PARTICLE SENSOR PERFORMANCE & DURABILITY
A Consortium of SwRI

Spark-Plug Sized Exhaust Particle Sensors for OBD and Emissions Monitoring

SOUTHWEST RESEARCH INSTITUTE®

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Background

PARTICLE SENSOR PERFORMANCE & DURABILITY

- PSPD-I was completed in May, 2015
  - Year 1 focus was on Sensor Performance
  - Year 2 focus was on Sensor performance as a function of durability
- PSPD-II on going
  - Year 1 focus on sensor variability, sensor cross sensitivity and charge/conductivity of exhaust particles from different engine technologies

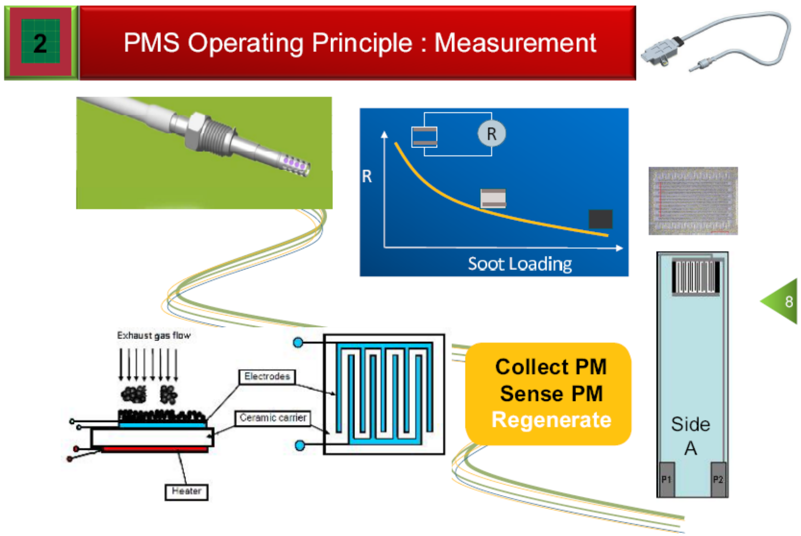
Particle Sensor Applications

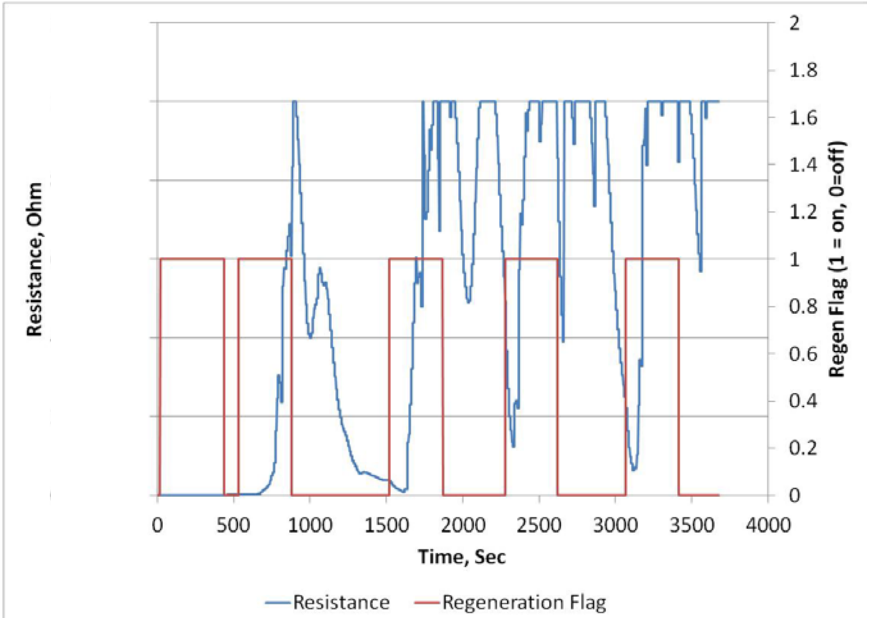
- Onboard vehicles downstream of exhaust particle filters for:
  - OBD Requirement (highway vehicles, potentially nonroad)
    - CARB Heavy-Duty & Light-Duty On-Highway: 2016 Enforcement
    - Light-Duty Gasoline: 2019 Enforcement
  - Leak detection and durability
    - QA/QC
    - In-use screening
  - Onboard vehicles engine out
    - Active particle emissions control
    - Engine mapping (real world)
    - EGR cooler diagnostics through particle dynamics
- Retrofit applications
- In-use testing (simple systems)
- Smoke meter replacement (laboratory use)
- Onboard for continuous in-use emissions monitoring

- Sensor Technology in the Market Place

Electric Resistance Cumulative Sensor-Electricfil

- 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)

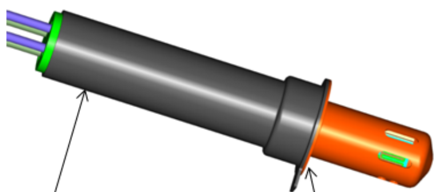




Electric Resistance Cumulative Sensor- Stoneridge

Stoneridge Soot Sensor

Stoneridge

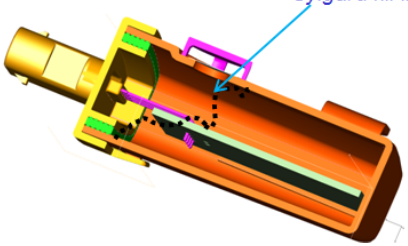


Soot Sensor Operation

- Electrodes deposited onto a ceramic substrate
- Electrodes initially are open circuit
- As soot gets deposited onto substrate, a resistance develops across electrodes
- This change in resistance directly correlates to the soot concentration
- When resistance reaches a certain level the on board heater turns on and burns the soot free

Functionality Includes:

- Self diagnostics
- Soot measurement
- CAN 2b interface
  - Soot concentration
  - Error codes
  - Sensor status



