Particle Sensor Performance & Durability for OBD Applications & Beyond

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Particle Sensor Performance & Durability

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San Antonio, Texas

Brief

- **This work was developed in Year 1 & 2 of SwRI Particle Sensor & Durability Consortium (PSPD)**
  - **The focus of Year 1 was on sensor performance**
  - **The focus of Year 2 was on sensor performance as function of durability**

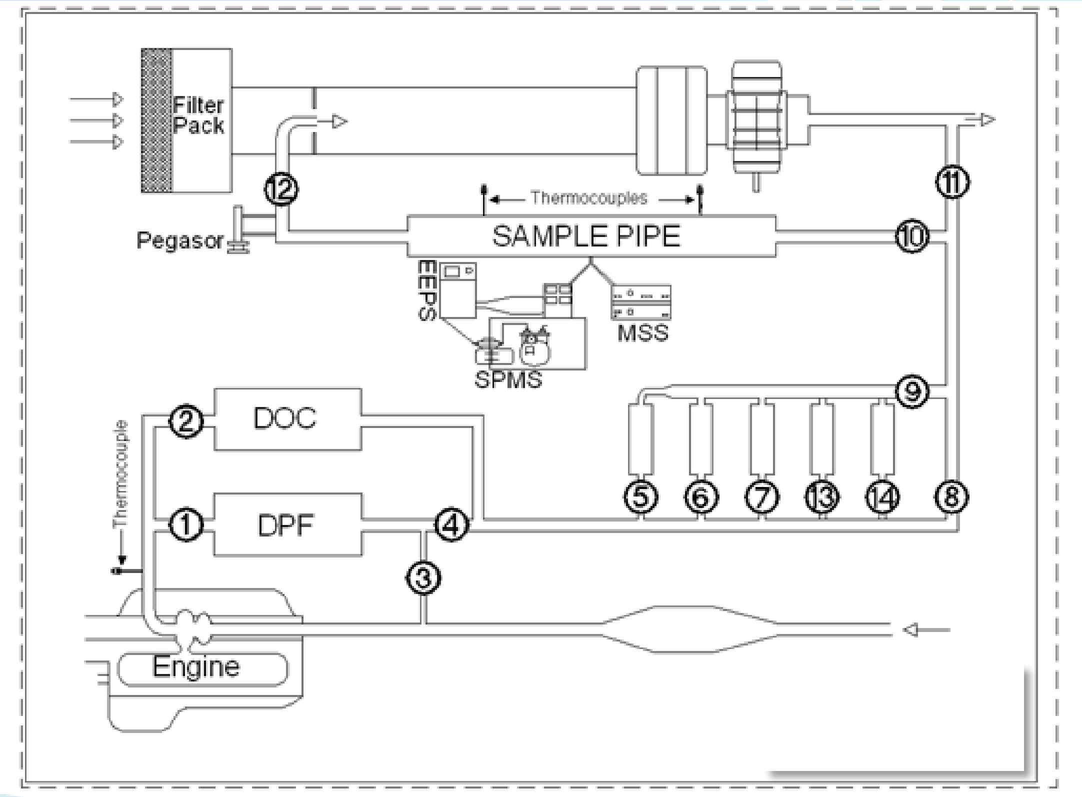
Particle Sensor Applications

- Onboard vehicles downstream of exhaust particle filters for:
  - OBD Requirement (highway vehicles, potentially nonroad)
    - CARB Heavy-Duty On-Highway: 2016 Enforcement
  - Leak detection and durability
    - QA/QC
    - In-use screening
  - Onboard vehicles engine out
    - Active particle emissions control
    - Engine mapping (real world)
    - EGR cooler diagnostics through particle dynamics
- Ambient emission data on local and global level
- Retrofit applications
- In-use testing (simple system)
- Smoke meter replacement (laboratory use)

