State of Spark-Plug Sized Exhaust Sensors for Real World Emissions Monitoring

SOUTHWEST RESEARCH INSTITUTE®

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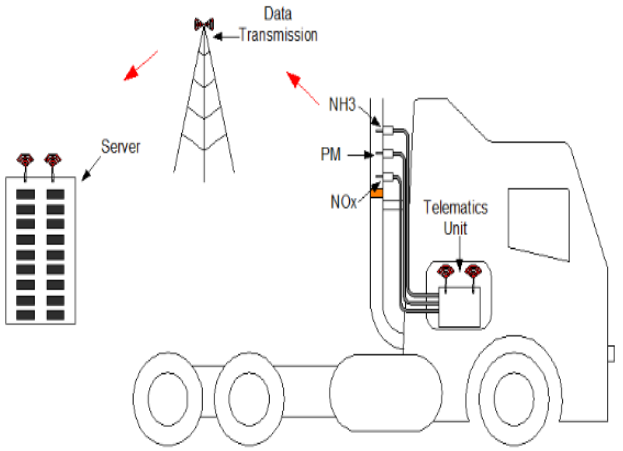
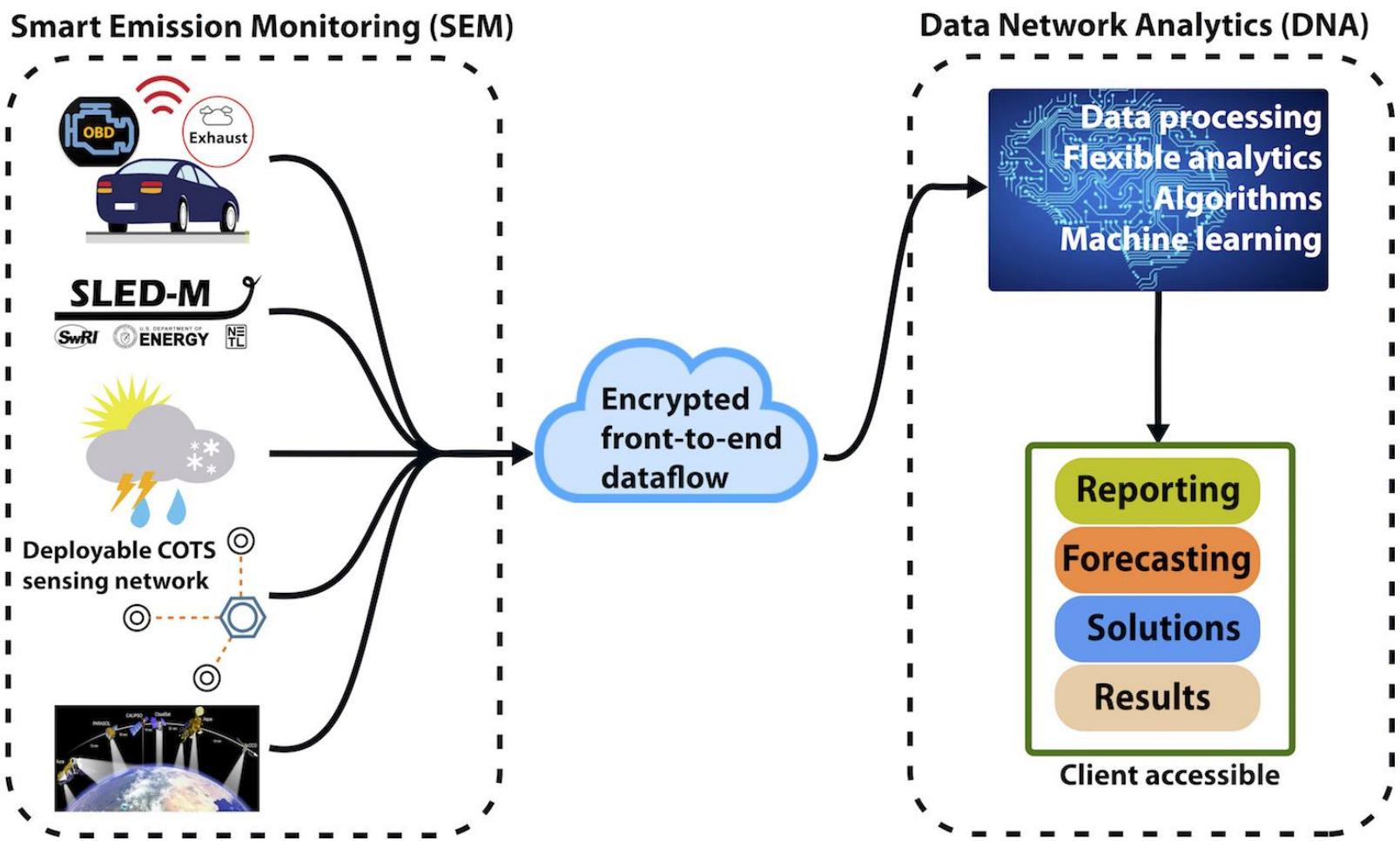
Background