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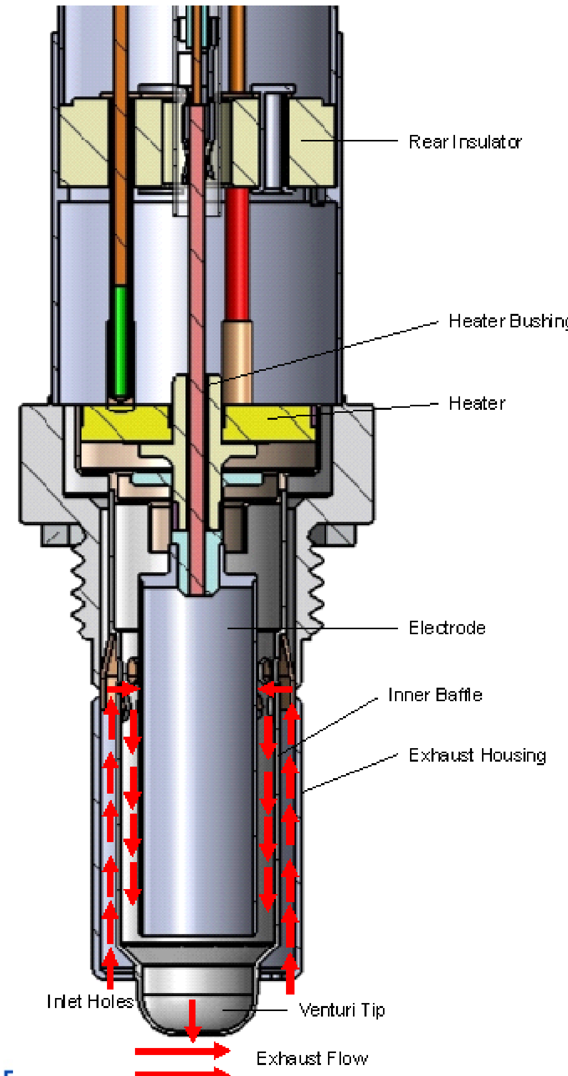
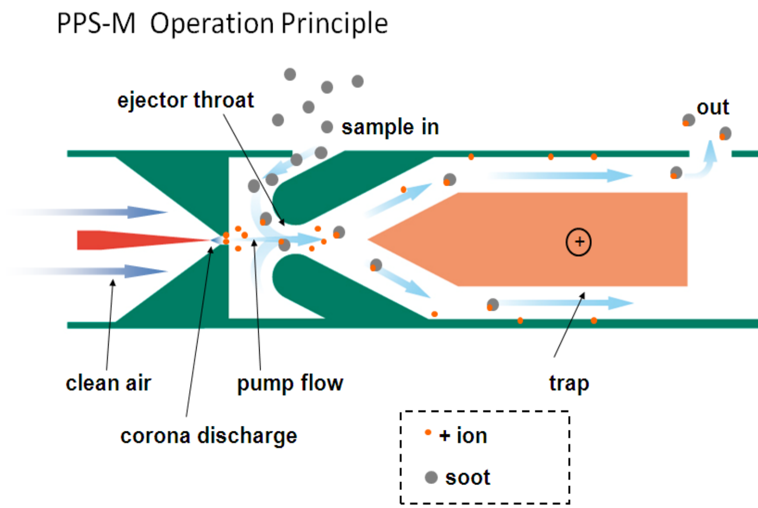
Real Time Sensor- Emisense

