Advanced Radio Frequency-Based Sensors for Monitoring Diesel Particulate Filter Loading and Regeneration

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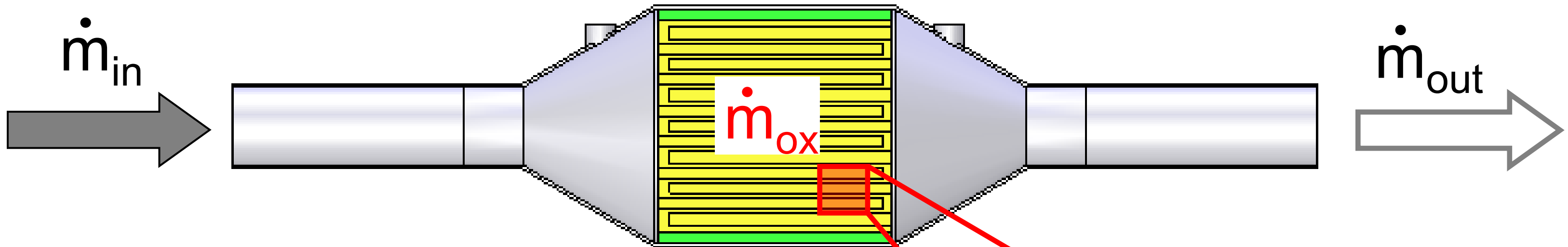
Alexander Sappok*, Leslie Bromberg**
Filter Sensing Technologies, Inc.

Jim Parks, Vitaly Prikhodko
Oak Ridge National Laboratory

***MIT Sloan Automotive Laboratory, **MIT Plasma Science and Fusion Center**

DPF PM Load Estimation Complicated by Many Factors



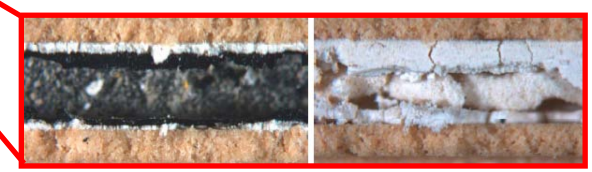


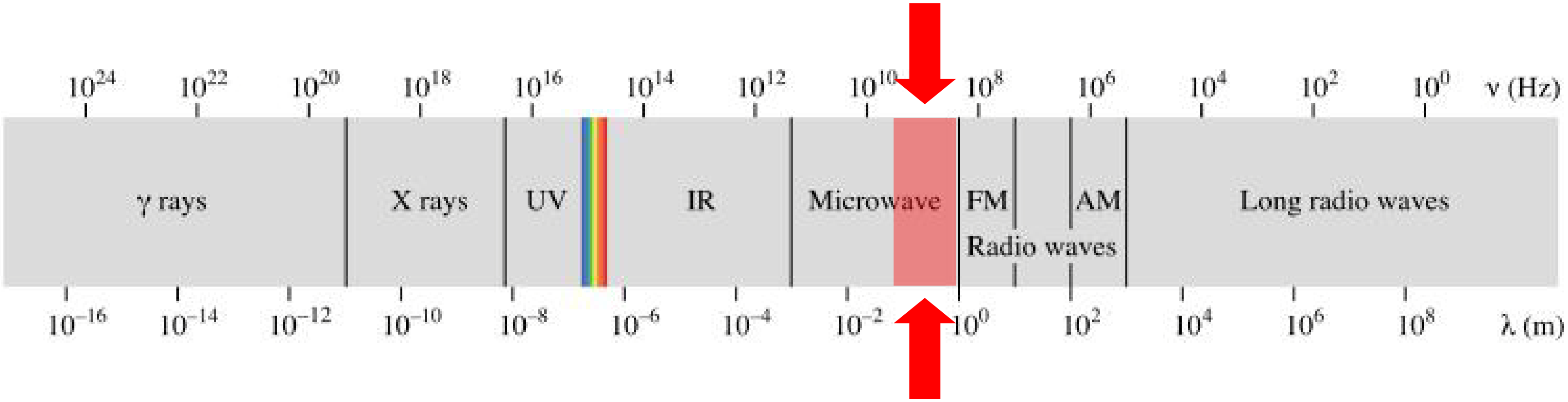
Image: Corning, Deer 2006

- **Factors Impacting PM Levels in DPF**
  - **Engine-out emissions ($\dot{m}_{in}$)**
    Fuel, lubricant, operating conditions
  - **Quality of regeneration and/or passive oxidation ($\dot{m}_{ox}$)**
    DPF configuration, exhaust conditions & composition, time
  - **Tailpipe-out emissions ($\dot{m}_{out}$)**
    DPF health/integrity (OBD)
- **State of DPF Changes with Time**
  - Ash build-up reduces PM storage capacity and alters PM distribution
  - Ash may comprise > 80% of trapped mass after 150K miles[1]

Variability (up to 50%) in ΔP-based estimates of DPF PM[2].

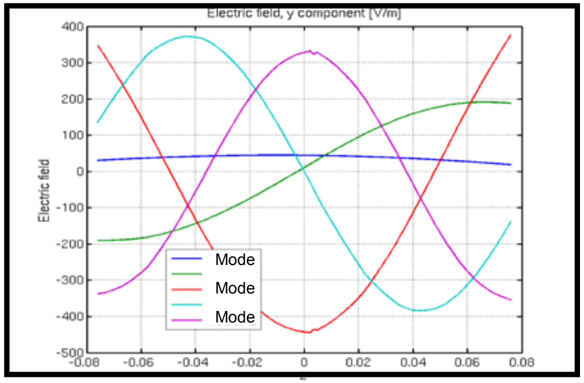
[1]SAE 2010-01-0811, [2]SAE 2008-01-0618, 2008-01-0620, 2009-01-1262

RF Sensing and Cavity Resonance Techniques



Microwave Cavity Resonance

- Resonant modes established in conducting cavities at specific frequencies
- Signal characteristics affected by material through which the wave travels
- Cavity resonance techniques since 1940's



Applications for DPF Measurements

1980s – General Motors

1990s – Atomic Energy Canada, Engine Control Sys.