- Vehicle certification and emission monitoring are currently done on a small sample of vehicles:
  - In laboratory
  - In-use
- The development cost for engine onboard diagnostics (OBD) for vehicle emission compliance is becoming a huge burden for the engine manufactuers
- There is a desire to increase emission monitoring onboard vehicles via sensors in order to reduce or minimize OBD requirements
- The development of a robust and accurate sensing technology and data transmission by 2027:
  - could eliminate the need for both laboratory and in-use certification and reduce the burden of OBD
  - focus on the verification and OBD of onboard sensors



SwRI SEMNA Concept



Future of Onboard Emission Monitoring

- Exhaust sensors for Onboard emission monitoring
  - Particles: Number, Mass
  - Gases: NO_X, NO_2, N_2O, CO_2, CO, CH_4, NH3, SO2

Tickets for Violators 😔

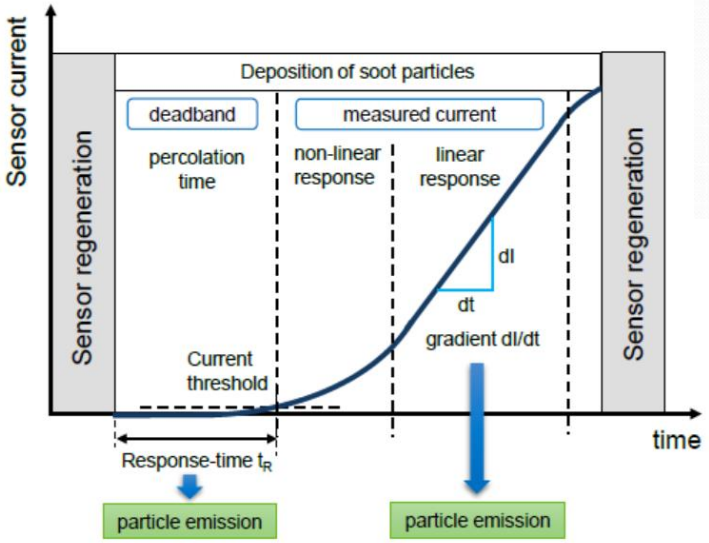
Repair Your Vehicle

Emission Inventory

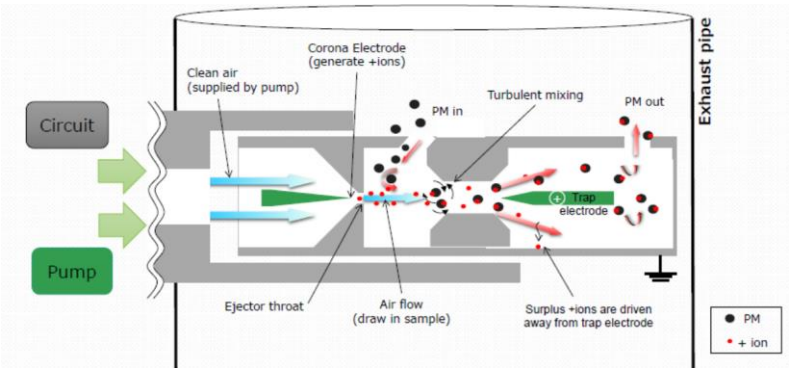
- State of the Art Exhaust Sensors

PM Sensing Principles

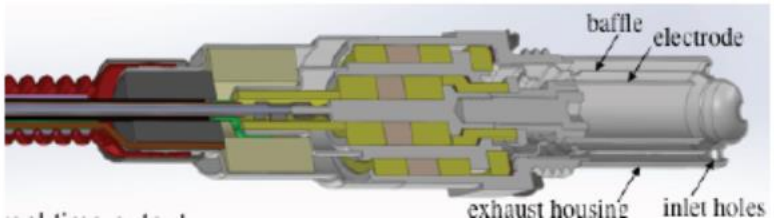
- Electric resistatnce-base technology: Bosch, Denso, Stonerdige
- Particle charging and net escaping current: NGK/NTK
- Natural charge, particle electric mobility deposition and release: CoorsTek



Resitive Base (adapted from Bosch…SwRI Symposium)



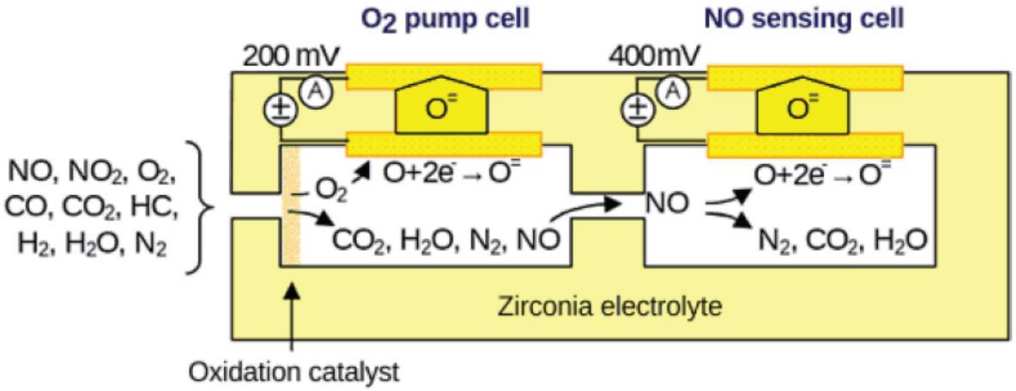
Adapted from NGK/NTK SwRI Symposium…… Latest design with no pump or ion trap