- 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

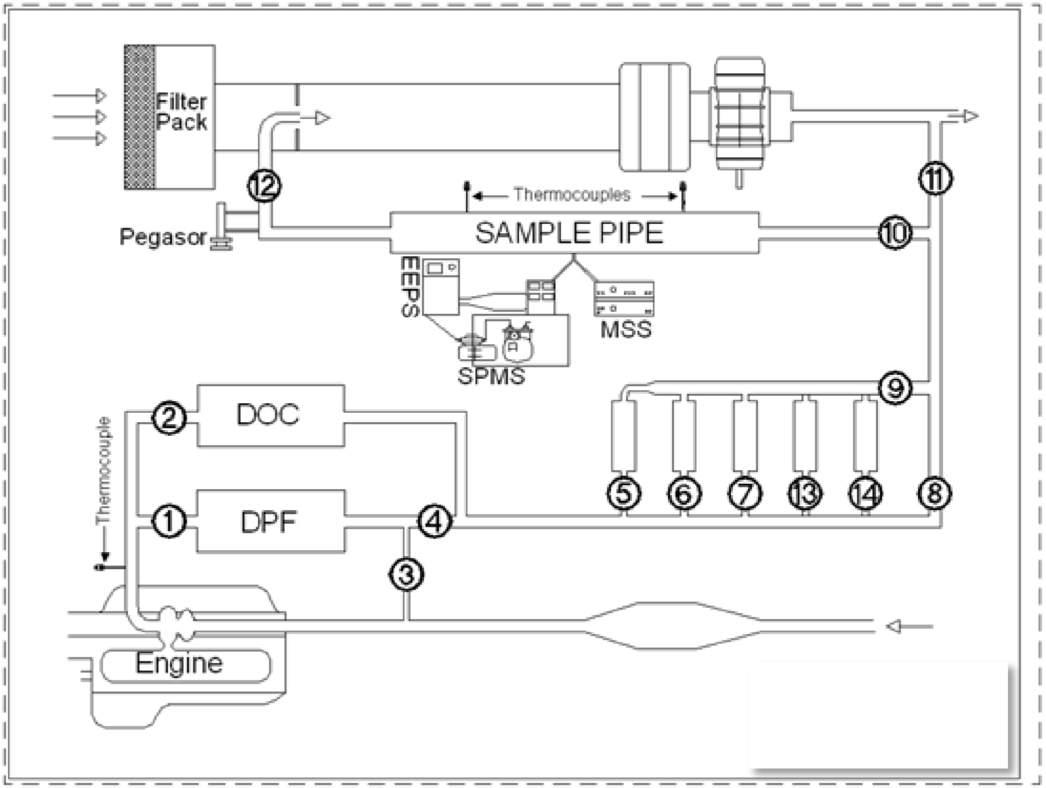


Real Time Sensor- NGK-NTK

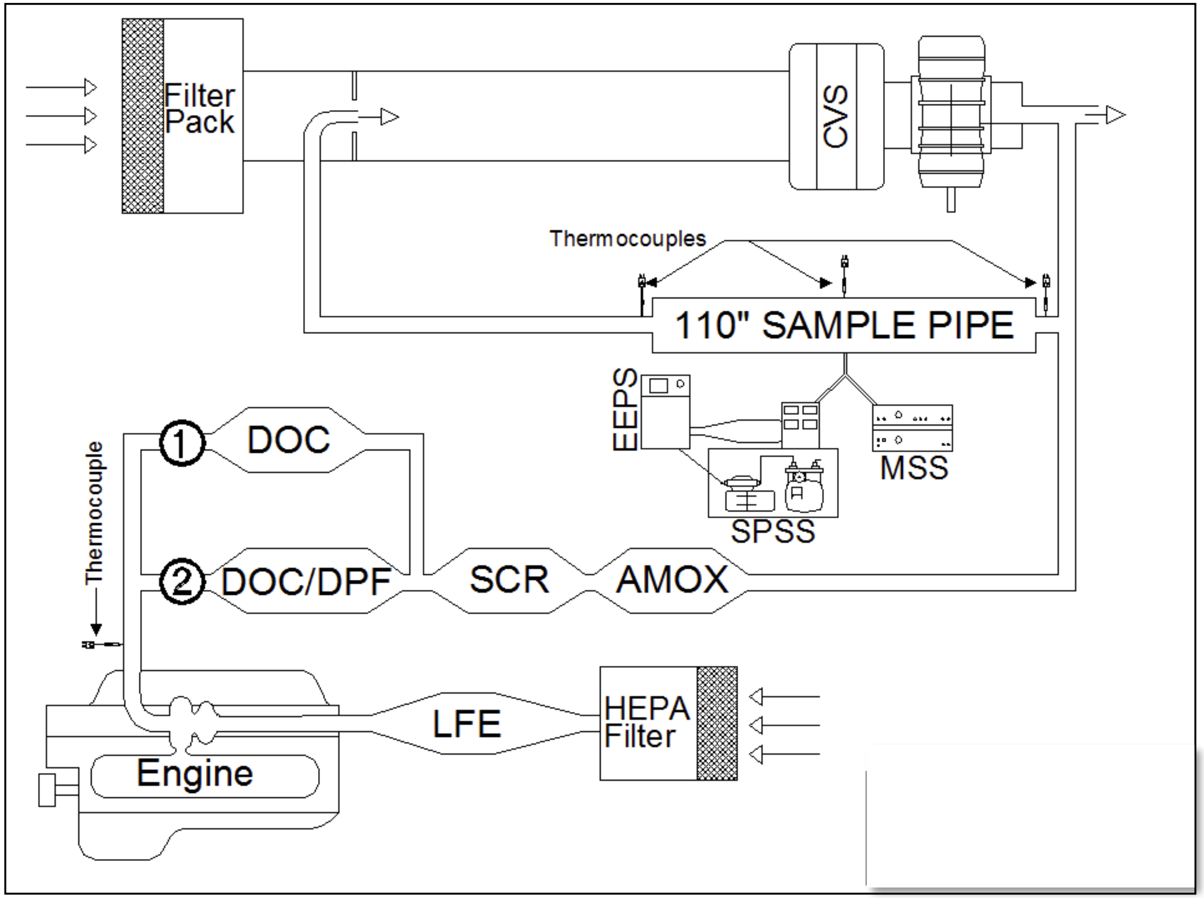
- Air driven by an external pump is ionized via a positive corona needle to charge the particles
- The high velocity ionized air creates a low pressure region where exhaust enters and mixes with it.
- The excess ions are trapped
  - Newest design does not include an ion trap
- The positively charged 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



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



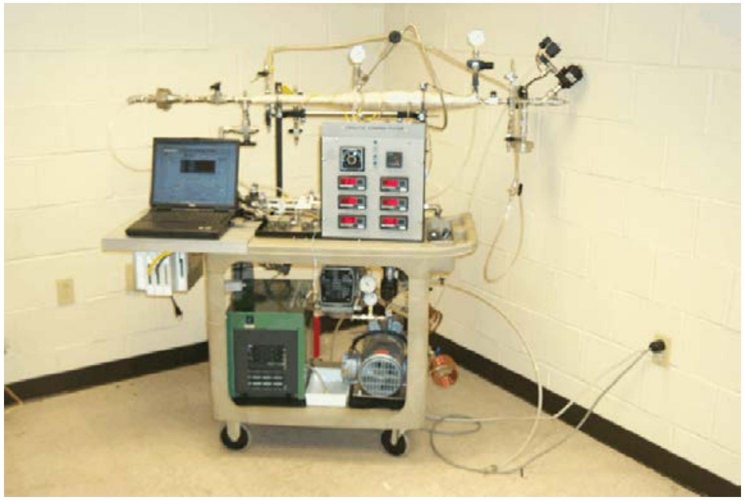
Engine Test Cell Setup - Year 2
2011 Heavy-Duty Diesel Engine



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

PSPD-I Year I Test Matrix

PSPD PARTICLE SENSOR PERFORMANCE & DURABILITY

Performance Evaluation

	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			

- Each condition repeated at 1, 3, 7, 10, 15 mg/m^3
- Entire matrix repeated for geo. number mean diameter (GNMD) of size distribution at ~55 nm and ~80 nm
- Total of over 336 data points

Short-term survivability

- Ammonia exposure
  - Same engine with urea injection
  - 8 hours of exposure at ~500 ppm concentration
  - FTIR used to measure ammonia concentration
- High temperature exposure
  - 8 hours of exposure at 700 °C using High gas temperature burner
- Pressure exposure (offline)
  - 1 hour of sub-atmospheric (0.75 atm) and positive pressure (1.25 atm)

