Development of a real-time electronic particulate matter (PM) sensor for diesel OBD applications and comparison with laboratory instruments

Klaus Allmendinger

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EXTENDED ABSTRACT

The design of an electronic non-ionizing PM sensor sensitive enough for reliable diesel particle filter failure detection is presented, as well as test results comparing a set of sensors to laboratory instruments.

The sensor operating principle is based on a charge transfer mechanism where exhaust gas containing combustion generated particles are drawn through the sensor by aerodynamic forces created by the flow of exhaust gas past the sensor. Inside the sensor the exhaust gas is directed at a cylindrical electrode mounted within a cylindrical flow guide tube within the sensor, and the gas flows parallel to the electrode towards the gas exit. The electrode is connected to the positive terminal of a floating voltage source that charges the electrode to approximately 1000V. The resulting field between electrode and flow guide tube has a strength of about 700-1000 kV/m.

The sensor is designed such that soot particles attach to the electrode and form filamentous structures extending radialy away from the electrode surface under the influence of the electric field. It is hypothesized that because of the resulting microstructure of the electric field near the tips of those structures a very high surface charge density results at those tips. This high surface charge density can impart on particles that touch those tips a relatively high number of elementary charges per particle. This number of elementary charges per particle is more that 2 orders of magnitude higher than what is calculated from the surface charge density of a cylindrical electrode itself.

The resulting charge loss from particles acquiring charge from the electrode via the filamentous structures and subsequent depositing that charge on grounded parts of the exhaust system is measured as current.

Also described in the presentation is the “Insulator Challenge”. Because of the low currents and high operating voltage of the sensor the physical electrical insulation of the electrode is of prime importance. Any current flowing through or on the surface of the insulator adds to the current caused by particle charge transfer and causes measurement

errors. Electrically conductive soot accumulation on the insulator must therefore be prevented.

The multi-pronged approach to the “Insulator Challenge” is described, which includes moving the insulator out of the exhaust pipe and its high temperatures, constructing the sensor such that particles have to follow a tortuous path to the insulator, providing an electrostatic soot filter as part of the electrode in the path to the insulator and embedding a heater in the insulator to burn off accumulated soot periodically.

The second part of the presentation shows the test results using a set of sensors in a heavy duty vehicle on a chassis dyno at UC Riversides CERT laboratory and at Southwest Research Institute (SWRI) on an engine dynamometer using a Detroit Diesel 14Liter engine.

At the UC Riverside testing seven sensors were tested in an exhaust pipe extension of the vehicle. The sensors were compared to a TSI Dusttrak instrument. The results of a heavy duty urban drive cycle with various shift points and acceleration/deceleration runs are presented. The seven sensors show fast and consistent response with good correlation to the TSI Dusttrak instrument.

The goals for the SWRI testing were to determine the sensor accuracy and precision (repeatability) of the tests. Also data was gathered to shed further light on the operating principle of the sensor.

71 steady state and transient runs were performed. Particle size, number, mass and charge distribution were varied and the engine conditions, particle mass concentration and particle number concentration and size distribution were measured. A total of 10 sensors were used, but only 7 were used for all runs. Of those 7, two sensors developed mechanical failures and therefore the results show the data from the remaining 5 sensors.

Particle mass concentration was measured with an AVL Micro Soot Sensor (AVL MSS) and particle number and size distribution were measured with a TSI Engine Exhaust Particle Sizer (EEPS).

The results for 23 representative steady state runs are shown. These runs include repeats of runs with identical conditions as previous runs and only those runs where the engine and exhaust conditions could be held fairly constant were selected.

The results showed that the sensors correlate well with each other with an R^2 of > 0.99, and that the sensor outputs are very repeatable for identical exhaust conditions.

In addition the results showed that sensors vary in their basic sensitivity (in $nA/mg/m^3$) by up to +- 7% from each other. The sensitivity of the sensor outputs was then for each sensor normalized to the average gain of the sensors by applying a constant multiplication factor to each sensor. This operation simulated a factory calibration for the sensors.

The results showed further that the sensitivity of the sensors shows a strong exhaust temperature dependency. The average sensitivity of the sensors was fitted to a 3rd order polynomial and the polynomial applied to all sensors for temperature correction.

No statistically significant dependency of the sensor current to exhaust flow, back pressure, particle size distribution or particle charge distribution was observed.

The resulting temperature corrected sensor output was compared to the particle mass concentration measured with the AVL MSS.

The results show that the temperature corrected sensor output correlates well, with an R^2 of ~0.98 with the particle mass concentration measured by the AVL MSS.

Further, below a particle mass concentration of 2mg/m^3, the sensor is capable of resolving the particle mass concentration to +- 0.5 mg/m^3, and in the range 2mg/m^3 to 12 mg/m^3 a resolution of better than 1.6 mg/m3 is achieved over a temperature range of 217 to 420 ^{o}C.

In conclusion the particle sensor described in the presentation shows promise as on-board diagnostic sensor for diesel applications.

15th ETH Conference on Combustion Generated Nanoparticles

Development of a Real-Time Electronic Particulate Matter (PM) Sensor for Diesel OBD Applications and Comparison with Laboratory Instruments

Klaus Allmendinger
EmiSense Technologies, LLC

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Presentation Structure

- Sensor Background
    - Introduction
    - Design and Operation
- Test Results
    - UCR Drive Cycle Testing
    - Southwest Research Institute (SWRI) Laboratory Testing

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Why this Sensor is Needed

European Commision Proposal (March 2011) for New European Drive Cycle (NEDC) PM Limits and OBD Thresholds (Fault Indicator Trigger)