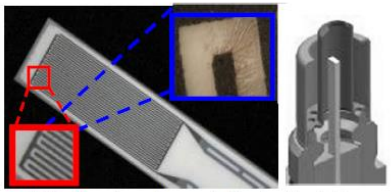
Adapted from Coorstek…SwRI Symposium)

NO_X Sensing Principle of Operation: Commercial Sensors

- NO_X sensors are mainly oxygen measurement sensors inferring NO_X
  - CO and HC should be oxidized first to avoid interference
  - NO_2 should be reduced to NO prior to the NO sensing stage
  - Oxidation of ammonia in the first chamber to NO can cause ammonia interference



Bosch NOx & PM Sensors


IDE; Sensing element; Protection tube

- NOx Sensor
  - Operates according to the amperometric double chamber principle
  - 0-3000 ppm measuring range
  - ±10 ppm measurement accuracy at 90 ppm
  - 1800 ms response time

Commercially Available Sensors

- Cumulative PM Sensor
  - Operates based on resistance measurement
  - Soot particles deposited on electrode structure and form conductive soot trails between the electrodes
  - Prior to each measurement phase, the sensor element is regenerated through heating
  - 250,000 km lifespan
  - < 850 C Exhaust Temperature

Denso NOx & PM Sensors

- NOx
  - Direct gas flow to sensor cell – 1 chamber structure
  - Residual oxygen cancelled by "monitor" cell
  - 0-2000 ppm measuring range
  - ±10 ppm measurement accuracy at ≤ 100 ppm
  - 1800 ms response time
  - ≤ 60 sec light-off time

Commercially Available

- Cumulative PM Sensor
  - Operates based on resistance measurement
  - Prior to each measurement phase, the sensor element is regenerated through heating