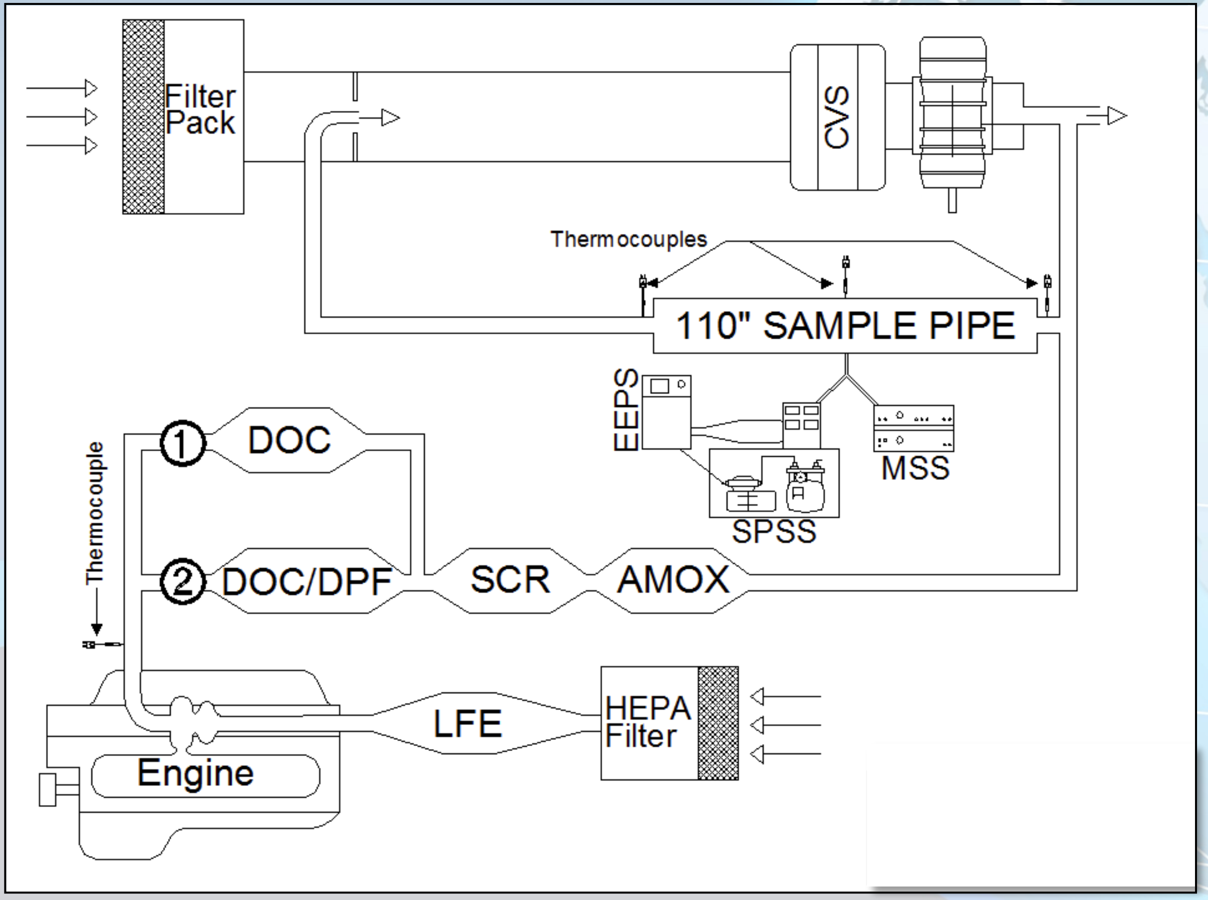
Objectives

- To investigate exhaust particle sensor performance and durability using diesel engine platform under varying:
  - Exhaust temperature
  - Exhaust velocity
  - Exhaust particle concentration, size distribution, and composition
- To determine performance and survivability under:
  - Short term engine operation (few days)
  - Long term engine operation (1400 hours) using accelerated particle emissions

Engine Test Cell Setup - Year 1
1998 Heavy-Duty Diesel Engine



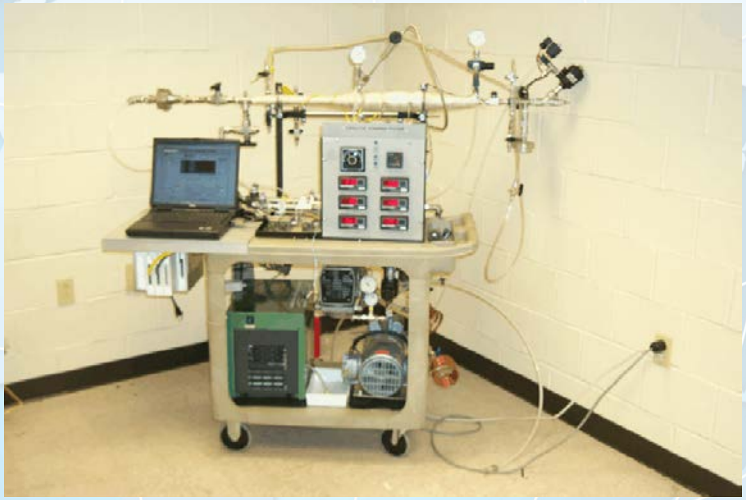
Engine Test Cell Setup - Year 2
2011 Heavy-Duty Diesel Engine



Reference Particle Instruments

TSI EEPS (Size, Number)

AVL MSS (Soot Mass)