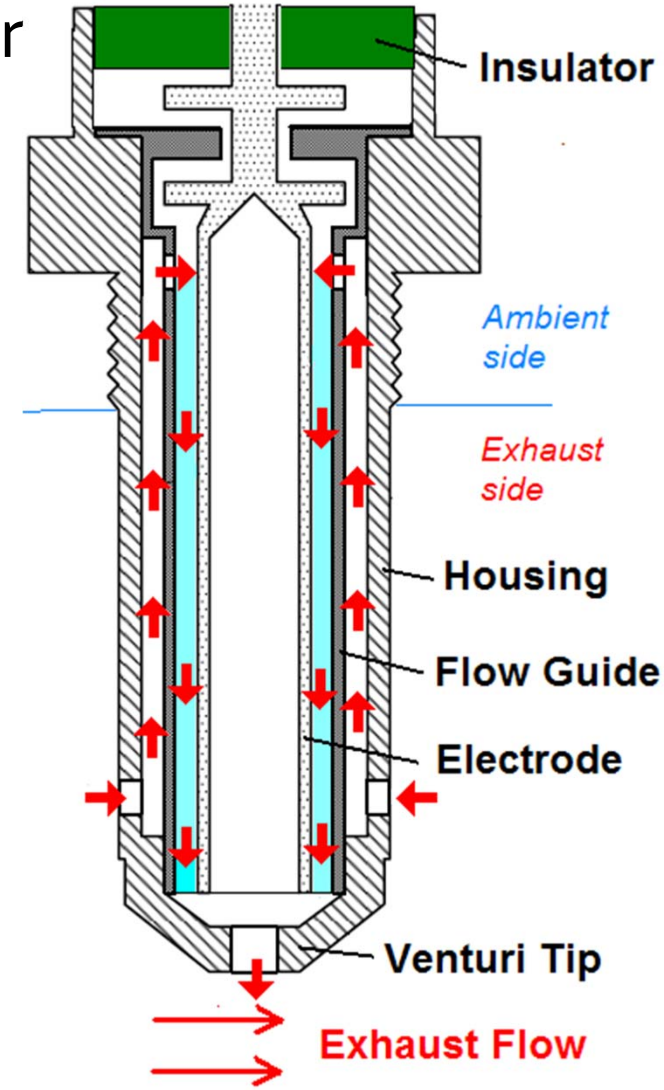
	EURO-6 PM Emissions Limit	**OBD Stage 1 Threshold**	**OBD Stage 2 Threshold**
PM (mass):	4.5mg/km (3.33 mg/m^3)*	**20mg/km** (14.8 mg/m^3)*	**9mg/km** (6.7 mg/m^3)*
PN (count):	6x10^{11}	Requirements postponed for lack of adequate sensing technology.	

- **Required sensor must be robust, cost-effective, and with a measurement limit and resolution of <3mg/m^3**

* Calculations / Assumptions:
NEDC duration: 1220sec; NEDC average speed: ~33.6 km/h; NEDC avergage distance:11.4 km; Assumed density of exhaust gas = 1.3 kg/m^3. Modern 2 Liter common rail diesel passenger car creates ~20kg exhaust gas/NEDC -> 1.35 m^3/km

Sensor Introduction

- Venturi draws gas through sensor
- Gas flows past high voltage electrode (~1KV)
- Particles acquire charge from electrode, deposit charge on grounded parts
- Charge loss current from electrode is measured



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Challenges

1. **High signal strength** enables use of low-cost electronics components across temperature range
2. **Low cost target** means using off-the shelf parts if possible
3. **Insulator performance and sealing** are critical to avoid false positives and drift
4. **Understanding of basic principles** to inform ongoing design logic.
5. **Small size** (same as other exhaust sensors) for easy vehicle integration

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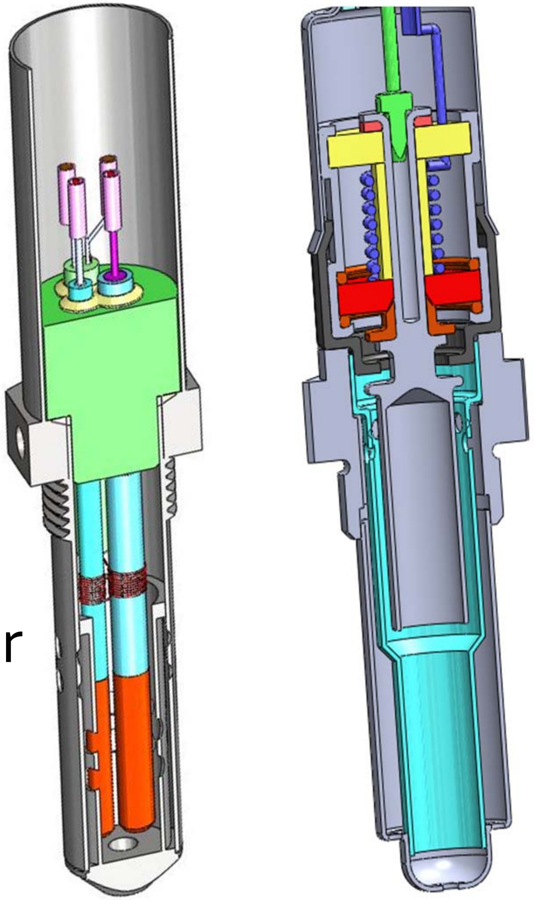
Signal Strength

- Single electrode design has sufficient signal current to use low cost electronics*
- Size is similar to conventional O_2 sensors