Under Devlopment

Continental NOx Sensor

- NOx Sensor
  - 0-1500 ppm measuring range
  - ±10 ppm measurement accuracy at low concentrations
  - 3 cavity system with 3 pumping electrodes
  - Zirconia based multilayer ceramics

Commercially Available

StoneRidge PM Sensor

- Cumulative PM sensor
- Resistive-Based Technology Sensor
- Accumulation of soot over a period of time to get a the accumulated PM mass then regeneration to start the process again

Commercially Available

CoorsTek Sensors

NOx Sensor

- Based on AC impedance, 2 electrodes, porous YSZ electrolyte, directly in the gas to be analyzed
- Oscillating signal is applied and resulting wave distortion and pulse response is analyzed

Under Devlopment

PM Sensor

- Real Time output of PM mass concentration
  - ~1 kV to concentric electrostatic trap
  - Current proportional to PM
  - Captured soot grows filamentous dendrites
    - Growth to critical height

Available for Licensing

Delphi Ammonia Sensor

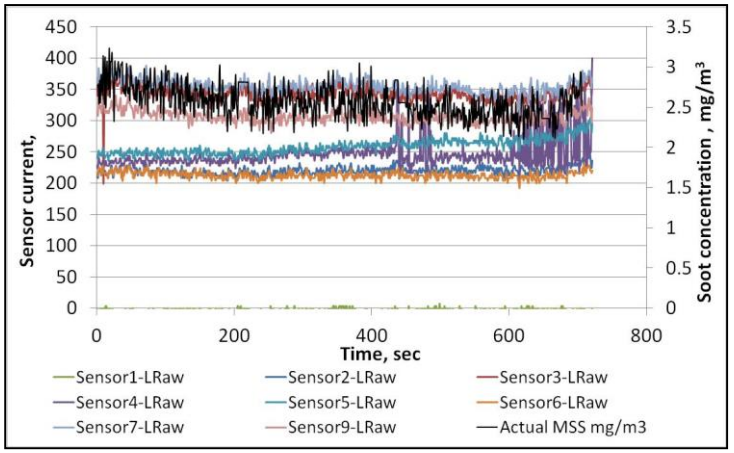
Picture courtesy: Delphi

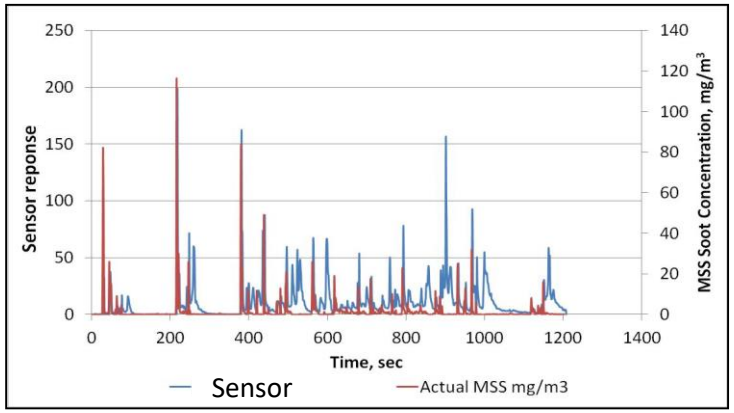
Commercially Available

- Operates on non-equilibrium electrochemical sensing principle
- Has two electrodes and the presence of NH_3 causes a potential difference between the electrodes
  - This voltage difference is proportional to NH_3 concentration in exhaust
- NH_3 detection range 0 to 100 ppm
- Typical temperature operational range: 200 °C to 450 °C
- Typical T90 response time 5 sec or lesser