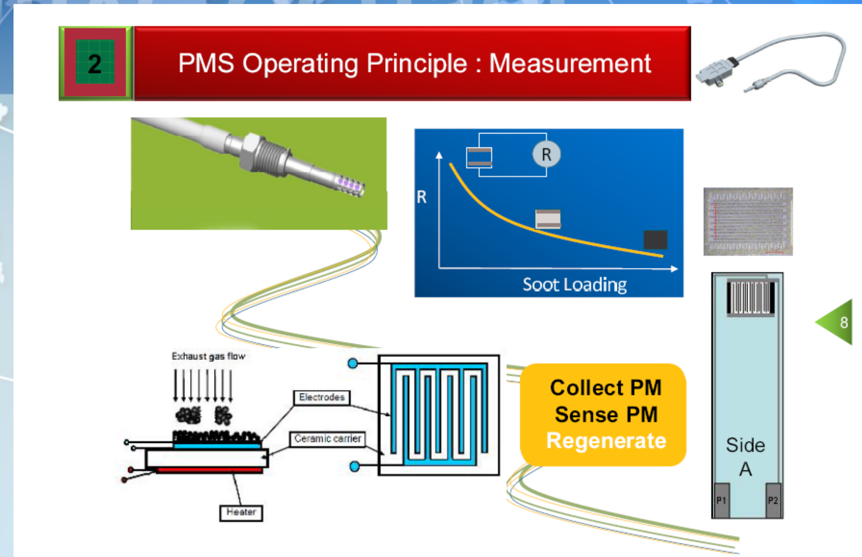


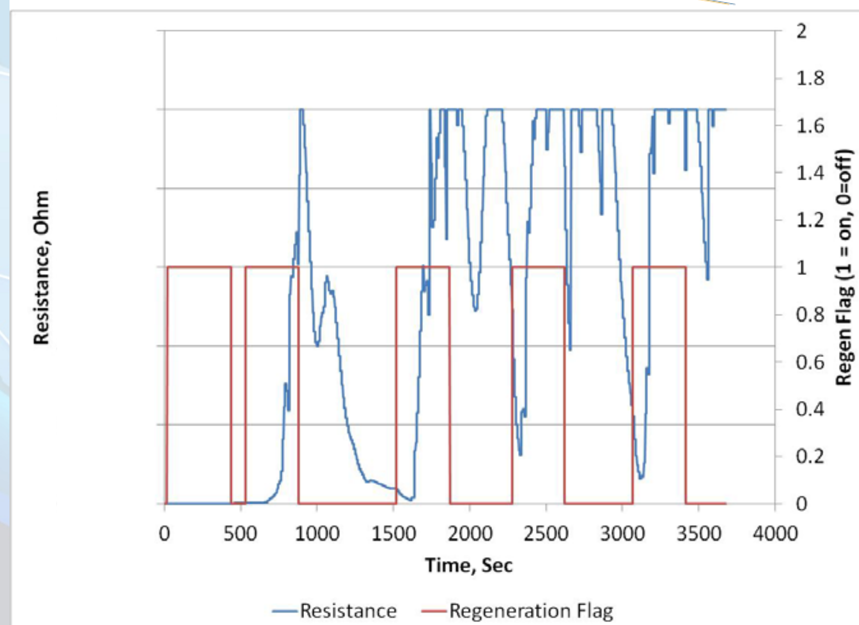
SwRI SPSS, Facilitate Solid Particle Measurement (Used Upstream of EEPS)

Full Flow CVS and Part 1065 Filter measurement were also included for transient testing

