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In-Use Particulate Filter State of Health Monitoring: Prognostics and Diagnostics using Radio Frequency Sensing

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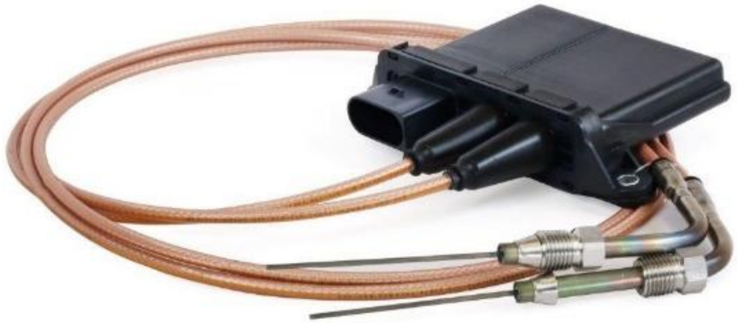
www.ctscorp.com



Agenda and Presentation Outline

PM Sensing Approaches

RF Sensor Description and Operation

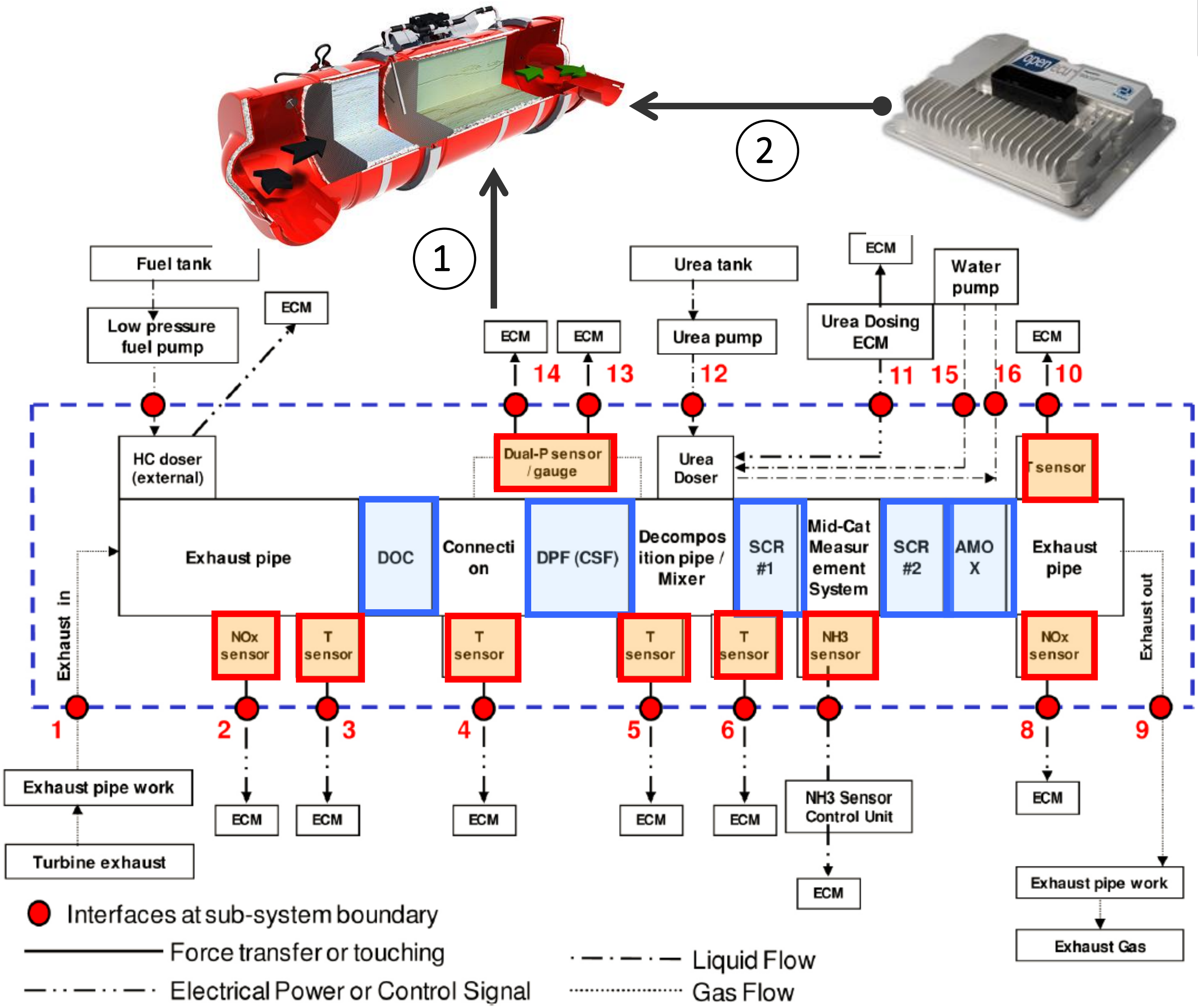
Examples: Applications for Filter Control

Case Studies: Particulate Filter Diagnostics

I. On-Road Preventative Diagnostics
II. Direct Detection of Filter Failures
III. Diesel Filter PM Slip Detection (DPF)
IV. Gasoline Filter PM Slip Detection (GPF)

Conclusions and Outlook

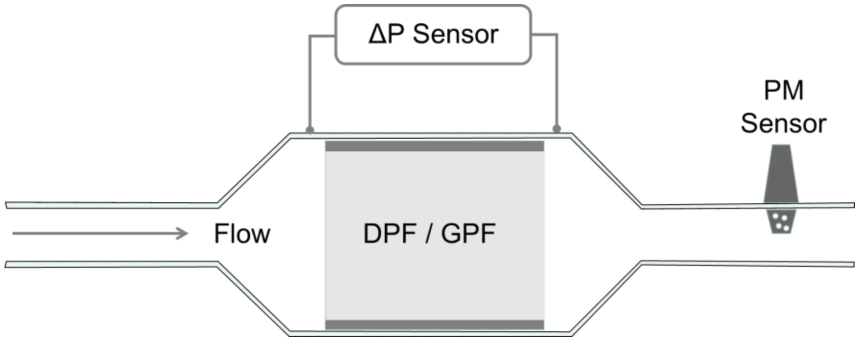
Current Determination of Filter/Catalyst State is Indirect



Stanton, D., "Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle Greenhouse Gas Regulations," SAE Int. J. Engines 6(3):1395-1480, 2013

Overview: Approaches to Filter Diagnostics

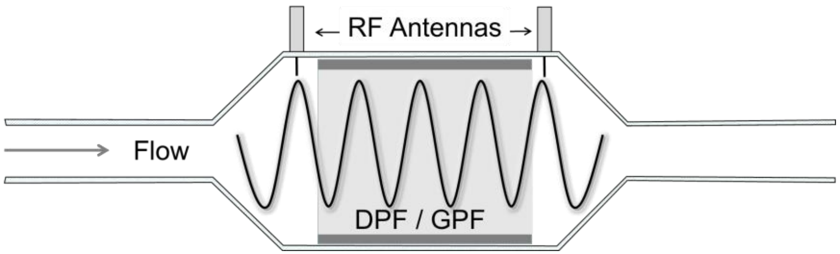
Current Approach



Reactive diagnostic (after part failed)

Proposed RF Approach

→ Filter is the Sensor!



Prognostics (warning before failure)

Accumulation Exhaust PM Sensors

- Local Measurement: samples only a portion of engine exhaust downstream of filter.
- Non-Continuous Monitor: requires periodic regeneration.
- Reactive: monitors PM downstream of filter.
- Provides little information on soot concentrations below sensor threshold.
- Active sensing element – sensor conditioning.

RF Measurement Approach

- Bulk Measurement: Samples full exhaust stream passing through filter.
- Continuous Monitor: functions even with engine off (no flow).
- Proactive: sensitive to upstream emissions entering DPF / GPF.
- Direct (real-time) measurements of particulate filter state.
- Passive sensor – rod antenna.

RF Measurement System and Operation

- Antenna (RF Probe), similar size to exhaust temperature sensor
- Stainless steel rod-type antenna (passive component)

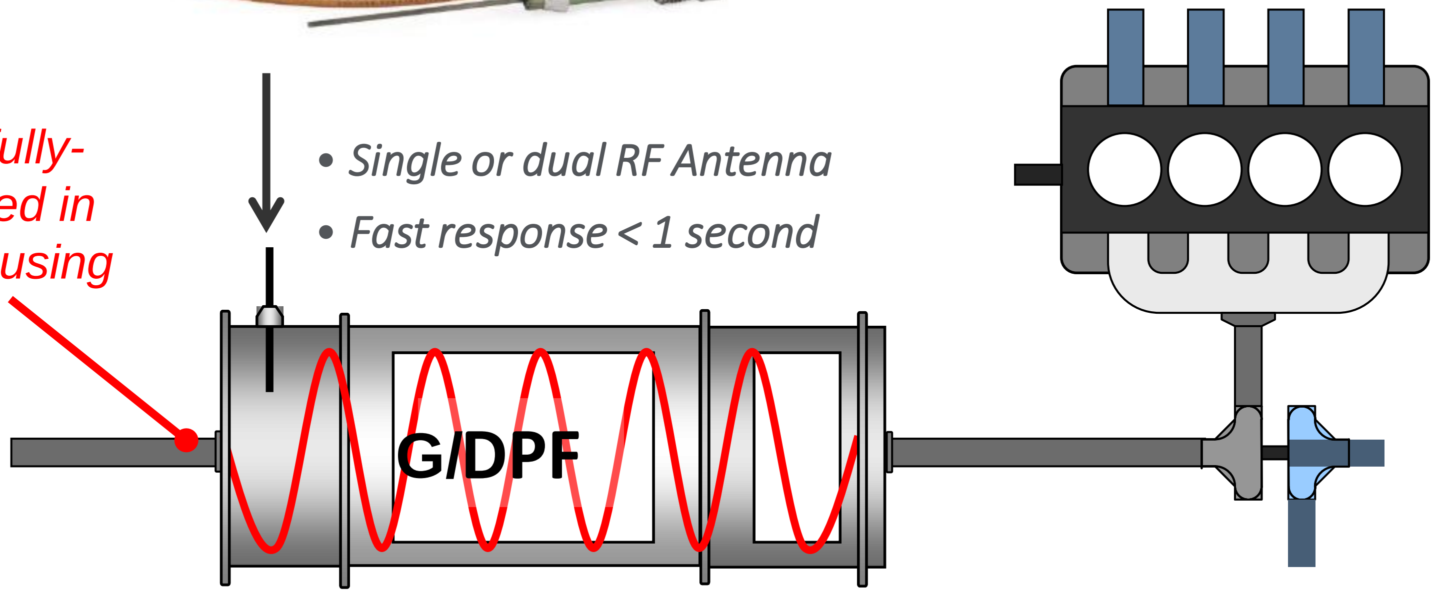
RF Control Unit Measures

GPF/DPF Loading:

1. Filter Loading
2. Loading Type (PM vs. Ash)
3. Spatial Distribution
4. Filter Diagnostics

Signal fully-contained in DPF housing

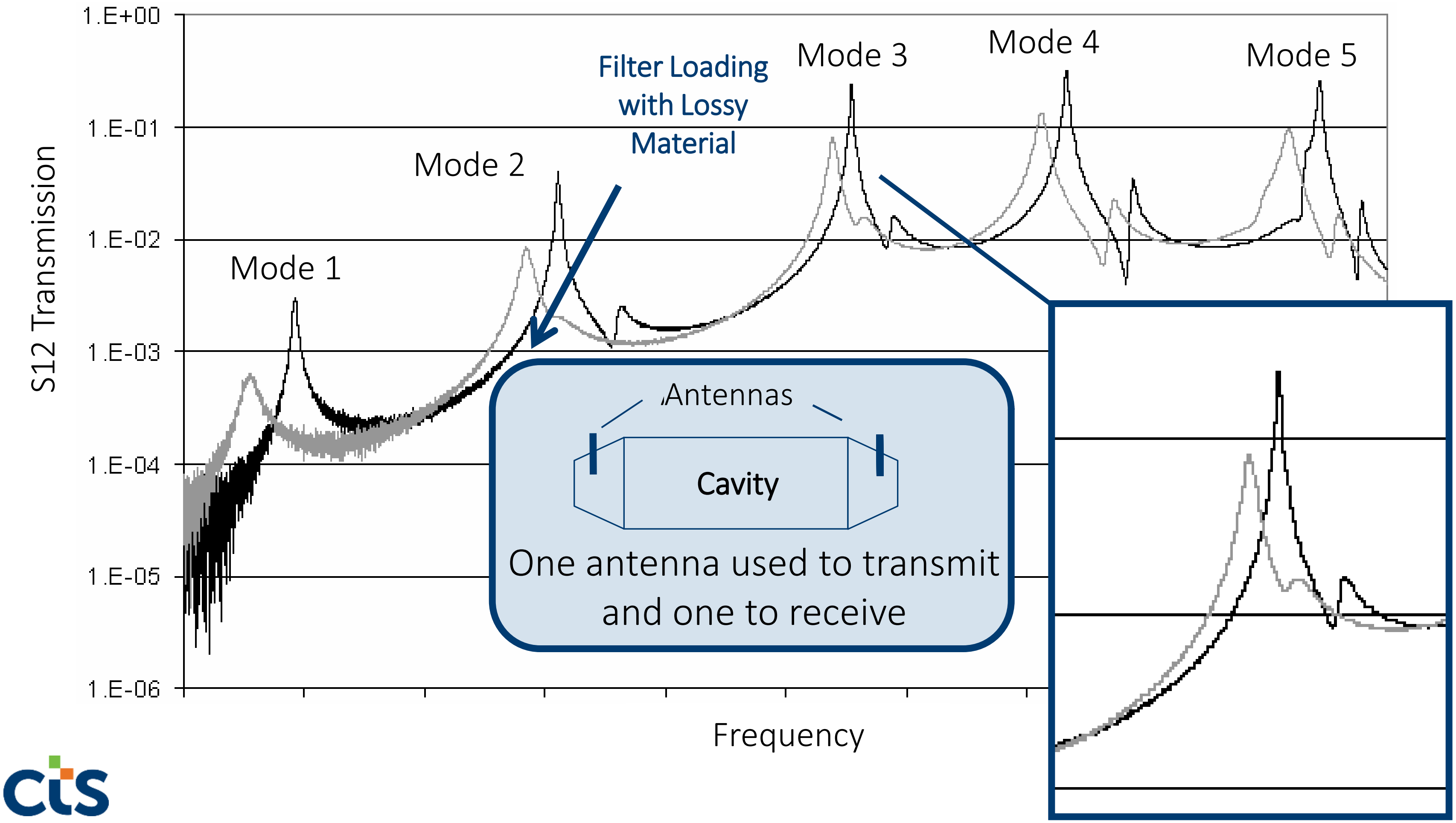
- *Single or dual RF Antenna*
- *Fast response < 1 second*



RF sensor responds <u>directly</u> to changes in filter dielectric properties

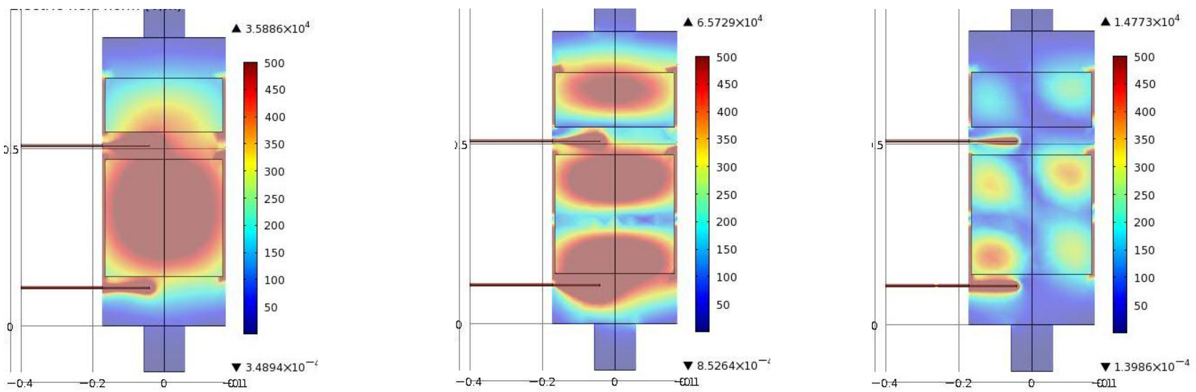
Example of RF System Operation: Transmission

- Multiple modes exist in the cavity depending on frequency of operation
- Mode structure (field profiles, direction) depend on the geometry and the frequency

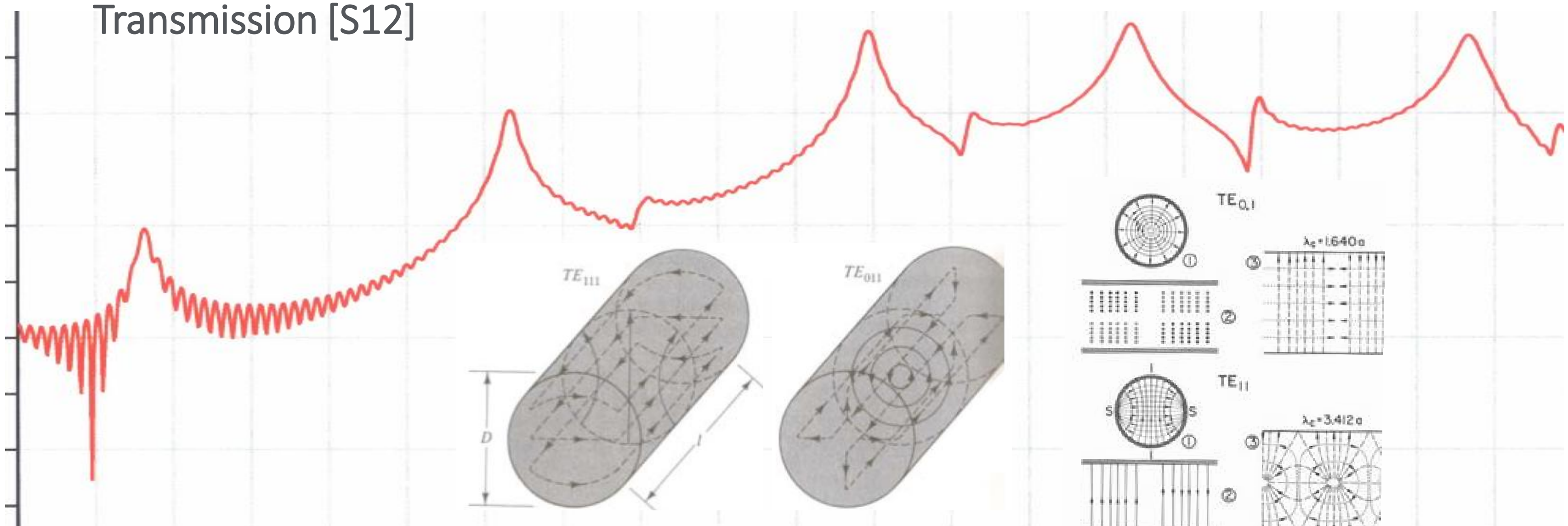


Resonances Provide Spatial Measurement Sensitivity

Electric Field Distribution and Spatial Resolution



Transmission [S12]



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

Frequency

Technical Highlights: DOE Program and Partner Testing

- Develop RF sensors
- Sensor calibration
- PM/Ash loading

- Pressure drop (OE)
- Gravimetric PM
- Gravimetric Ash

- Advanced DPF materials
- Mercedes engine test (LD)
- Navistar engine test (HD)

- ΔP + Models
- AVL micro-soot
- Gravimetric PM/Ash

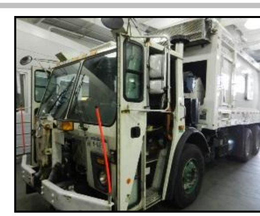
- AVL benchmarking
- TEOM benchmarking
- Fuels & adv. combustion

- AVL micro-soot, TEOM
- Pressure drop
- Gravimetric PM/Ash

- Controls development
- DDC engine platform
- 2013+ aftertreatment

- Stock OEM controls (*ΔP + Model*)
- Gravimetric PM/Ash

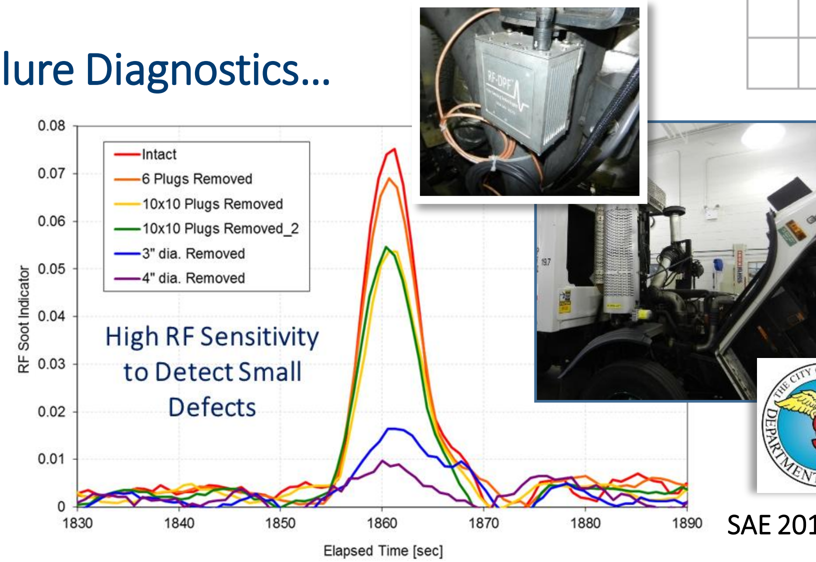
- On-road fleet test
- Volvo/Mack trucks ('09 & '13)
- 24 Months total, up to 4 trucks