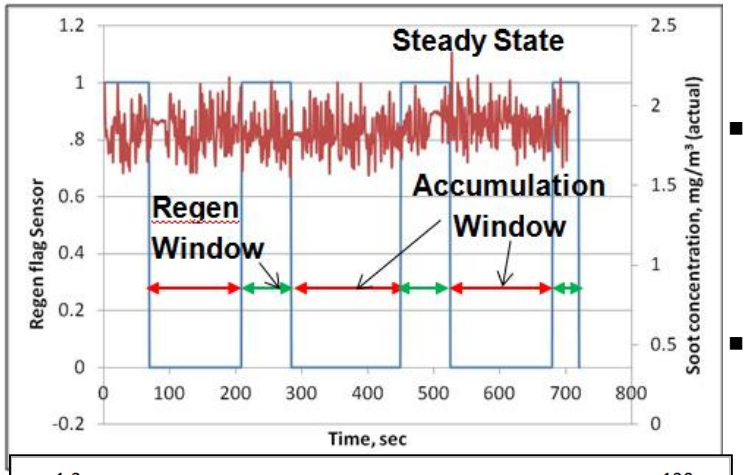
PM Results – Example of Steady-State (SS) & Transient Sensor Response

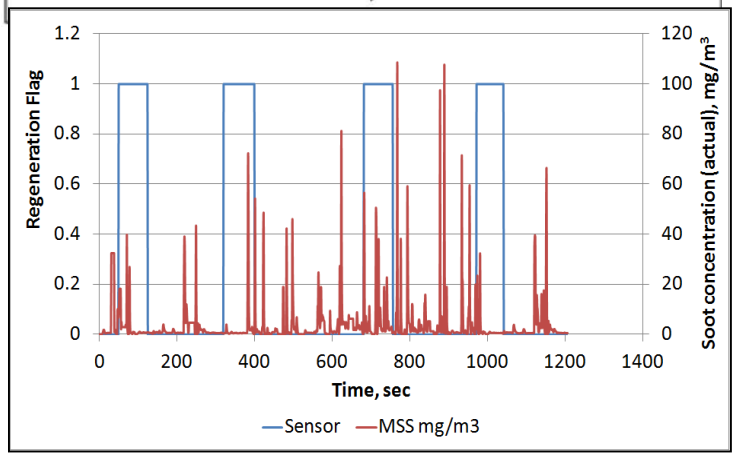
Real time Sensor





Cumulative-type Sensor

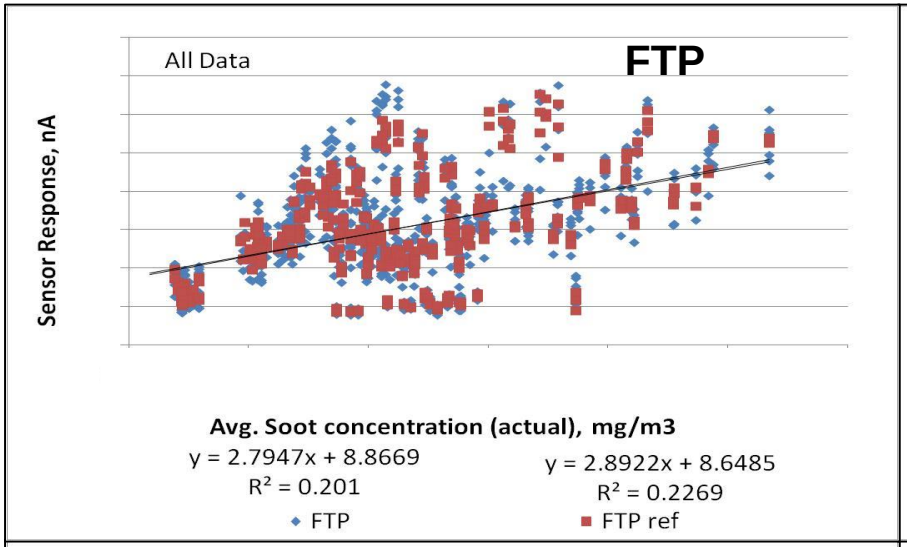


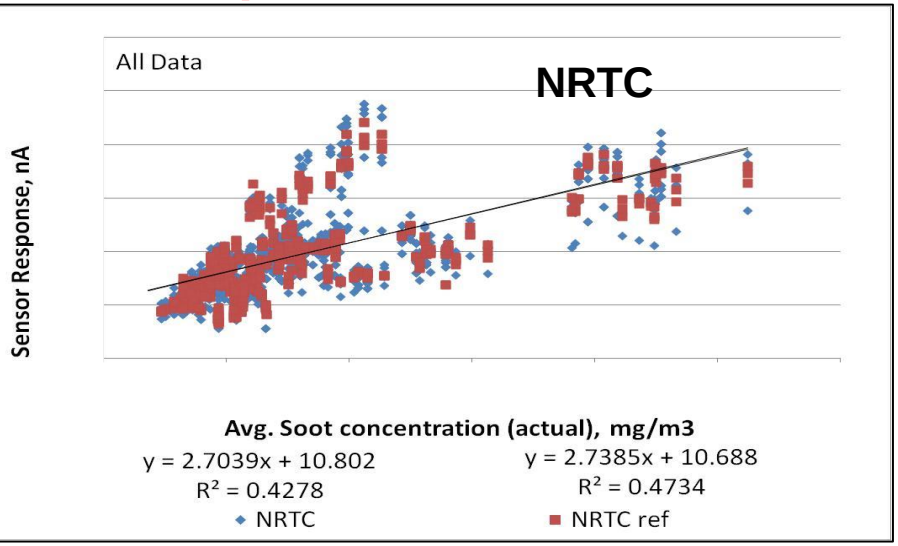


