Development and Demonstration of an Electronic Particulate Matter Sensor for Both Engine-Out and Post-DPF Exhaust Monitoring

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Outline

- Introduction
  - Emission limits, market requirements
  - Project Goals
  - Electronic PM sensor principle of operation
  - Previous on-vehicle engine-out results
- Experimental Setup
- Results
- Summary
- Future Efforts

Diesel Particulate Matter (PM)
Emission limits

- Demanding emission legislation has created a need for low-cost, sensitive, accurate, and robust PM sensors for OBD
- Light-duty vehicles (chassis-certified): 0.01 g/mi
- Heavy-duty engines (engine-certified): 0.01 g/bhp-hr (~3.3 mg/m^3)[1]
- Heavy-duty vehicles must have an OBD system capable of detecting a failure of the DPF resulting in PM emissions of 1.5 times (~4.9 mg/m3) the emission limit [2]

1. Assuming 550 bhp and 28000 SLPM

2. U.S EPA, Code of Federal Regulations, Part 86, "Control of Emissions from New and In-use Highway Vehicles and Engines", Sections §86.005-17 and §86.007-11 July 2008 revision.

Market Requirements

- Diesel and Homogeneous Charge Compression Ignition (HCCI) Engines
  - New diagnostic tools needed for sensing and control of:
    - Particulate filter failure detection and regeneration (OBD)
    - Engine transients
    - Real-time feedback
    - EGR (Exhaust gas re-circulation)

- Present Techniques for Particulate Measurement
  - Expensive & bulky
  - Not suitable for on-board measurements

