Advanced DPF Sensors for Next Generation DPFs

Enabling Improved Fuel Economy and Filter Service Life

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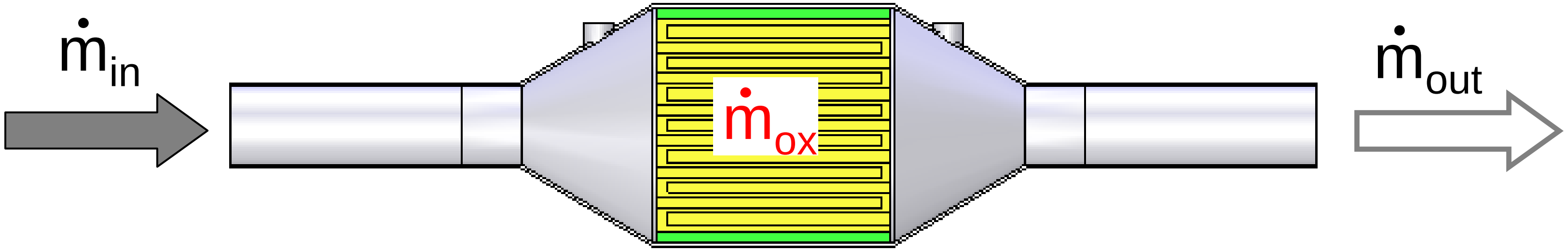
Many Factors Affect DPF Soot Load Estimation



- Amount of Soot in DPF Affected by Numerous Parameters
  - Engine-out emissions ($\dot{m}_{in}$)
    - Fuel, lubricant, operating conditions
  - Quality of regeneration and/or passive oxidation ($\dot{m}_{ox}$)
    - DPF configuration/architecture, exhaust conditions & composition, time
  - Tailpipe-out emissions ($\dot{m}_{out}$)
    - DPF health/integrity (OBD)

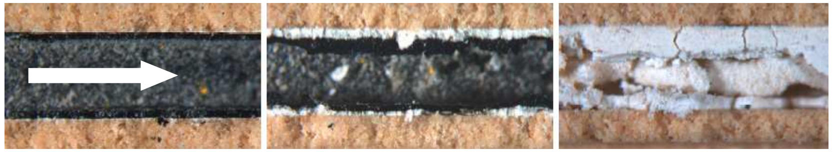


Image: Corning, Deer 2006

- State of DPF Changes with Time
  - Ash build-up reduces PM storage capacity
  - Ash alters soot distribution in DPF (local PM load)
  - Ash may comprise > 80% of trapped mass after 150K miles*

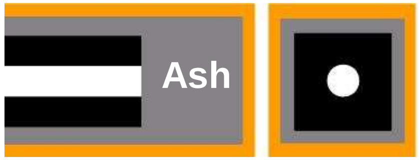
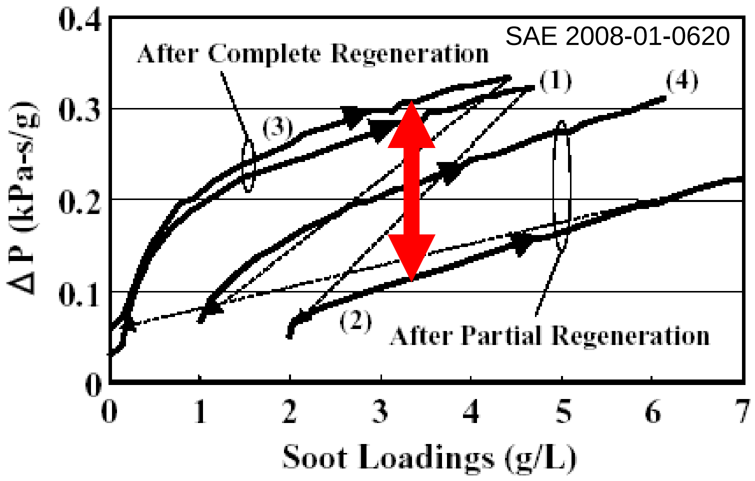


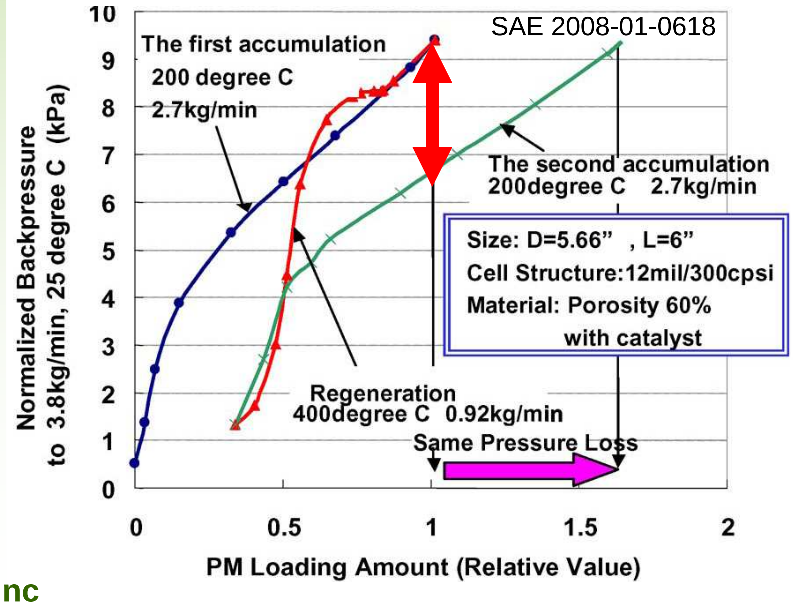
Image: SAE 2010-01-0811

* SAE 2010-01-0811

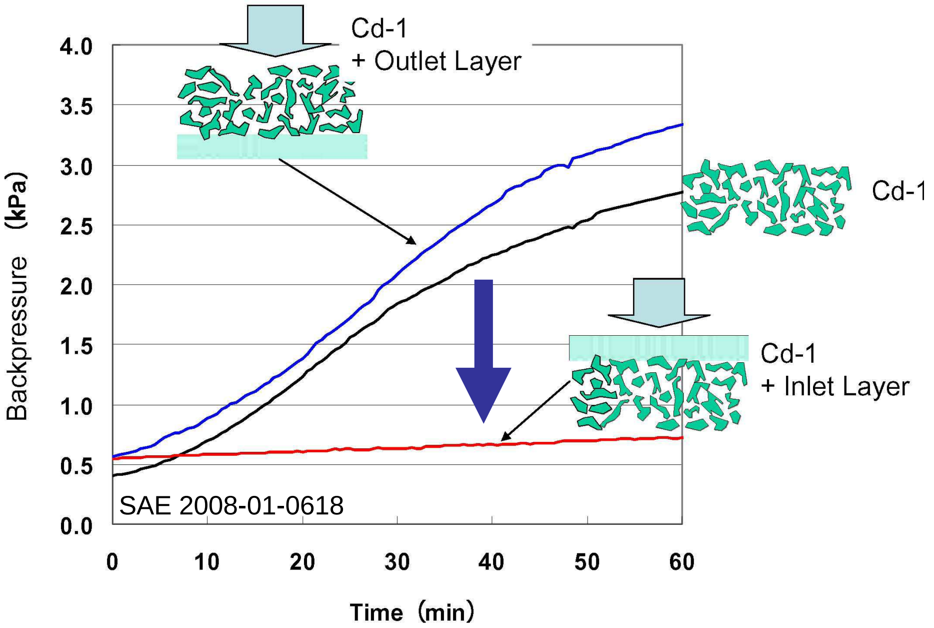
DPFs Provide Challenge for Pressure Measurements

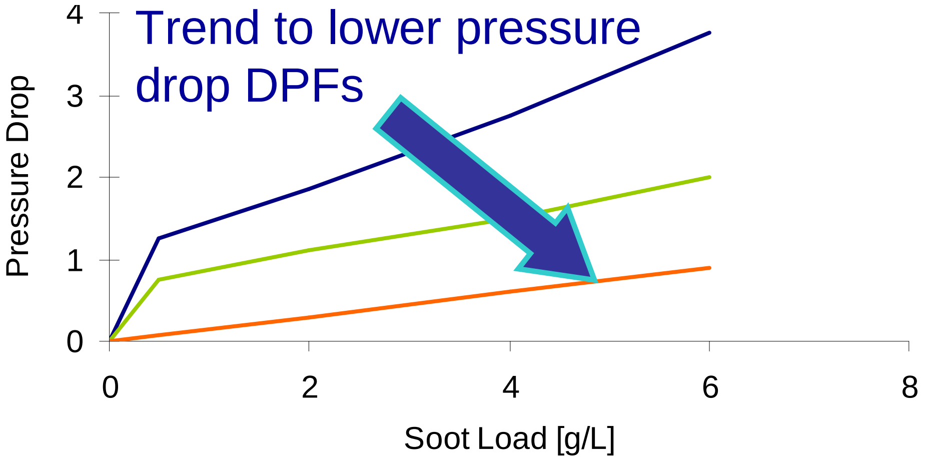
Large variation in pressure drop for same soot level





Advanced DPFs exhibit lower pressure drop sensitivity





Models Compensate Pressure Measurements

- **Differential pressure sensors <u>and</u> predictive models**
    - Pressure drop affected by flow, temperature, distribution of material
    - Significant efforts devoted to predictive model development
        - Models generally calibrated for specific engine and fuel
        - Current measurement systems relatively inflexible

- **DPF is never clean – Ash builds over service life**
    - Requires means of compensating for ash effects in models

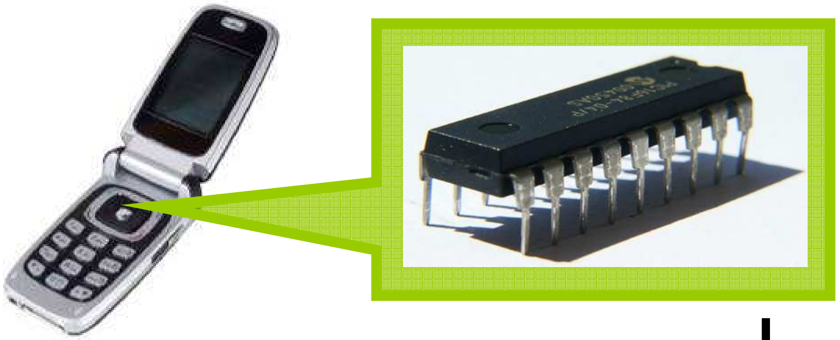
- **Measurement inaccuracies lead to inefficient operation**
    - Error can be **50%** of pressure drop measurement/estimation*
    - Implies DPFs regenerated up to **~ 2X** more than necessary
    - Large safety factors built into models