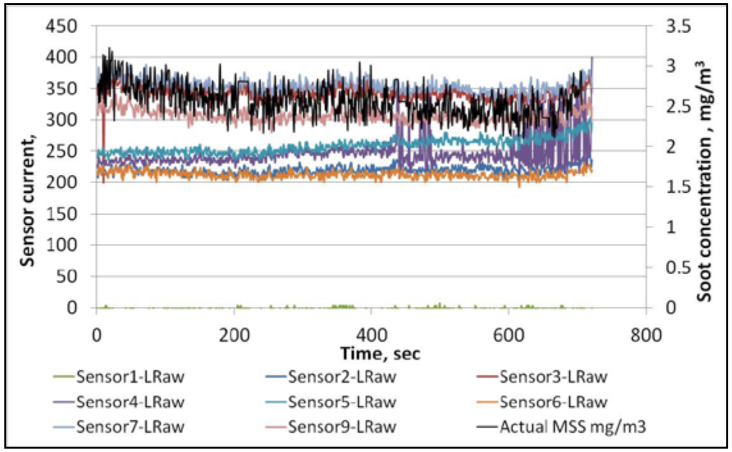
Sensor Experiments Test Matrix – Year 2

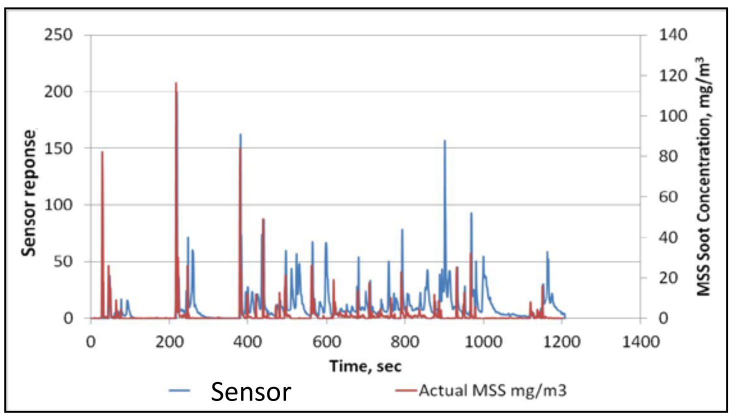
- Sample sensors were subjected to 50,000 miles of durability with accelerated soot exposure
  - 0-20,000 miles: DPF out with PM level of 0.001 g/hp-hr
  - 20,000-30,000 miles: PM level of 0.01 g/hp-hr
  - 30,000-50,000 miles: PM level of 0.02 g/hp-hr
  - **Equivalent to 520,000 miles of particle exposure 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)

Results – Example of Steady-State (SS) & Transient Sensor Response

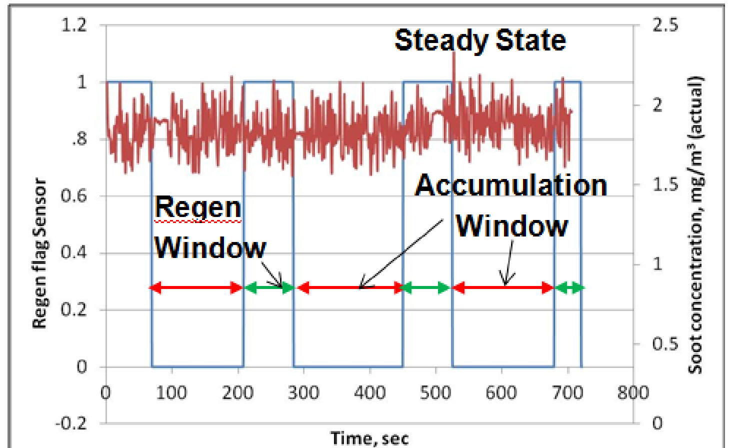
PSPD
PARTICLE SENSOR PERFORMANCE & DURABILITY

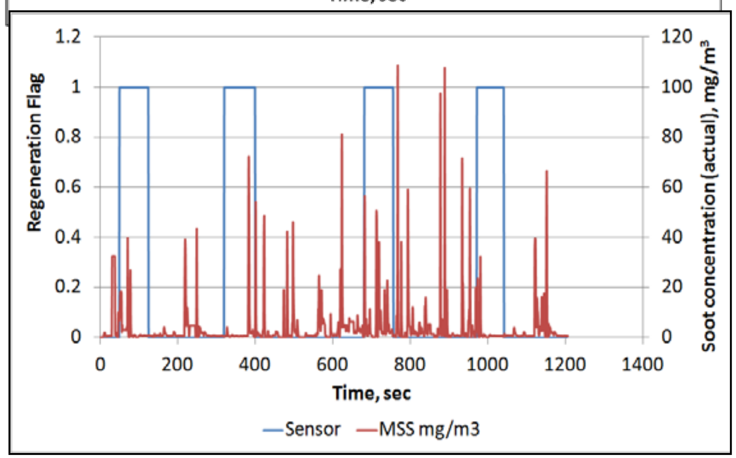
Real time Sensor





Cumulative-type Sensor





- Real time sensors track Micro-soot sensor reasonably well
- For Cumulative sensors, Rate of change of resistance can be correlated with rate of change of soot mass seen by the sensor

Results – Examples of Sensor Sensitivity Response with Soot Concentration (GNMD ~ 55 nm, SS)