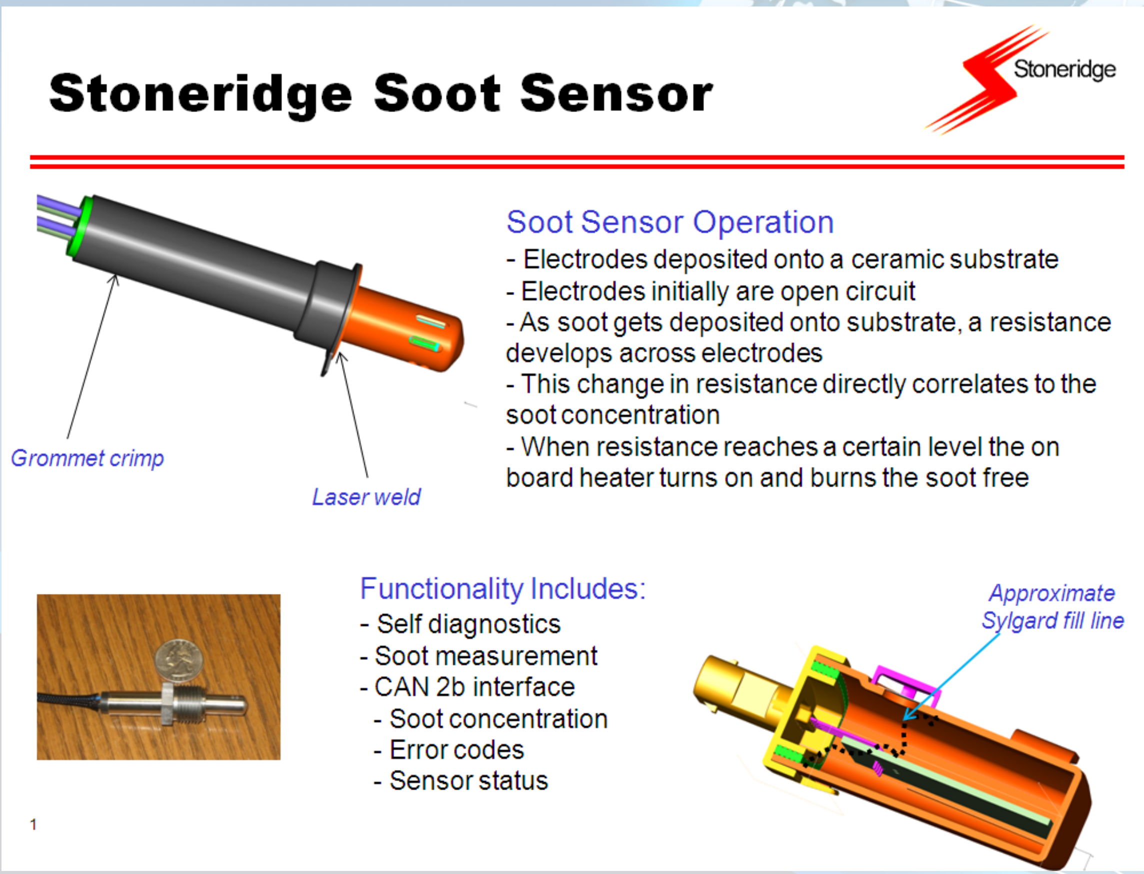
Electricfil Cumulative Sensor

- **Particles collect on an electrode with high electric resistor**
- **Electric resistance decrease with soot loading**
- **As resistance reaches a threshold, sensor is regenerated, and the process starts again**
- **Change in resistance over time is determined between:**
  - **End of Regeneration and Beginning of Regeneration**
- **This sensor provides integrated soot accumulation on the sensor surface over a period of time:**
  - **Time will be short if the concentration is high**
  - **Time will be long if the concentration is low**
  - **For an engine producing ~0.03 g/hp-hr, four regeneration events took place in 20 minutes**
- **Even if the sensor is very accurate, particle deposition will have to be proportional to engine exhaust to get a proper weighting to exhaust emissions, especially under transient operation (a very challenging fluid dynamic problem)**