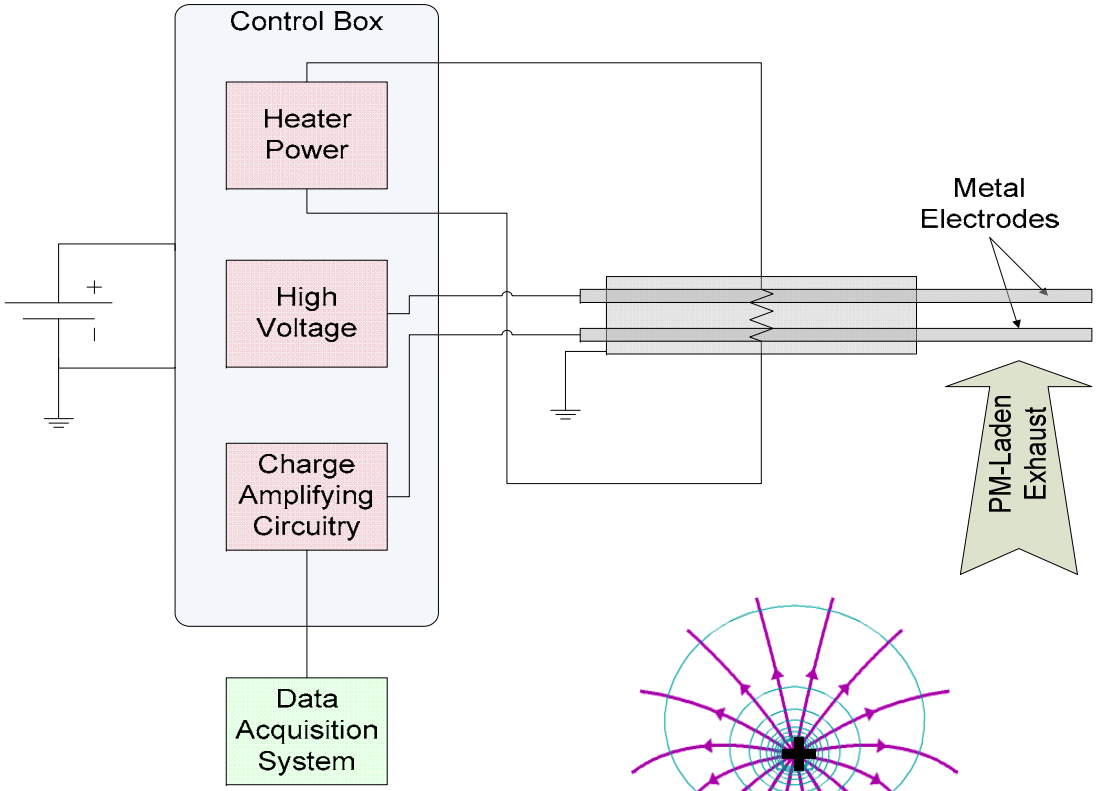
Project Goals

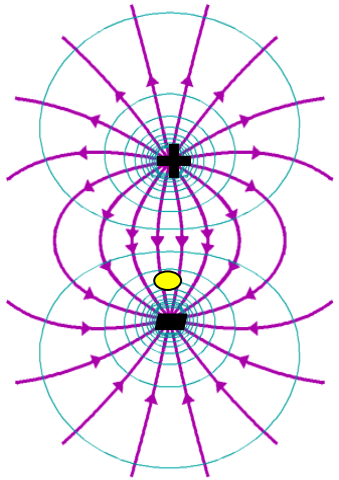
- Develop and demonstrate a low-cost electronic PM sensor that is capable of measuring PM for both engine-out and post-DPF conditions

- Commercialize sensor for post-DPF applications

Sensor Principle of Operation

- Soot particles in exhaust carrying a natural electric charge and are accelerated toward sensor electrode by a strong electric field and neutral particles are charged and detected.