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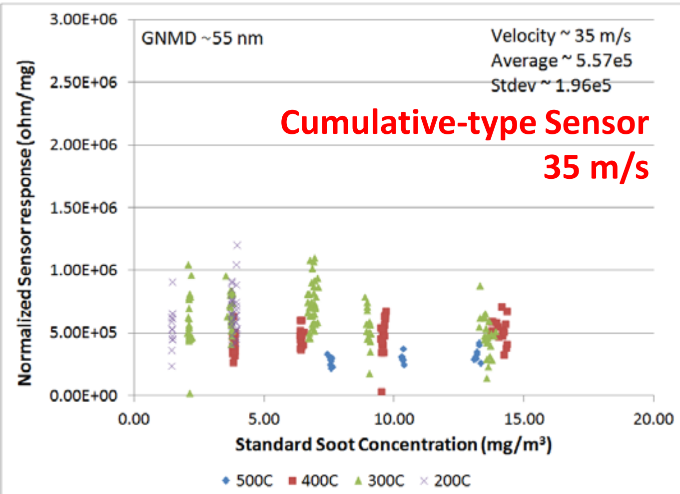
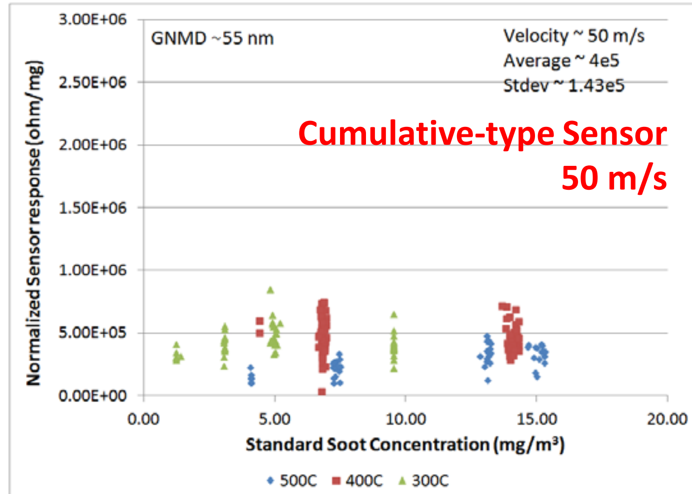
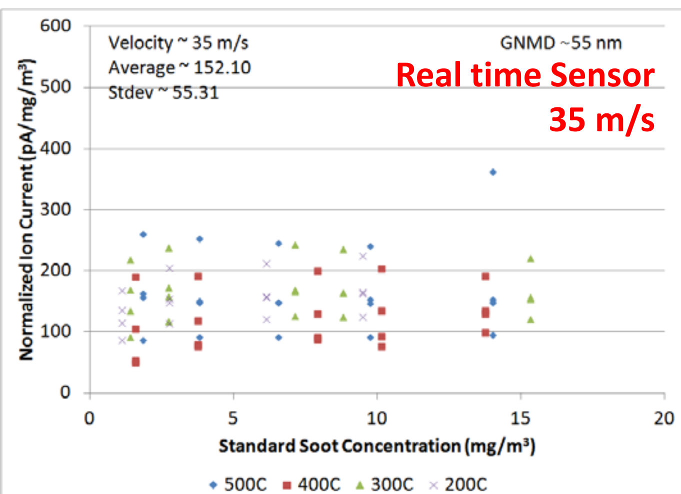
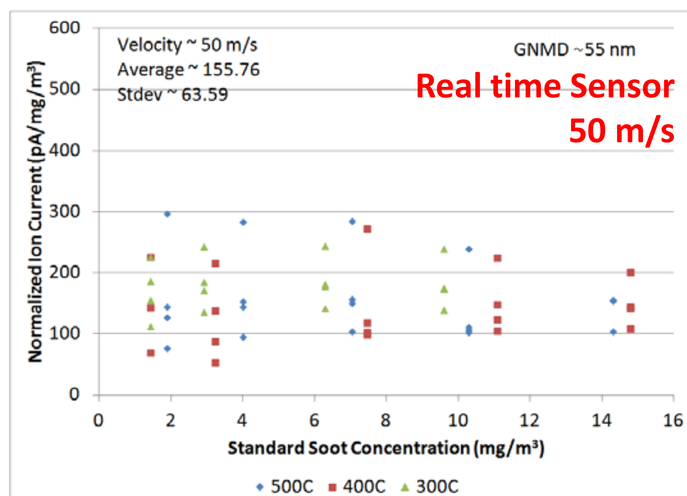