- **On-board diagnostic (OBD) requirements difficult to meet**

Current methods provide <u>indirect</u> estimate of DPF loading

* SAE 2008-01-0618, SAE 2008-01-0620

RF-DPF™ Sensor Operation



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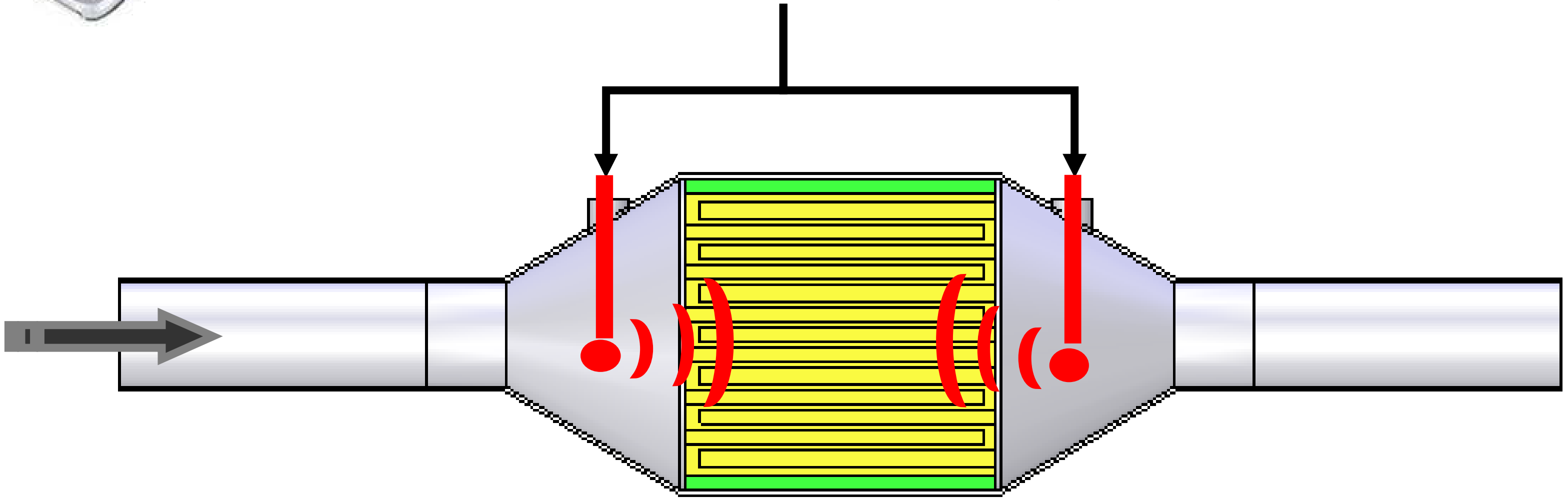
1. **Amount**
2. **Type**
3. **Distribution**
4. **Filter Failures**

± X



- **Direct measurement of soot and ash in DPF**
  - ❑ Optimize DPF regeneration strategy, thermal management, ash cleaning
  - ❑ Determine start and end of regeneration
- **Direct measurement of soot distribution in DPF**
  - ❑ Control regeneration based on local soot levels
- **Potential to detect filter failures and malfunctions (OBD)**

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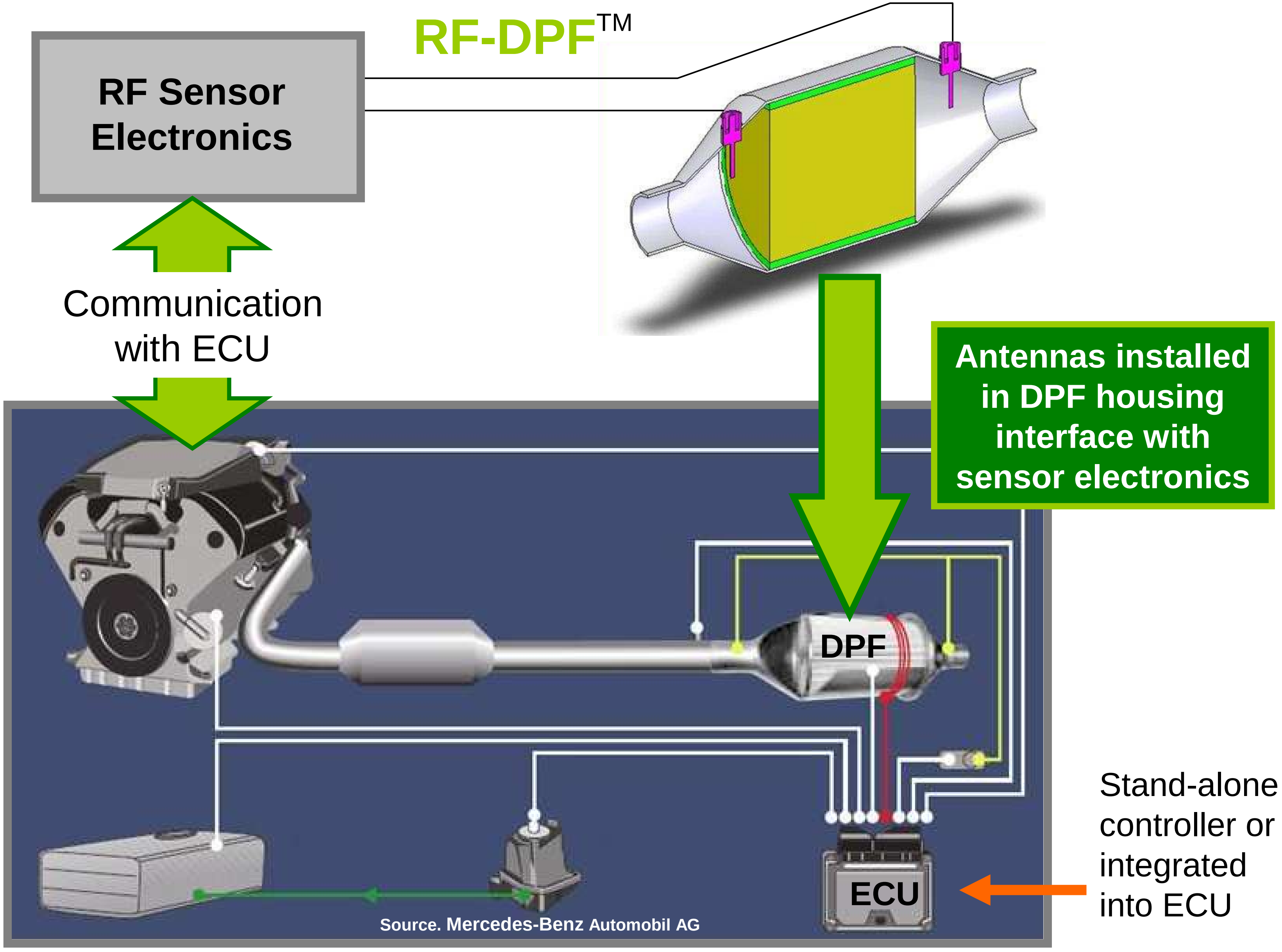
RF Measurement System Lay-Out