*3-9nA / mg / m^3 vs ~0.2 – 0.7 nA / mg / m^3 for earlier design

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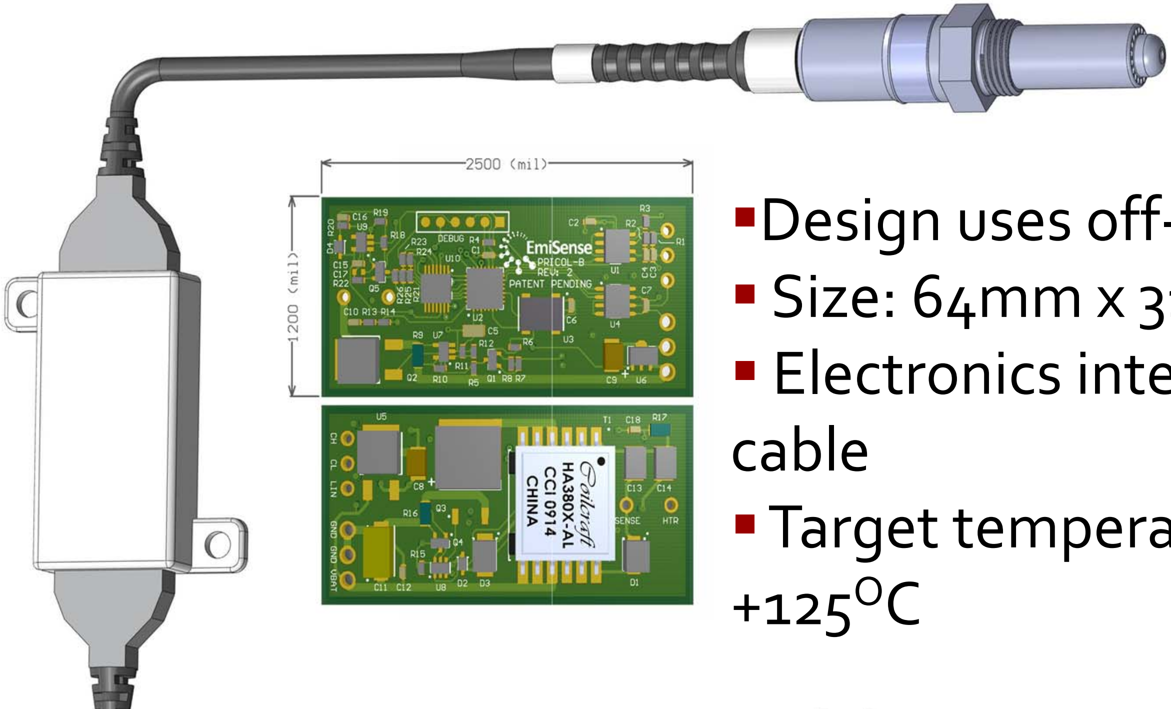
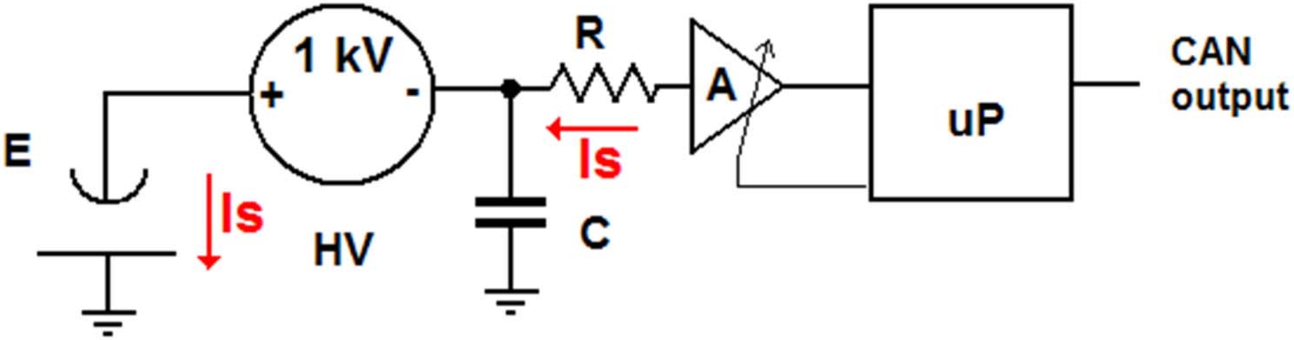
HV Generation and Signal Processing

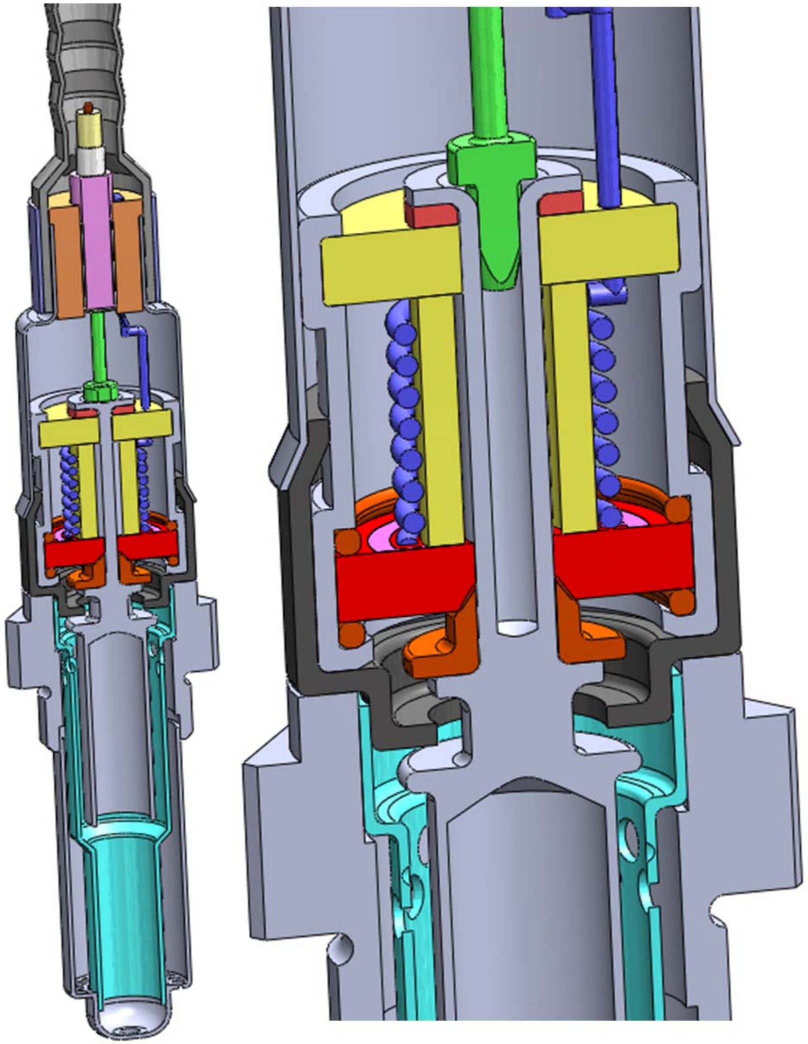


- Design uses off-the-shelf components
- Size: 64mm x 31mm x 14mm
- Electronics integrated in sealed sensor cable
- Target temperature range -40 to +125°C