- Rate of charge deposition on sensing electrode is proportional to PM content.
- Time resolutions down to 20 ms depending on electronics configuration





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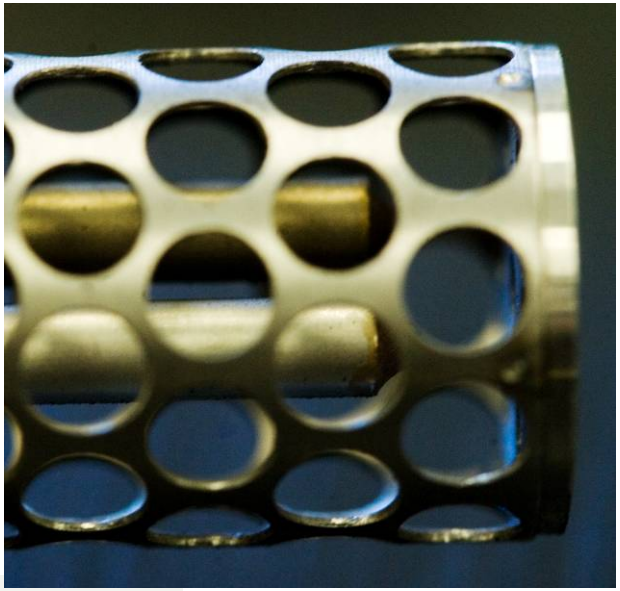
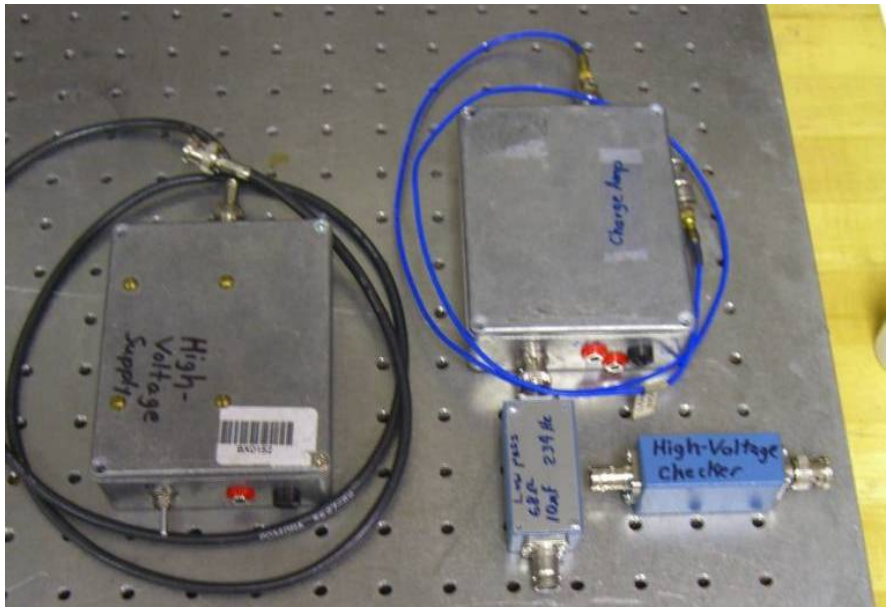
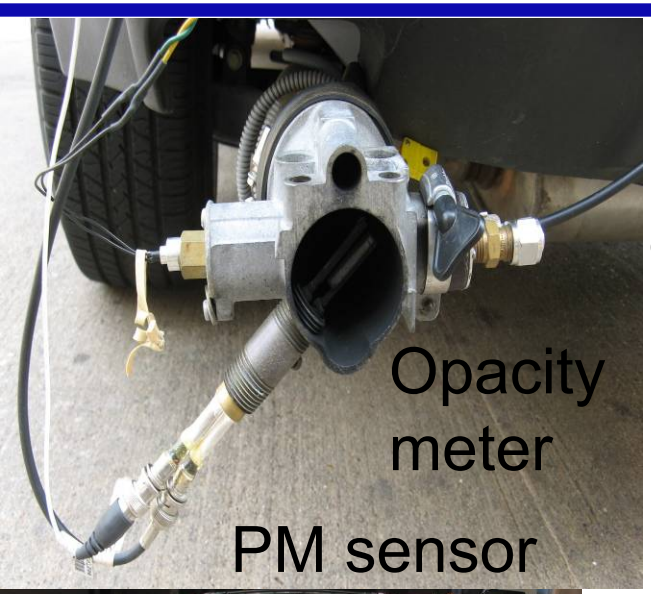
PM Sensor Electrical Requirements