- Stock Volvo/Mack DPF controls
- On-road durability

Applications of RF Sensing for Particulate Filters

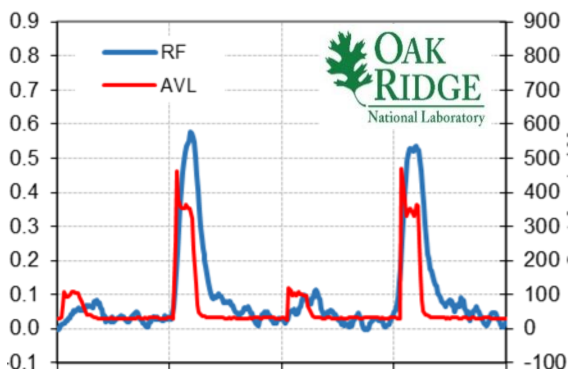
1. Early Warning Fault Detection and System Failure Diagnostics…



SAE 2017-01-0950

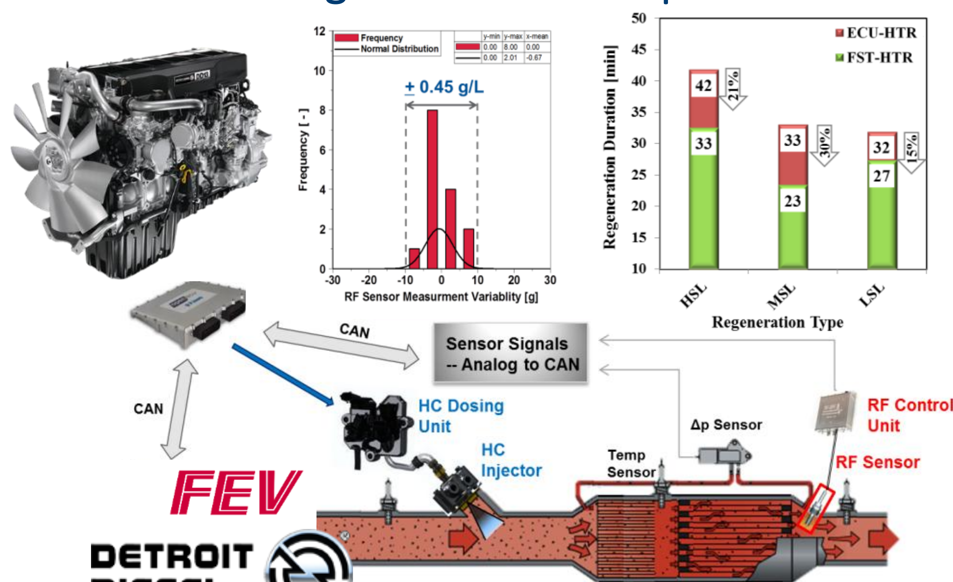
2. Fast Response "Real-Time" Particulate Filter Measurements…

Images: AVL



SAE 2016-01-0918

3. Direct Particulate Filter Feedback Control and Reduced Engine Fuel Consumption…



SAE 2015-01-0996

CASE STUDY I: Heavy-Duty Diesel On-Road Evaluations

Generation 1

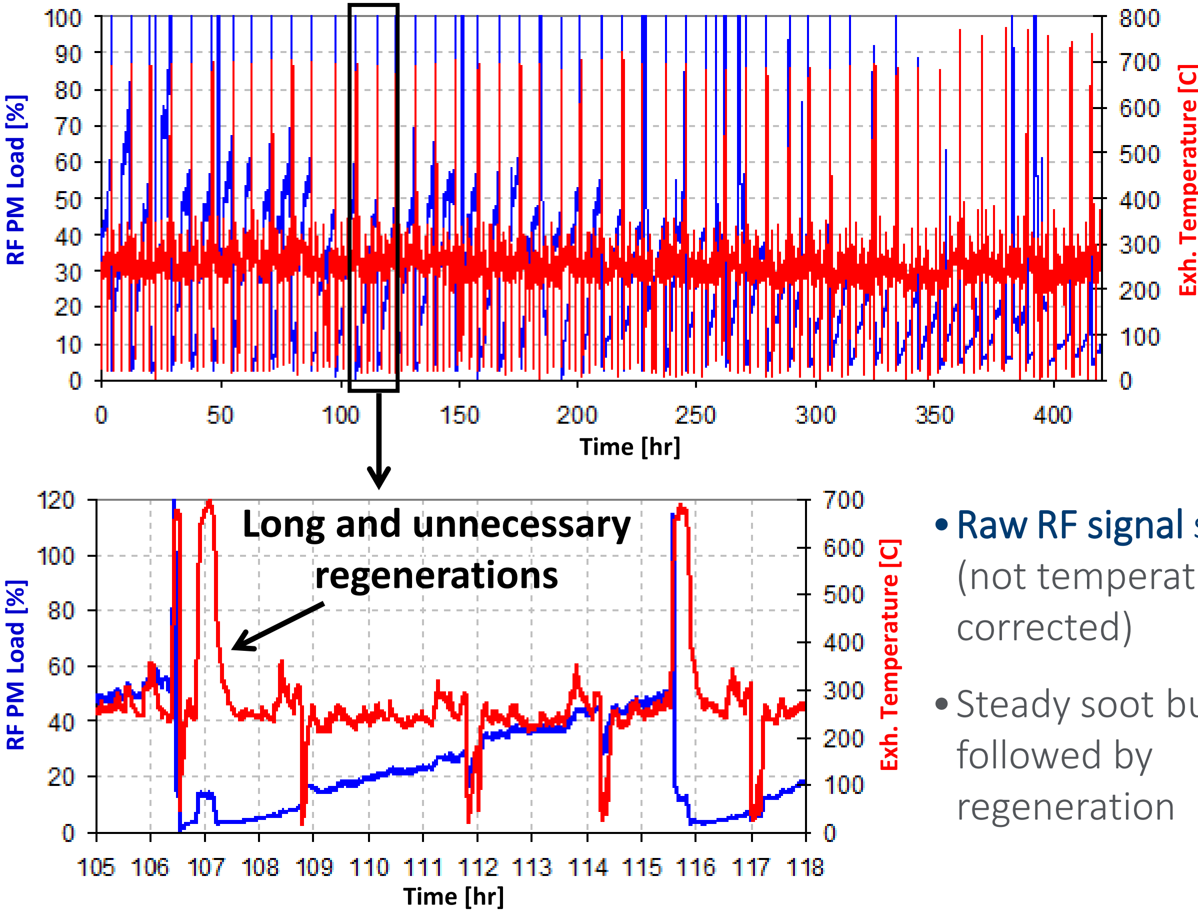
Generation 2

RF System Configuration (Mack MP-7) DSNY Fleet

- MY 2009 and MY 2010+ vehicles over four years (48 months)
- Antennas mounted directly into DPF assembly
- Control unit mounted external to aftertreatment system
- Real-time monitoring and logging of DPF loading state
- System operation with stock OEM controls

Typical On-Road Operation and RF Sensor Response

Four Mack (MP-7) Fleet Vehicles

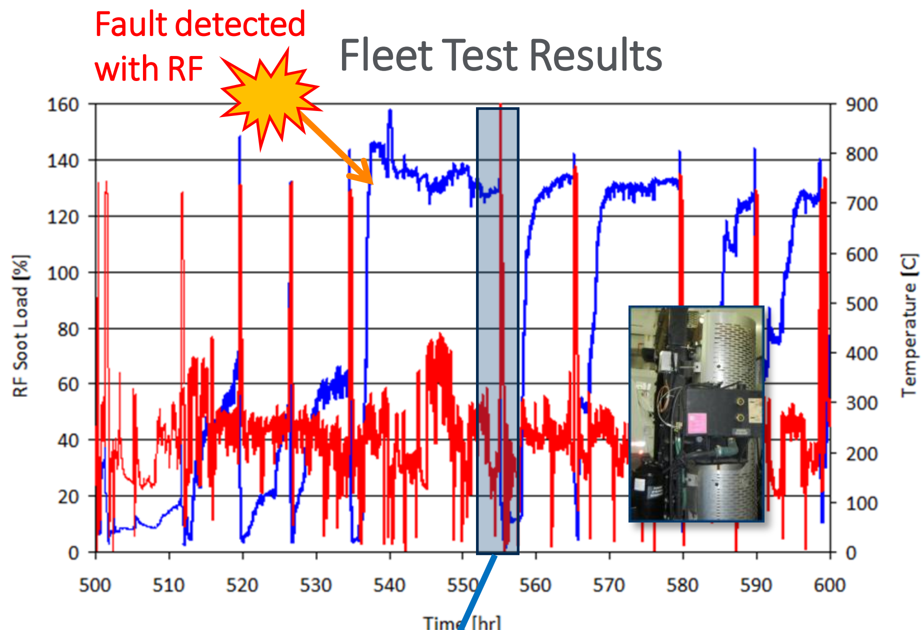


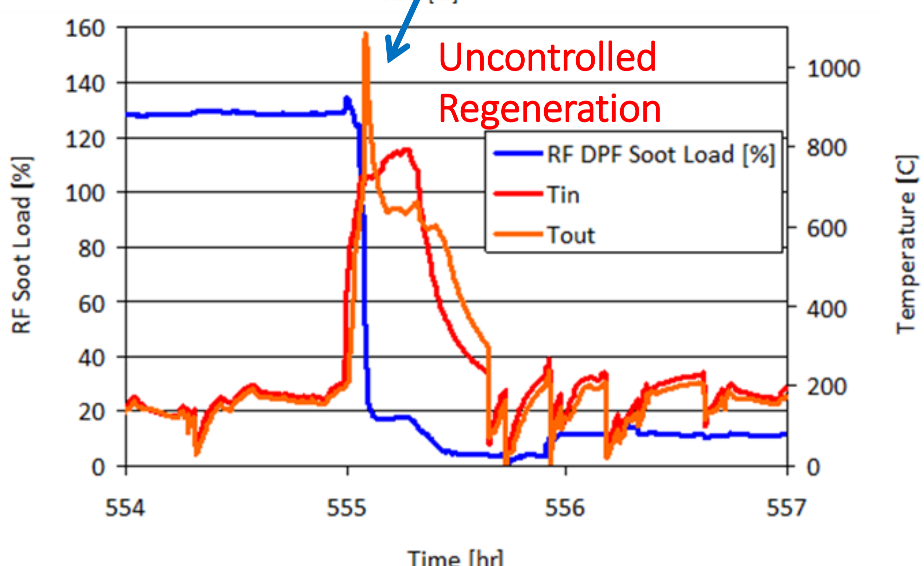
- **Raw RF signal** shown (not temperature corrected)
- Steady soot build-up followed by regeneration

- OE control results in regeneration 4%-5% of time vehicles are in operation (**NYC** urban drive cycles)
- RF control reduces regeneration frequency and duration for these applications