Insulator Challenge

- Insulation integrity is critical to avoid current leaks (false positives)
- Insulators become conductive at high temperatures
- Surface contaminants can create leakage path
- Moisture in back of sensor can create leakage path



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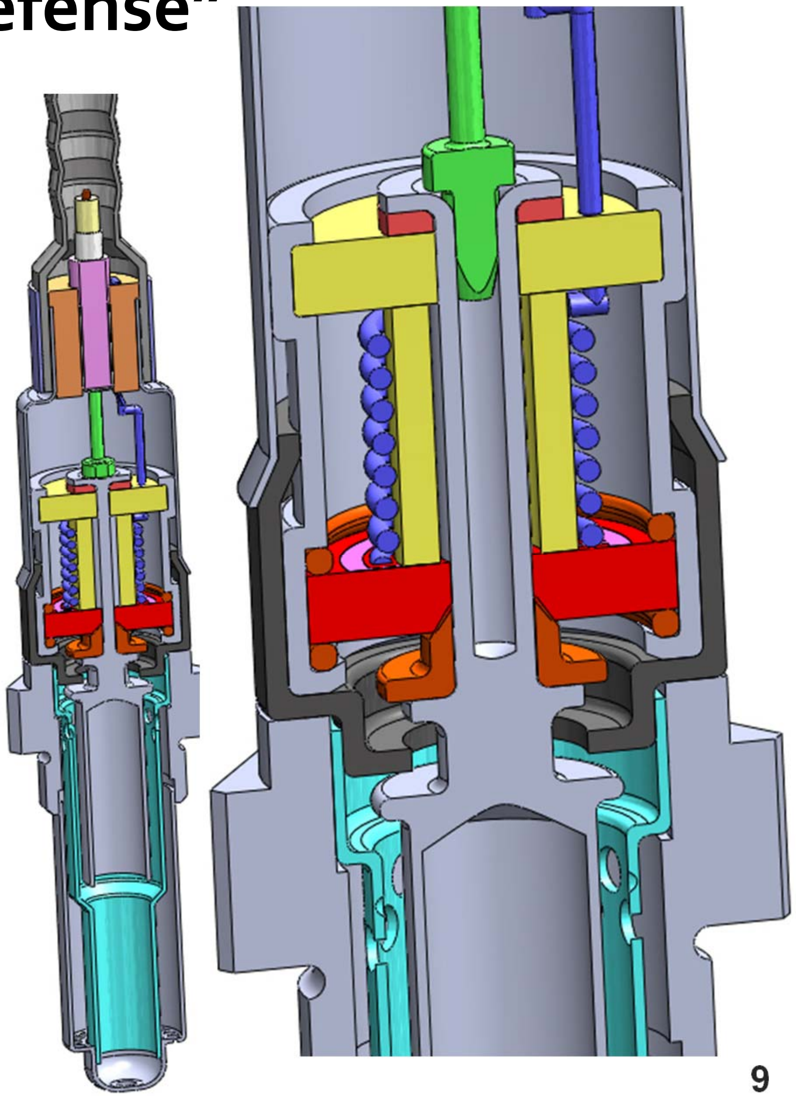
Insulator Solution

Solution: Multiple "Layers of Defense"

1. Tortuous path between exhaust and insulator
2. Tortuous path uses electric field to act as electrostatic soot filter
3. Disk shaped insulator provides long current leakage path
4. Integrated heater can burn off accumulated soot
5. Double O-Ring and compression seal design prevents moisture leakage
6. Insulator located out of exhaust stream in "cold" ambient side of sensor
7. Insulator location prevents thermal shock



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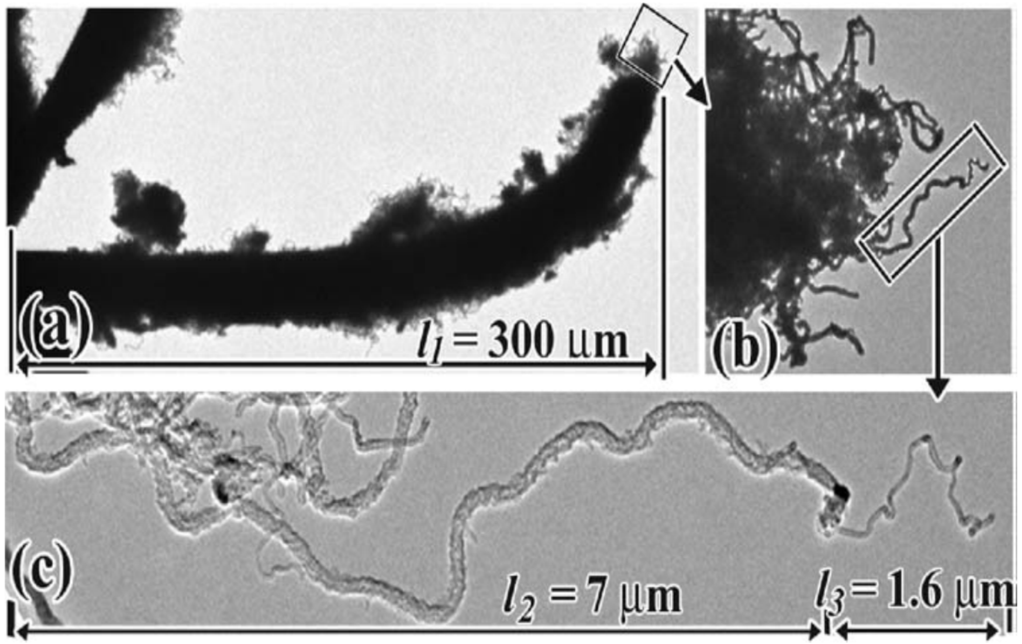
Basic Principles

Measured current is at least 2 orders of magnitude higher than expected current from direct charge transfer

Working hypothesis: Soot agglomerates on electrode surface as filamentous structures resulting in high surface charge density at structure tips.