- Average sensitivity for all data was 4.85e5 ohms/mg, with a COV of 36%

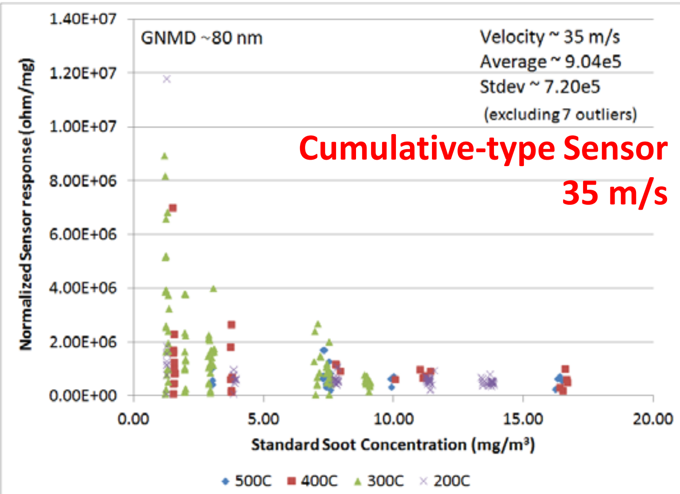


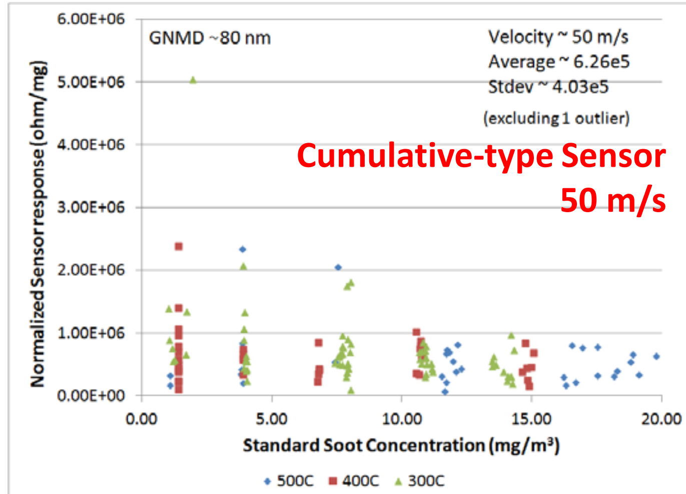


- Average sensitivity for all data was 150.09 pA, with a COV of 37%

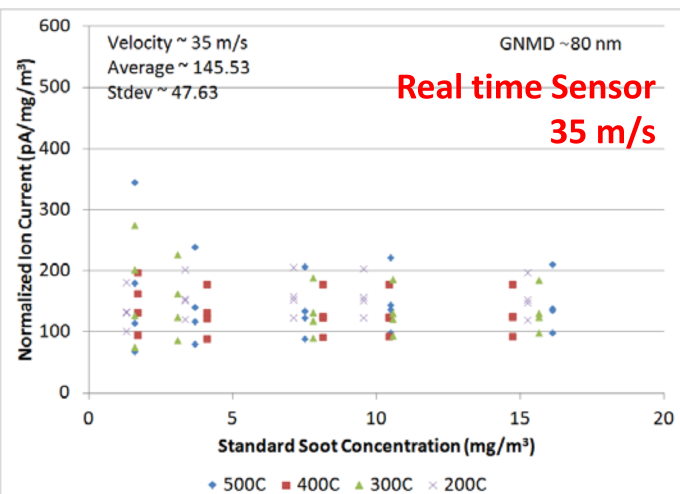
Results – Examples of Sensor Sensitivity Response with Soot Concentration (GNMD ~ 80nm, SS)

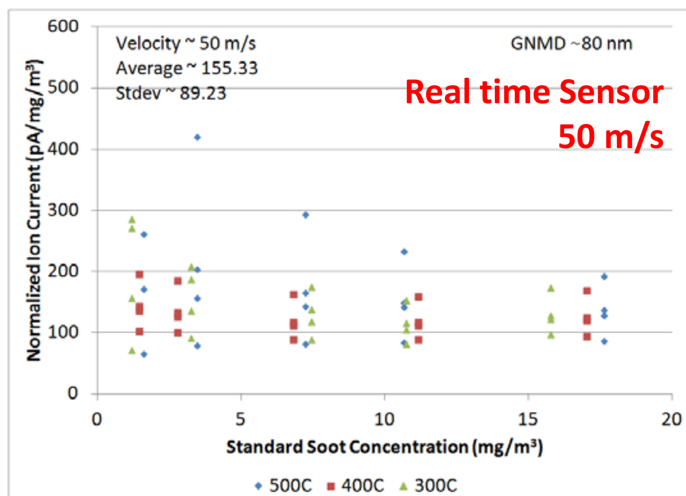
PARTICLE SENSOR PERFORMANCE & DURABILITY





- Average sensitivity for all data was 8.35e5 ohm/mg, with a COV of 73%

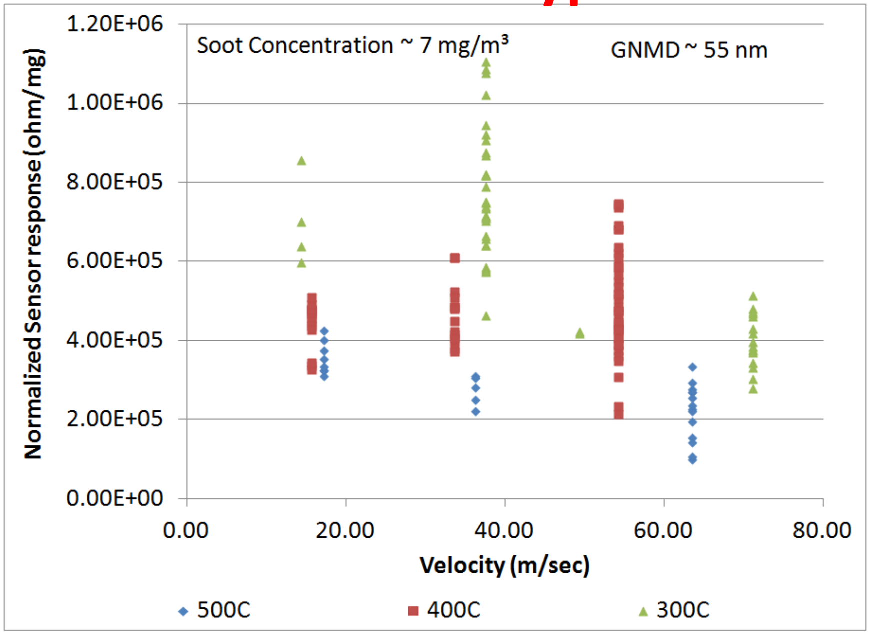




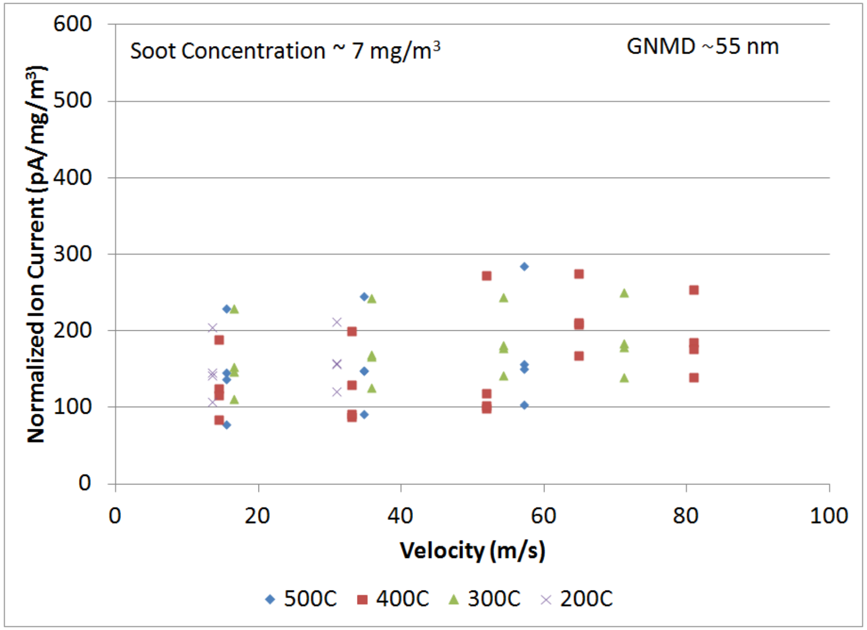
- Average sensitivity for all data was 139.76 pA, with a COV of 45%