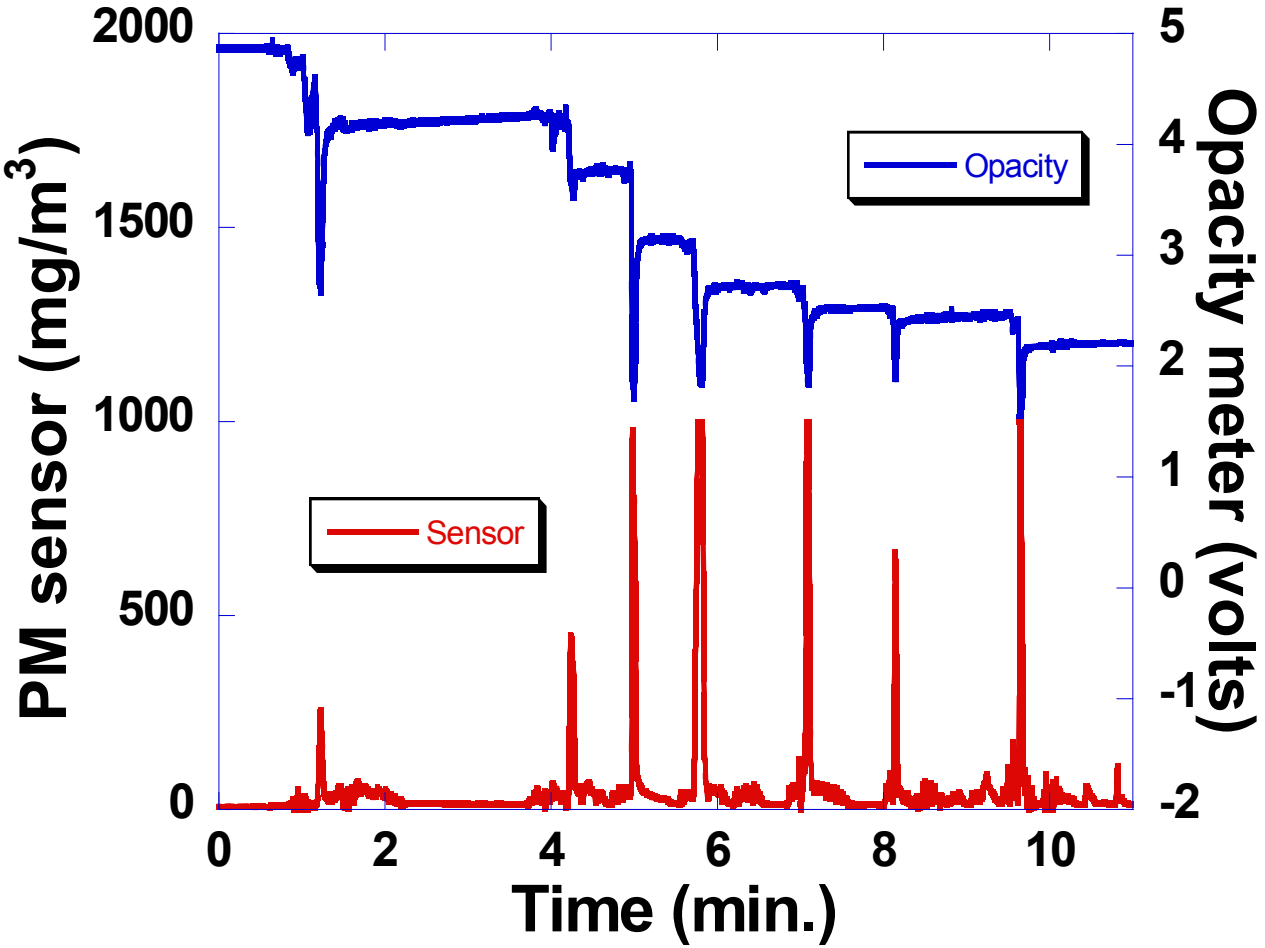
- PM sensor electronics are designed to operate using a vehicle's 12-V battery
- Power consumption is driven by its ~ 15W heater
- Output voltage ranges from 10 mV to 15V
- Output voltage is amplified by charge amplifier and associated electronics