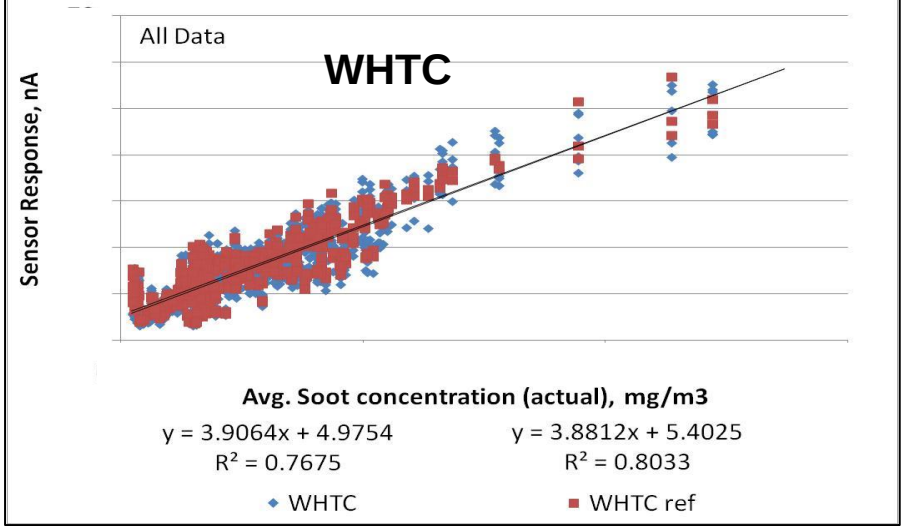
- Real time sensors track Micro-soot sensor reasonably well
- For Cumulative sensors, Rate of change of resistance can be correlated with rate of change of soot mass seen by the sensor

Transient Response (Cycle Basis)