2000s – Caterpillar, GE

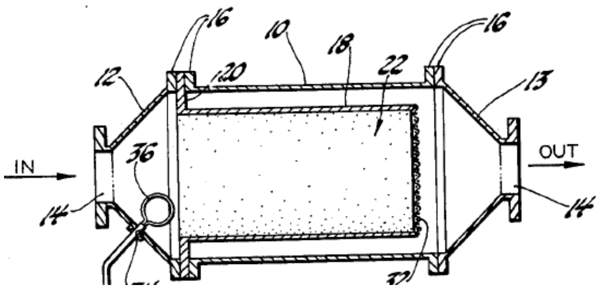


Image: U.S. 4477771

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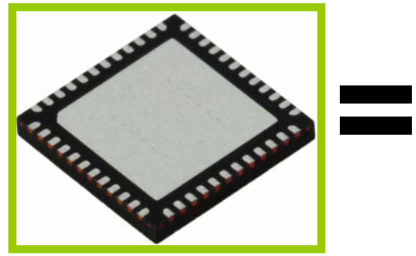
RF Sensor Operation



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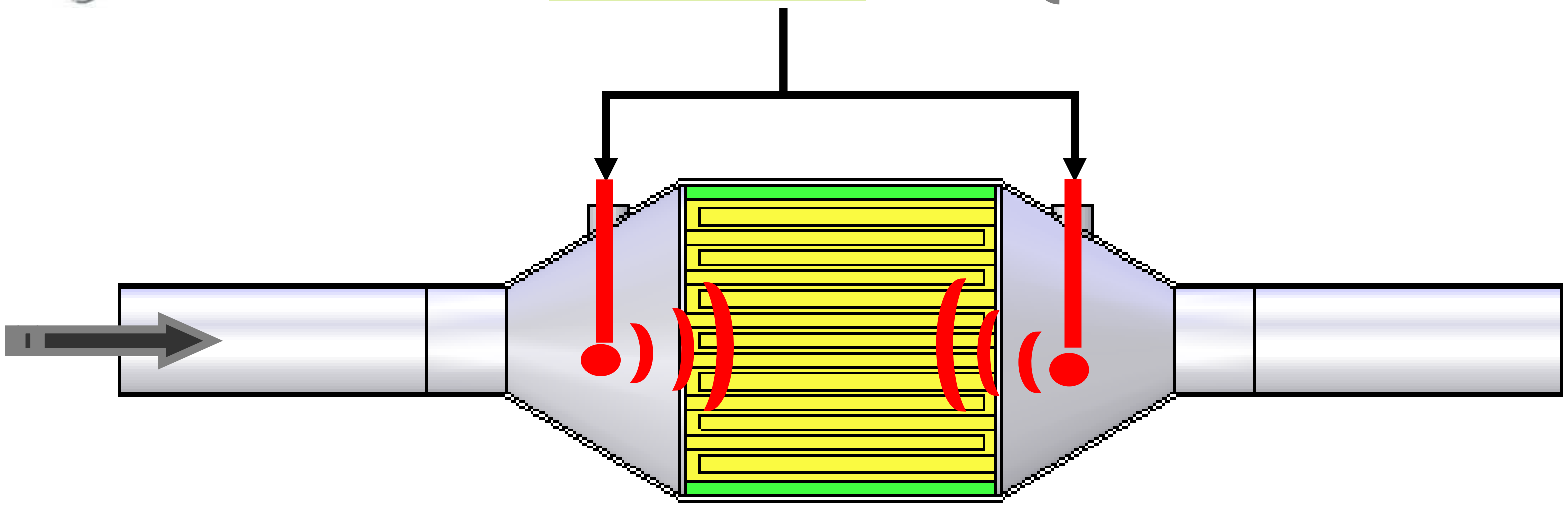
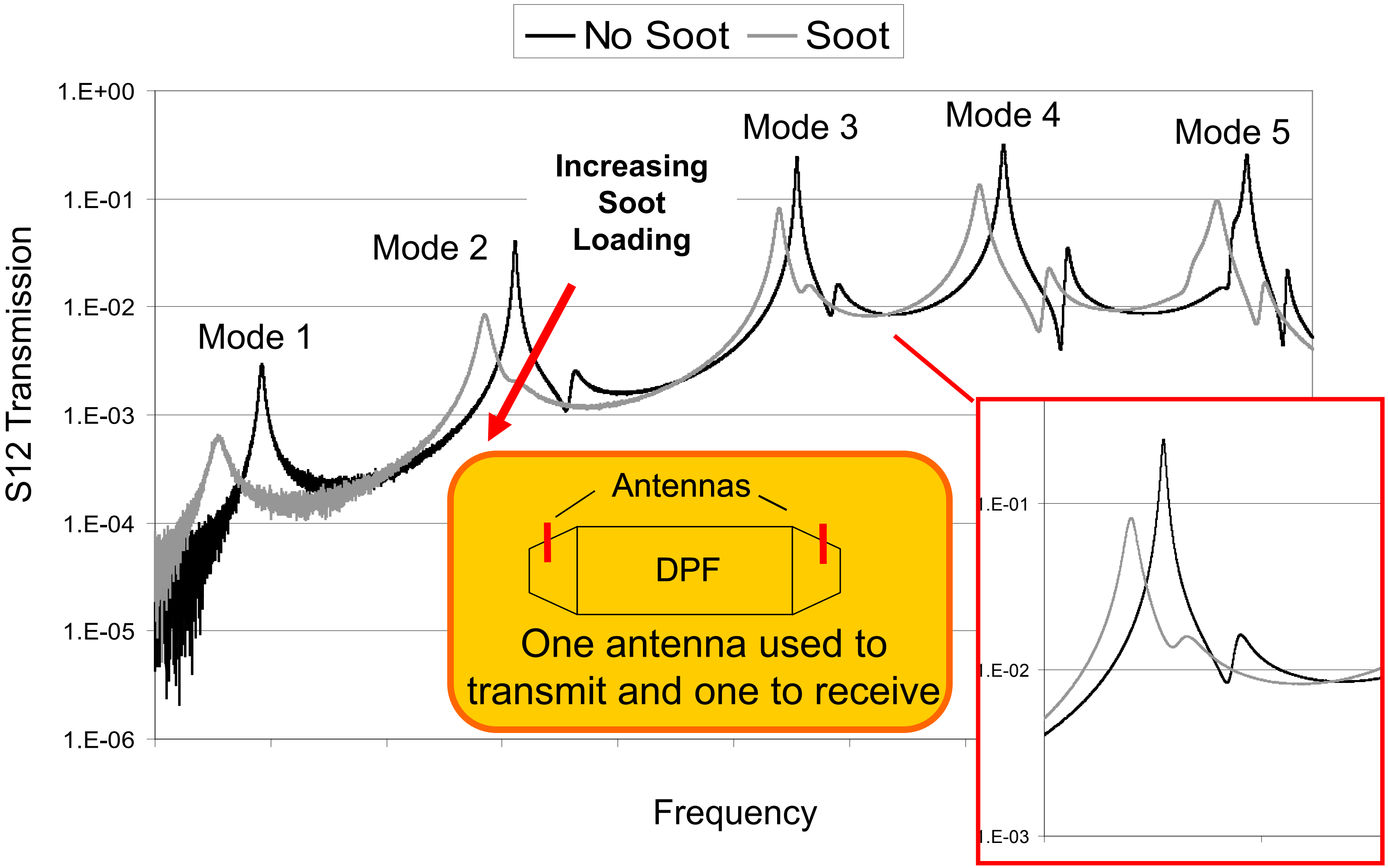
1. **Amount**
2. Type
3. **Distribution**
4. Filter Failures