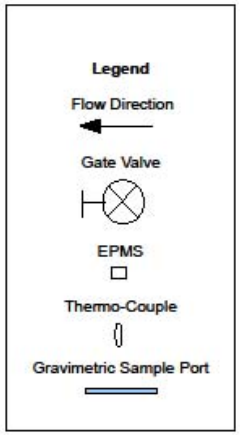
Vehicle Test Data Comparing Electronic PM Sensor and Opacity Meter



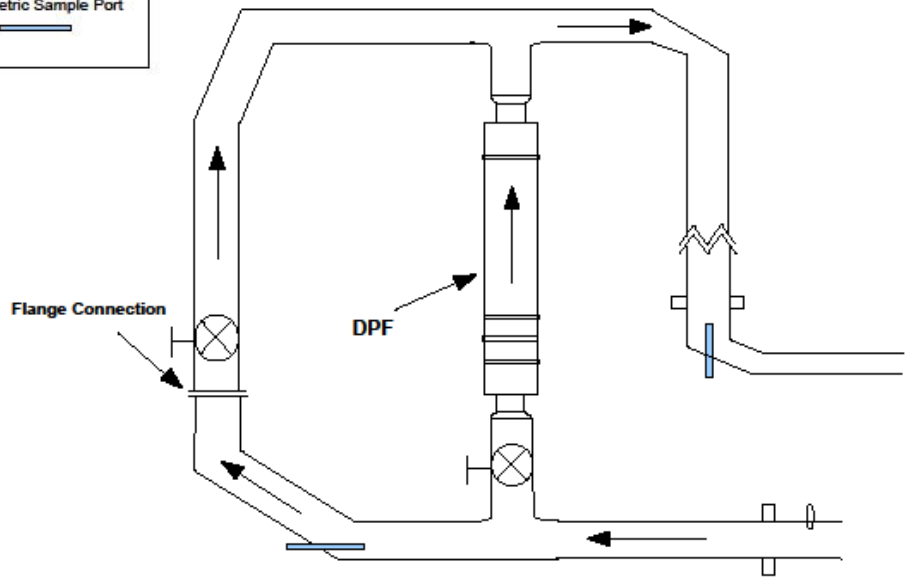


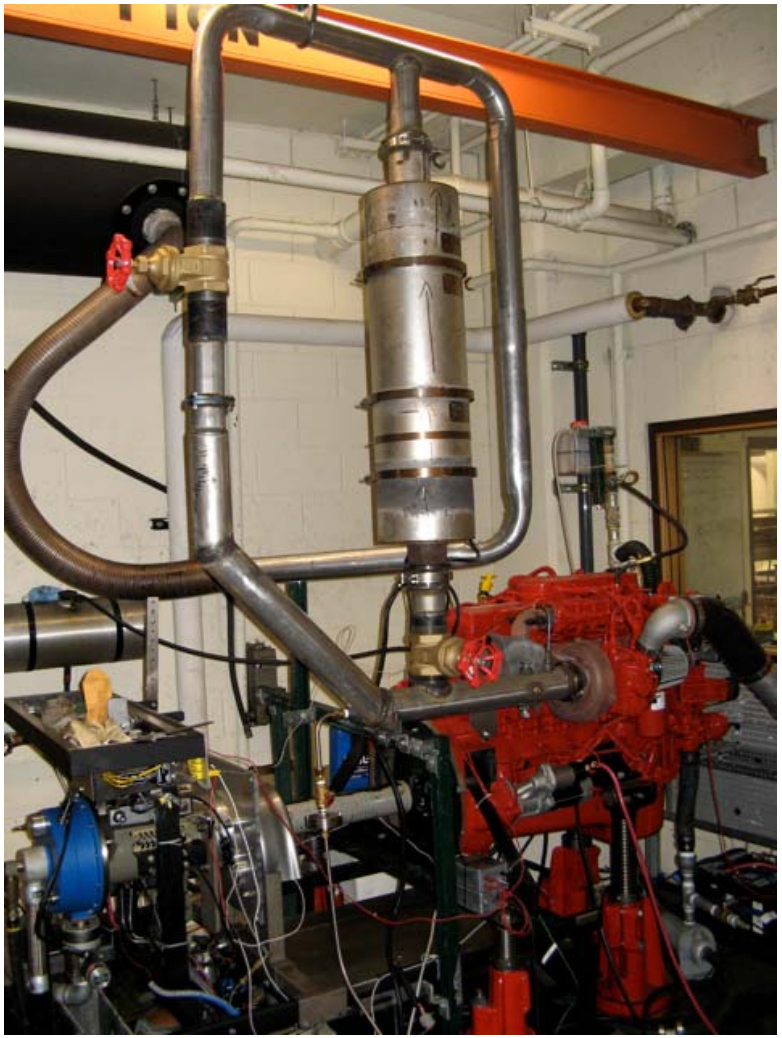
J.A. Osara, et al., "Measurements of Drive-Cycle Particulate Matter Emissions from a Light-Duty Diesel Vehicle Using an On-Board Electronic PM Sensor, Society of Automotive Engineers Paper 09FFL-0218