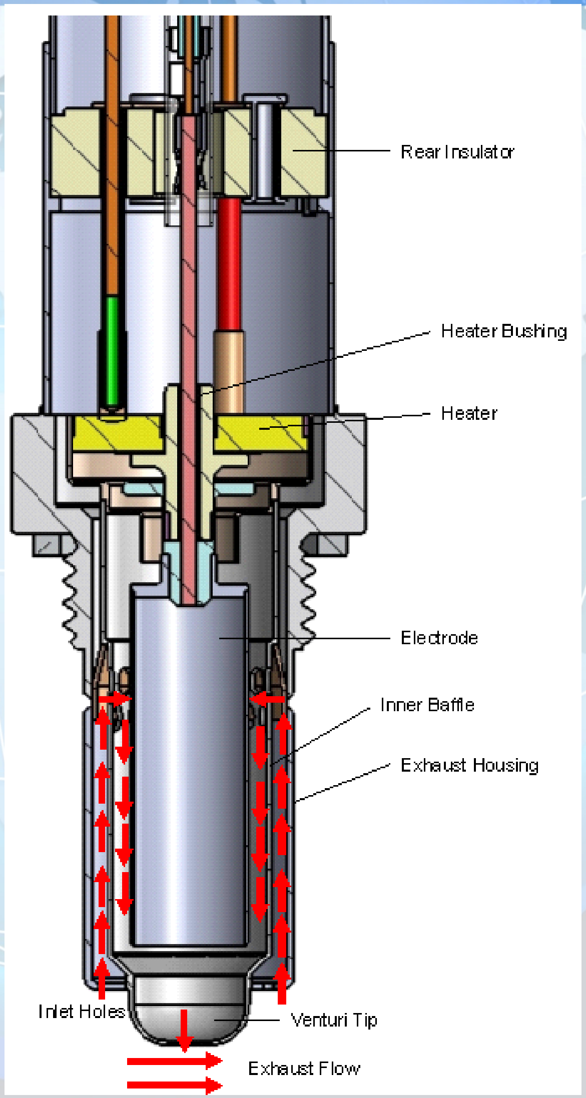


Stoneridge Cumulative Sensor



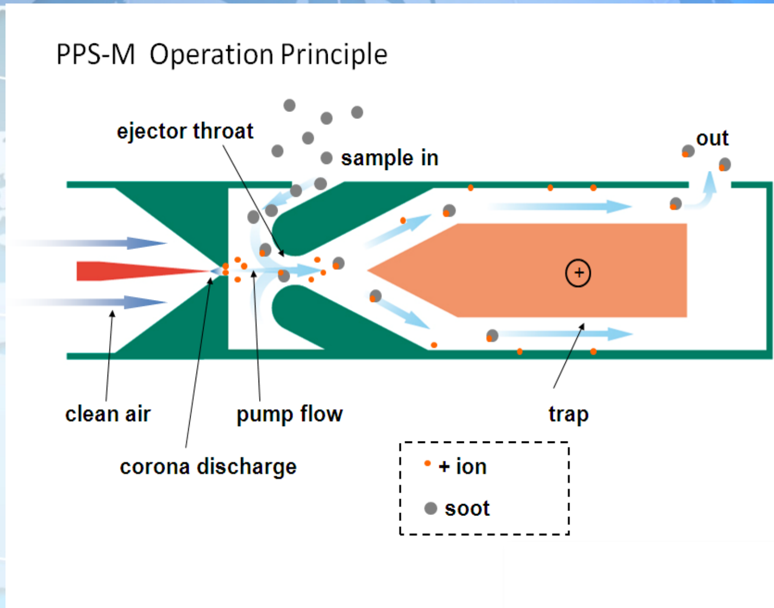
Emisense Real Time Sensor

- **A sample of exhaust is extracted into the sensor electrode region by a venturi using exhaust velocity**
- **Naturally charged particles are captured between two electrodes in a electric field**
- **Captured particles break away from the surface of the electrode due to high charge buildup**
- **Electrometer current is an output associated with particle release from the electrode surface.**
  - **Better understanding of sensor fundamental performance is currently being developed by the sensor manufacturer**



NGK-NTK Real Time Sensor

- **Air driven by an external pump is ionized via a positive corona needle to charge the particles**
- **The high velocity ionized air creates a low pressure region where exhaust enters and mixes with it.**
- **The excess ions are trapped**
  - **Newest design does not include an ion trap**
- **The positively charged particles enter and escape a Faraday cup creating a net total charge that is proportional to particle concentration**
- **No trapping of particles is required for this method to work**



Sensor Experiments Test Matrix – Year 1

	Nominal Sample Zone Temperature of 500 °C				
Nominal Velocity, m/sec	10	30	50		
	Nominal Sample Zone Temperature of 390 °C to 440°C				
Nominal Velocity, m/sec	10	30	50	70	90
	Nominal Sample Zone Temperature of 300 °C				
Nominal Velocity, m/sec	10	30	50	70	
	Nominal Sample Zone Temperature of 200 °C				
Nominal Velocity, m/sec	10	30			

Also varied particle concentration and size distribution at each of the conditions above