This agglomeration (or a surrogate) is *required* to provide natural signal amplification.



Source: http://www.physics.bc.edu/emxrd/APL8705311005-CNT-FE.pdf

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PM-Trac^{TM} Sensor

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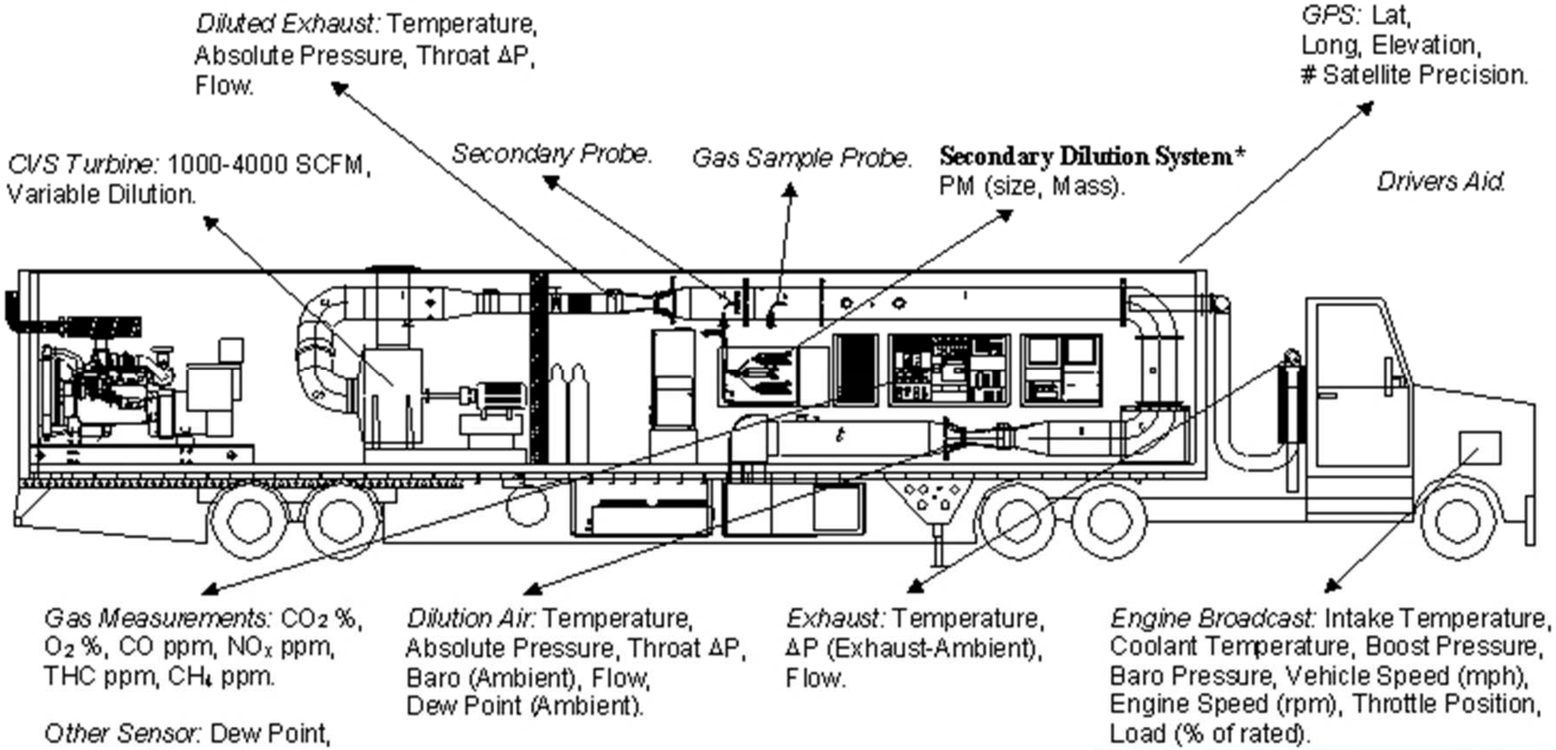
UCR-CERT Drive Cycle Dyno Testing



Diluted Exhaust: Temperature, Absolute Pressure, Throat ΔP, Flow.

GPS: Lat, Long, Elevation, # Satellite Precision.

CVS Turbine: 1000-4000 SCFM, Variable Dilution.

Secondary Probe.

Gas Sample Probe.

Secondary Dilution System* PM (size, Mass).

Drivers Aid.

Gas Measurements: CO_2 %, O_2 %, CO ppm, NO_x ppm, THC ppm, CH_4 ppm.

Other Sensor: Dew Point, Ambient Temperature, Control room temperature, Ambient Baro, Trailer Speed (rpm), CVS Inlet Temperature.

Dilution Air: Temperature, Absolute Pressure, Throat ΔP, Baro (Ambient), Flow, Dew Point (Ambient).

Exhaust: Temperature, ΔP (Exhaust-Ambient), Flow.

Engine Broadcast: Intake Temperature, Coolant Temperature, Boost Pressure, Baro Pressure, Vehicle Speed (mph), Engine Speed (rpm), Throttle Position, Load (% of rated).