PM Sensor Testing for Simulated DPF Failure

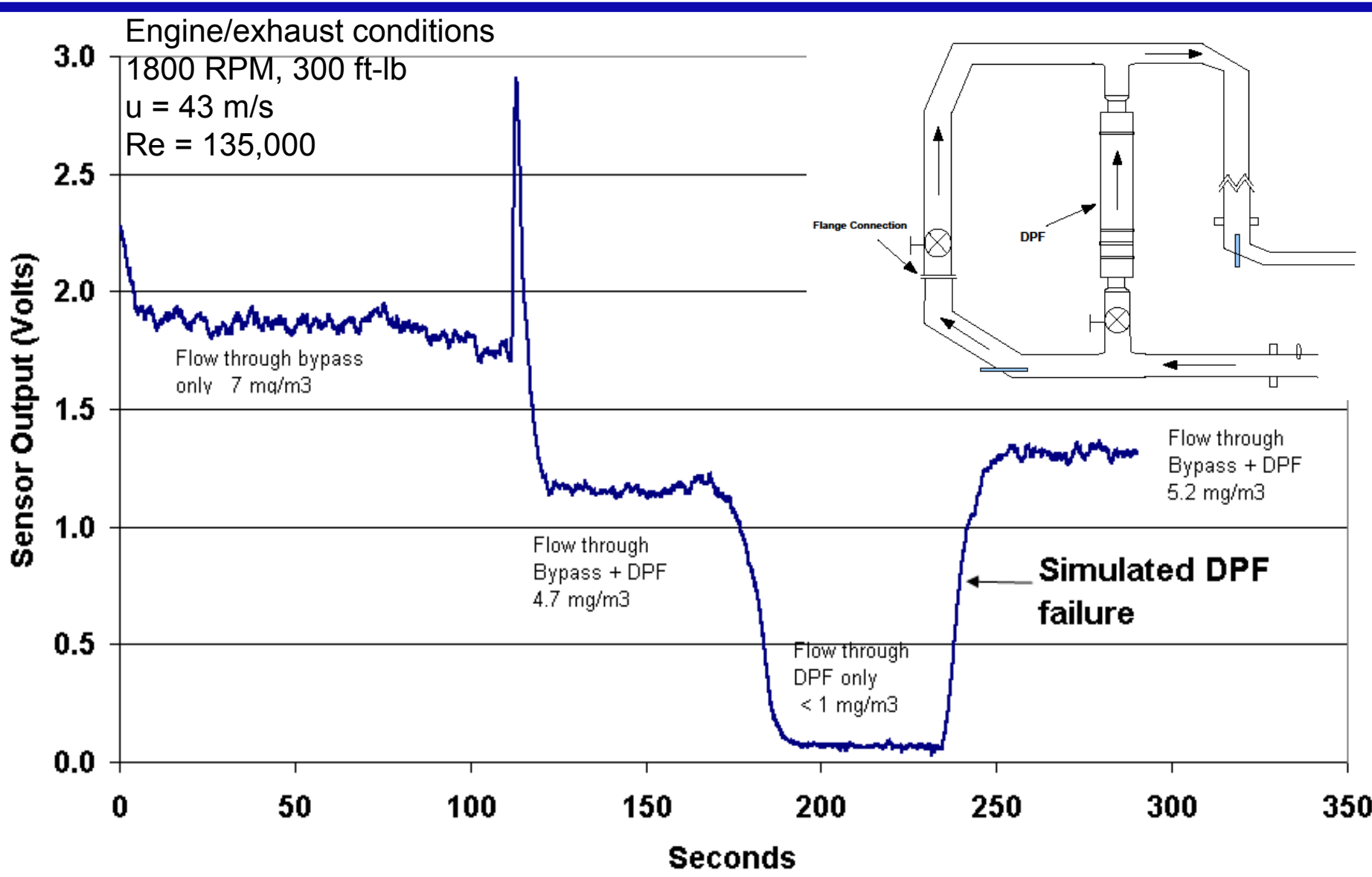


- Testing performed at UT Austin using 6.7L Cummins turbo diesel engine with DPF
- By-pass valve opened to simulate DPF failure



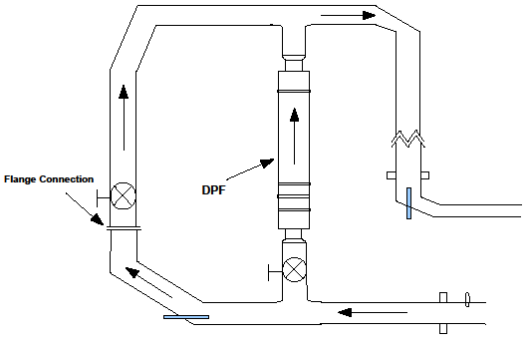


PM Sensor Detects Simulated DPF Failure



PM Sensors Measure Both Engine-Out and Post-DPF PM Concentrations

Engine/exhaust conditions
1800 RPM, 300 ft-lb
u = 43 m/s
Re = 135,000



PM30 Upstream: mean = 2.03(V) std = 0.056 (V)
PM29 Downstream: mean = 0.08(V) std = 0.01 (V

Engine-out (PM 30 upstream)
7 to 10 mg/m3
(estimated from historical runs)

Post-DPF (PM29 downstream)
0.9 mg/m3 (gravimetric (220 < t (s)< 1750))

Sensor Output (V)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)

PM Sensor Performance Summary

- Electronic PM sensor is capable of measuring time-resolved PM emissions from a diesel engine in steady-state and transient operation at engine-out and post-DPF PM concentrations
- The electronic PM sensor is capable of measuring PM concentrations over 4 orders of magnitude
- PM concentration measurements below 1 mg/m^3 dry mass were demonstrated
- Low pass filtering allows trade-offs in time-response versus signal-to-noise (S/N)

Electronic PM Sensor Benefits

- High resolution for low PM levels (<1 mg/m3)
- Capable of detecting DPF failure or determining when to regenerate DPF (OBD)
- Does not require dilution
- Capable of measuring engine-out PM
- Sub-second response time
- Operates at typical exhaust gas temperatures
- Self-cleaning probes
- Low cost

Future Efforts

- Perform additional simulated DPF-failure testing over wide range of engine and bypass conditions and determine limits of detection
- Determine if heater is required for post-DPF measurements
- Develop electronics and sensor for OBD vehicle integration (work with OEMs/Tier 1supplier)
- Obtain long-term post-DOF performance
- Develop better understanding of mechanism(s)