RF-DPF™

RF Sensor Electronics

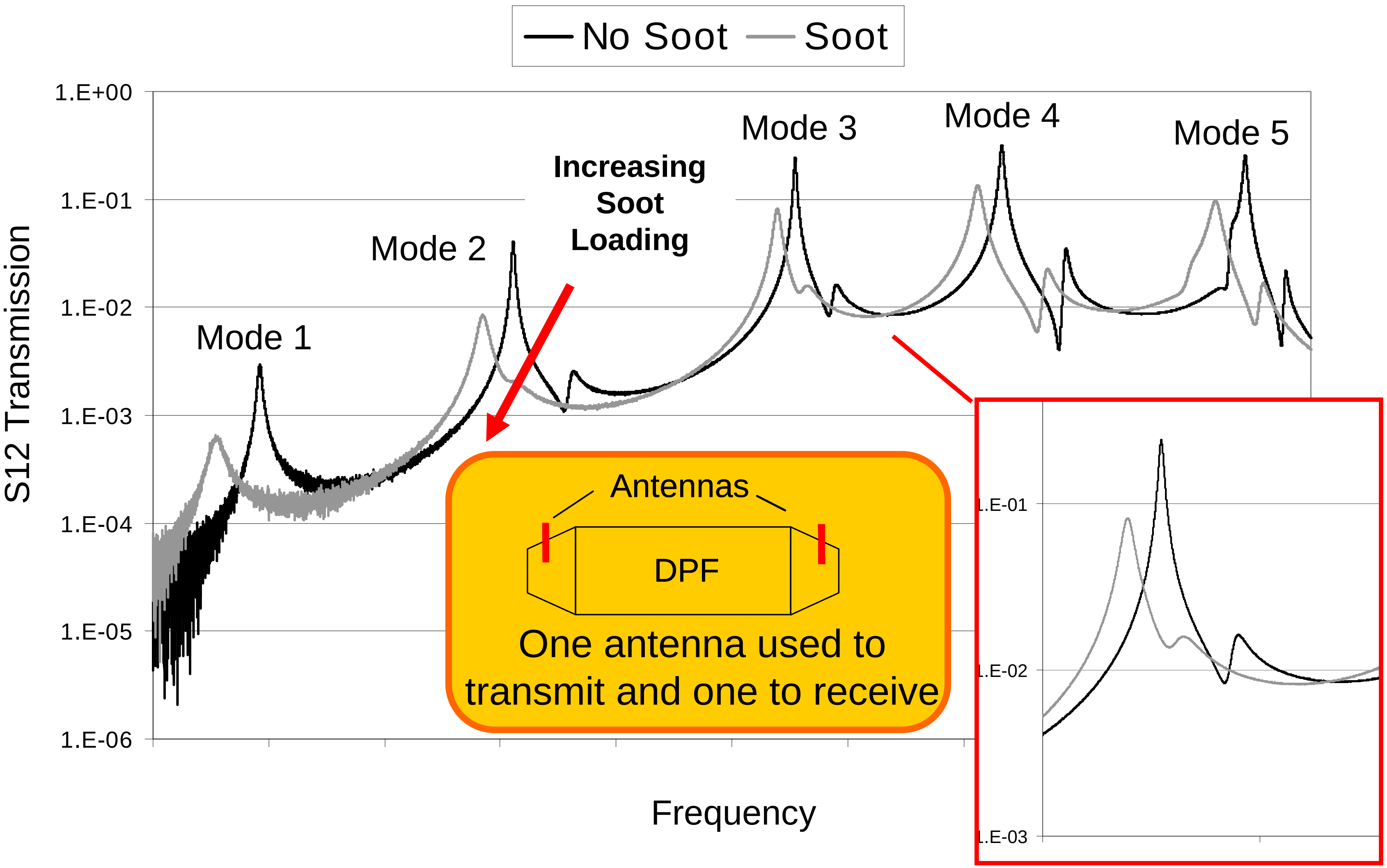
Communication with ECU

Antennas installed in DPF housing interface with sensor electronics

Stand-alone controller or integrated into ECU

Source. Mercedes-Benz Automobil AG

RF System Operation: Transmission

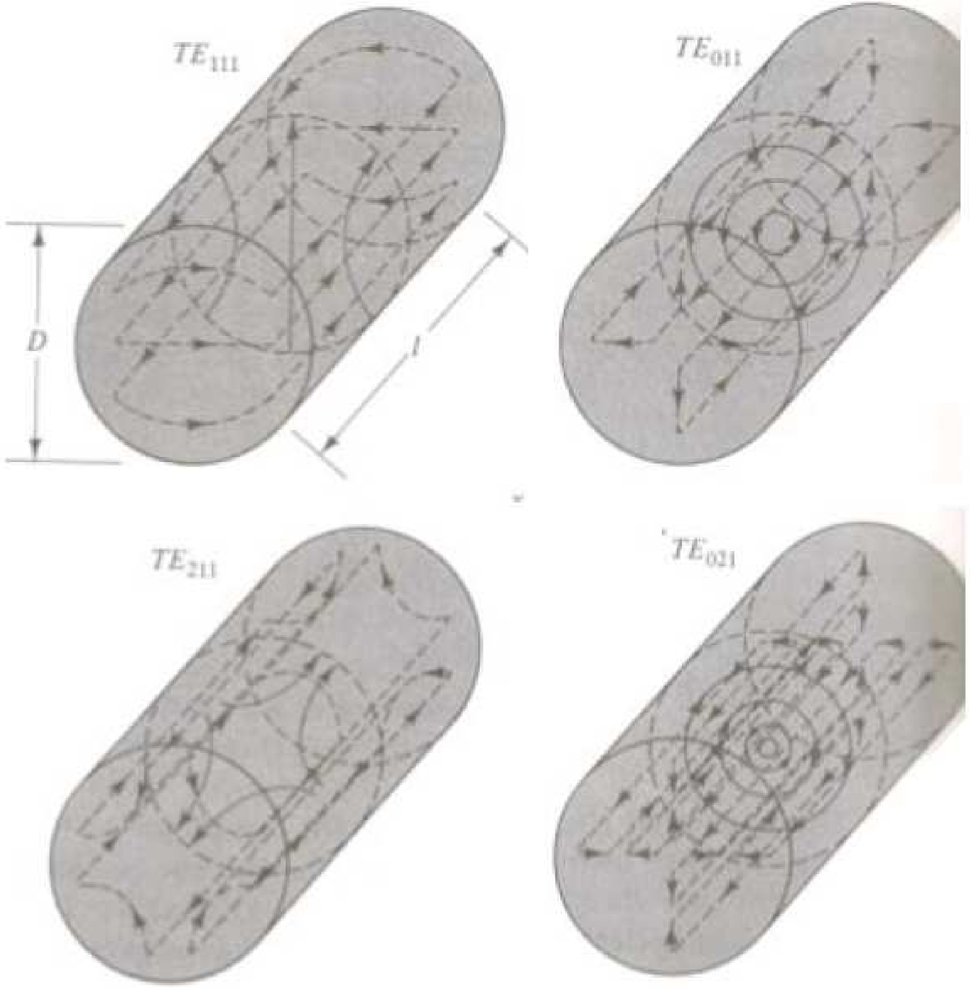


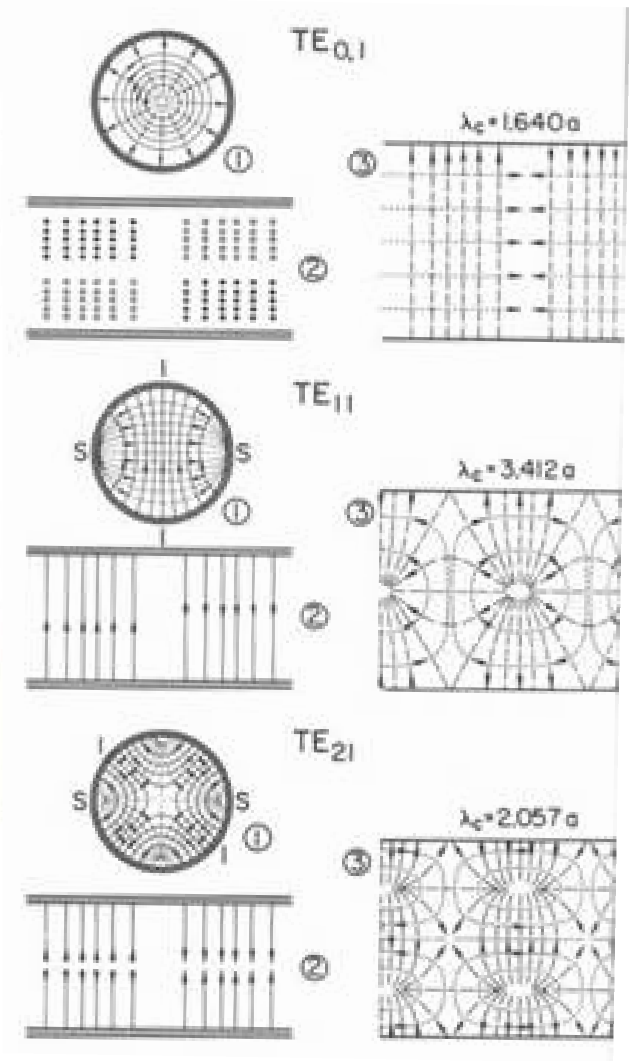
One antenna used to transmit and one to receive

Filter resonant modes established over a range of frequencies allow for the determination of spatial distribution of collected material.

Resonant Mode Electric Field Distribution

Typical electric field profiles for standard cylindrical geometries





Images: Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

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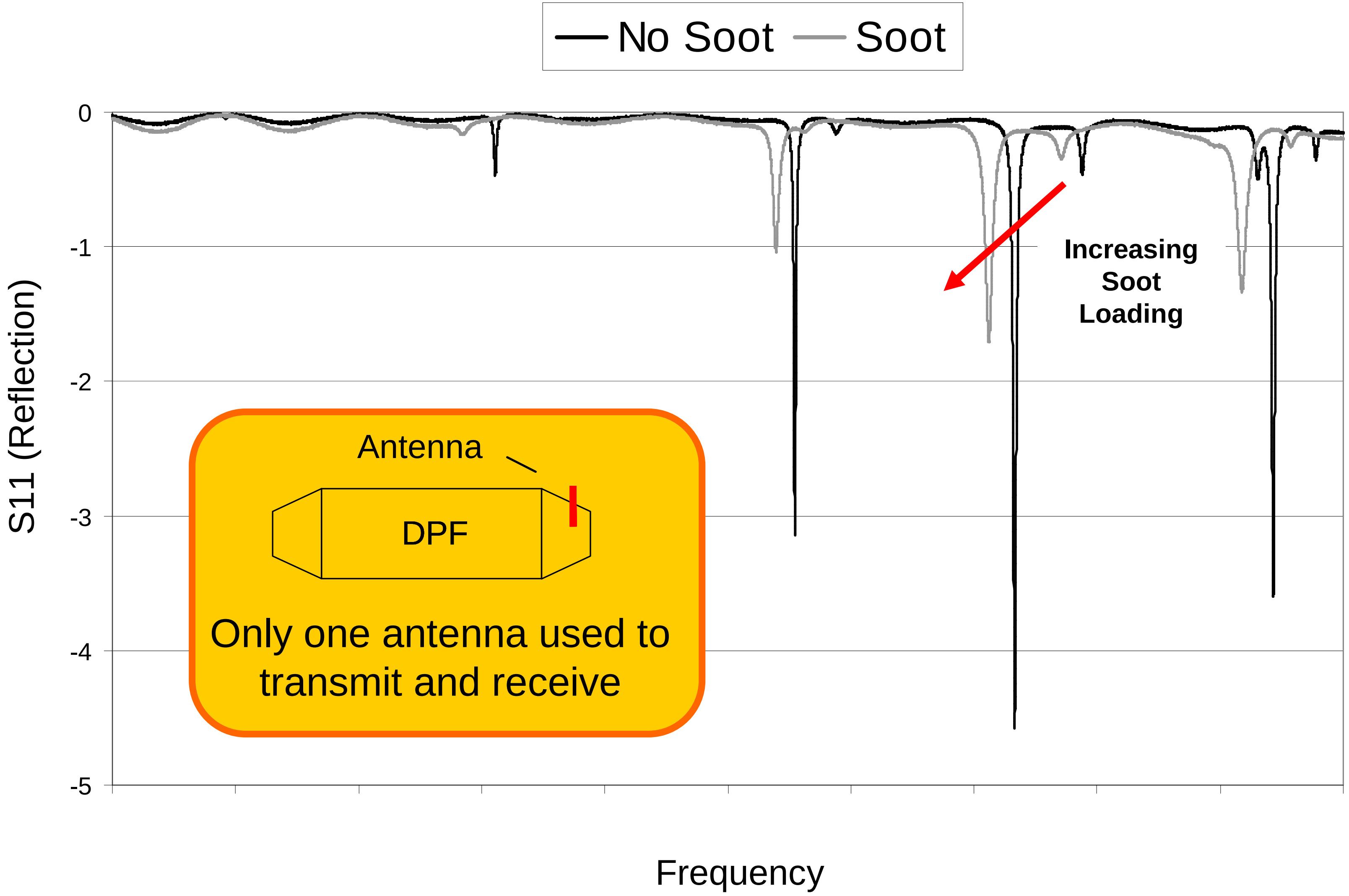
Signal Sensitive to Soot Loading of Filter: Reflection



Only one antenna used to transmit and receive

Filter resonant modes may also be established using one antenna to transmit and receive. Other configurations and detection methods also possible.

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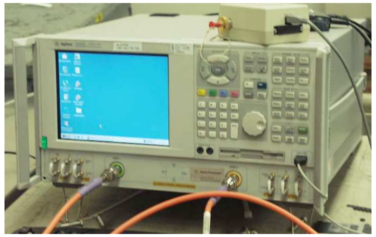
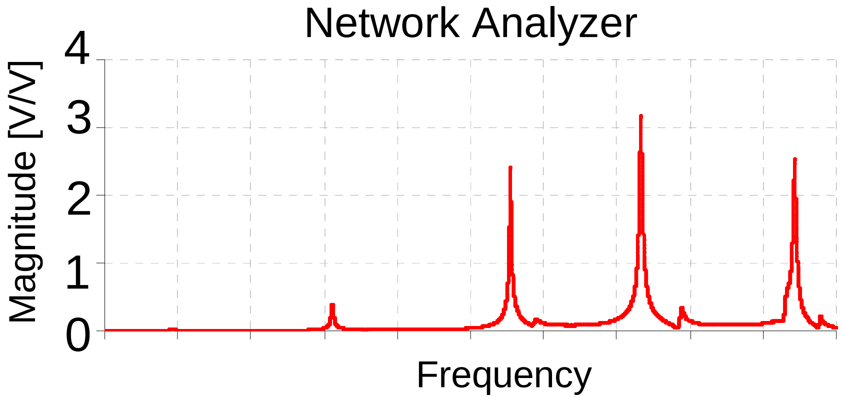
System Development Overview

Proof-of-Concept (CLEERS 2006)