SAE 2014-01-2349

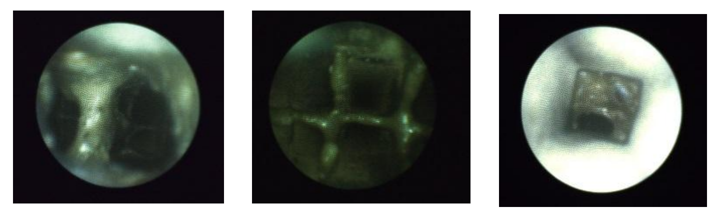
Example: Early Detection BEFORE Filter Failure





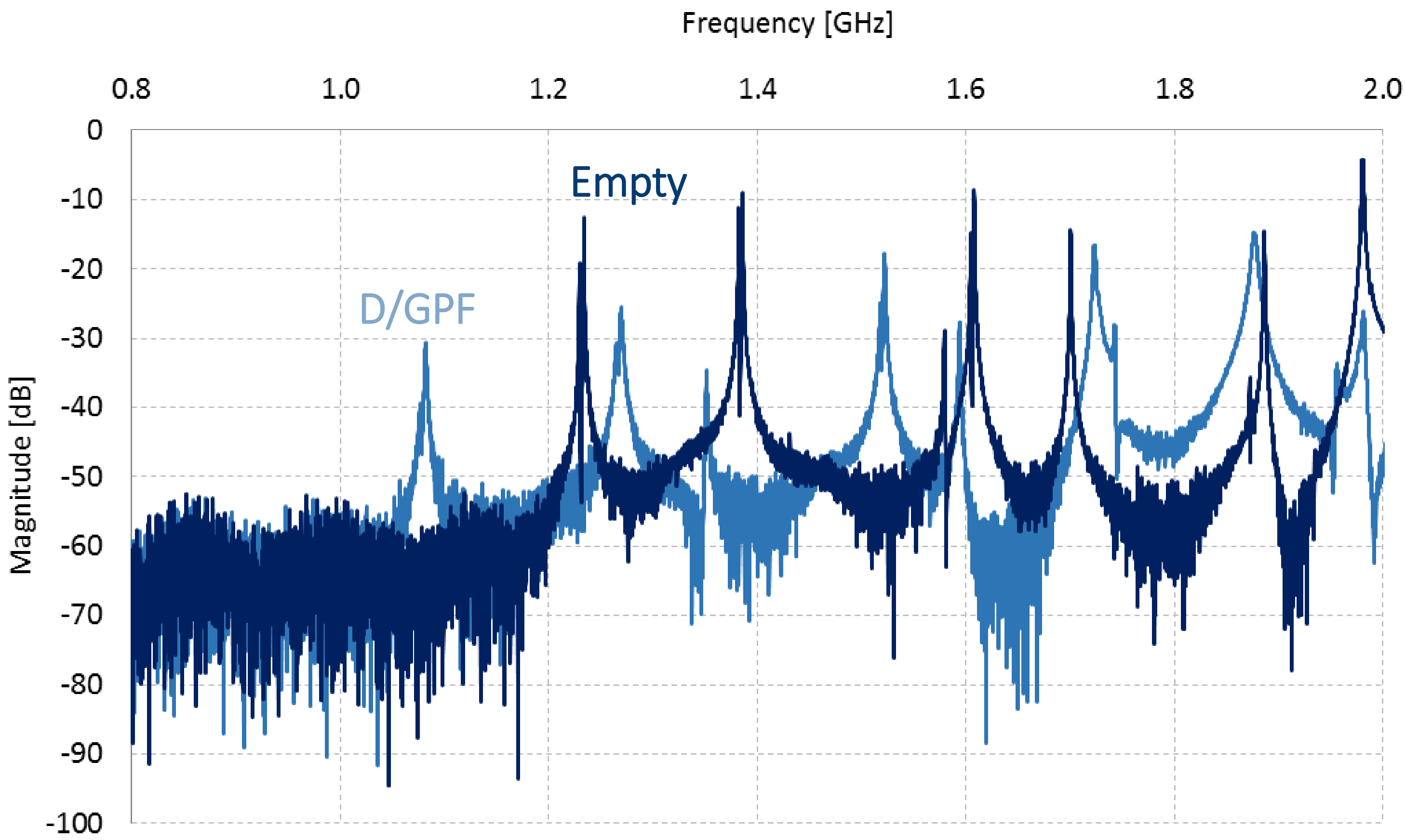
RF Sensor detects high soot condition 20 hrs before uncontrolled regen and filter failure → Early Warning

- Soot loads quickly into the filter due to high engine-out PM condition



- Large exotherm upon initiation of regeneration results in DPF failure and soot slip
- Application for preventative diagnostics BEFORE emissions system failure

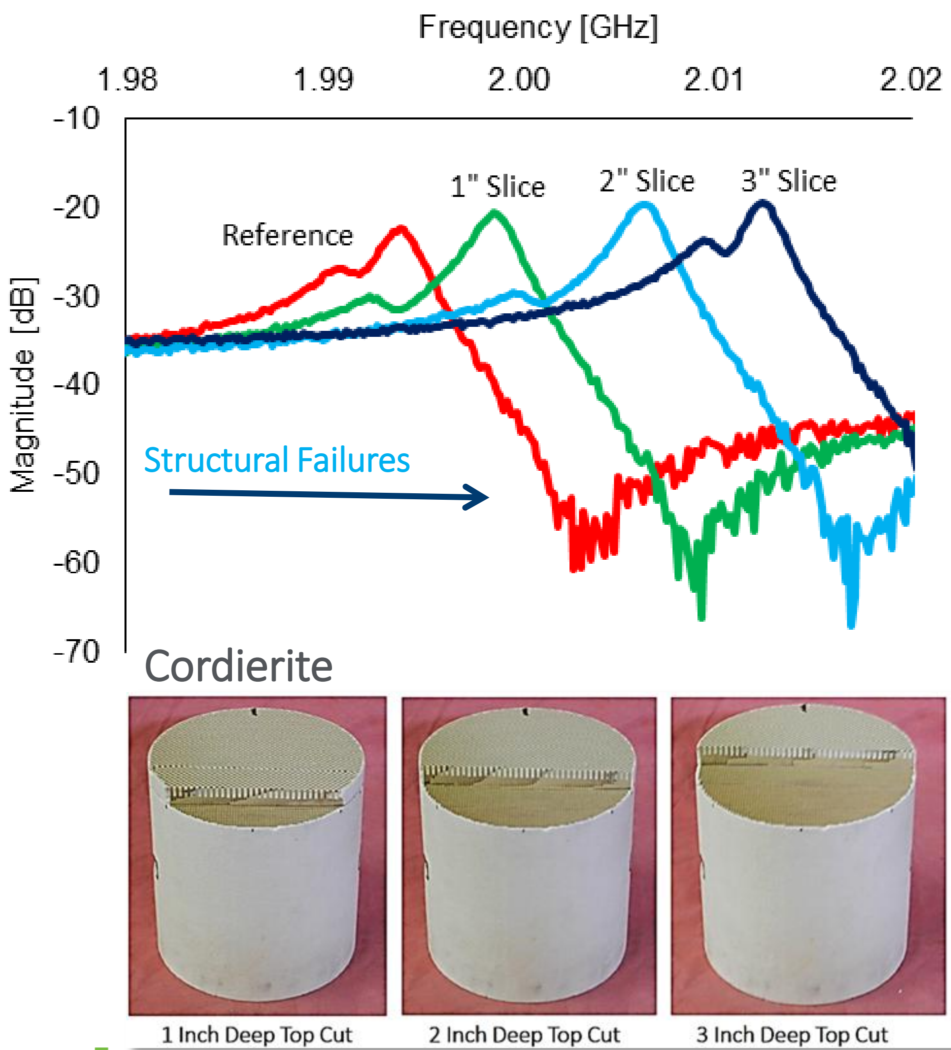
CASE STUDY II: Missing Component - Filter or Catalyst



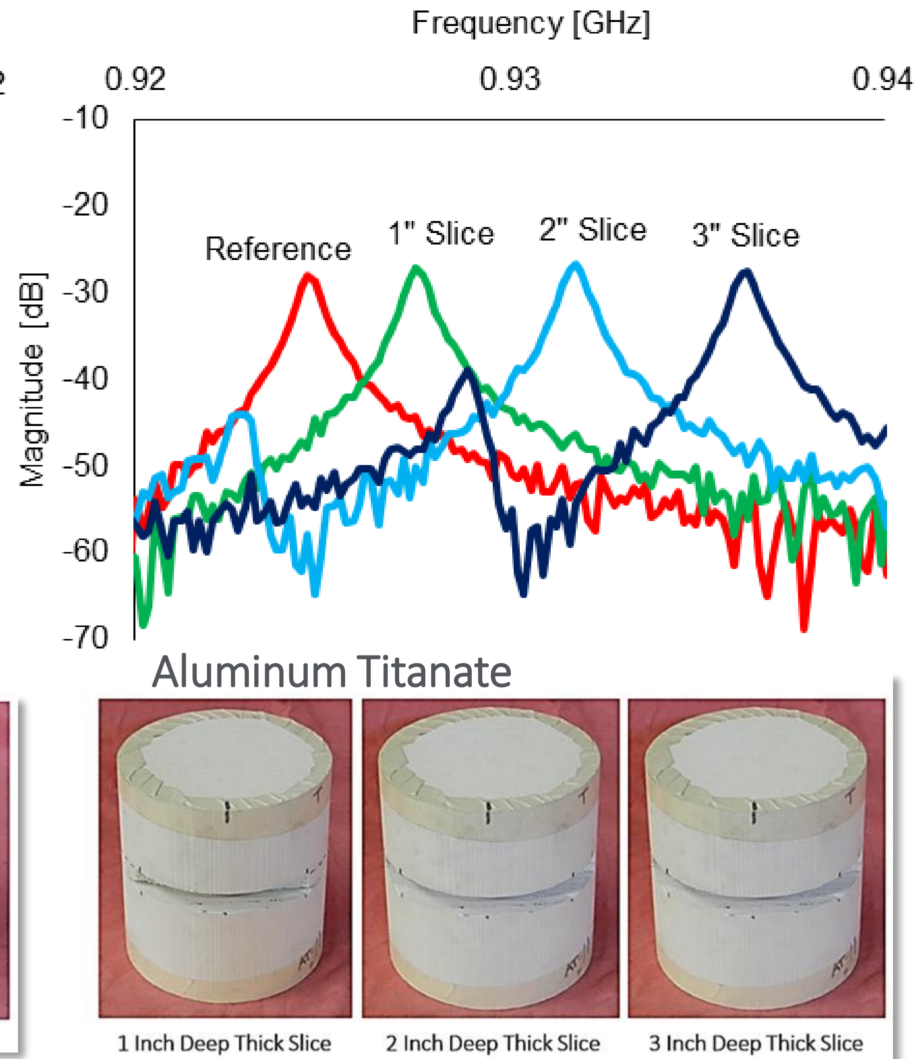
- Continuously monitors whether DPF/GPF or catalyst is present in system
- Not limited to filters: Non-intrusive monitor of DOC, SCR, LNT, TWC, NH3 slip
- Functions even when engine is off – ceramic substrate results in cavity "loading"