Backup slides follow

Sensor Output Empirical Correlation

$$\text{Sensor (V)} = (5.75\text{x}10^{-5})\, C_{PM}\, V_{applied}\, \exp(0.62U)\, L\, S^{-1.28}$$

Sensor(V) = Sensor output in volts

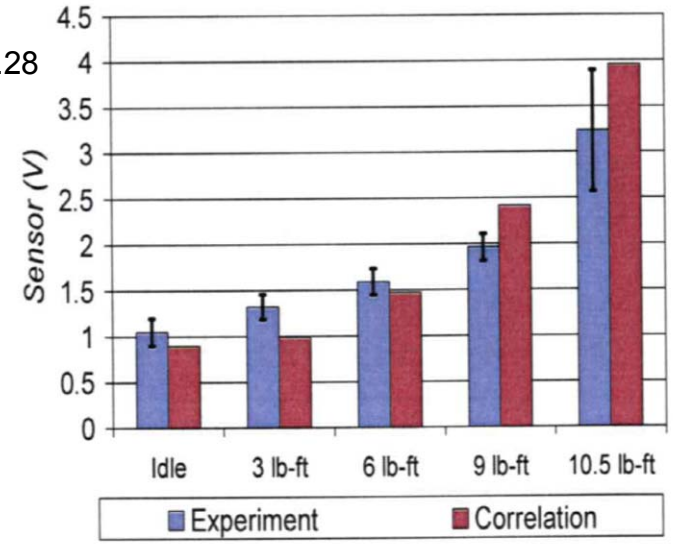
C_{PM} = Exhaust PM Concentration (g/m^3)

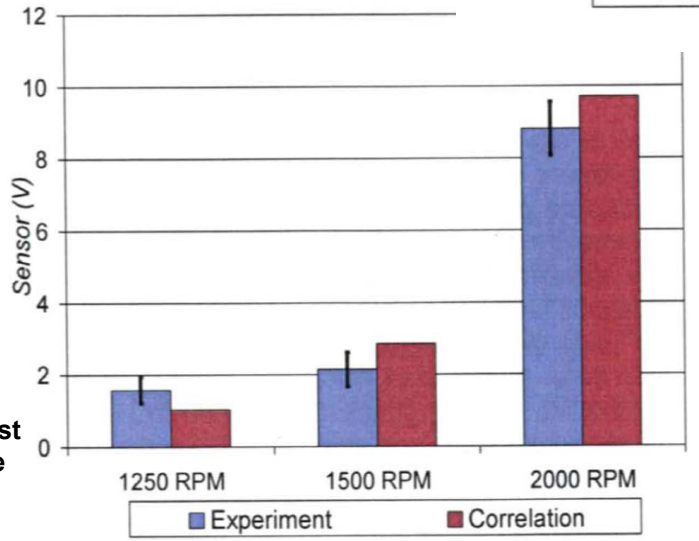
$V_{Applied}$ = Applied bias voltage

U = Exhaust gas velocity (m/s)

L = Electrode length (m)

S = Electrode spacing (m)





Warey, A. and Hall, M.J., "Performance Characteristics of a New On-Board Engine Exhaust Particulate Matter Sensor," Society of Automotive Engineers Paper 2005-01-3792