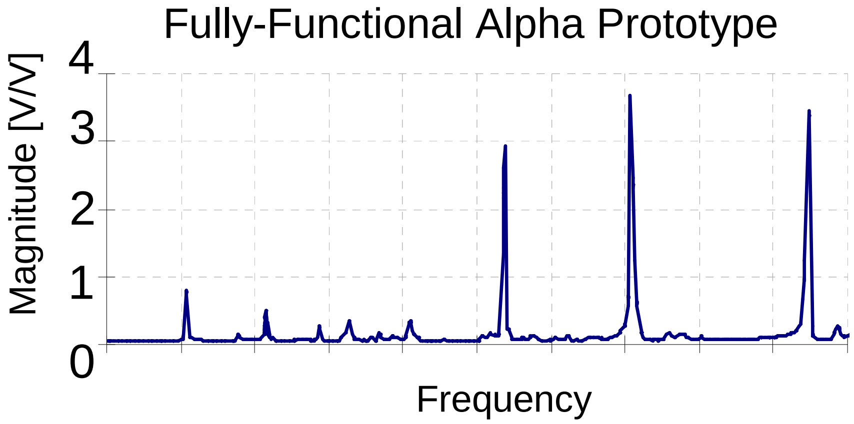
Network Analyzer





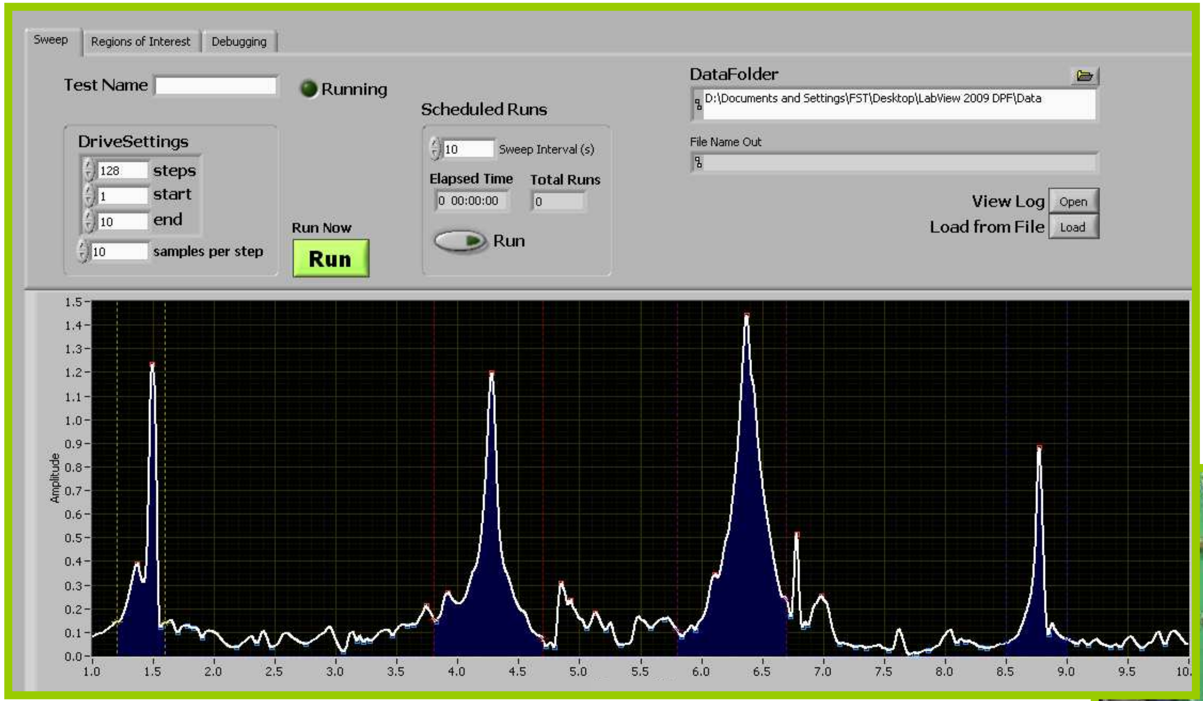
Pre-Production Prototype: Testing

Alpha Prototype



Initial system performance matches laboratory measurement equipment

FST RF-DPF Development System



Test Name

DriveSettings
128 steps
1 start
10 end
10 samples per step

Scheduled Runs
10 Sweep Interval (s)
Elapsed Time 0 00:00:00
Total Runs 0

DataFolder D:\Documents and Settings\FST\Desktop\LabView 2009 DPF\Data

File Name Out

View Log

Load from File

RF-DPF Installed and Studied at ORNL

FST RF-DPF System

- Software integrates data acquisition and signal analysis
- Real-time display of DPF loading information
- Current set-up with USB interface to laptop

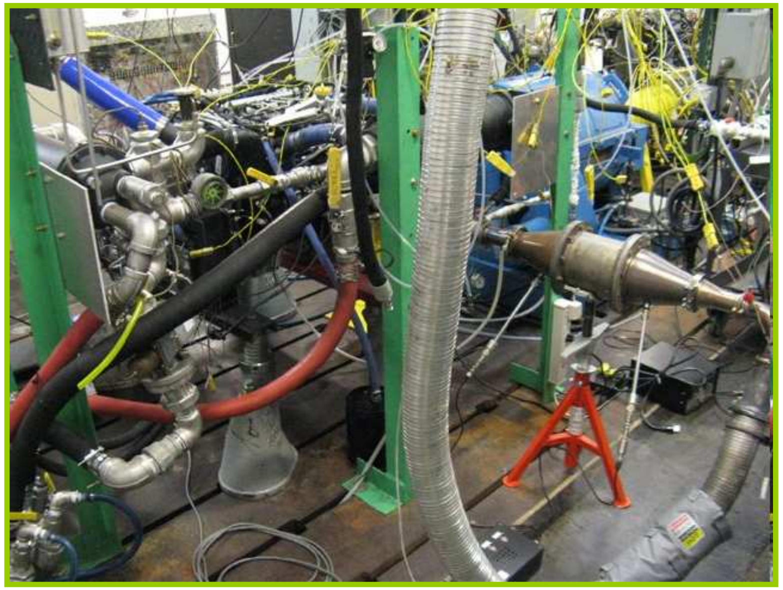
RF Sensor Studies at ORNL

Oak Ridge National Laboratory

- RF-DPF™ sensor prototype installed on 1.9L GM turbo diesel engine
- Steady-state and transient testing
- Various aftertreatment system configurations
- PM and gaseous emissions measured during testing

Research Highlights

- **Repeatability** – steady-state loading and regeneration
- **Sensitivity** – detect low-level soot emissions and accumulation
- **Dynamic Response** – evaluation over modified FTP cycle



Steady-State Soot Loading and Regeneration

GM Engine Operation (Loading)

- High Engine-Out PM: 1500 rpm, 50 ft-lb
- Low Engine-Out PM: 1000 rpm, 15 ft-lb, 25 ft-lb

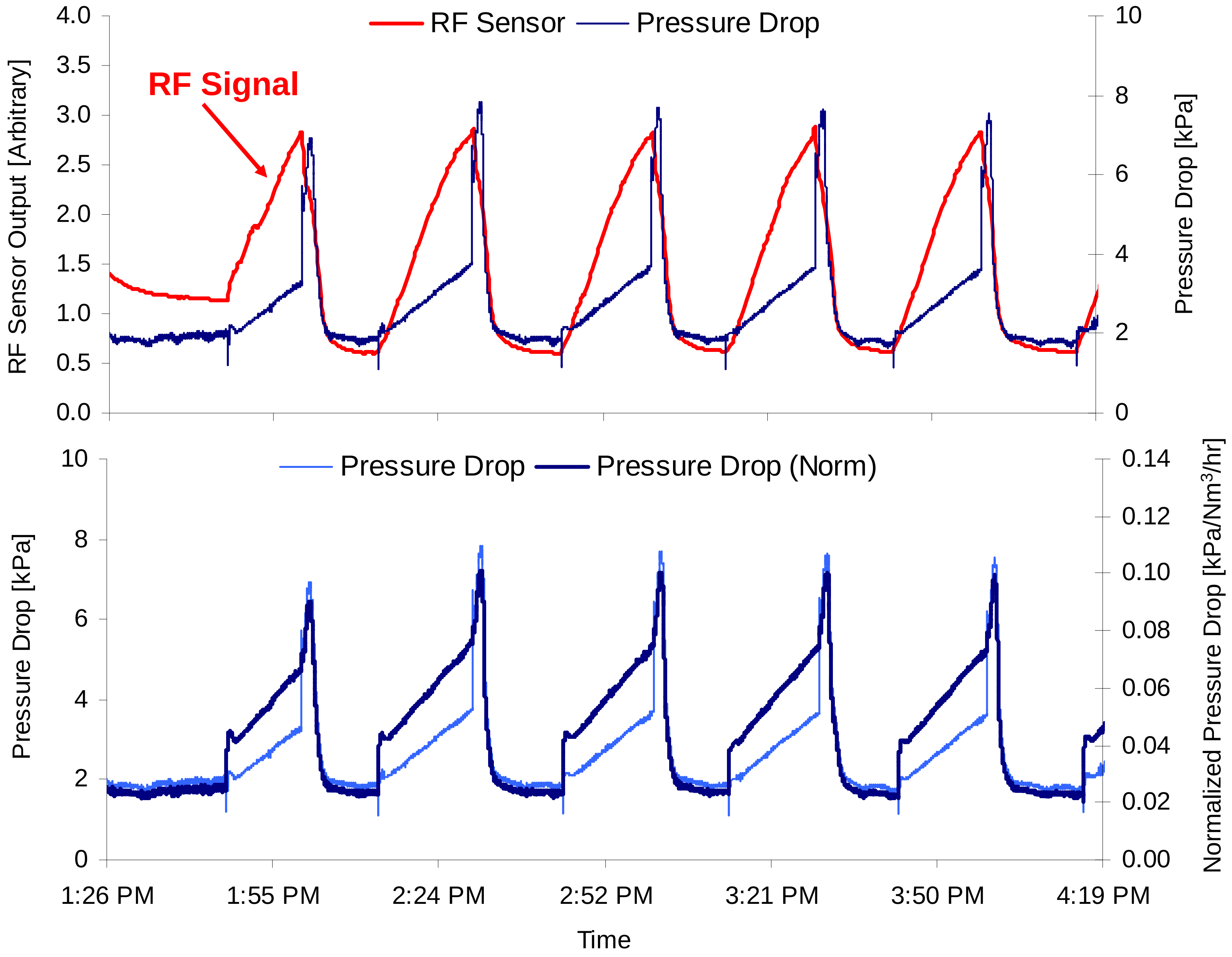
GM Engine Operation (Regeneration)

- Engine Speed – 1500 rpm
- Engine Load – 50 ft-lb
- Regeneration initiated via in-cylinder post-injection

Aftertreatment System Configuration

- DOC + C-DPF (separate cans)
- DPF – Cordierite with Pt catalyst

Comparison with Pressure Drop (Steady-State)



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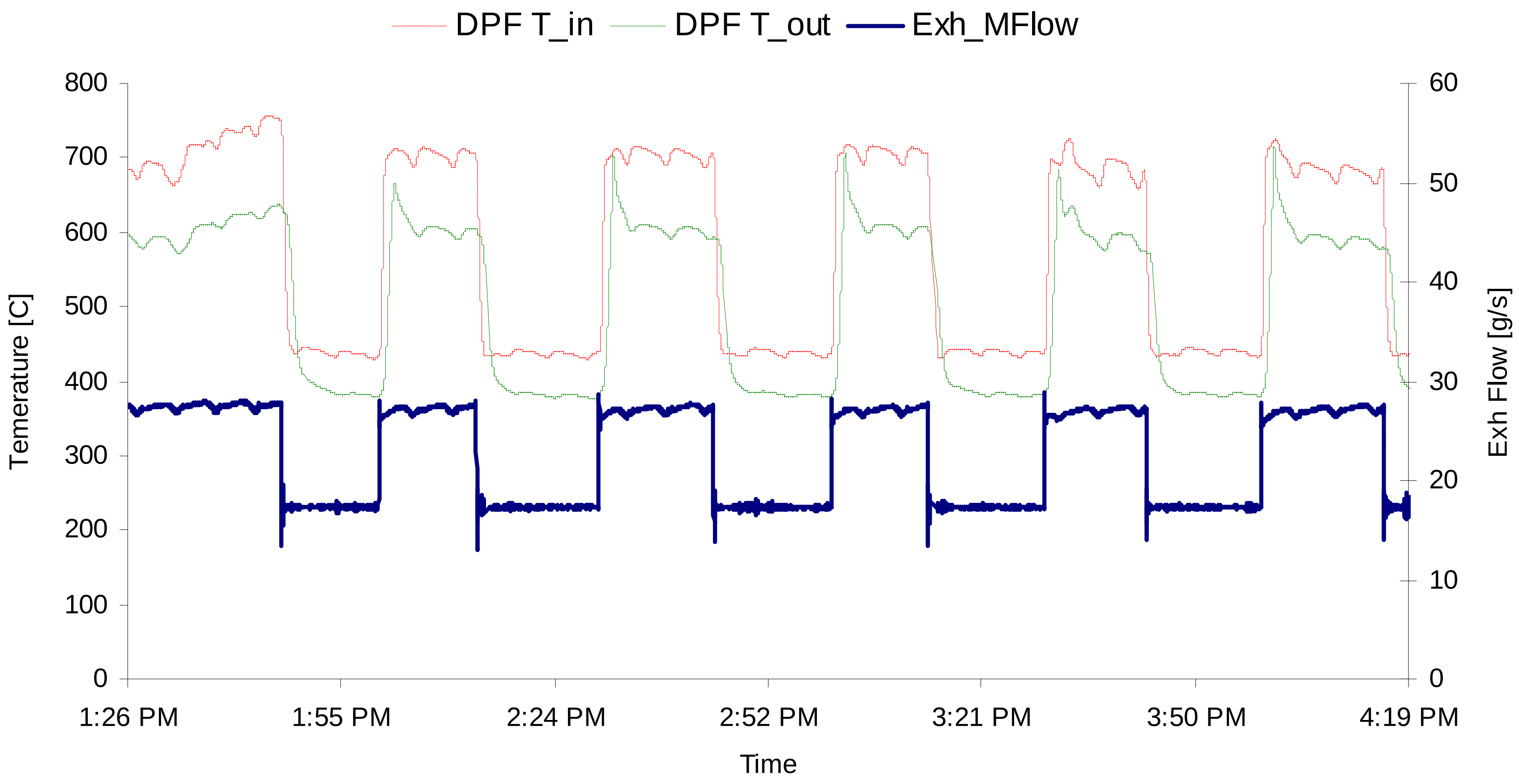
Exhaust Conditions During Test Cycle