RF Sensitivity to Directly Detect Structural Failures

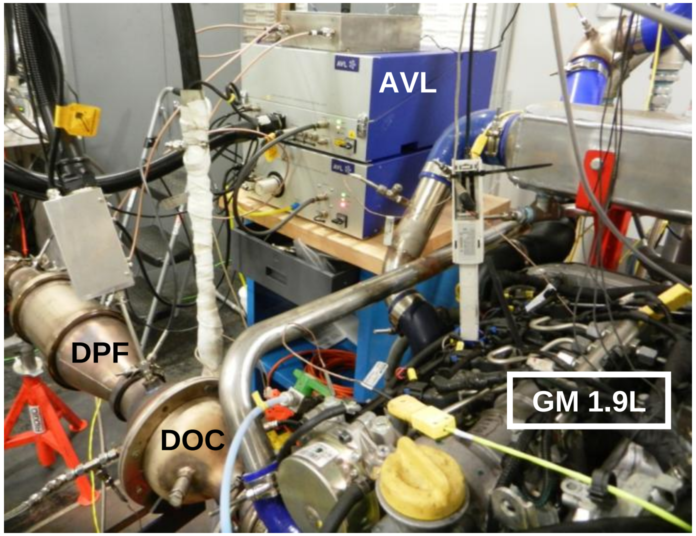
Simulated Defects: End Plug Removal



Simulated Defects: Radial Cut

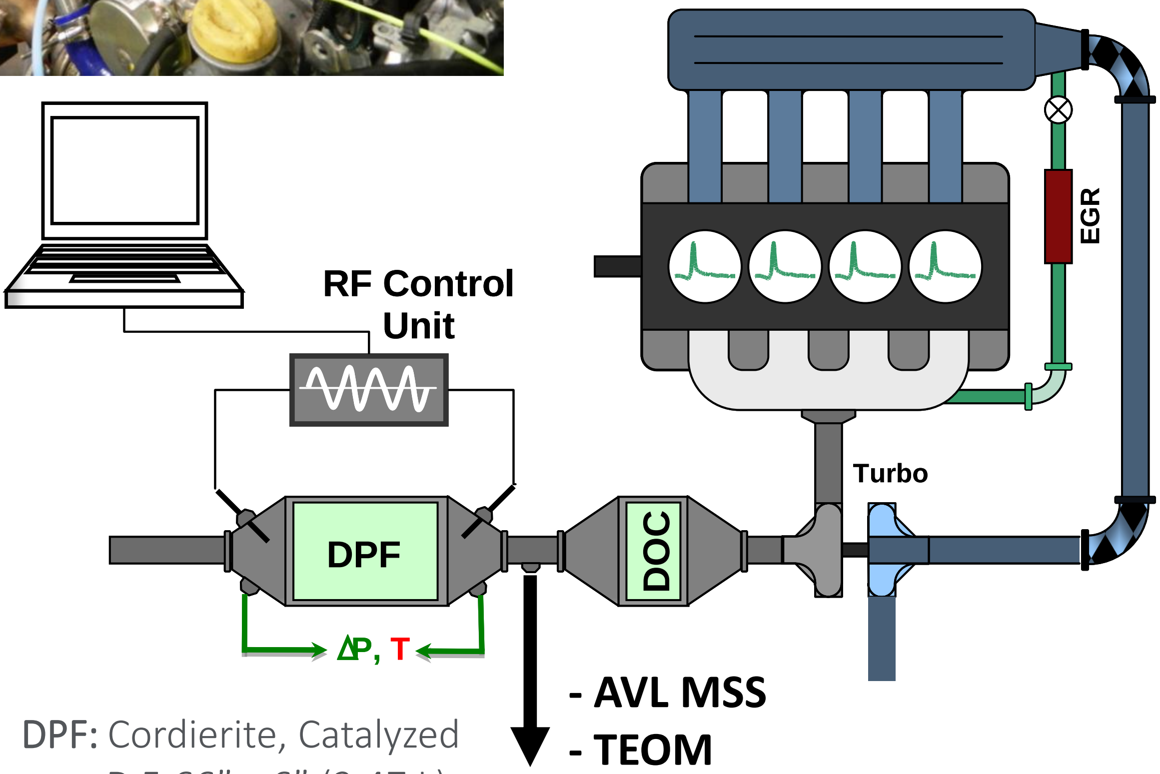


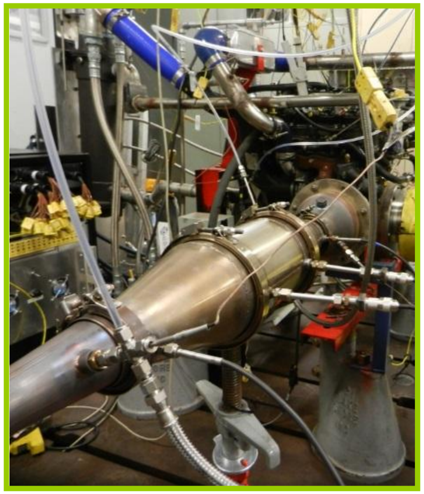
CASE STUDY III: Test Cell and Engine Setup for DPF OBD



Engine Dynamometer Testing

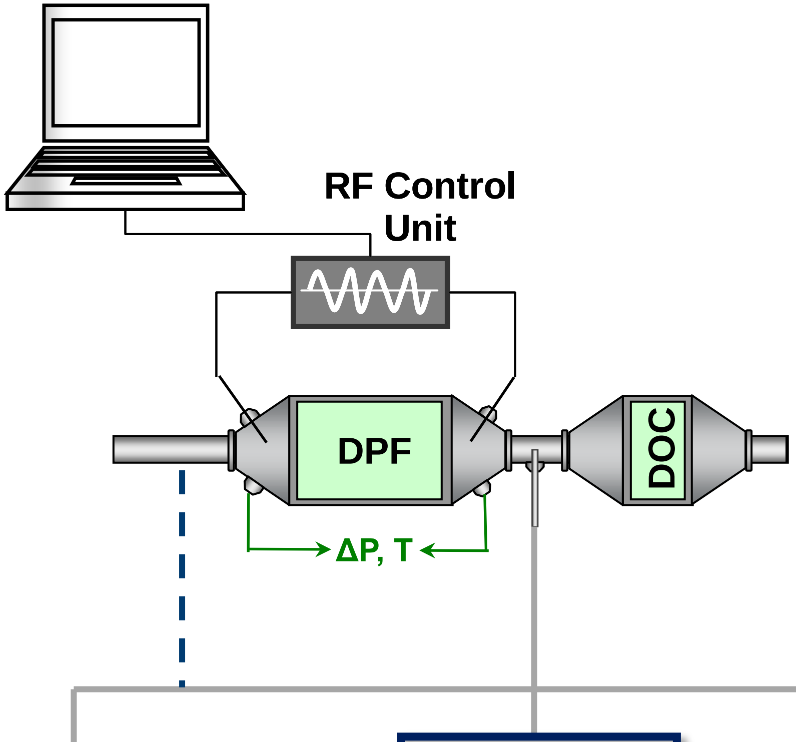
- Testing on 1.9L GM turbo diesel engine
- Transient mode evaluation of RF response
- AVL MSS and TEOM measurements for comparison with RF and gravimetric PM

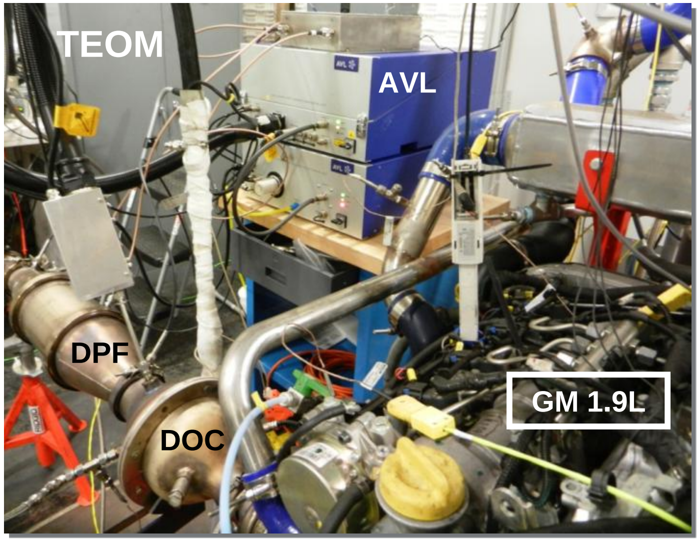




DPF: Cordierite, Catalyzed
D 5.66" x 6" (2.47 L)

Measurement System and Emissions Sampling

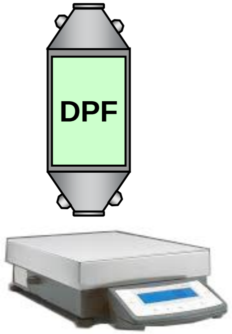




MKS FTIR:
NH_3, N_2O, NO, NO_2, CO etc.