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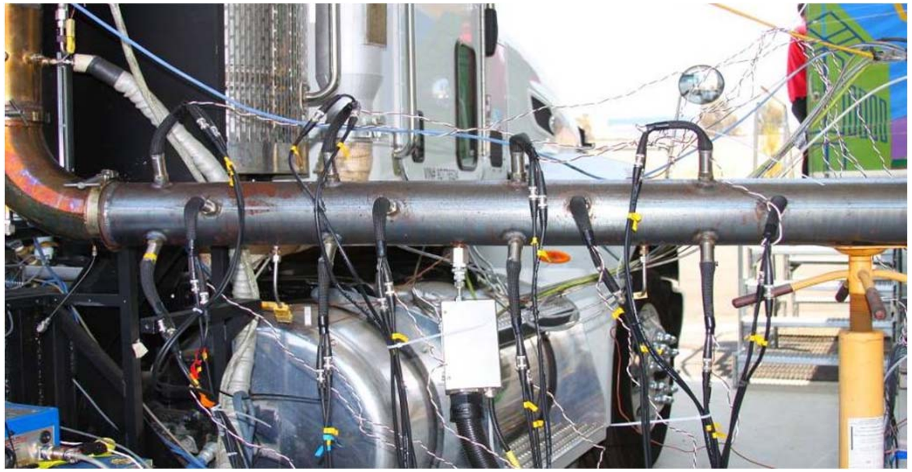
UCR-CERT Drive Cycle Dyno Testing



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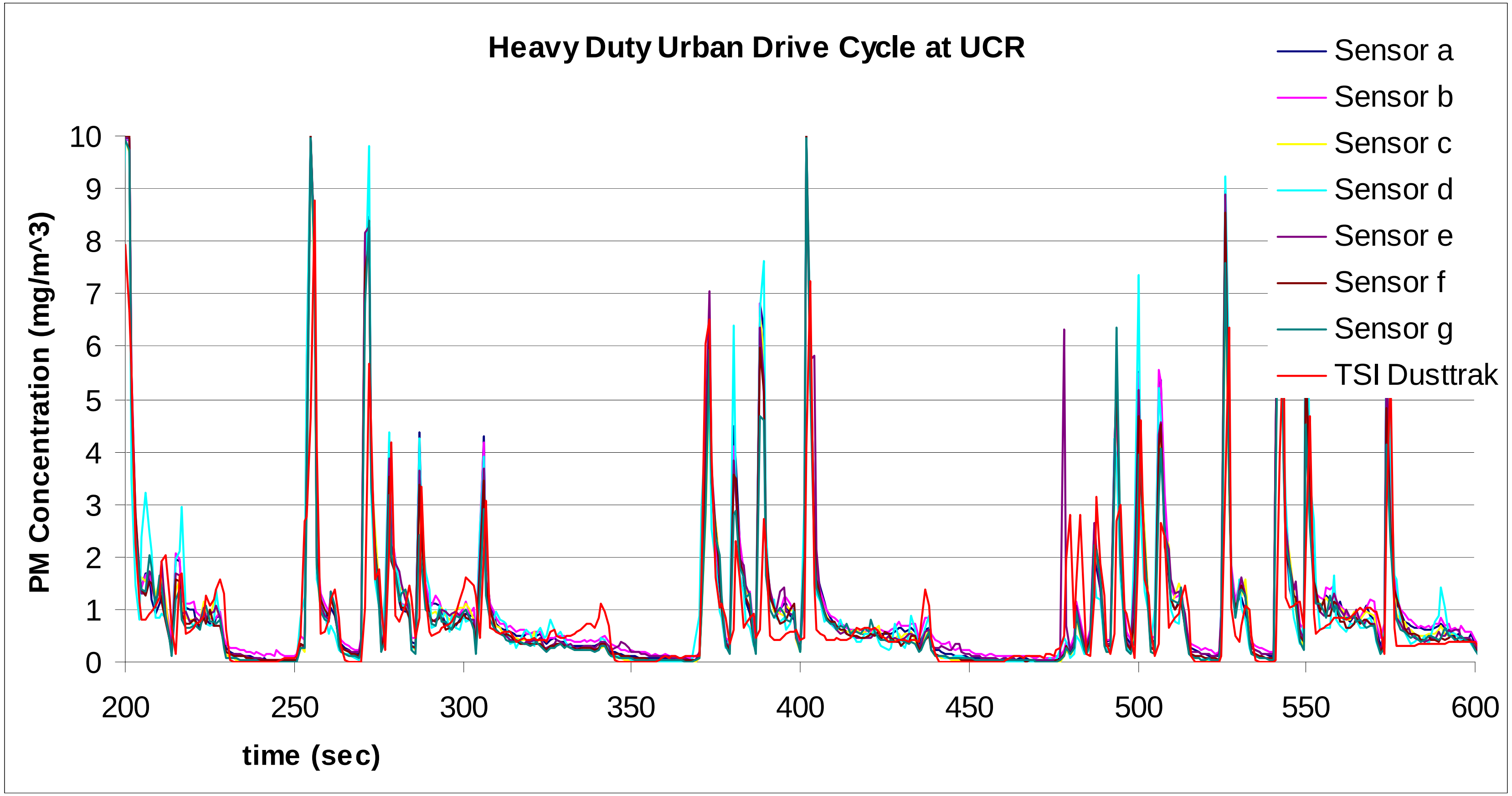
UCR-CERT Drive Cycle Dyno Testing



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Multiple sensors correlate very well with lab instrument, including real-time transients.

PM-Trac^{TM} Sensor

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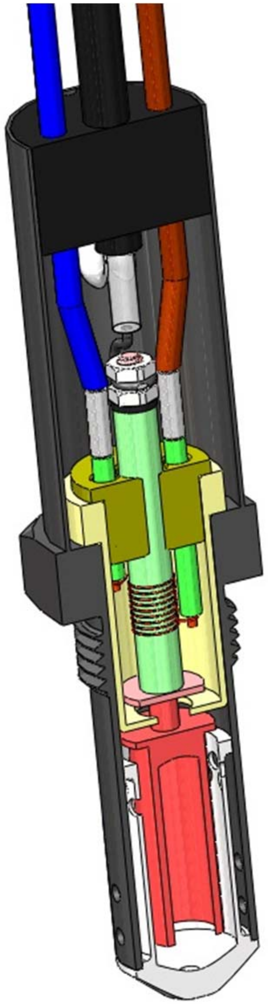
SWRI Testing Goals