- Pressure drop directly affected by exhaust flow rate and temperature variations
- DPF inlet temperatures ranged from 400 ℃ to 700 ° C + over course of test
- Engine operated at high PM emissions condition for rapid DPF soot loading

RF Sensor Response to Low-Level PM Loading Rates

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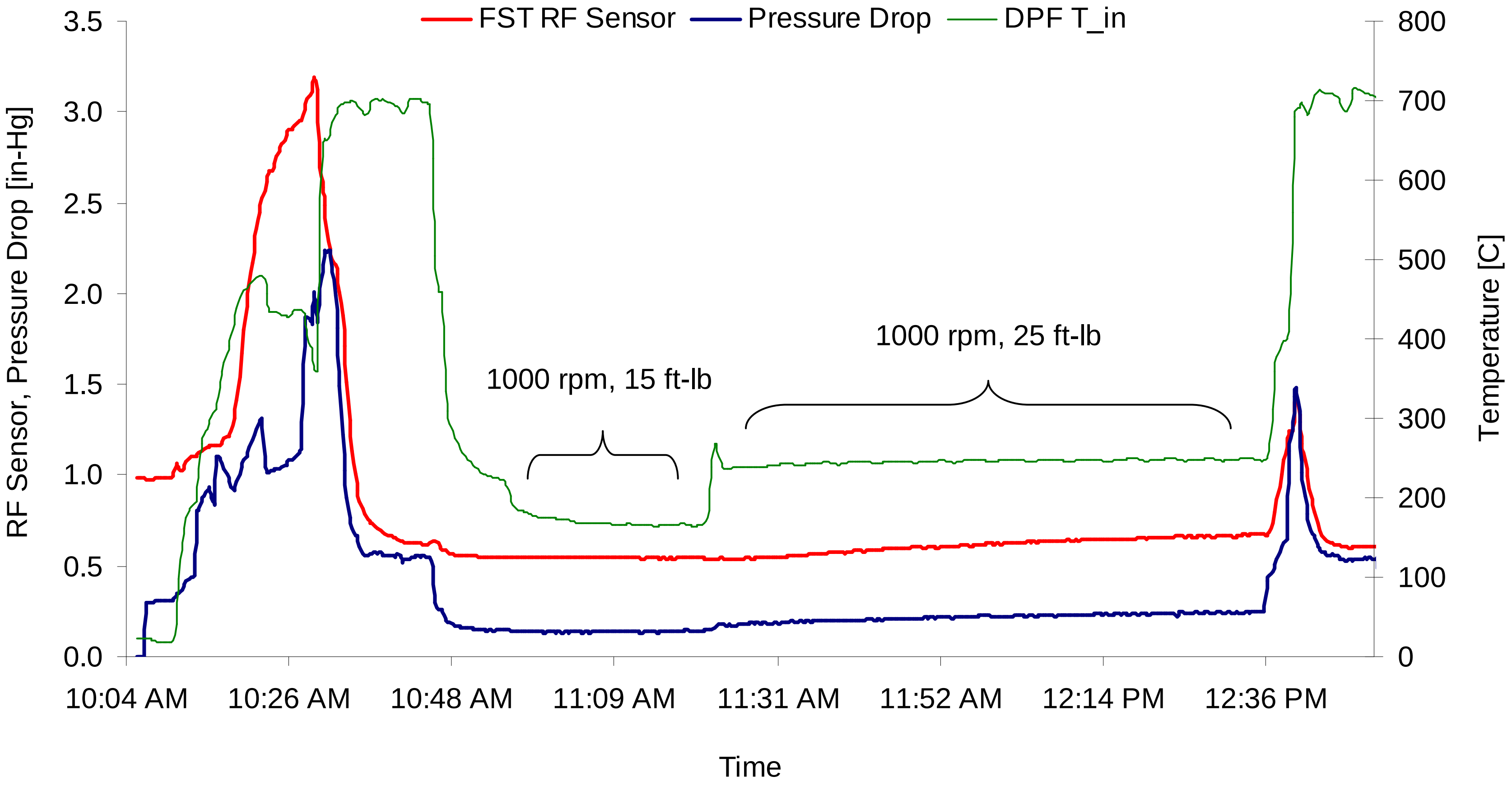

- RF sensor and pressure drop exhibit similar response to low-level soot loading
- RF sensor response more stable during regeneration events

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Ad Hoc FTP Cycle Simulation: *Transient*

GM Engine Operation (Loading)

- Ad Hoc FTP cycle simulation

GM Engine Operation (Regeneration)

- Engine Speed – 1500 rpm
- Engine Load – 50 ft-lb
- Regeneration initiated via in-cylinder post-injection

Aftertreatment System Configuration

- DOC + C-DPF (separate cans)
- DPF – Cordierite with Pt catalyst

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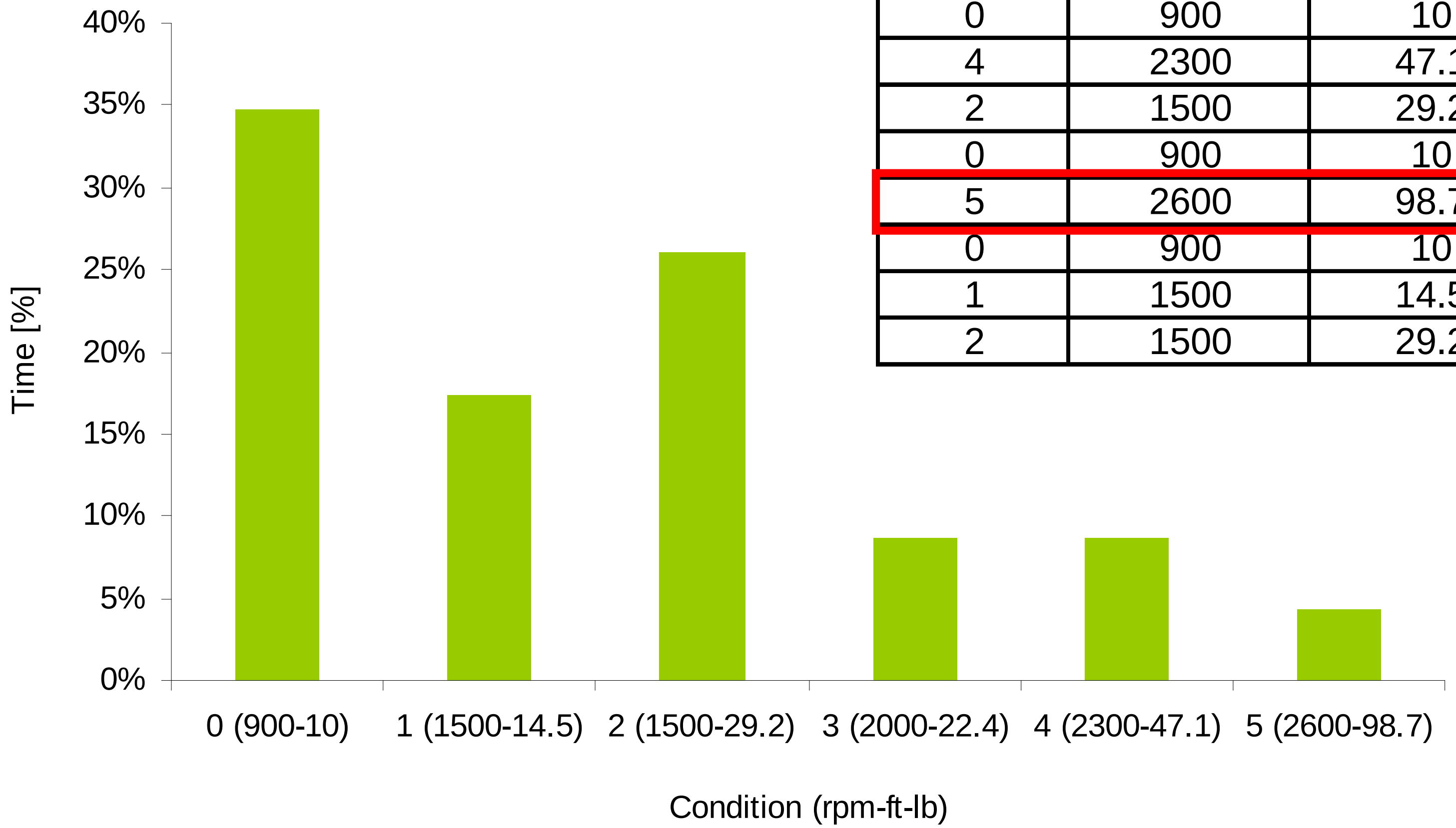
Ad Hoc FTP Cycle Engine Operating Conditions

- Most of cycle fairly low speed and load
- Short duration high soot emissions

Run	Speed [rpm]	Load [ft-lb]
0	900	10
2	1500	29.2
3	2000	22.4
1	1500	14.5
0	900	10
4	2300	47.1
2	1500	29.2
0	900	10
5	2600	98.7
0	900	10
1	1500	14.5
2	1500	29.2



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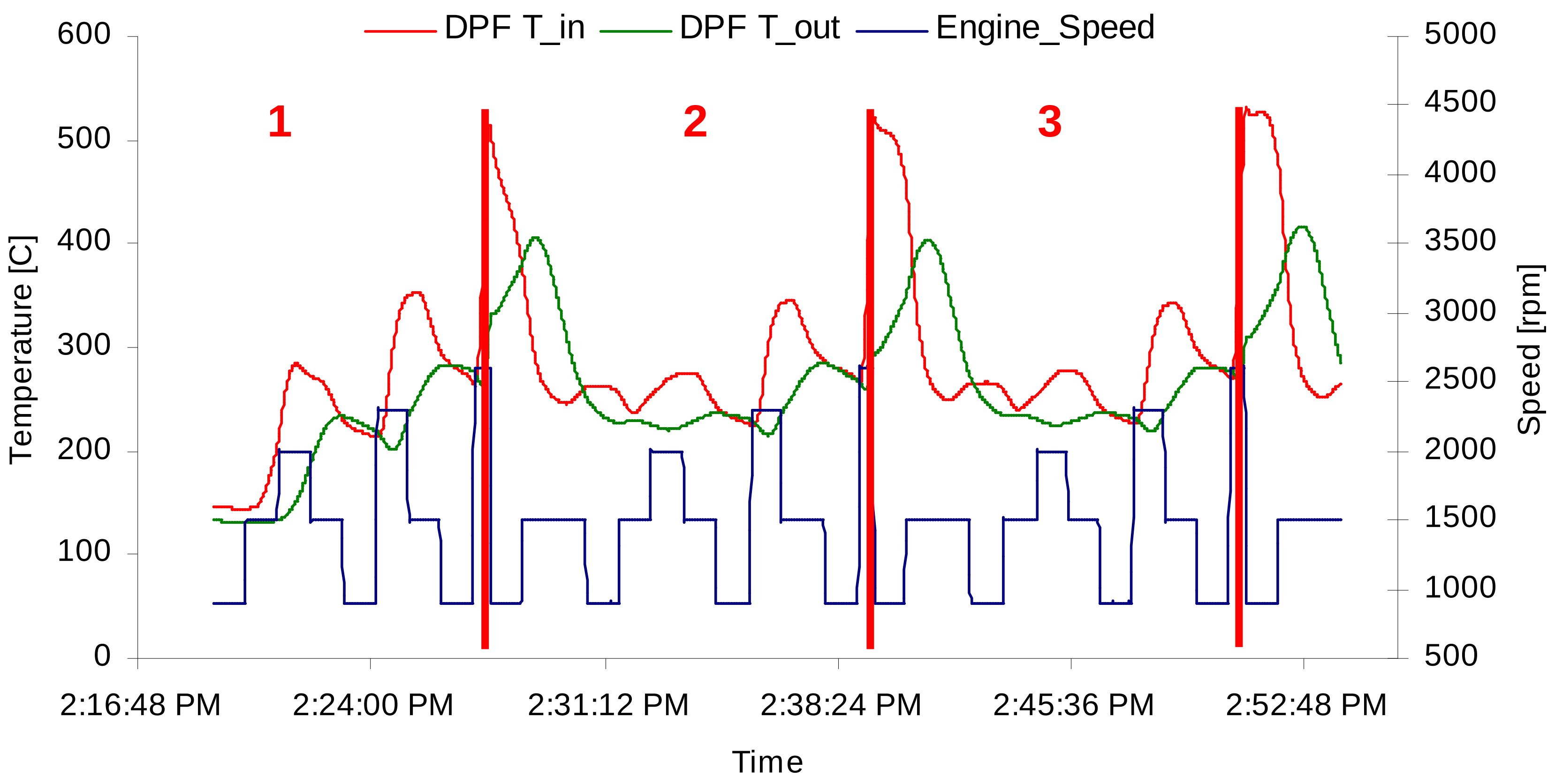
Ad Hoc FTP Cycle Details and Exhaust Conditions