Results – Examples of Sensor Sensitivity Response with Velocity (GNMD ~ 55 nm,SS)

Cumulative-type Sensor



Real time Sensor

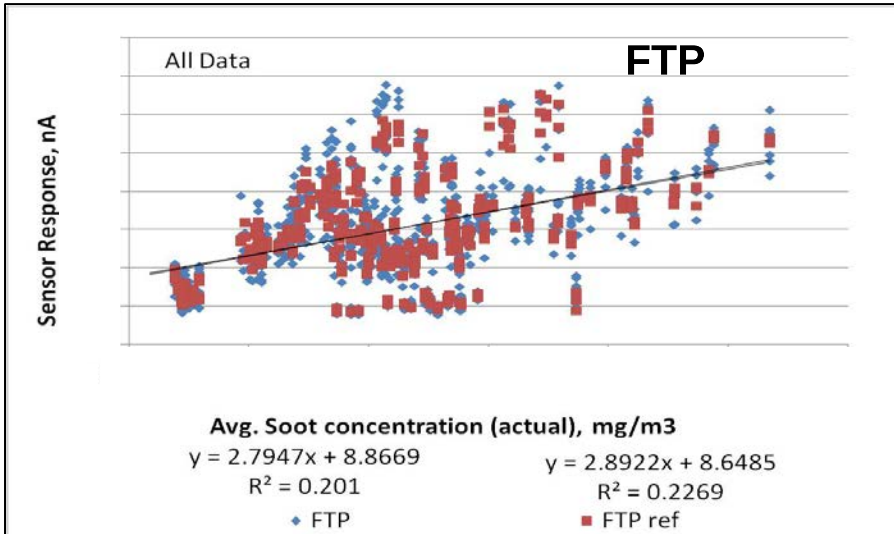


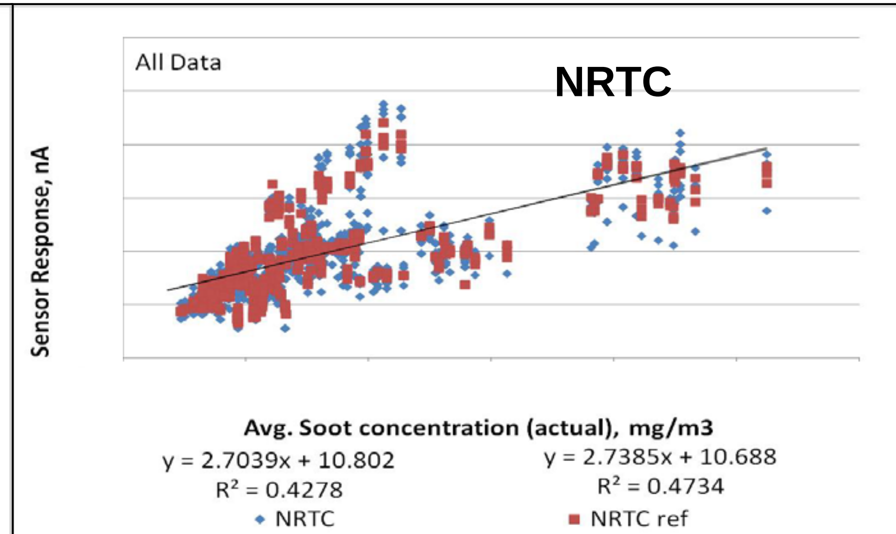
- Slight decrease in sensitivity was observed with increasing velocity

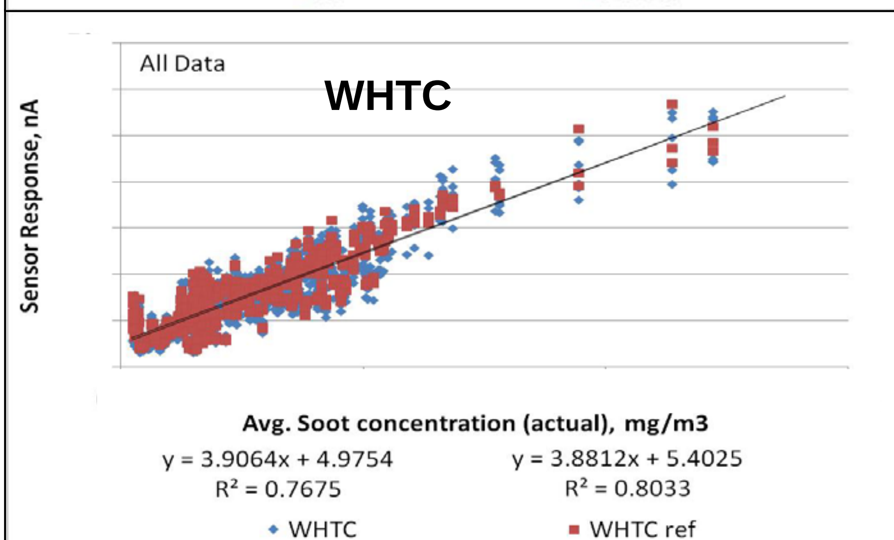
- Slight increase in sensitivity was observed with increasing velocity

Transient Response (Cycle Basis)

Real time Sensor Example







- Correlation and slope seemed to be cycle dependent
- Similar observations made with Cumulative-type Sensors
- R^2 and slope lowest for FTP and highest for WHTC
- Includes all sensor data from 0-mile, 1000-mile, 20,000-mile-post, 30,000-mile and 50,000-mile Performance Checks

Results – Examples of Sensor Sensitivity Response After Multiple Exposures (SS)