Real time Sensor Example



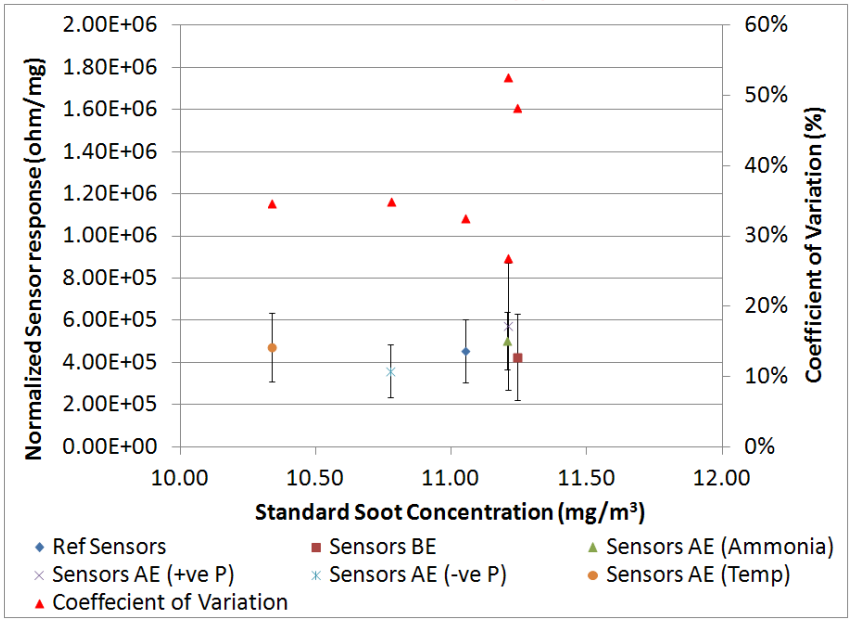




- Correlation and slope seemed to be cycle dependent
- Similar observations made with Cumulative-type Sensors
- R^2 and slope lowest for FTP and highest for WHTC
- Includes all sensor data from 0-mile, 1000-mile, 20,000-mile, 30,000-mile and 50,000-mile Performance Checks

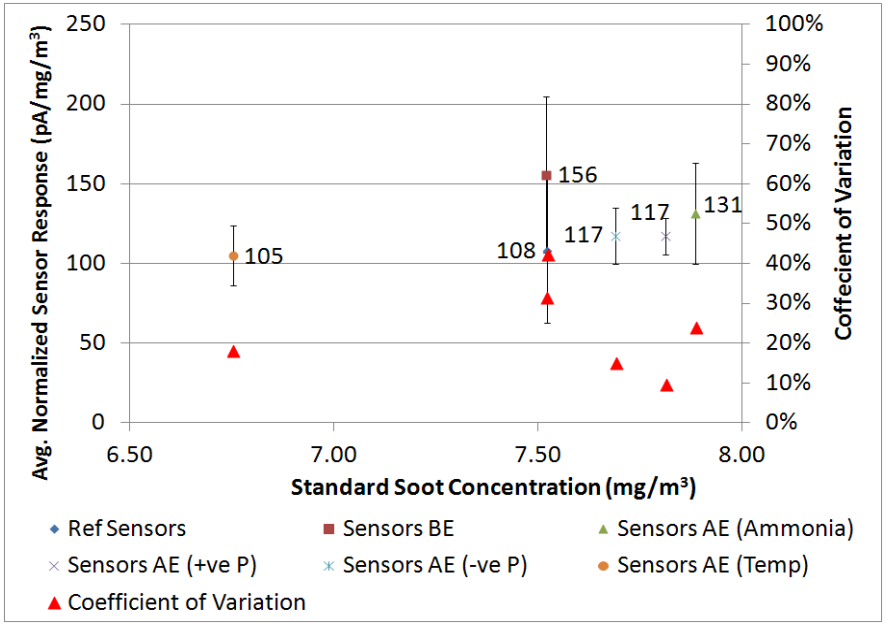
Results – Examples of Sensor Sensitivity Response After Multiple Exposures (SS)

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



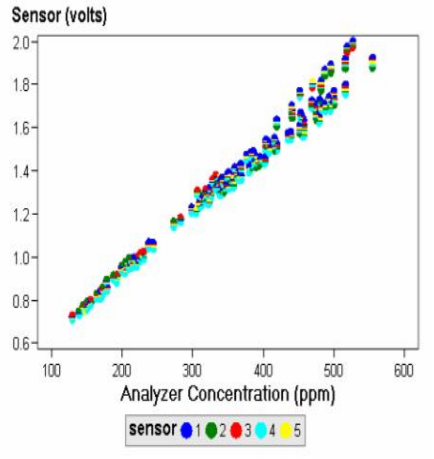
- COV ranged from 10% to 40%
- Normalized sensor response ranged from 108 to 155 (pAx40)/(mg/m³)
- The average normalized current for all sensors after all exposures was 135.4 pA/mg/m³ with a COV of 36%

- Particle sensor results are derived from past data of SwRI Particle Sensor and Durability Consortium (PSPD). PSPD is ongoing and Year 2 final meeting will be held at SwRI on July 11, 2019.