- Engine operating conditions varied every 30 to 60 seconds
- Large variation in DPF inlet and outlet temperatures and exhaust flow rates vary over duration of test cycle
- Test cycle repeated 3X consecutively on multiple days

Tapered Element Oscillating Microbalance (TEOM)

Range	0 to 5,000,000 µg/m^3
Resolution	0.1 µg/m^3
Precision	±1.5 µg/m^3 (1-hour ave), ±0.5 µg/m^3 (24-hour ave)
MDL	10 nanograms
Main Flow Rate	0.5 to 4 l/min
Operating Range	Sampled Air -40 to 60 ℃. Weather protected in range of 2-40 ℃
Power Required	120 VAC/60Hz: 5.25A; 240 VAC/50 Hz, 3.25A
Weight	Sensor Unit: 40 lb (18 kg), Control Unit: 32 lb (15 kg)

- Requires exhaust sampling system including mini-dilution tunnel and proper sample conditioning

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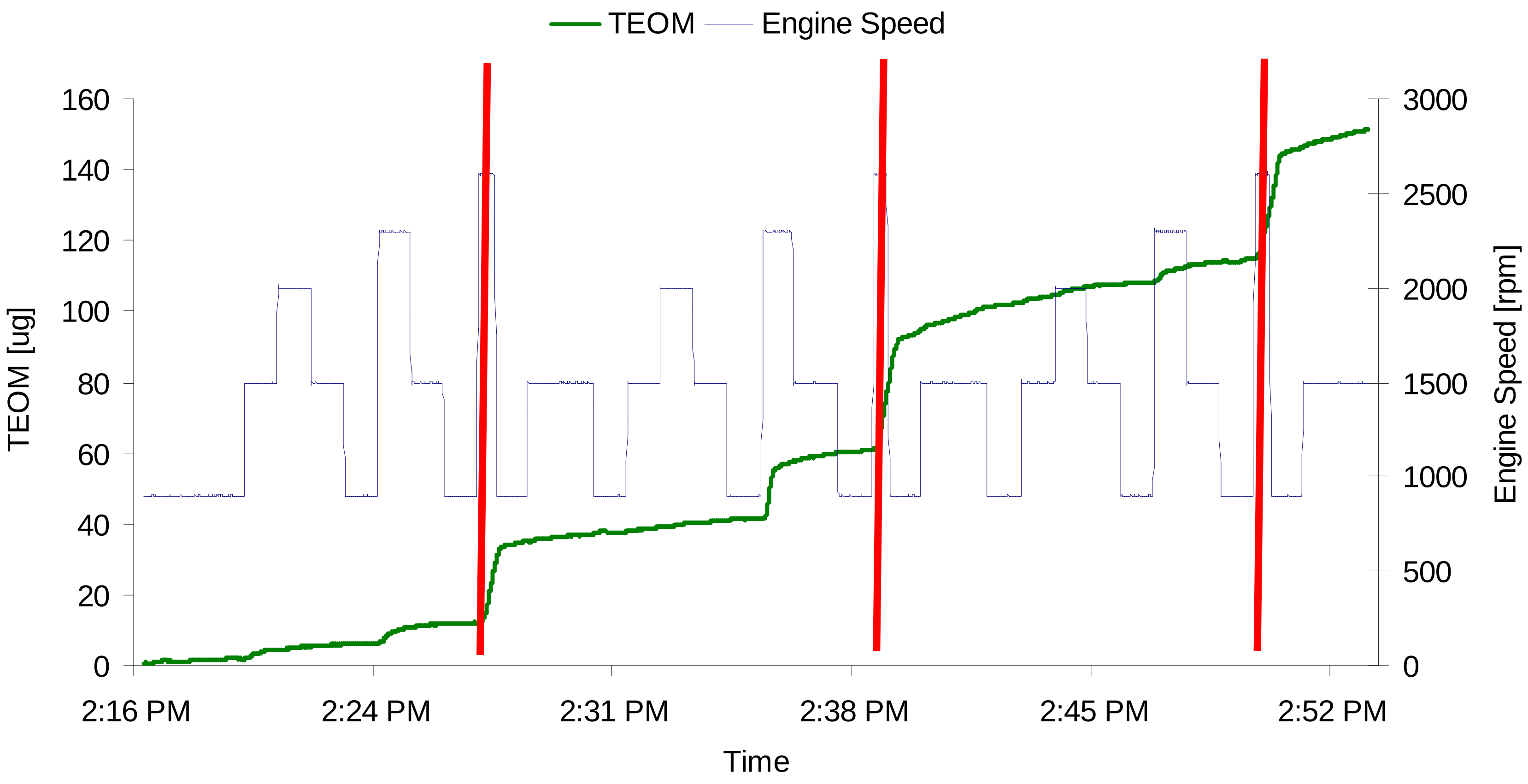
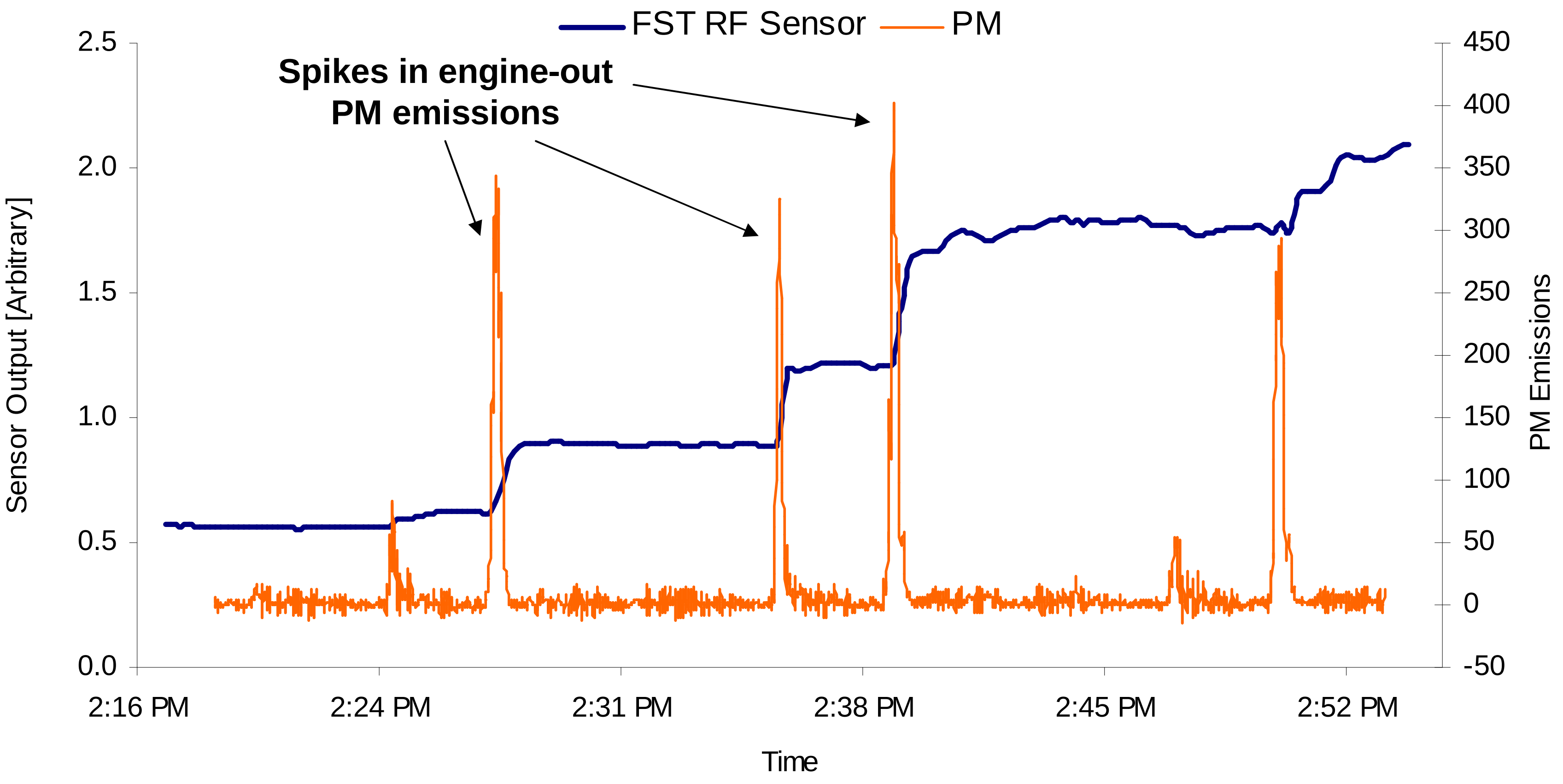
Cumulative Soot Emissions Over Test Cycle (TEOM)



- TEOM measures total engine-out soot emissions over test cycle (mass)
- PM sampled between DOC outlet and DPF inlet
- Slope of TEOM measurements indicates soot emissions rate

FST RF Sensor Dynamic Response



- RF sensor accurately captures transient spikes in engine-out soot emissions over test cycle
- PM emissions simultaneously measured via TEOM, DMM, and gravimetric sampling