Opportunities for RF-Based Sensing

- Direct measurement of PM levels in the DPF
- Distinguish ash from particulate matter
- Information related to PM and ash spatial distribution
- Potential to detect localized filter failures (OBD)

RF System Operation: Transmission



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

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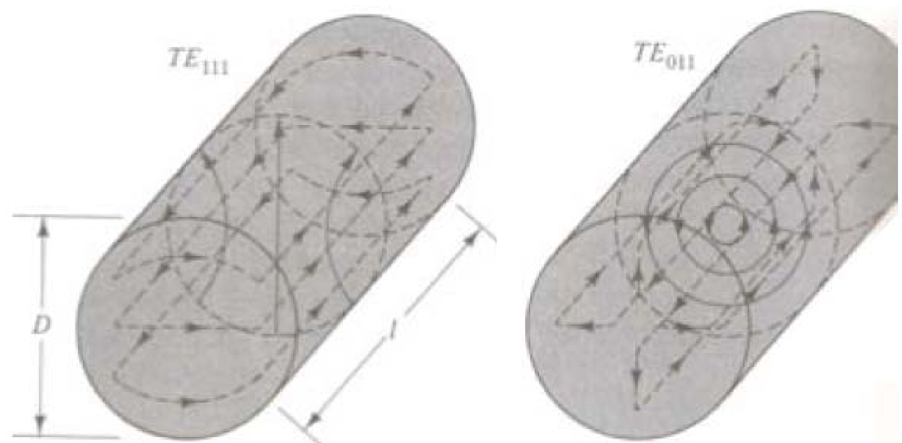
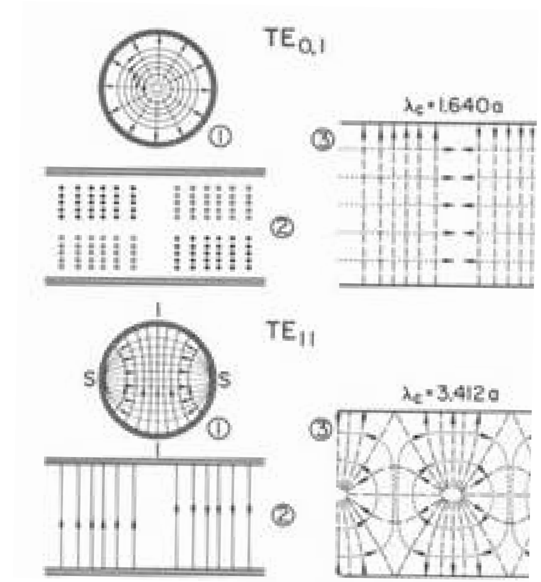
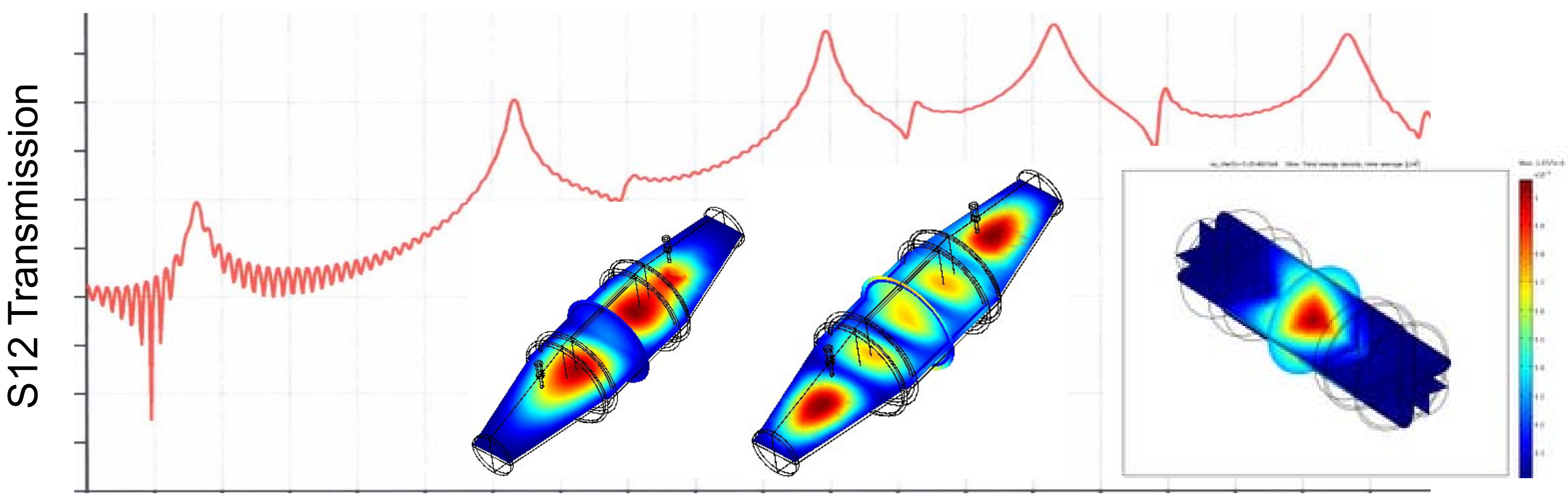
Resonant Modes used to Monitor Spatial Distribution