AVL Micro Soot Sensor:
transient soot concentration measurements

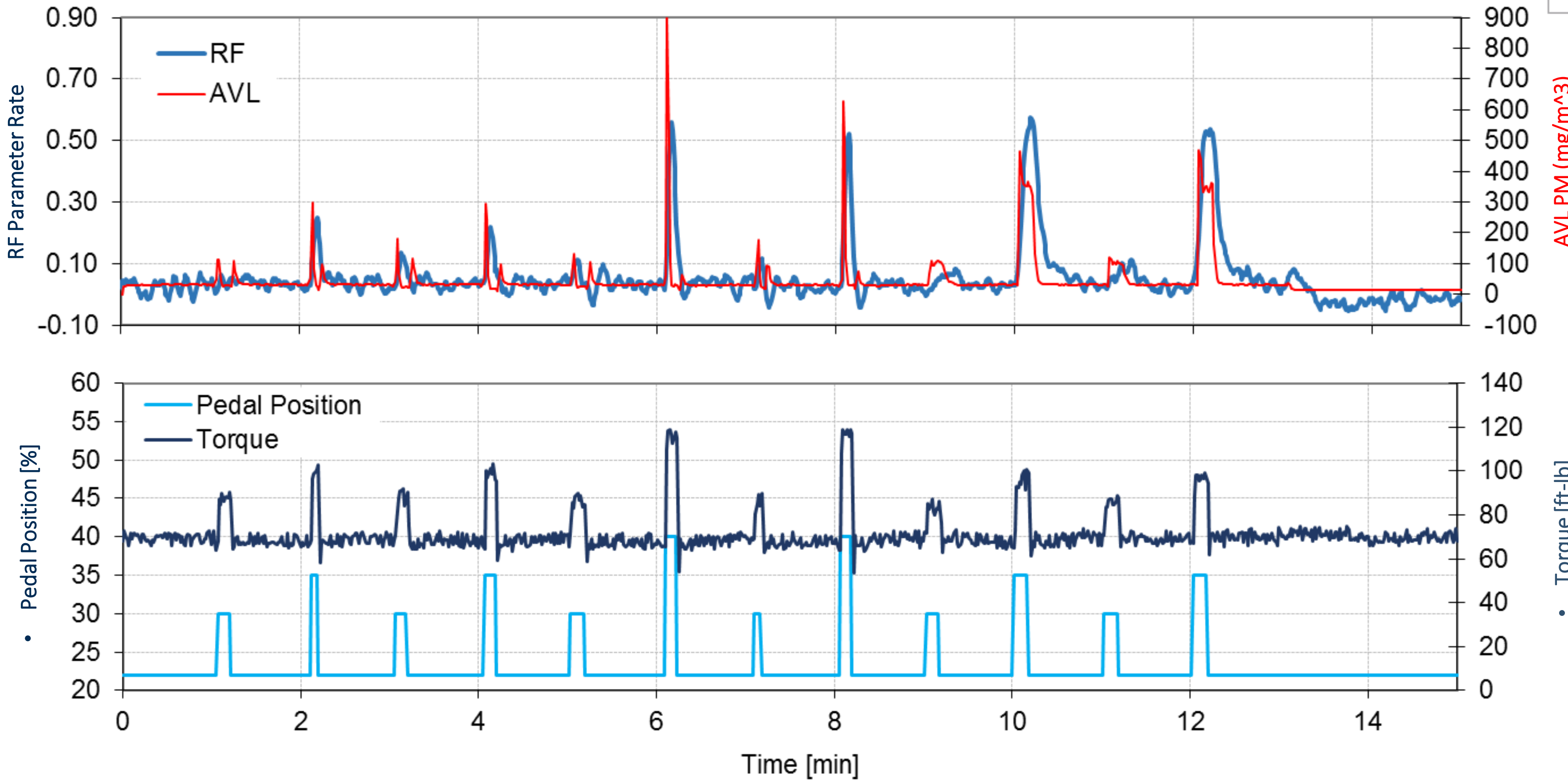
TEOM 1105:
real time (1 sec) direct PM mass measurement



Sartorius CP34001S:
gravimetric PM mass loaded measurement

Transient Event Monitoring – Engine-Out PM Emissions

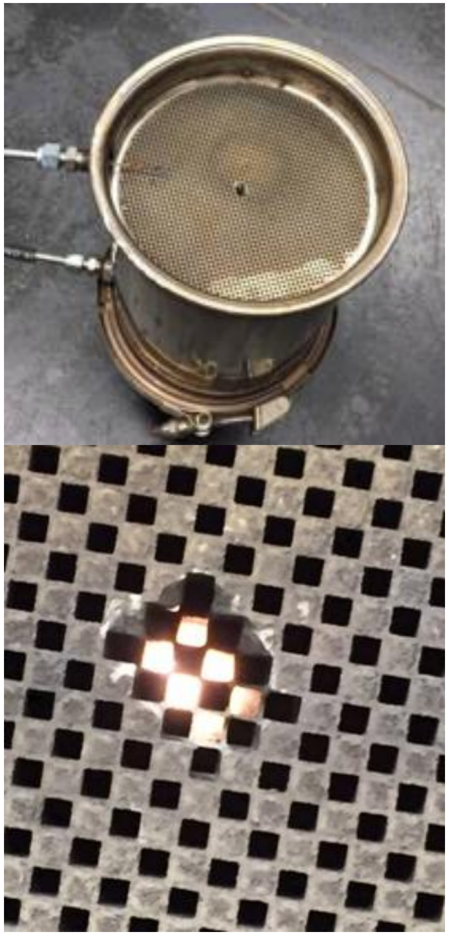
RF Derivative Response to Pedal Tip-In Events



- Derivative or RF DPF soot load measurements well-correlated to AVL MSS
- Fast response RF sensing may enable use of DPF/GPF as engine-out PM sensor

Artificially-Induced DPF Soot Slip

6 Plugs Removed
0.24% Face Area



10x10 Square Removed
4.0% Face Area

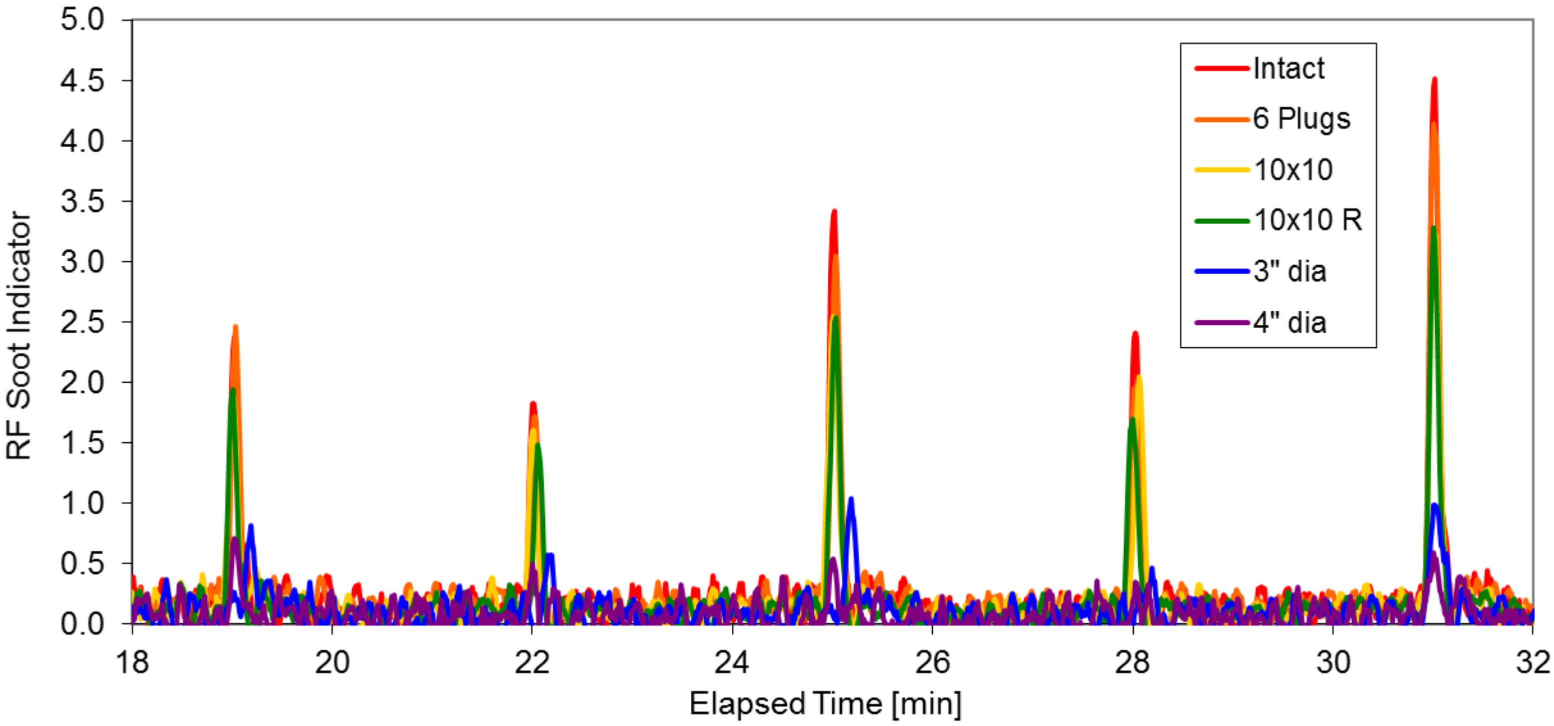
3 inch Diameter
Removed
28% Face Area

4 inch Diameter
Removed
52% Face Area

End plugs from DPF outlet face removed to simulate failure modes of varying severity

DPF Diagnostics – Failure Detection (Soot Slip)

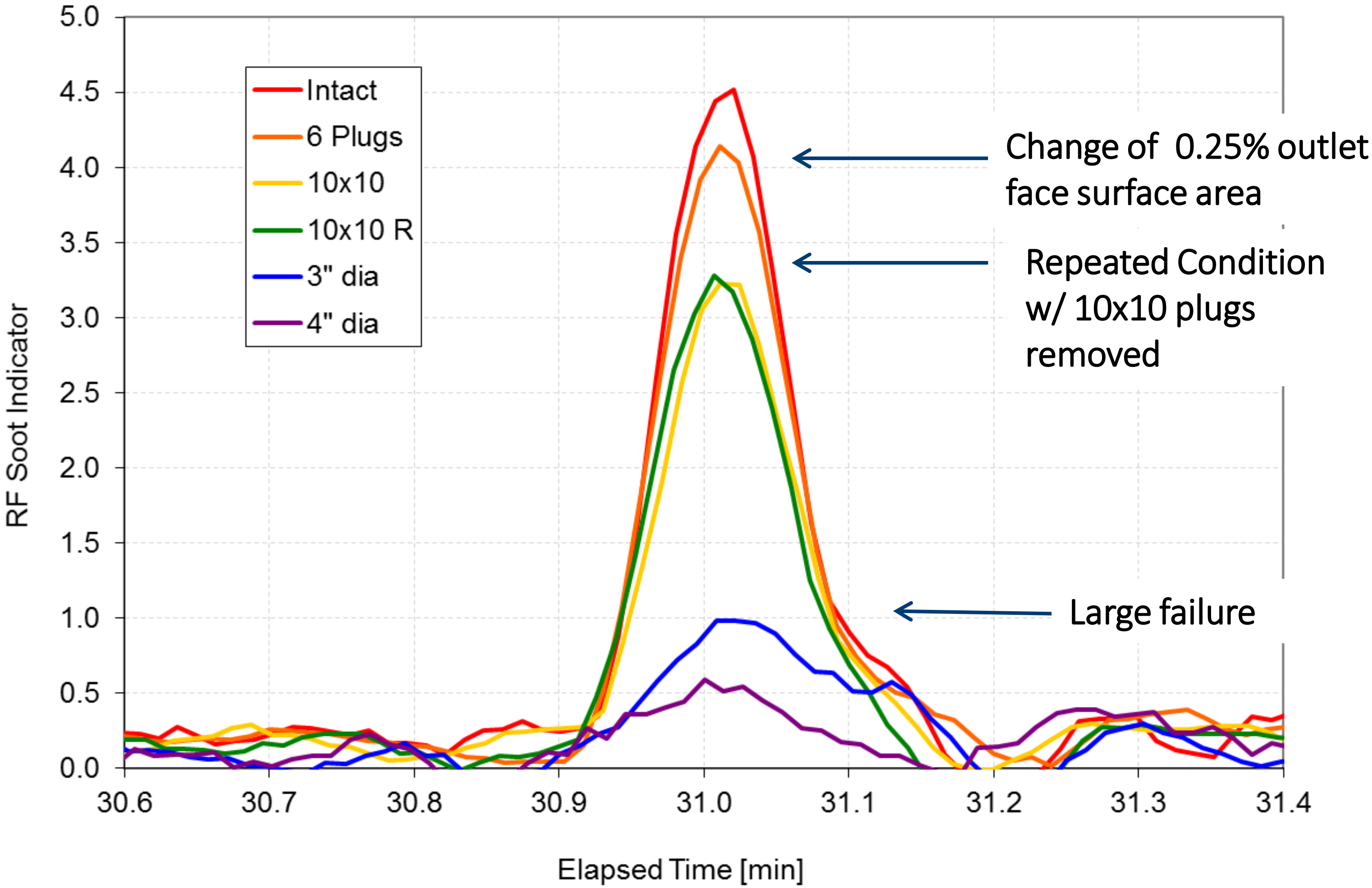
- Tip-In events performed at regular intervals and varying DPF health conditions
- Engine operated at1500 rpm and 22% pedal with tip-ins every 3 minutes alternating between 35% (short spikes) and 40% (tall spikes) pedal positions
- Full tip-in test repeated at each DPF defect condition
- RF derivative response at each DPF health state shown