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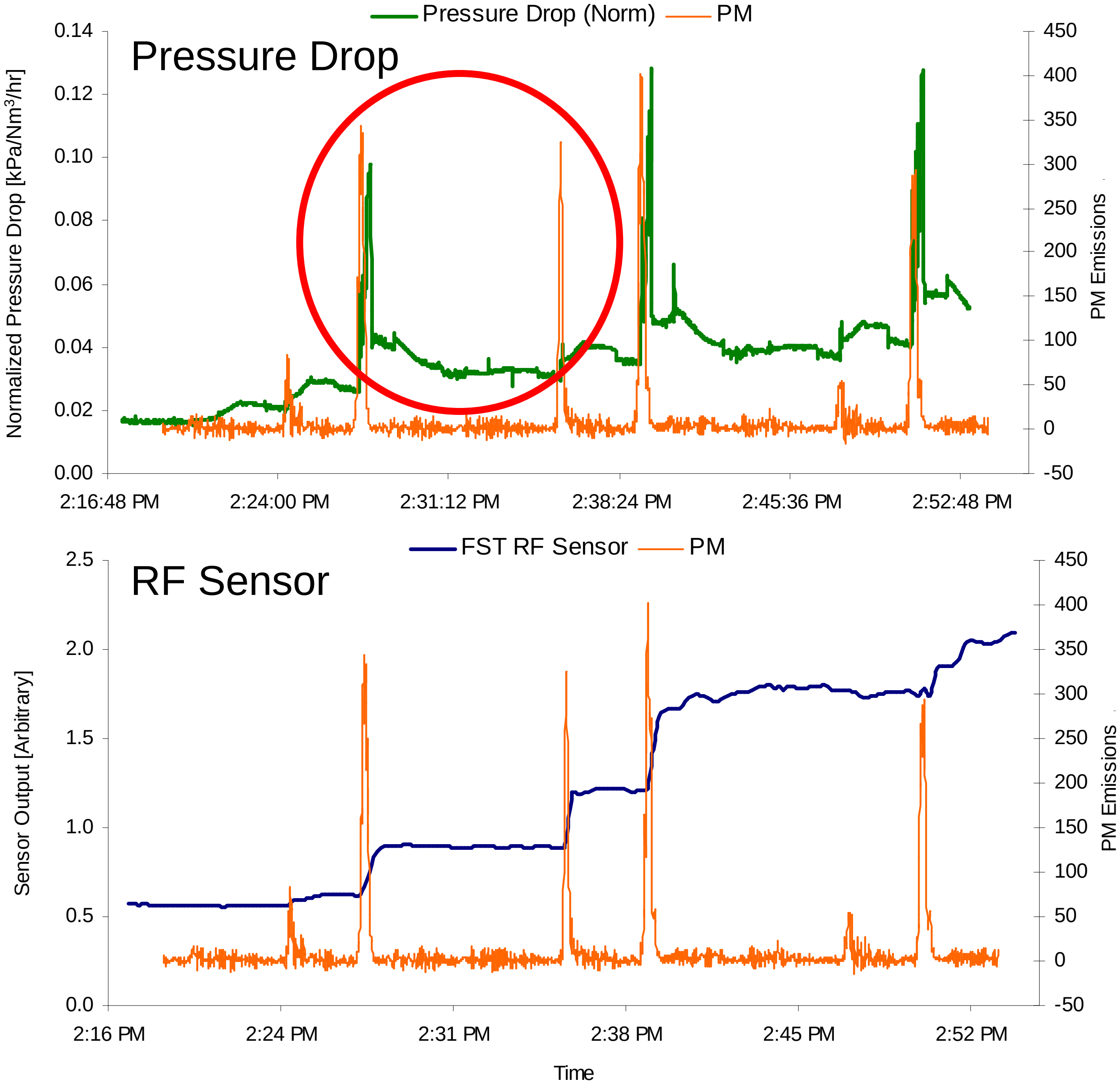
Comparison of RF Sensor and Delta P with PM



Pressure Drop

- Transient response normalized by exhaust flow rate
- Large variability in pressure sensor response to PM emissions

FST RF-DPF™

- Good transient response and repeatability
- Not affected by exhaust flow rate variations

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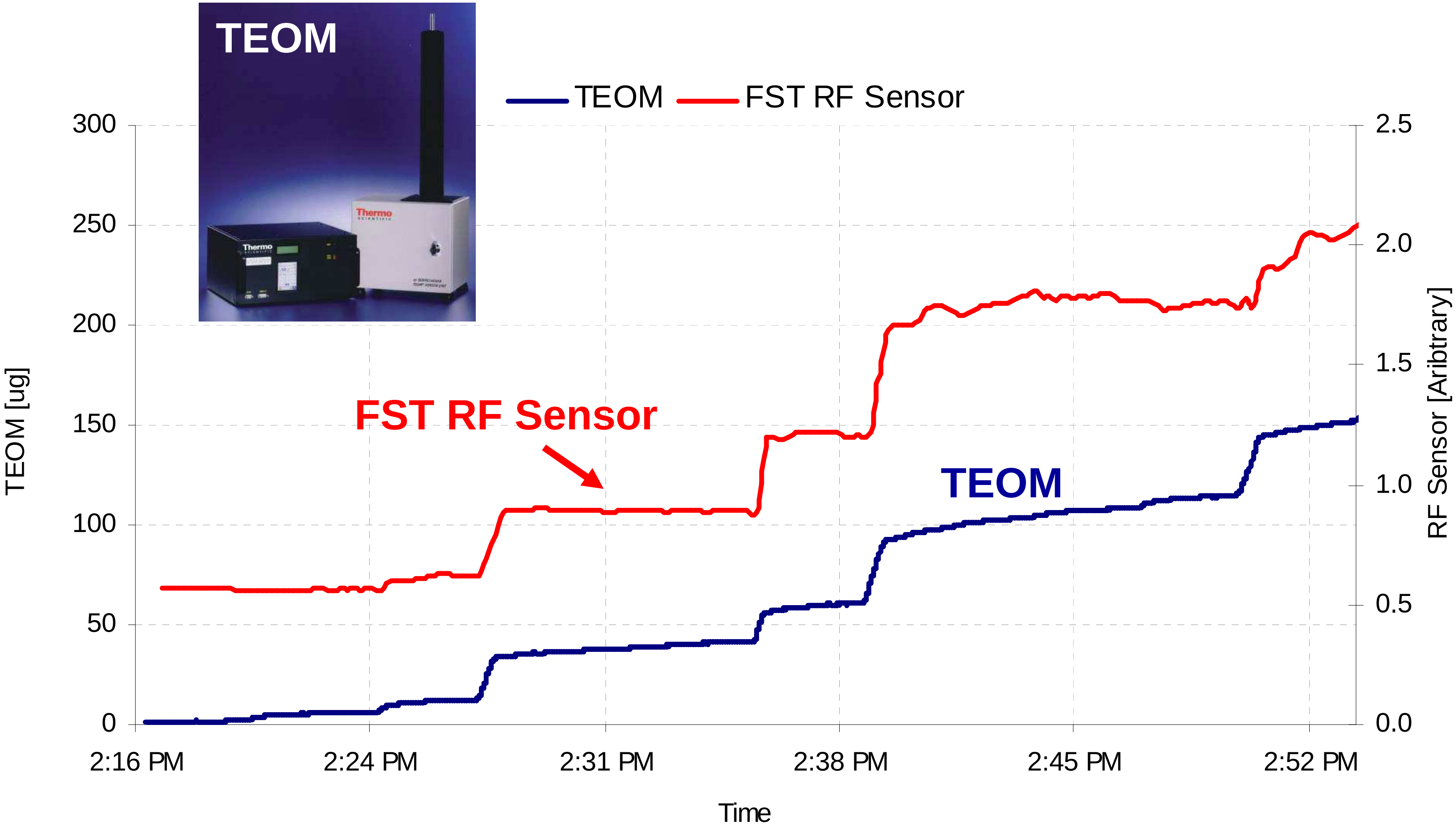
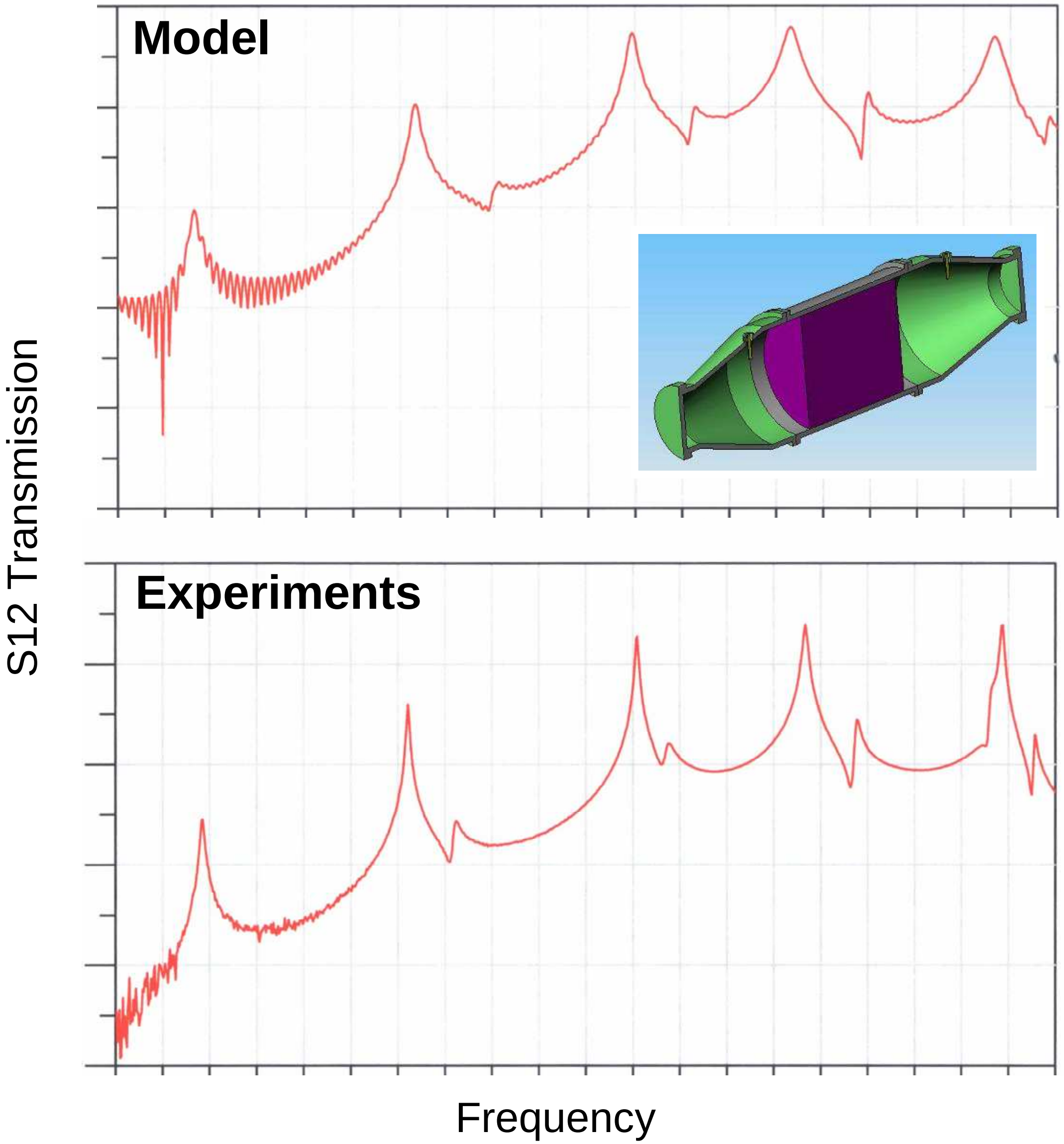
Comparison of RF Sensor with TEOM

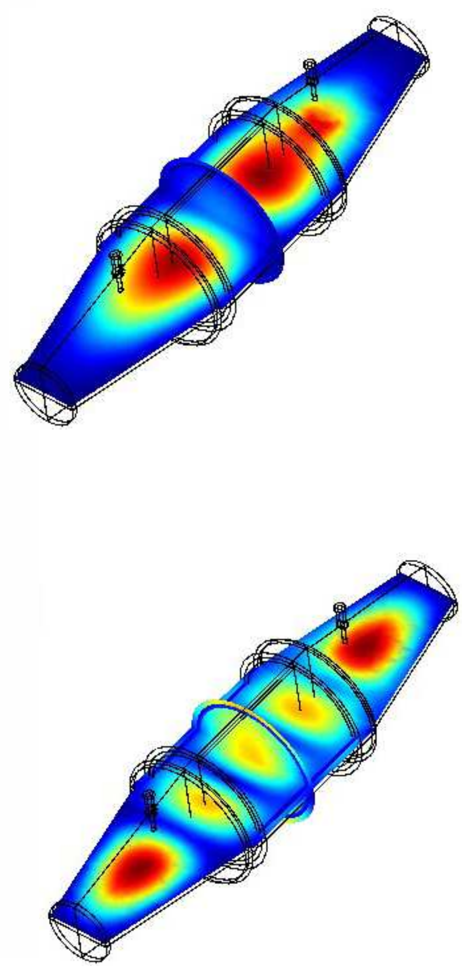


- RF sensor prototype shows good agreement with TEOM measurements over cycle
- Possible passive soot oxidation on DPF during test cycle not captured by TEOM
- RF sensor accurately captures transient events