Typical Resonant Mode Electric Field Profiles*



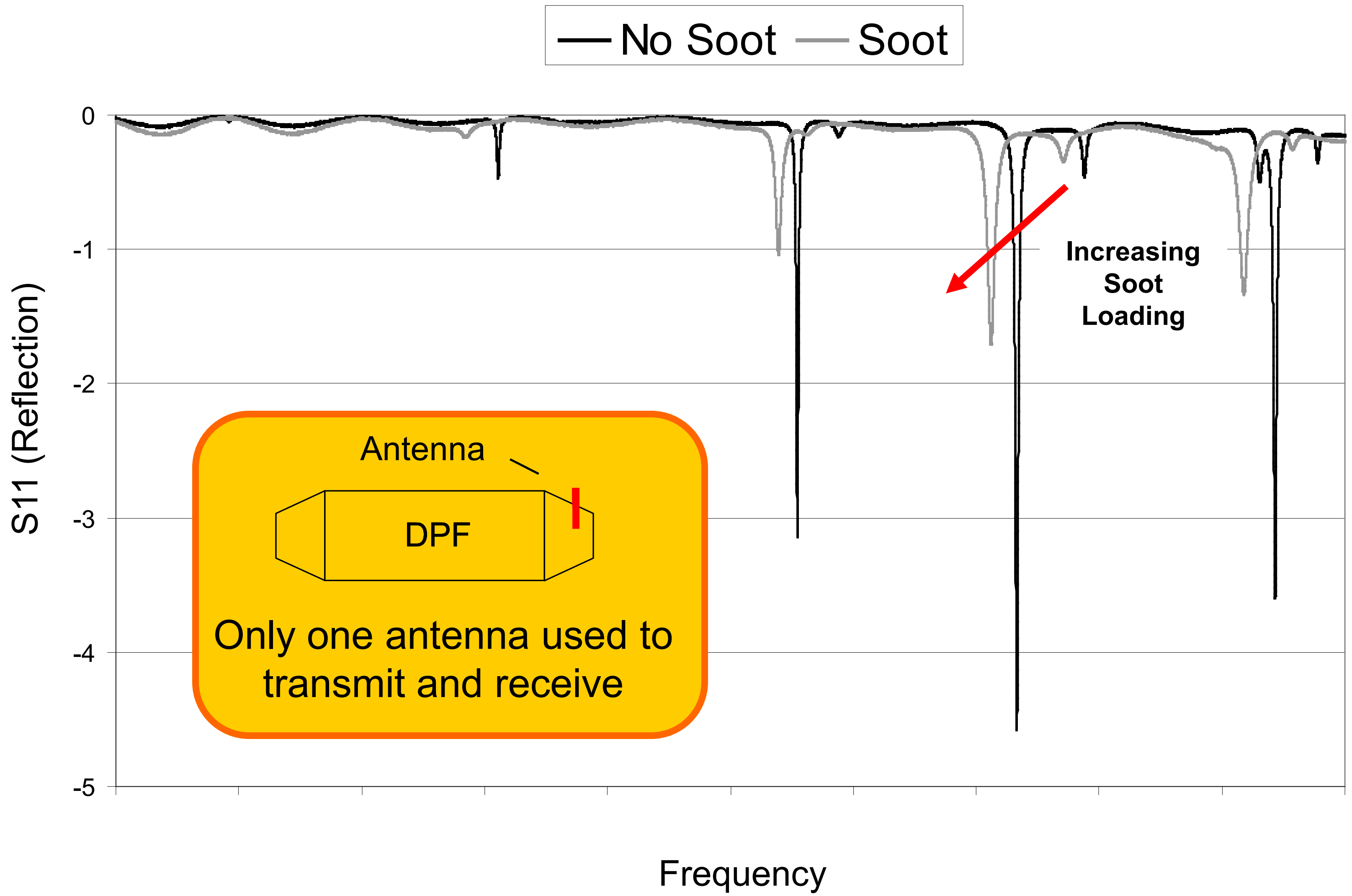


RF System Models for DPF-Specific Geometries



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

Signal Sensitive to Soot Loading of Filter: Reflection



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

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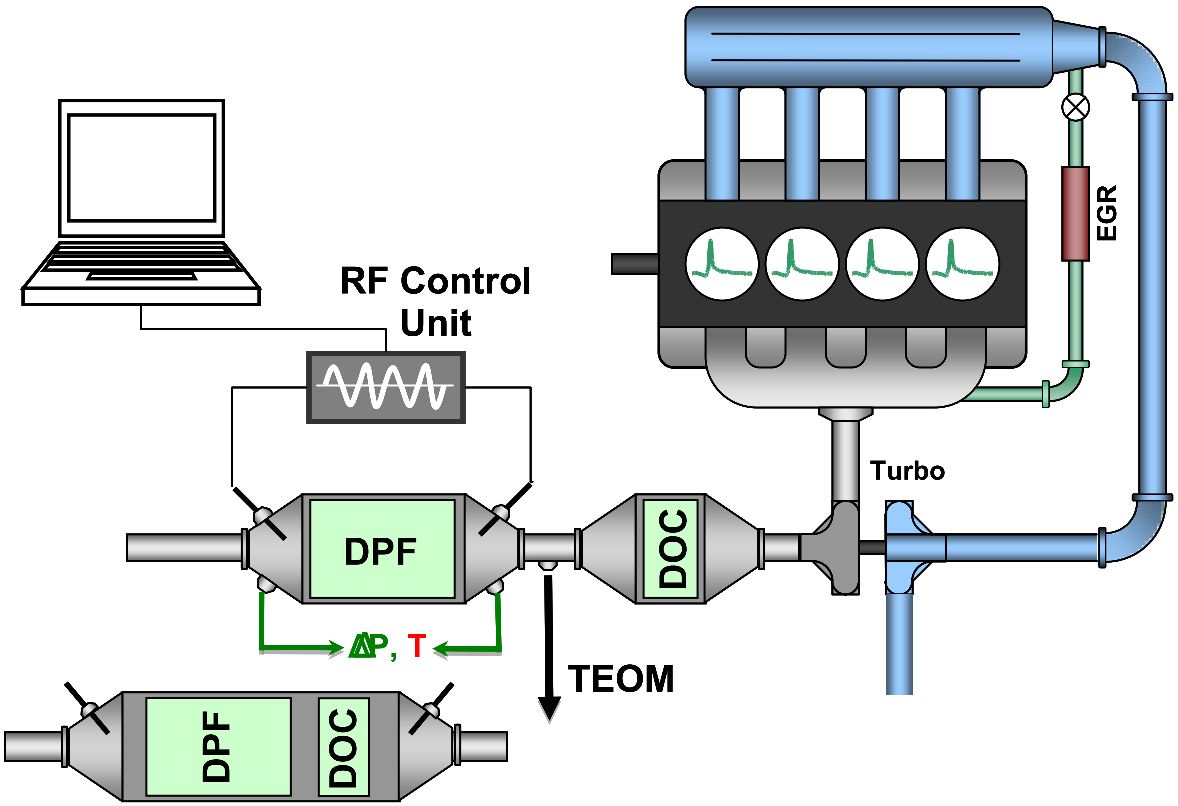
RF Sensor Test Configuration