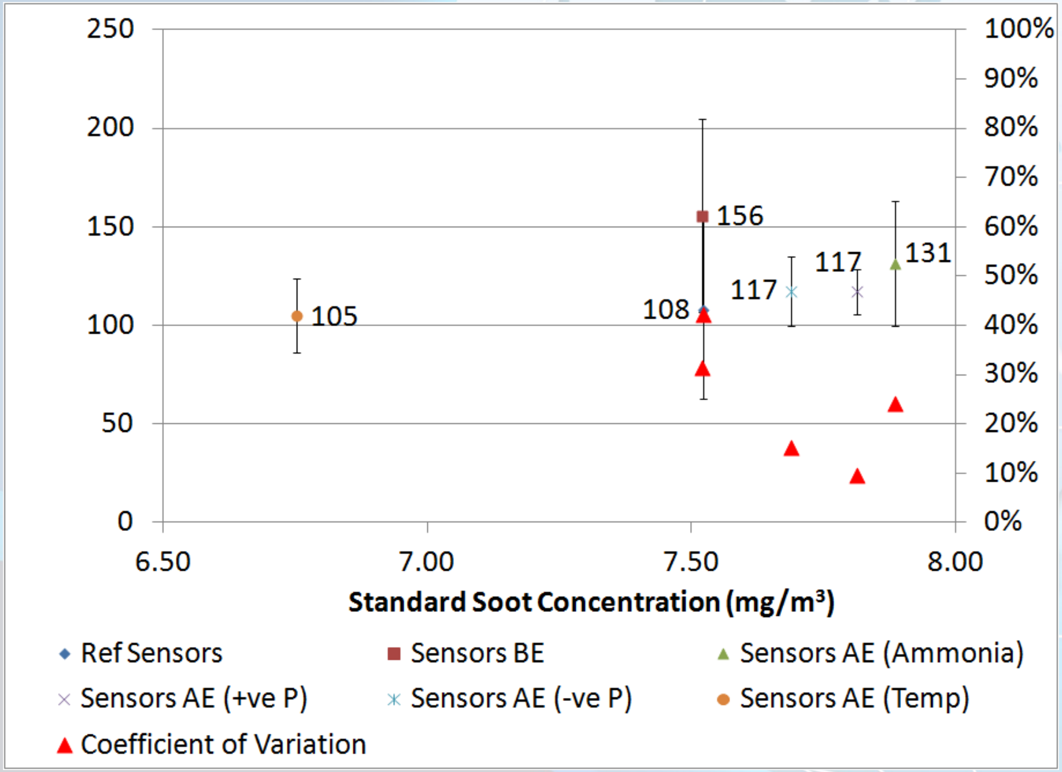
Sensor Experiments Test Matrix – Year 2

- Sample sensors were subjected to 50,000 miles of durability with accelerated soot exposure
  - 0-20,000 miles: DPF out with PM level of 0.001 g/hp-hr
  - 20,000-30,000 miles: PM level of 0.01 g/hp-hr
  - 30,000-50,000 miles: PM level of 0.02 g/hp-hr
  - Equivalent to 520,000 miles of particle exposure assuming a fully functional DPF at 0.001 g/hp-hr
- Performance checks conducted at 0 mile, 1000 miles, 20,000 miles, 30,000 miles and 50,000 miles
- Performance check involved
  - One steady-state condition (~5 mg/m^3, ~390°C, mean of particle size distribution ~ 50 nm)
  - FTP (three repeats), NRTC (three repeats), WHTC (three repeats)
  - Included sample and reference sensors totaling 27 sensors in parallel
- For performance checks, emission level was tuned to target 0.03 g/hp-hr (~90 mg/mile) for FTP cycle (OBD Threshold for HD on-highway)

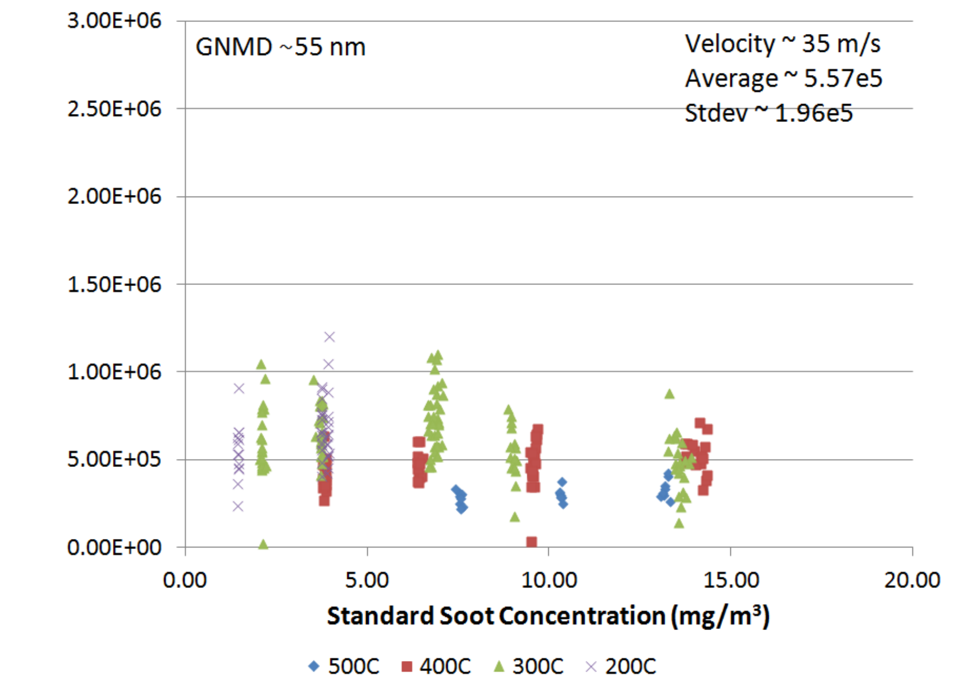
Other Sensor Exposures

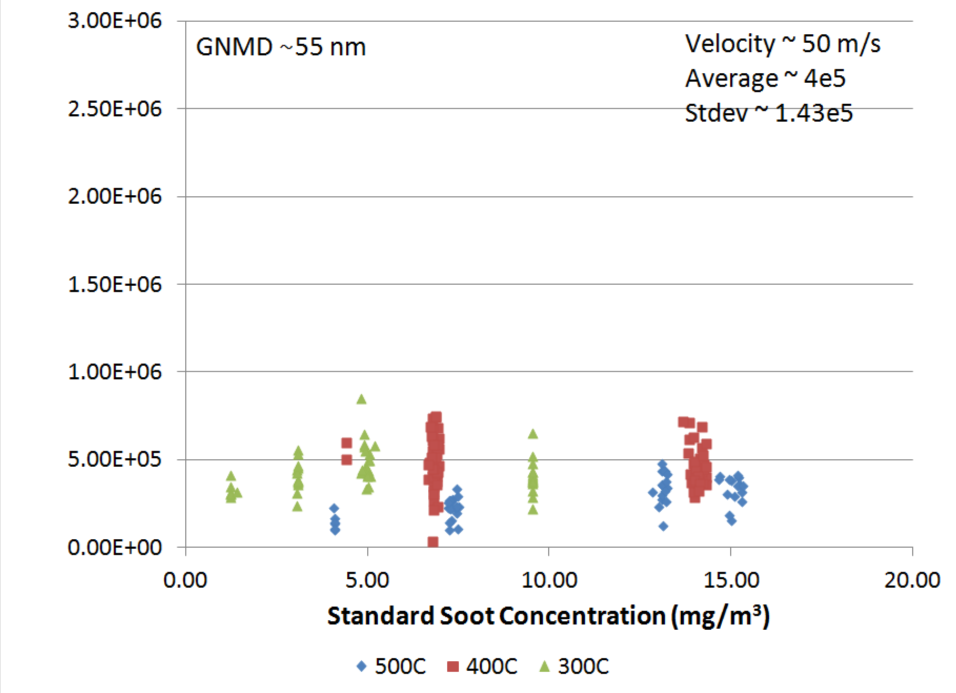
- Sensors were exposed to 8 hours of ammonia concentration of ~500 ppm
  - Same Engine used but with urea injection
  - FTIR was used to measure NH_3 concentration
- Sensors were exposed to 8 hours of 700C temperature
  - High gas temperature diesel burner with DPF was used for this work
- Sensors were exposed to sub-atmospheric pressure (0.75 atm) and positive pressure of (1.25 atm), (1 hour for each)
  - This work was performed off-line