- Test performance of proof of concept design
- Determine accuracy (measurement errors and dependencies)
- Determine precision (repeatability)
- Improve understanding of sensor operating principle
- Controlled variation of:
  - Particle size, number, mass and charge distribution
  - Exhaust temperature, flow rate and back pressure



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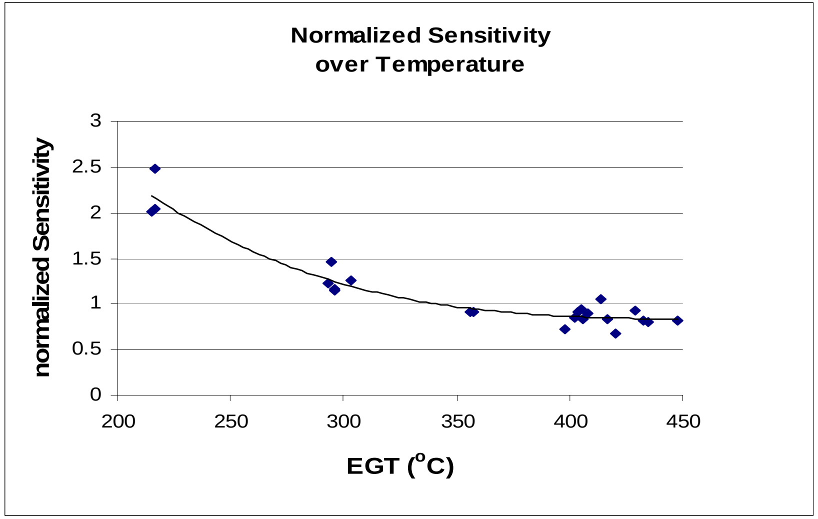
SWRI Test Conditions

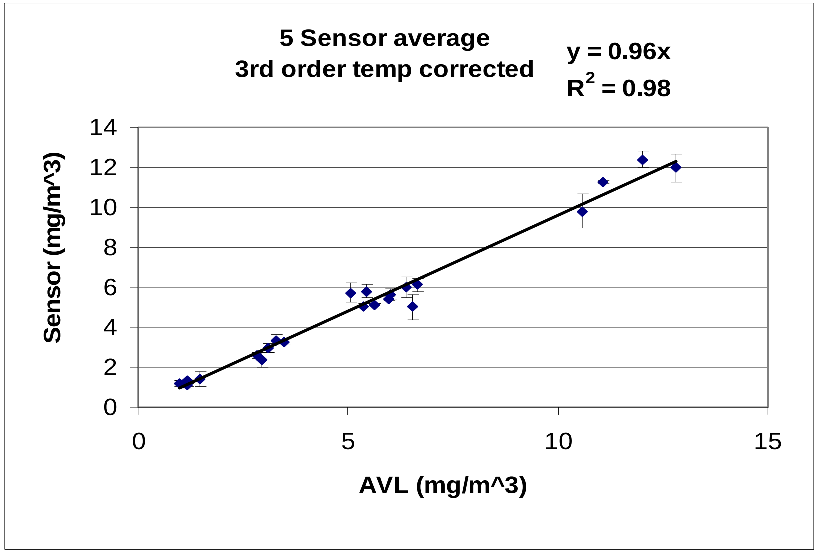
Test Setup and Conditions

- 14 Liter Detroit Diesel Engine
- 71 steady state and transient test conditions
- Temperature range (°C): 217 - 530
- Exhaust flow range (SCFM): 107 – 635
- Back pressure range (“H_2O): -2.4 – 30
- Particle # concentr. (#/cc) : $4x10^5 – 3x10^7$
- Particle mass (mg/m^3): 0.2 - 201
- Particle size GMD (nm): 51 - 115

Sensor Accuracy

- Exhaust gas temperature sensitivity was observed.
- Sensitivity changes by ~Factor 3 over temperature range from 217°C to 450 °C
- Generic temperature correction can be applied to sensor output
- Strong non-linear flow sensitivity was observed below 200 SCFM (< 9m/sec exhaust velocity).





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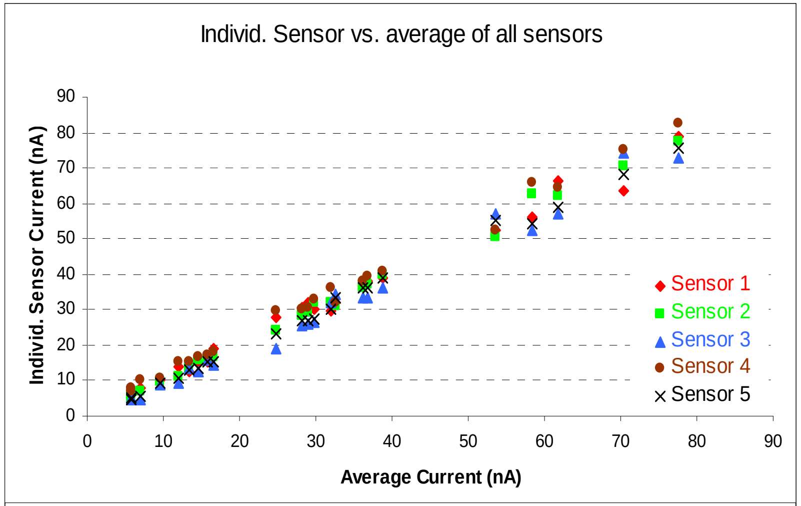
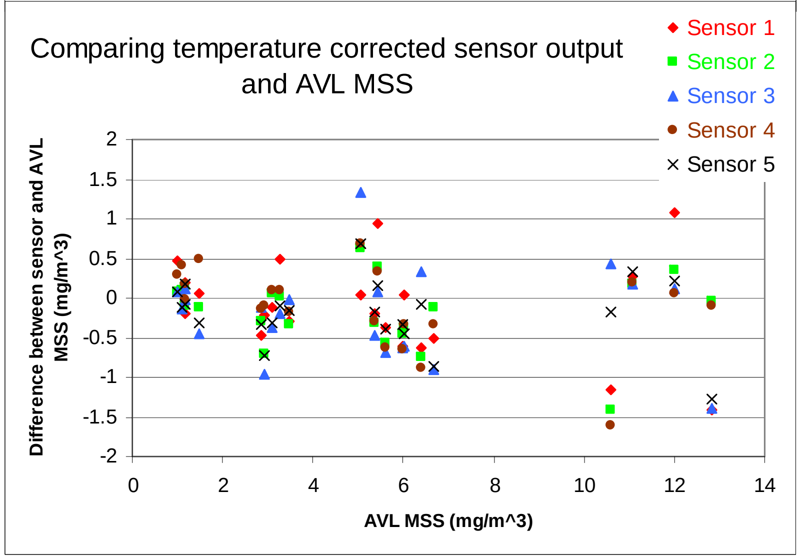
Sensor Precision (Repeatability)