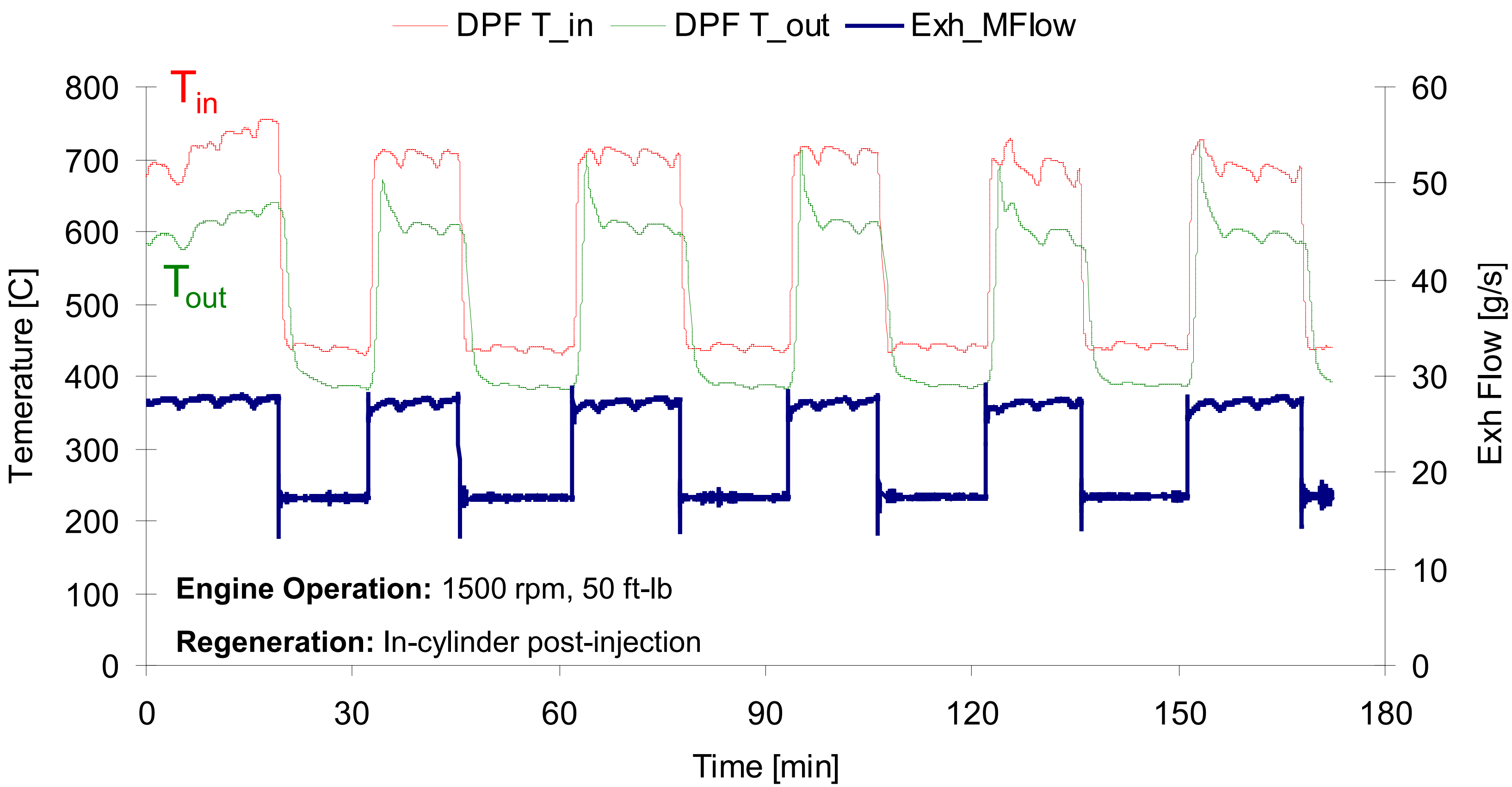
Engine Dynamometer Testing

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



DPF: Cordierite D 5.66” x 6”

Exhaust Conditions During Test Cycle



- Test conditions used for steady-state DPF loading and regeneration
- DPF inlet temperatures ranged from 400 C to 700 °C +
- Engine operated at high PM emissions condition for rapid DPF loading

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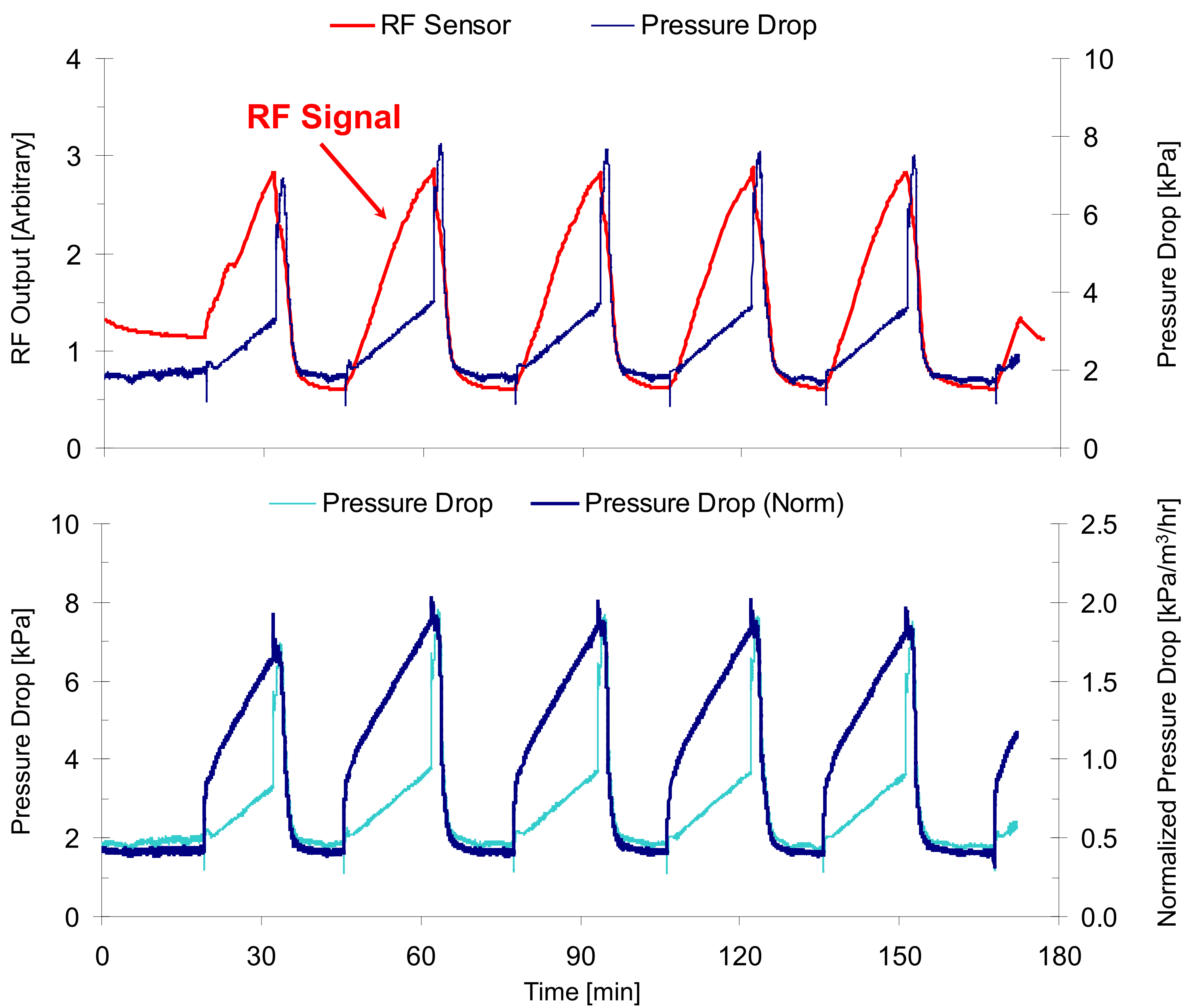
Comparison with Pressure Drop (Steady-State)