Results-Example of Sensor Sensitivity After Multiple Exposures



Results-Sensor Sensitivity Response at Different Velocities and different temperatures

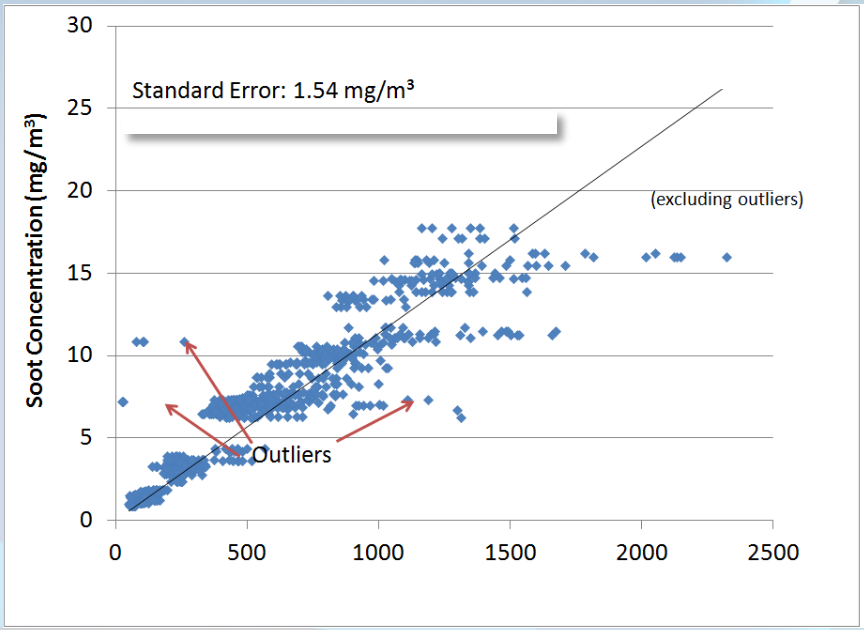


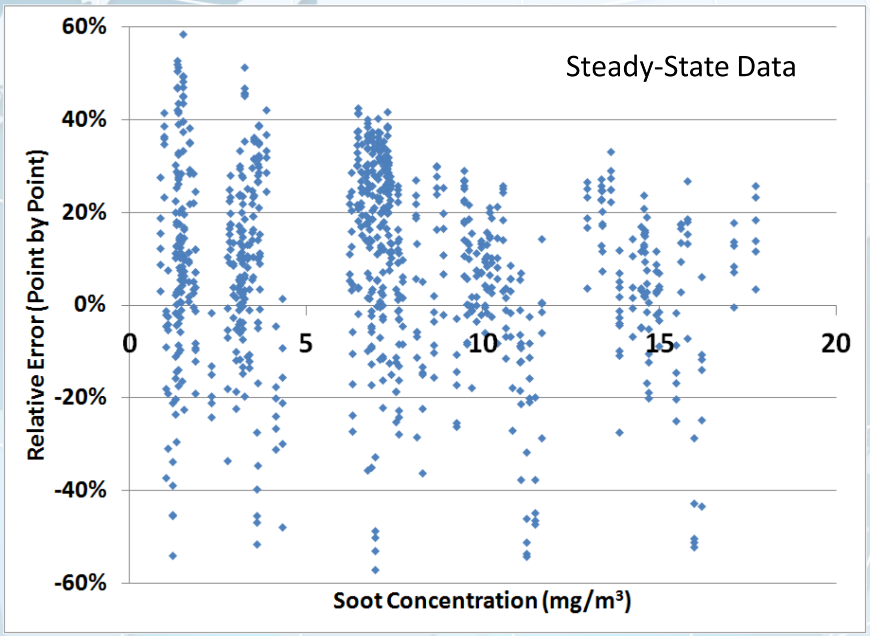


35 m/sec

50 m/sec

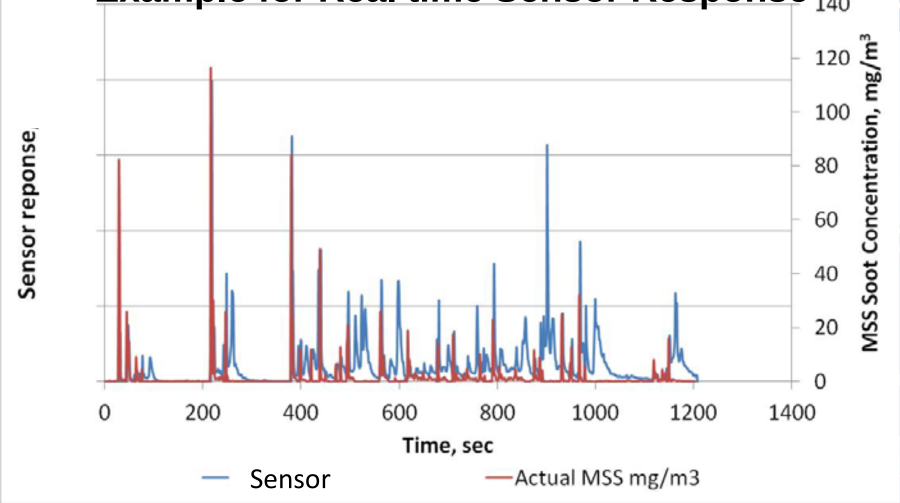
Correlation between Sensors and AVL MSS Soot Concentration (Steady-State (SS) Testing Only)



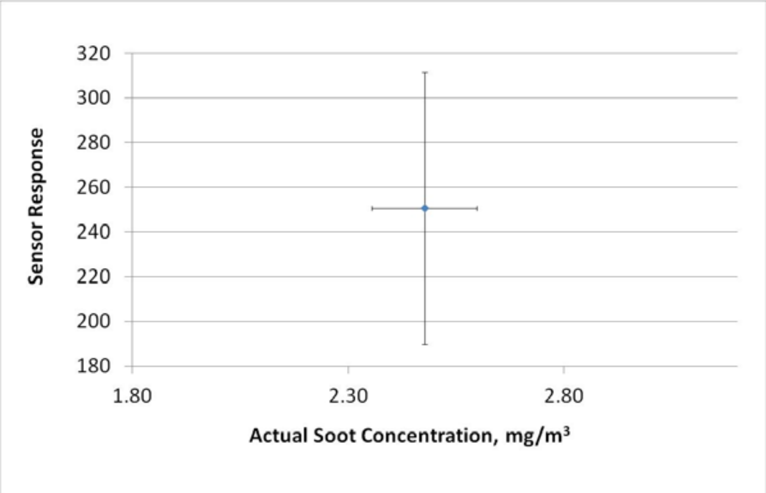


Sensor Response – Transient & SS

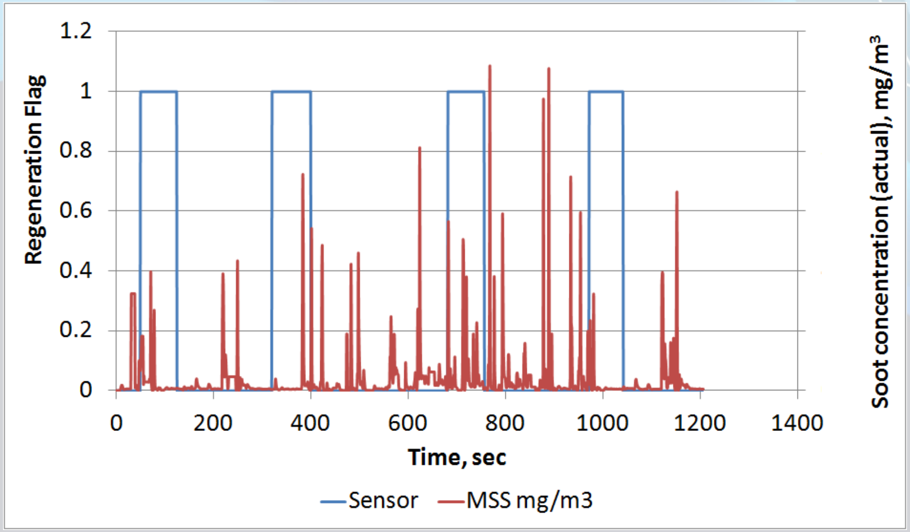
Example for Real time Sensor Response



Steady State Response



Example for Cumulative-Type Sensor Response



- **Real time sensors track Micro-soot sensor reasonably well**
- **Accumulator sensors correlate rate of change of sensor resistance with soot concentration**
- **Issue of Sensor Variability observed during SS tests**

Summary

- Significant progress has been made in spark-plug sized technology for sensing particle in engine exhaust
- It is critical to continue the development of this process with the help of engine and sensor manufactures and other interested stakeholders

Upcoming PSPD II of Consortium Activities (2015 – 2019)

- Kickoff Meeting in October 2015
- Particle Natural Charge and Conductivity Using Different Technology Engines
  - Several sensor technologies need such information
- Particle Sensor Variability & Accuracy Near Threshold
  - Sensor to sensor variability
  - Inherent variability of a sensor
- DPF Soot Leak and Particle Stratification Measurement
  - Optimal location of sensor in exhaust configuration

Acknowledgments

- **This work was funded by PSPD consortium members:**

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