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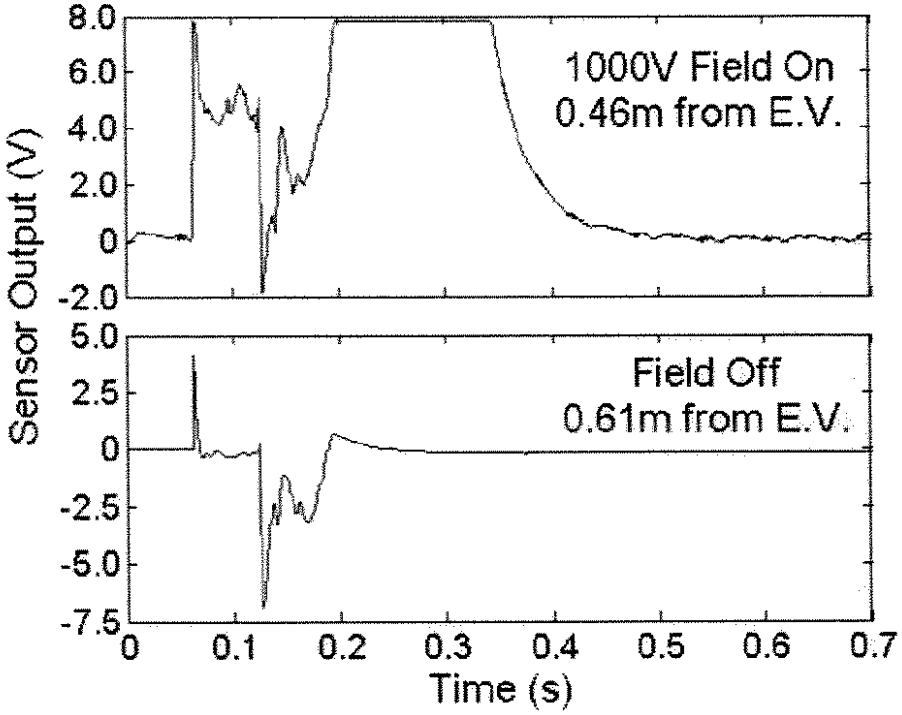
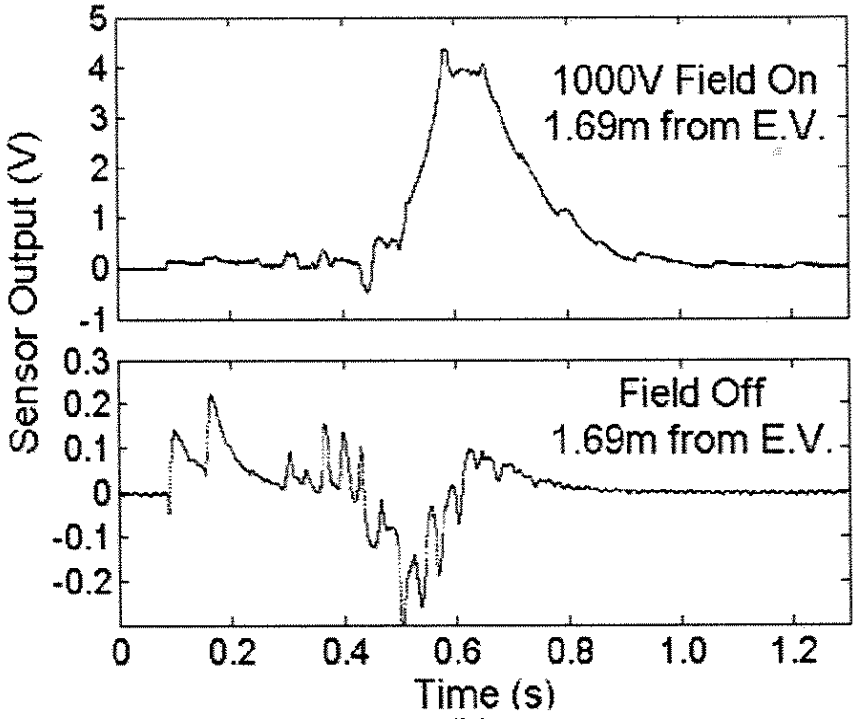
Influence of Applied Voltage





- In a charged particle stream, a small signal is produced by the natural charge which is amplified when the high voltage electrode is energized
- Amplitude of natural charge declines exponentially with downstream distance

Timothy T. Diller, Jude Osara, Matthew J. Hall, and Ronald D. Matthews, "Electronic Particulate Matter Sensor – Mechanisms and Application in a Modern Light-Duty Diesel Vehicle" Society of Automotive Engineers Paper 2009-01-0647

Influence of Exhaust Velocity On Sensor Output

- Velocity (U) dependence of PM sensor depends on PM charging mechanism

  - Close to engine where the PM signal is dominated by natural charge, PM signal increases with increasing U, due to higher flux of charged particles

  - Away from the engine where PM signal is dominated by induced charge, PM signal decreases with increasing U, due to reduced residence time for PM to get charged and interact with sensing electrode

- Velocity dependence may be less significant after DPF

- Hole pattern in sensor housing can be designed to minimize or maximize velocity effects