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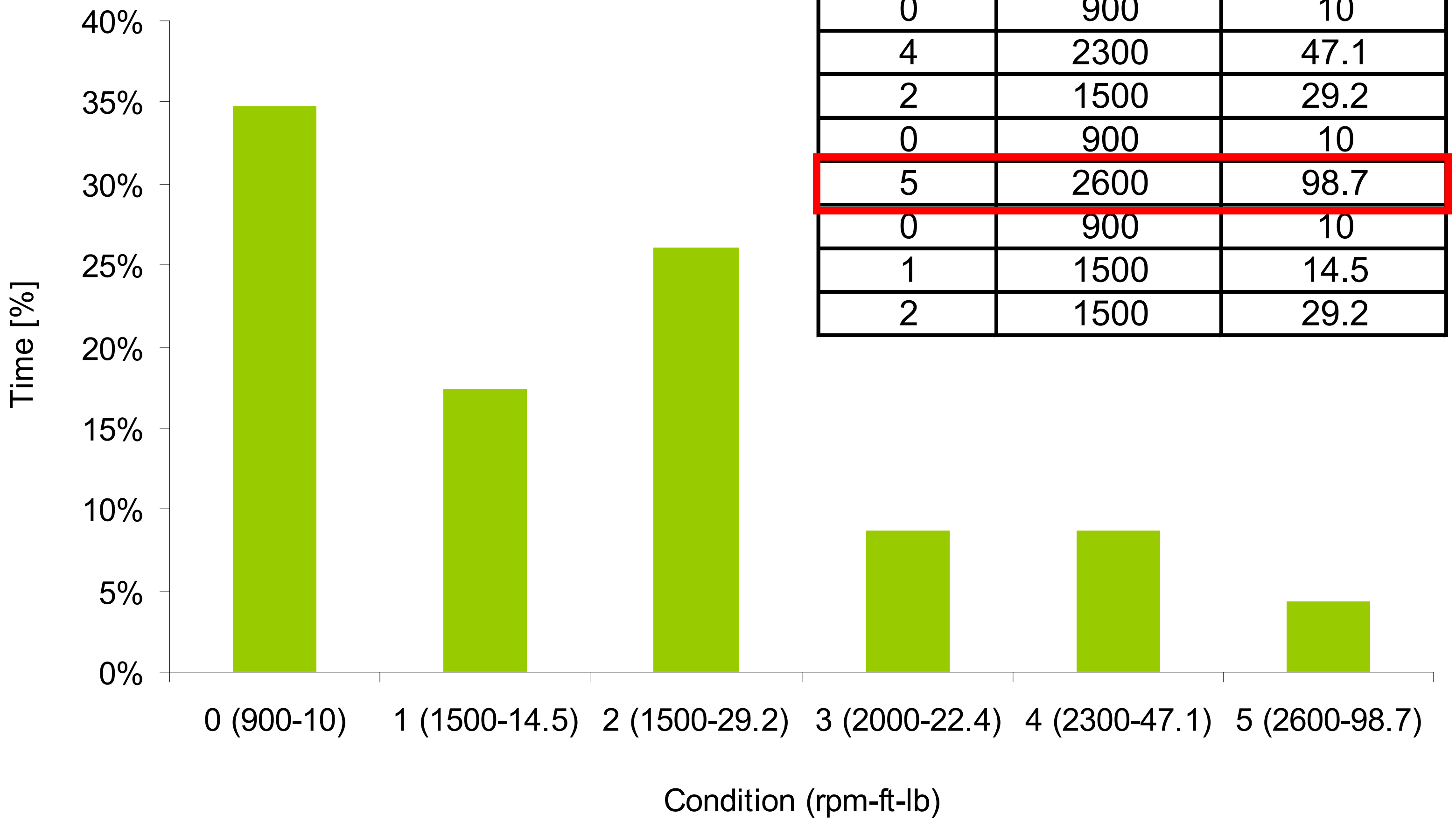
Modified FTP Cycle Engine Operating Conditions