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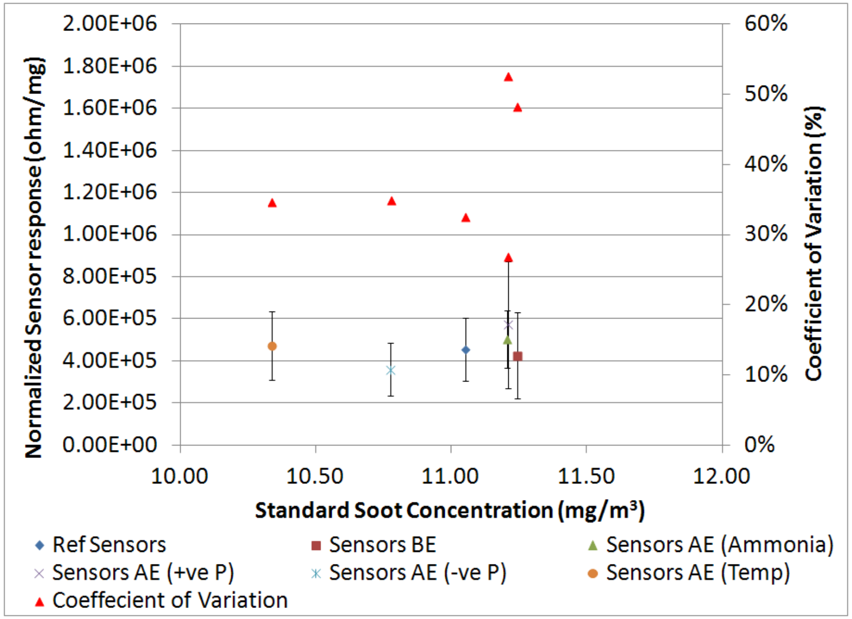
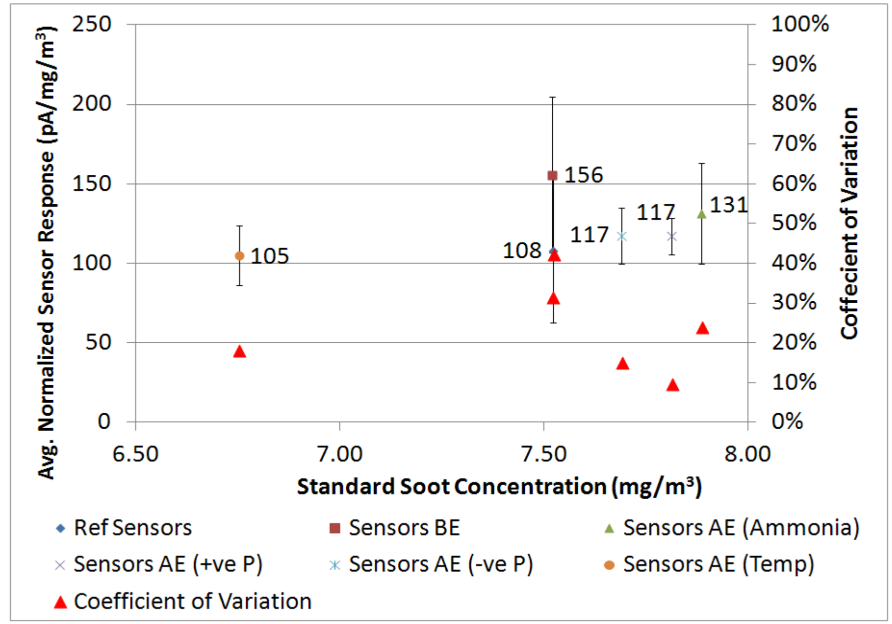
Cumulative-type Sensor



- COV ranged from 27% to 53%
- Normalized response ranged from 3.59e5 to 5.72e5 ohm/mg
- The average normalized output for all sensors after all exposures was 4.42e5 with a COV of 42%

Real time Sensor



- COV ranged from 10% to 40%
- Normalized sensor response ranged from 108 to 155 (pAx40)/(mg/m³)
- The average normalized current for all sensors after all exposures was 135.4 pA/mg/m³ with a COV of 36%

Summary

- Significant progress has been made in spark-plug sized technology for sensing particle in engine exhaust
- Sensors show some promising results for moving forward with their applications
- It is critical to continue the development of this process with the help of engine and sensor manufactures and other interested stakeholders

Acknowledgments

- This work was funded by PSPD consortium members:

PSPD-II Consortium Activities

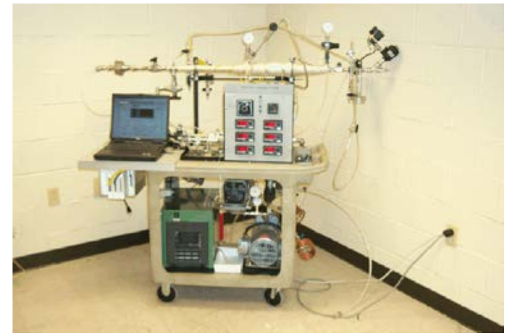
- Year 1 Kickoff Meeting held in January 2016
- Focus on
  - Particle Sensor Variability & Accuracy Near Threshold
    - Sensor to sensor variability
    - Inherent variability of a sensor
  - Particle Sensor Cross Sensitivity
    - To gases such as NO, NO_2, CO, NH_3
    - To ash loading
  - Particle Natural Charge and Conductivity Using Different Technology Engines
    - Fundamental knowledge needed by different sensing technologies

Reference Particle Instruments

PSPD-I

AVL MSS (Soot Mass)

TSI EEPS
(Size, Number)



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

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

Addition for PSPD-II

Eu PMP compliant Solid Particle Number System

RT-Ash

Full Flow CVS and Part 1065 Filter measurement

PSPD-II Members

PARTICLE SENSOR PERFORMANCE & DURABILITY

EmiSense

Continental
The Future in Motion

John Deere

HINO

BOSCH

NGK SPARK PLUGS

Stoneridge

DENSO

Southwest Research Institute®

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