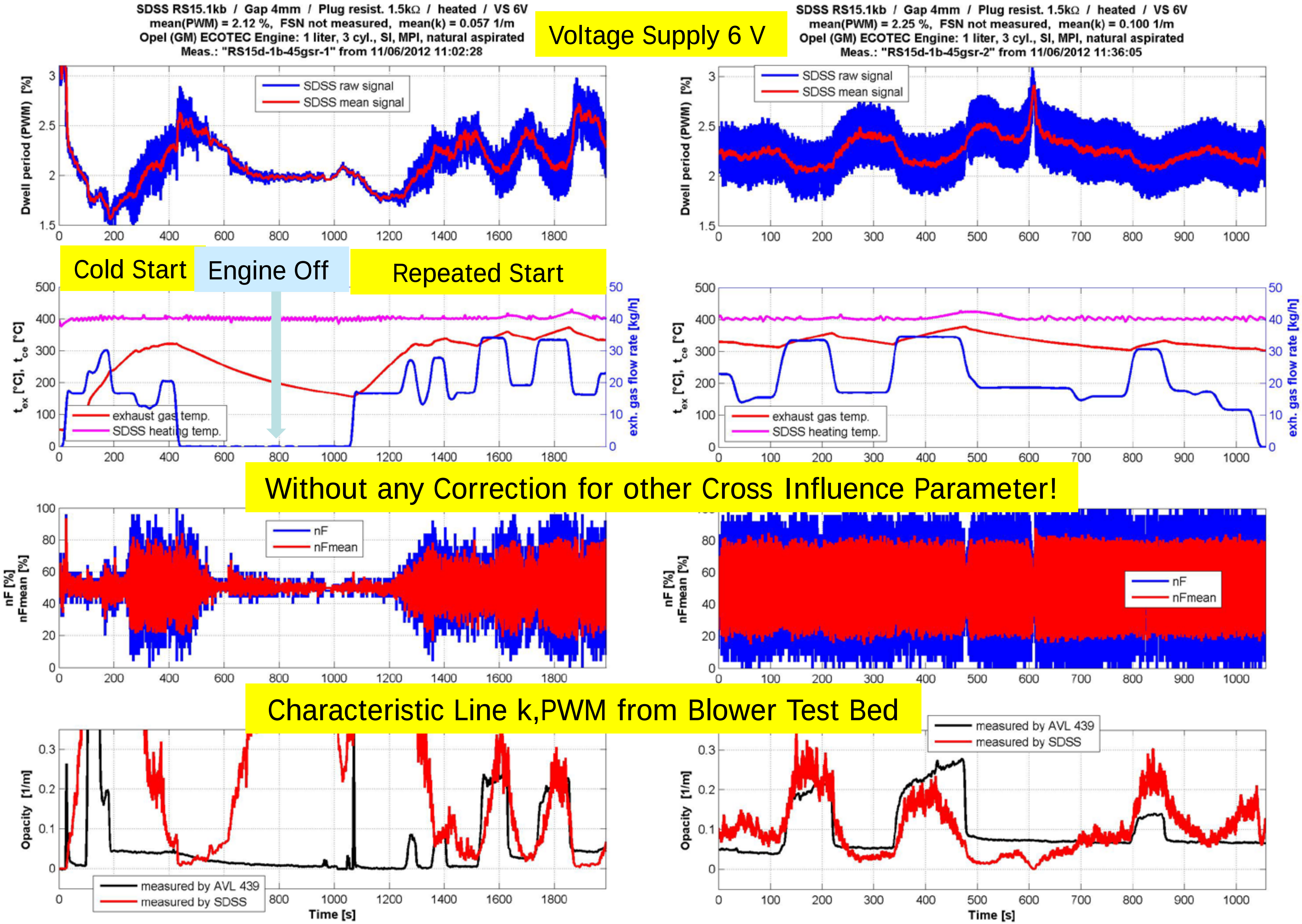
Without any Correction for other Cross Influence Parameter!




Voltage Supply 6 V

Without any Correction for other Cross Influence Parameter!

# FIRST MEASUREMENTS ON **SI MPI ENGINE** TEST BED



# CONCLUSION

1. The soot sensor needs a small amount of electrical energy during the whole measurement procedure (unheated ca 30 W, heated ca 70 W).
2. The manufacturing process of the heated soot sensor should not cause significant manufacturing problems.
3. The price of a soot sensor (without sensor ECU) should be somewhere between those of the spark and glow plugs.
4. The sensor ECU is quite simple (and therefore cheap) and can:
   - either be built as a separate unit (today's development stand),
   - or form a unit together with the ignition coil and perhaps with the soot sensor,
   - or still be integrated e.g. in the engine ECU.
5. The soot sensor and its ECU make up a so-called intelligent sensor, which can deliver the measured soot concentration to the engine ECU by means of a bus system (e.g. CAN).
6. The soot sensor can be used in front of and/or behind the soot filter.
7. The soot sensor is suitable to be used as a simple sensor for the detection of a certain soot concentration threshold. In this case it can be positioned e.g. behind the soot filter to determine the regeneration phase start (and eventually end) time and can also be integrated in **OBD I** procedure.
8. Alternatively it can be used for continuous measurements of the soot concentration. In this case the soot sensor can be integrated in the engine closed loop soot control. It also can be integrated in **OBD II** and **OBM** procedures.

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# OUTLOOK

- The cross influence parameter (e.g. sensor heating temperature, AFR, HC emission, exhaust gas temperature & mass flow rate etc) will be investigated in detail for the new SDSS variants.
- New SDSS prototypes will be manufactured and tested on Blower, SI MPI, SI DI and CI engines test beds.
- Correlation with gravimetric measurements and particle counters (PC) will be made.
- Industry partner for a further much more accelerated development of the SDSS will be searched.

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