- 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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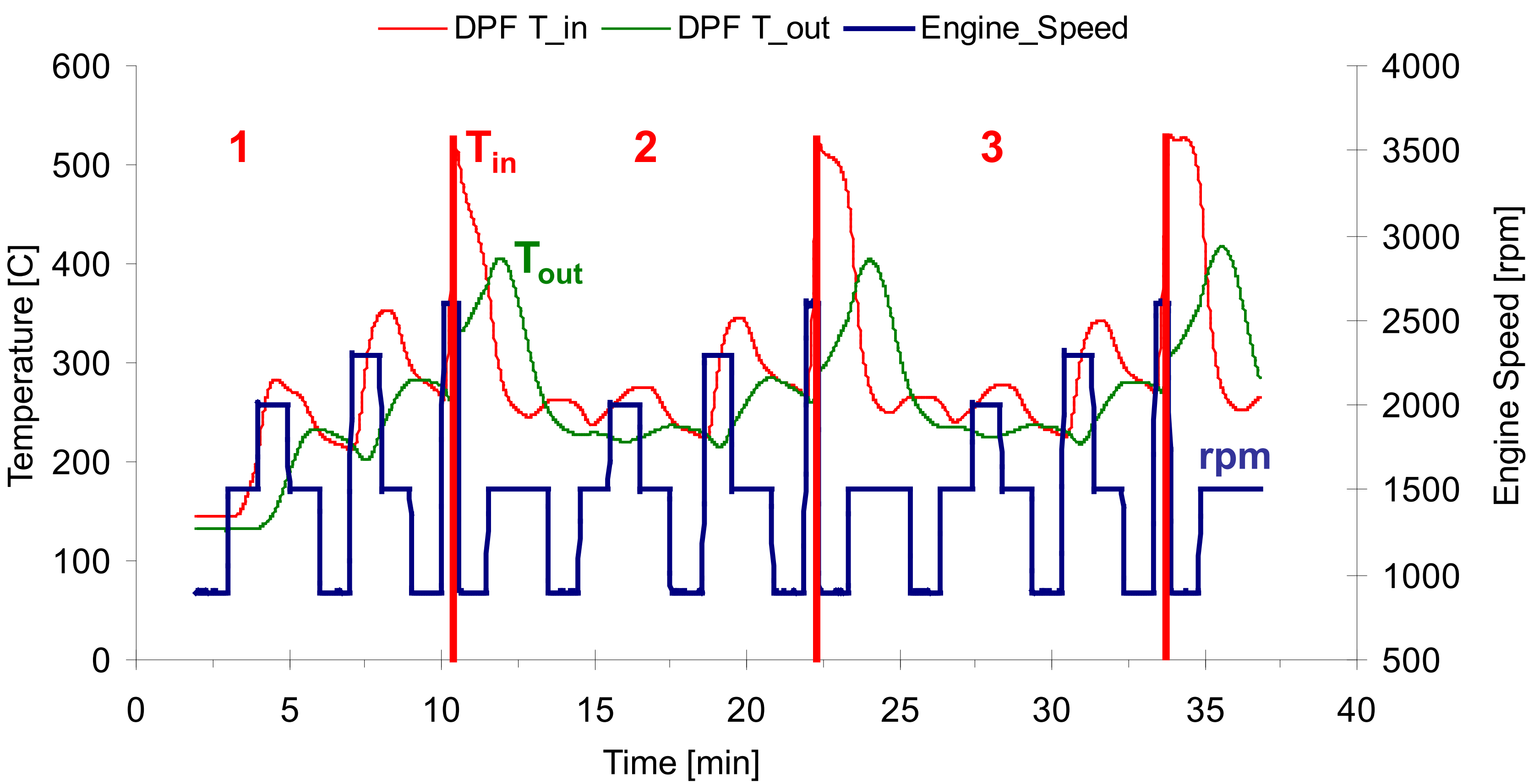
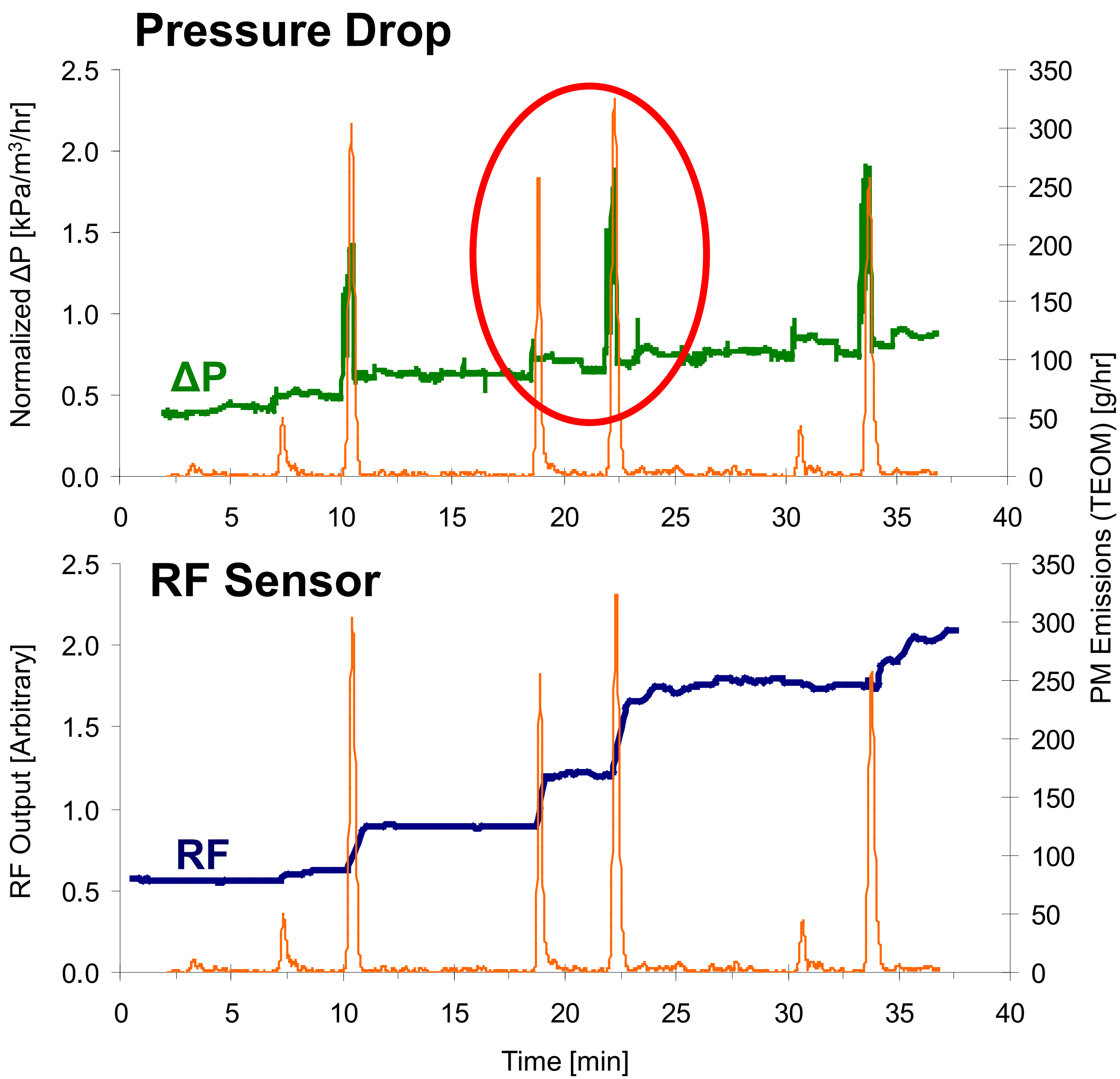
Modified FTP Cycle Details and Exhaust Conditions



- Engine operating conditions varied every 30 to 60 seconds
- Large variation in DPF inlet and outlet temperatures and exhaust flow rates
- Test cycle repeated 3X consecutively on multiple days
- Engine-out PM measured via TEOM at DPF inlet

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

RF Sensor

- Transient response similar to engine-out PM emissions
- Unaffected by exhaust flow rate variations