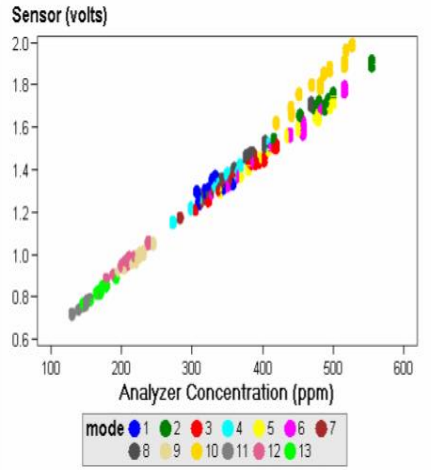
Nox Sensors

Sensor Position 1:

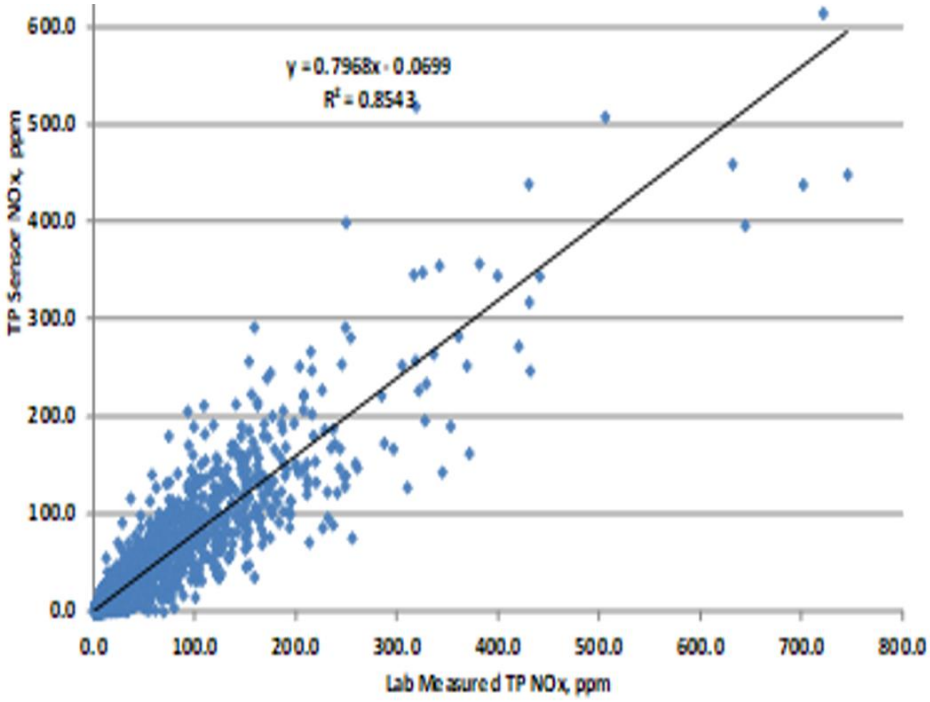
Sensor Voltage vs. Analyzer ppm



By Sensor



By Mode



Sensor data from current and previous SwRI programs. Sensors performance will be explored in the ultra low Nox region

Next Step (Focus on NOX/NH3)

- Define gaseous sensor performance characteristics as it relates to
  - Noise, repeatability, accuracy, linearity and response time as defined in CFR Part 1065 using bench testing
  - Understand sensor performance and interferences using laboratory based burner system such as SwRI ECTO-Lab
  - Better define improvements needed in relation to
    - Cold start operation
    - Low level concentration measurement and detection limit

This work has been approved but not officially processed for funding by the Truck and Engine Manufacturers Association (EMA) and EPA, with contribution from Sensor Manufacturers)

New Metric for Emissions Compliance….A Recommendation

- A CO_2 specific metric is most suited for future emission regulation conformity solely based on sensors, regardless of engine technology or engine size
- The determination of such conformity metric can utlize NO_X, PM, CO & CO_2 sensors to start with.
  - Emission compliance for criteria pollutants does not need to capture emission exposure directly but rather needs to be an input that can be changed to change the outcome of expoures
  - **g of NOx/Kg of CO2 (compliance, fundamental unit)**
  - Exhaust flow rate allows the determination of g/hr of NOx and g/hr of CO2