Filter Failures

DPF Diagnostics – Failure Detection (Soot Slip) Detail

Detection of soot slip (reduced filtration efficiency) with RF sensor



Testing conducted on coated cordierite particulate filter on 1.9L GM turbo-diesel engine

RF Signal Correlation to Reduced PM Trapping

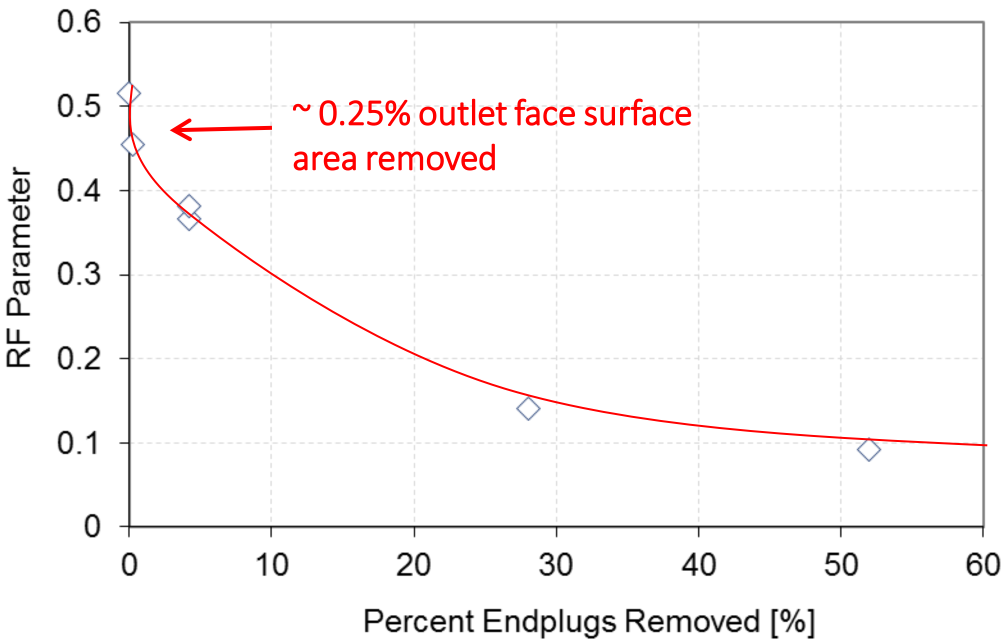
6 Plugs Removed
0.24% Face Area

10x10 Square
4.0% Face Area

3 inch Dia.
28% Face Area

4 inch Dia.
52% Face Area

Summary of filter failure conditions evaluated for increasing soot slip



RF Parameter Calculation

- The first forward difference of each test condition was performed to determine the relative, instantaneous soot loading rate
- Each peak was integrated over an equivalent time span to determine the total relative soot loaded during each tip-in

CASE STUDY IV: GPF Evaluations on Lean GDI

GPF Evaluations on BMW Lean Gasoline

- BMW N43B20 4-cylinder engine from MY2008 BMW 120i (E87) vehicle
- 2.0 liter naturally aspirated direct injection gasoline engine
- Cordierite GPF 5.2"D x 5"L, 200/8
- PM emissions sampling with AVL MSS

BMW N43B20 lean gasoline engine

BMW 120i lean gasoline vehicle on chassis dynamometer at ORNL

Engine Model Number	N43B20
Displaced volume	1995 cm^3
Number of cylinders	4
Number of valves	4 per cylinder
Stroke	90 mm
Bore	84 mm
Compression ratio	12.0:1
Rated Power	125 kW at 6700 rpm
Rated Torque	210 Nm at 4250 rpm

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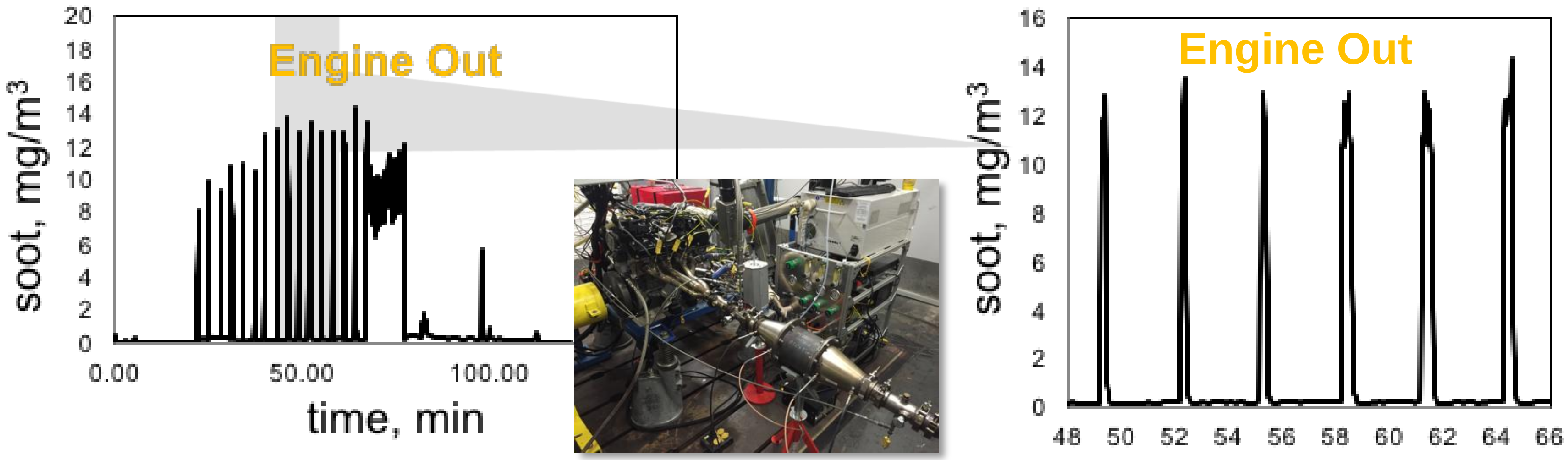
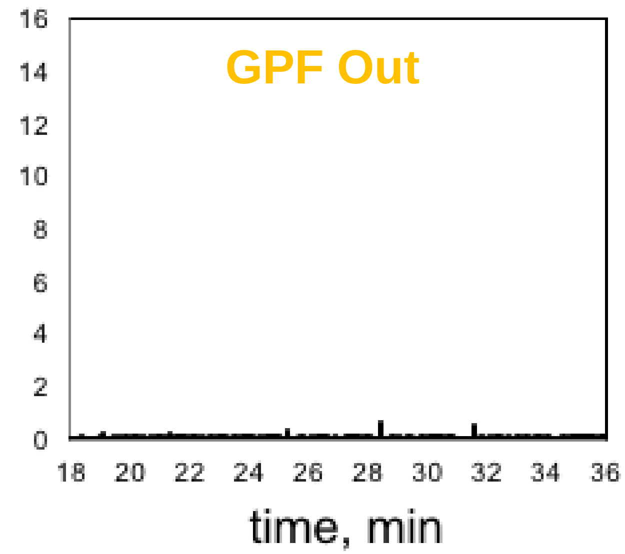
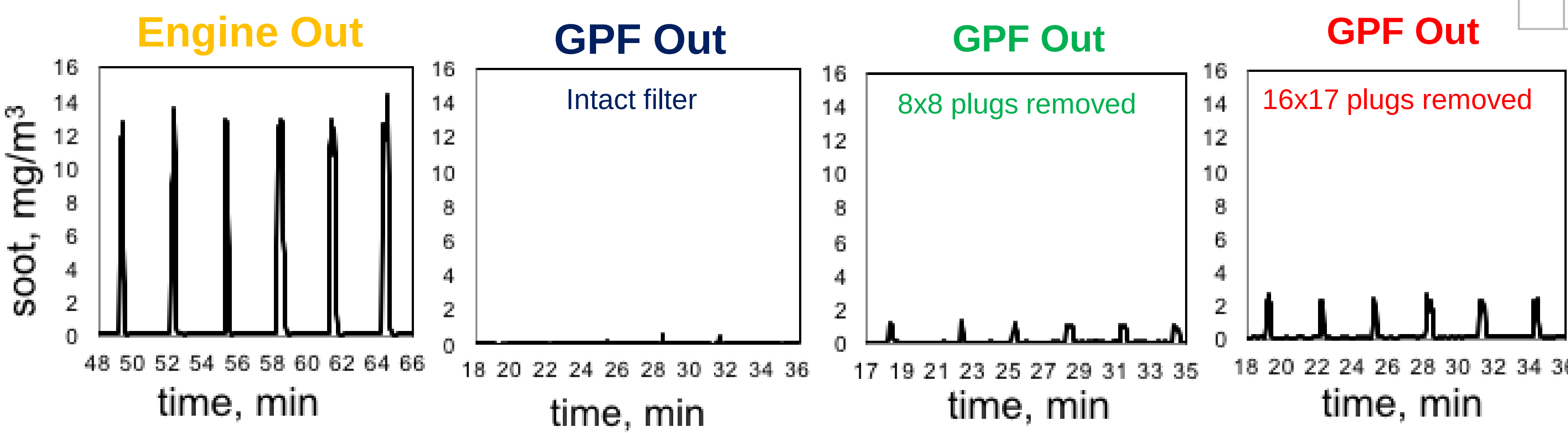
GPF Lean Stratified Tip-In Sequence