- R^2 Correlation between individual sensors and sensor average > 0.99
- Sensitivity of sensors (slope) differs by +- 7% from average
- Sensitivity tolerance can be improved by factory sensor calibration
- Measurement error < 1.6 mg/m3 for range 0 - 13 mg/m^3
- Measurement error <= 0.5 mg/m^3 for range 0-2 mg/m^3


Individ. Sensor vs. average of all sensors


Comparing temperature corrected sensor output and AVL MSS

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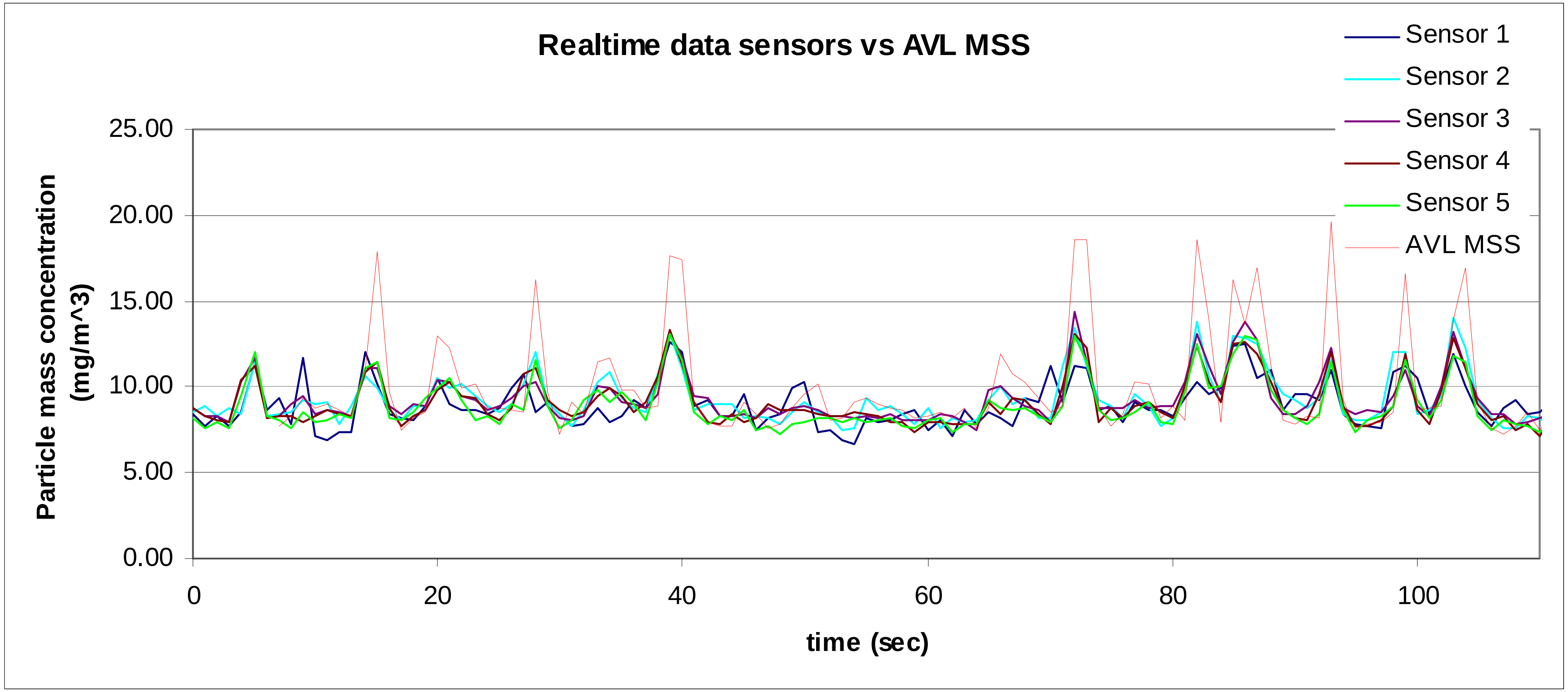
Sensor Response Speed



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Summary

1. Temperature-corrected PM-Trac^{TM} sensors correlate well with AVL MSS (particle mass) during steady state and transient operation
2. No strong correlations with exhaust flow (>200 SCFM), back pressure, or particle size distribution was observed
3. PM-Trac^{TM} sensors correlates poorly with particle number concentration (#/cc). Count can only be inferred indirectly.
4. PM-Trac^{TM} limit of detection: < 1 mg/m^3
5. Further work needs to be done to characterize temperature dependency for temperature ranges below 217 ^{O}C and above 450 ^{O}C
6. Further work needs to be done for gasoline applications (GDI).
7. We are working with academic partners to further understand the sensor charge transfer mechanisms.

PM-Trac^{TM} sensor should perform well for Diesel and GDI OBD applications

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The End

Credits:

From Emisense:

Jim Steppan
Brett Henderson
Anthoniraj Lourdhusamy
Patrick Thompson

From Watlow:

(our manufacturing partner for heavy duty applications)

Jörn Bullert
Maged Riad
Rick Williams

From SWRI:

Imad Khalek
Quiang Wei

From UCR-CERT:

Kent Johnson