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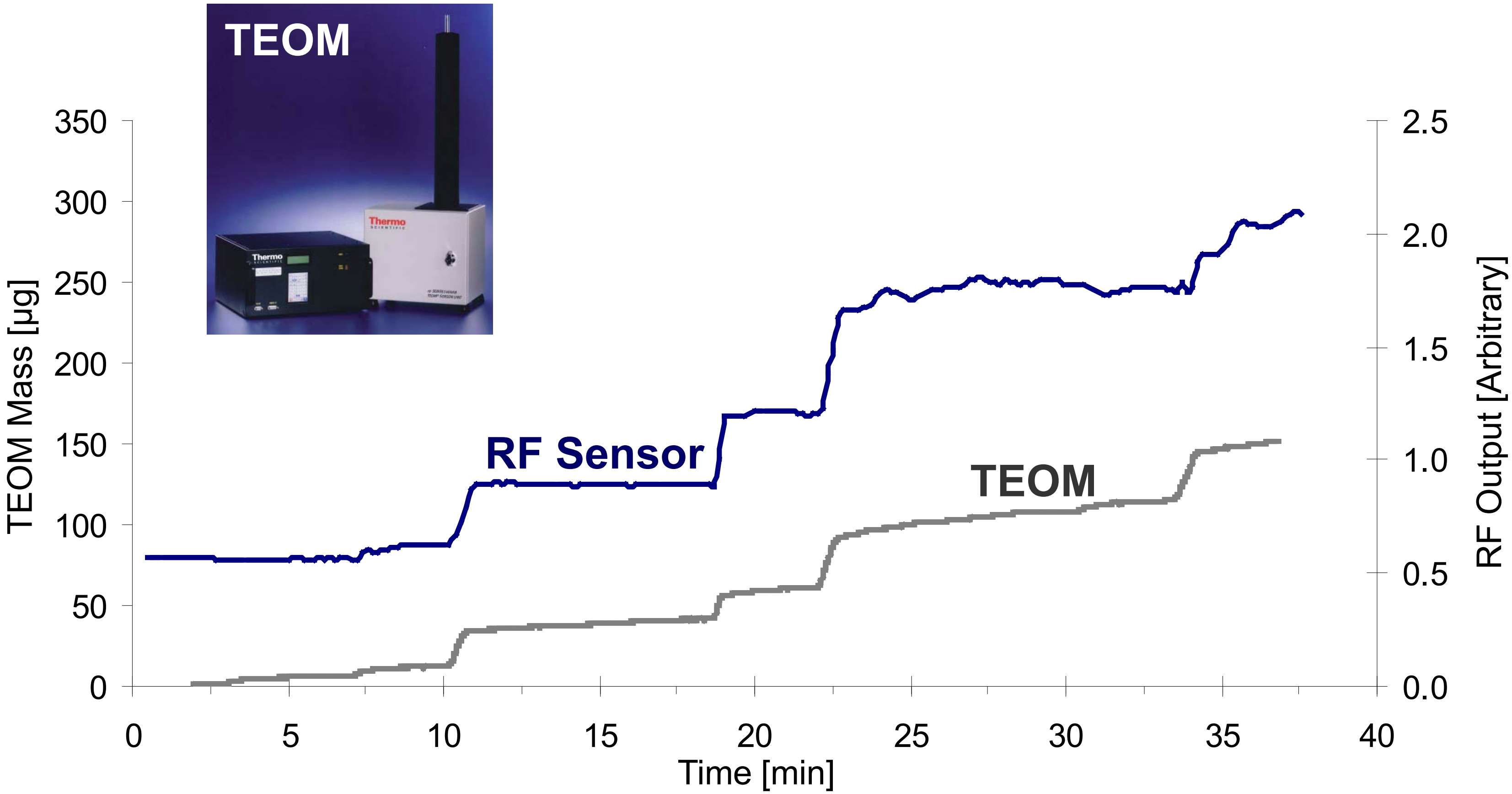
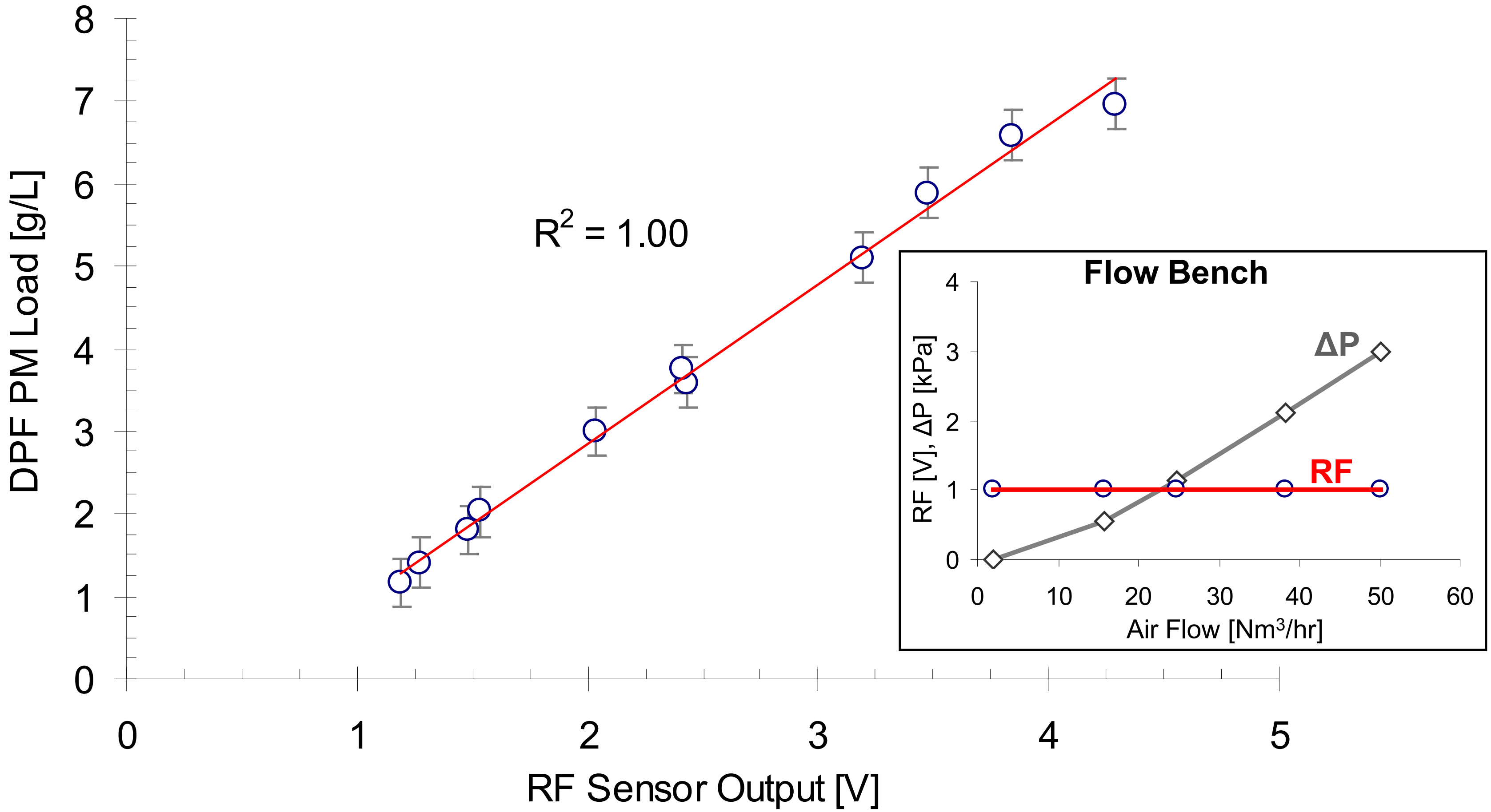
Comparison of RF Sensor with TEOM



- TEOM measures mass of PM on small filter sampled from exhaust
- Possible passive PM oxidation on DPF not captured by TEOM
- RF sensor well-correlated with TEOM response to transient events

RF Sensor Well-Correlated with Gravimetric Measurements



- Gravimetric and RF measurements of DPF soot load with hot filter
- RF sensor output linear over measurement range
- Flow bench results illustrate insensitivity of RF sensor to flow

RF Sensing: Summary and Conclusions

DPF Sensor, RF-DPF™, Development

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

Sensor Testing Highlights

- Good repeatability over successive loading and regeneration events
- Dynamic response and sensor performance over modified FTP cycle comparable to TEOM-type PM measurements
- RF sensor output well-correlated to gravimetric DPF PM measurements
- RF measurements insensitive to exhaust flow rate (even no flow) but require temperature compensation
- RF system models developed to understand DPF electric field profiles and correlation to spatial distribution (localized loading)

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alexander.sappok@dpfsensor.com

www.dpfsensor.com