RF System Models Show Spatial Resolution



DPF E-Field Profiles

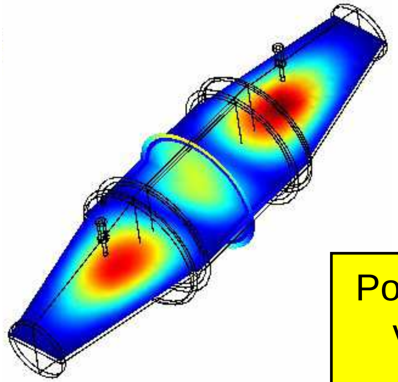


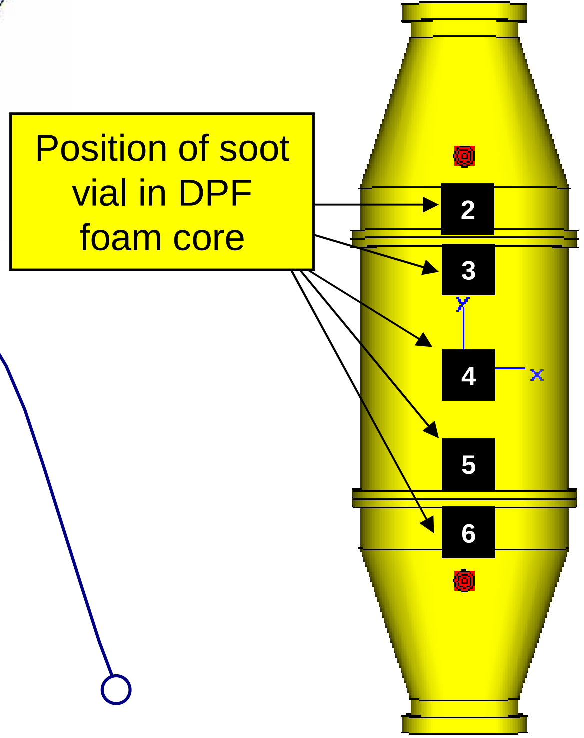
Resonant modes probe specific areas of DPF (localized measurements)

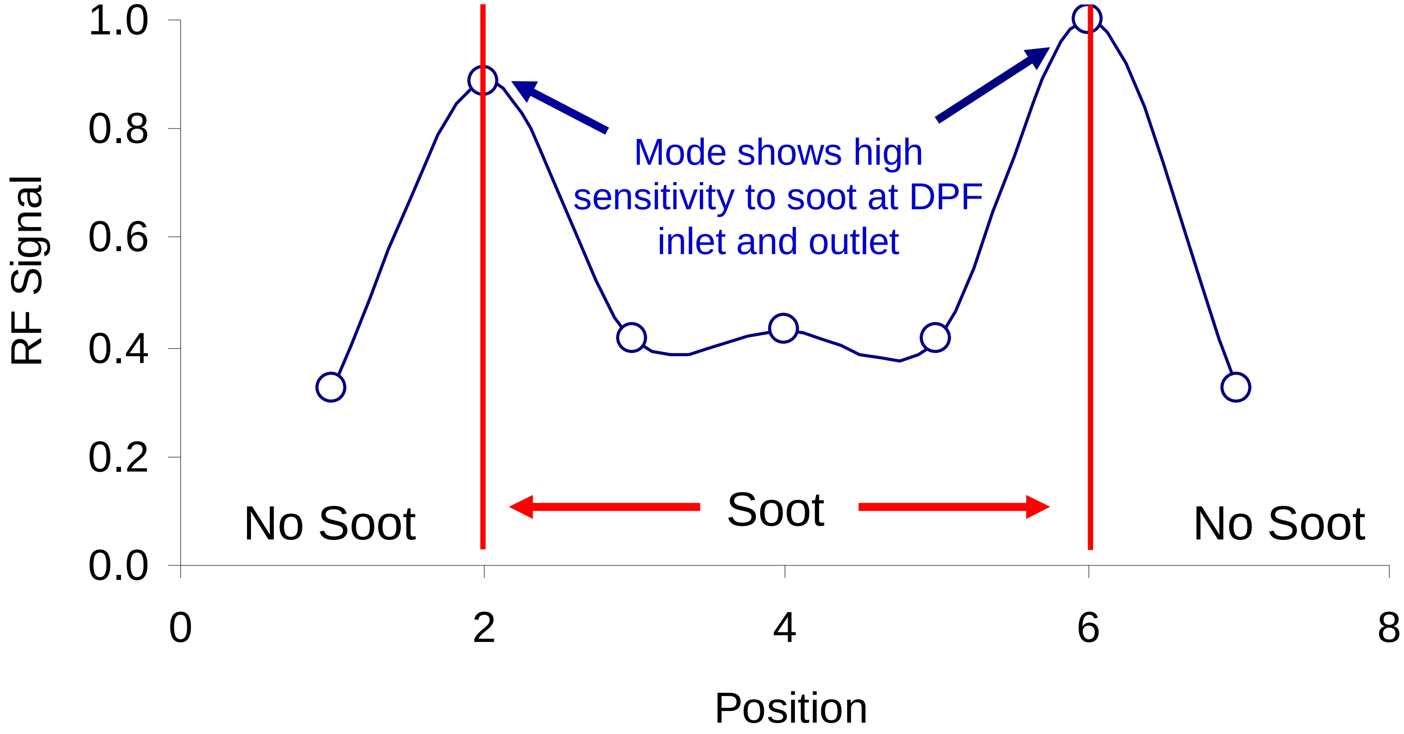
Model Validation (Axial Distribution) - Experiments

Spatial Resolution

- DPF replaced with foam core
- Soot vial placed in foam core at specified locations (2-6)

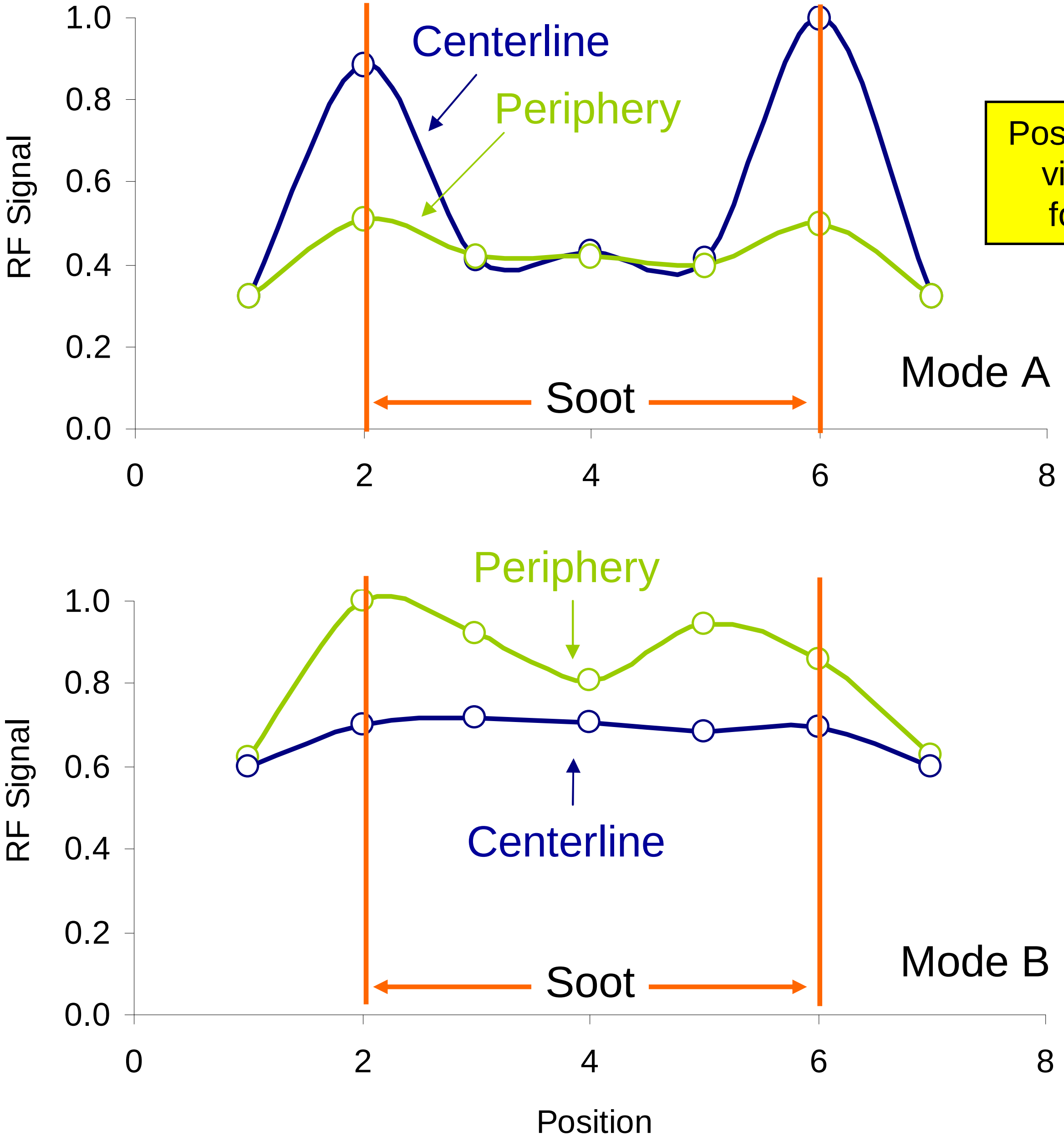




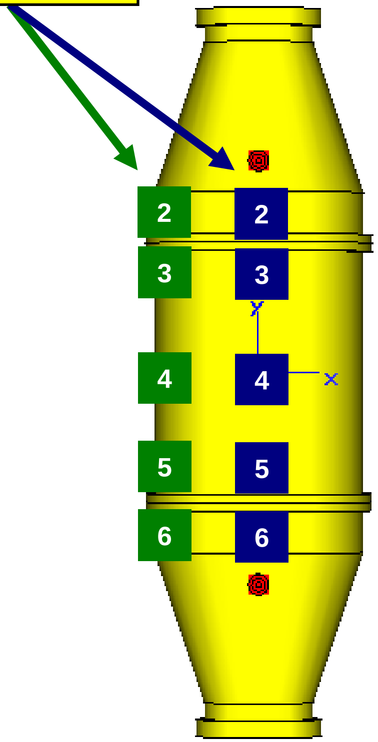


Inclusion of multiple modes provides information on soot distribution

Model Validation (Radial Distribution) - Experiments



Position of soot vial in DPF foam core



RF Sensor Performance and Development Summary

DPF Sensor, RF-DPF^{TM}, Development

- First-generation prototype system studied at ORNL
- Direct, real-time measurements of soot levels in DPF
- Applications for on-vehicle sensing

Prototype Testing Highlights

- Good repeatability over successive loading and regeneration events
- High sensitivity to detect even low rates of PM accumulation
- Dynamic response and sensor performance over ad hoc FTP cycle comparable to TEOM-type PM measurements
- RF system models developed to understand DPF electric field profiles
- Experiments confirm model results to monitor spatial distribution (localized loading) of material trapped on DPF

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