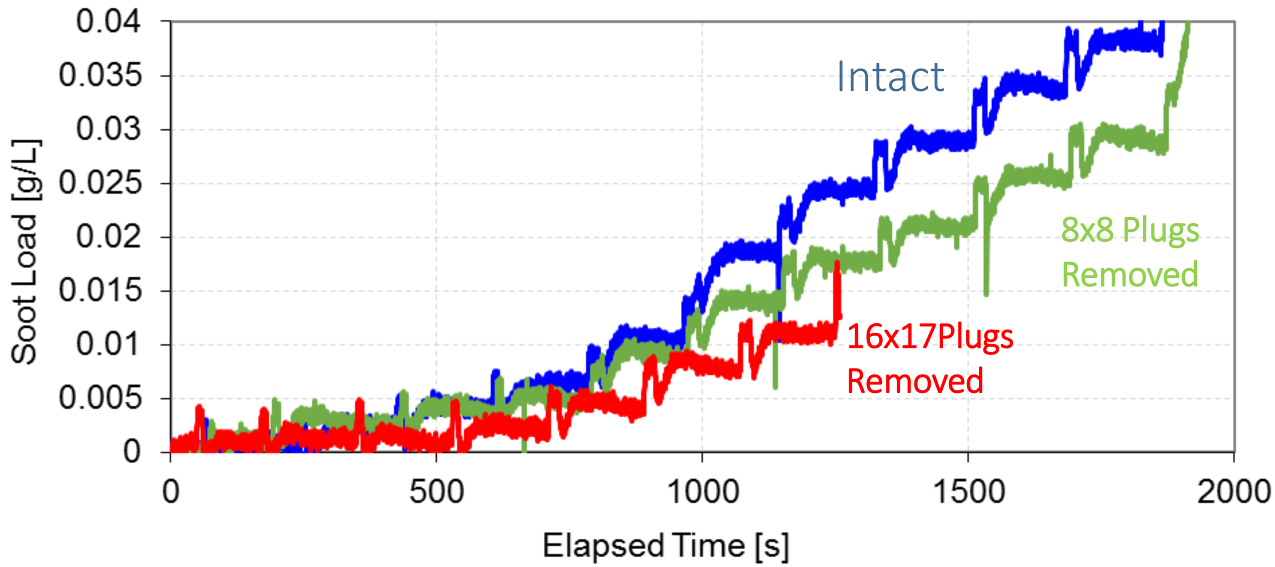


- 3 min stoichiometric and 10 - 20 sec lean stratified (tip-in, high soot) sequence at 2,000 rpm 50 ft-lb, followed by 10 min lean stratified operation and then high temperature regeneration at 3,000 rpm 65 ft-lb
- AVL MSS sampling before and after the GPF following repeated tests (not simultaneously)

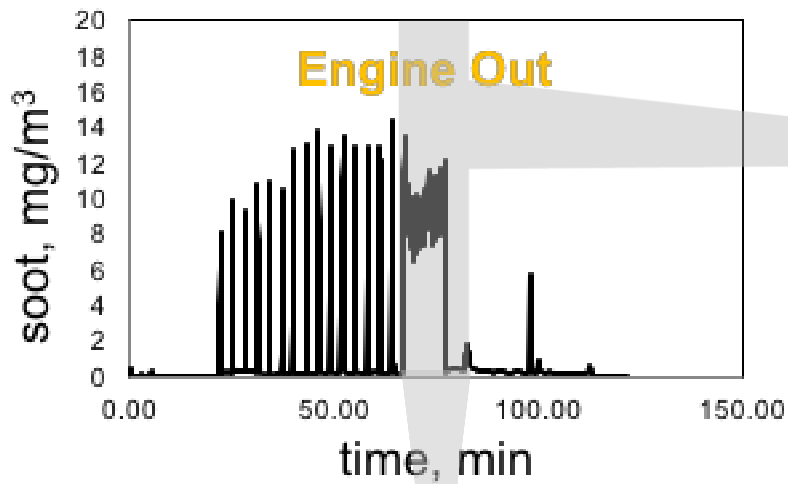
GPF Tip-In Sequence with End Plugs Removed

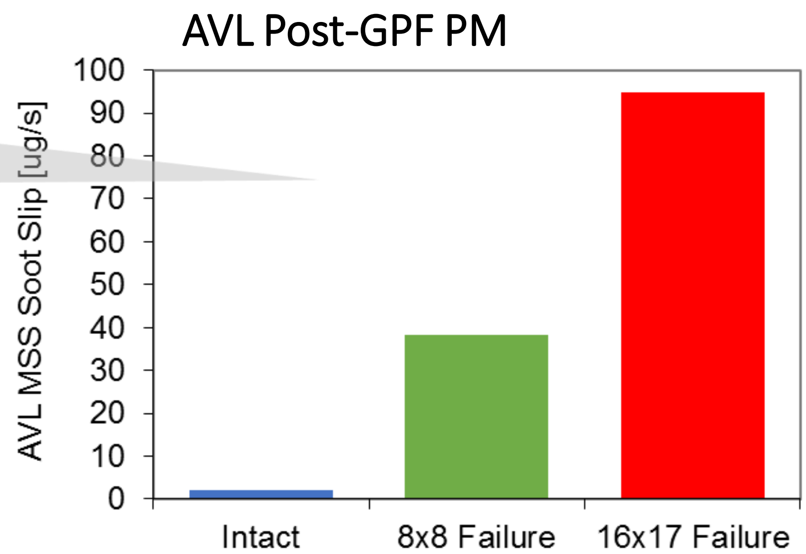


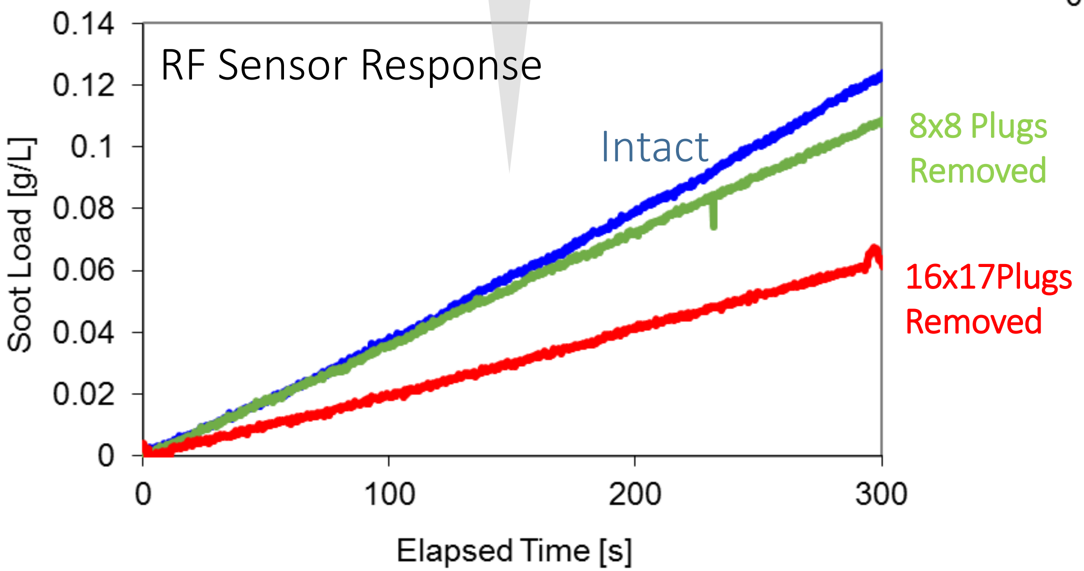
Reduced filtration efficiency measured with RF sensor on GPF



GPF Steady-State Operation with End-Plugs Removed







Steady-State Lean Operation

- Short duration lean operation with increasing number of GPF end plugs removed
- Reduction in PM loading rate measured via RF consistent with increased soot slip in exhaust measured via AVL MSS

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Summary and Conclusions

RF Sensing Applied to Diesel and Gasoline Particulate Filters

- RF signal transmitted through ceramic filter provides direct measurement of filter dielectric properties (filter state)
- Particulate filter soot load accuracy unaffected by ash levels in aged filters
- Direct feedback control based on DPF/GPF state
- Fast response (< 1 second) measurements of filter loading state demonstrated
- Continuous monitor over all operating conditions (even engine off)

Case Studies of Diagnostic Applications for RF Sensing

- **Preventative Diagnostics:** Early detection of upstream engine or system malfunctions that could lead to subsequent filter failure
    - *Heavy-duty fleet vehicle application: fault detection before DPF failure*
- **Reactive Diagnostics:** Detection of filter failure resulting in reduced trapping efficiency (soot slip) – physical defects to filter
    - *Gasoline & Diesel application – filter failure detection via reduced PM storage*
- Large failures and missing substrates detected through change in RF resonances

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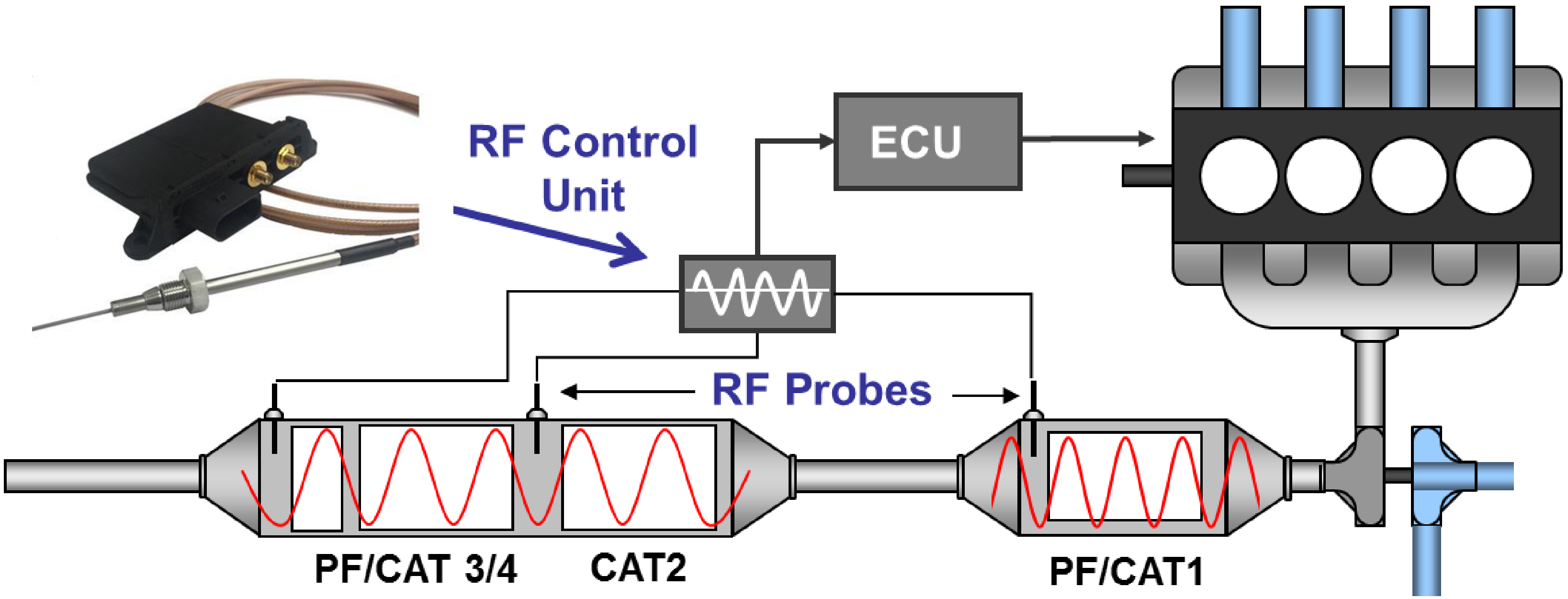
Current Work and Additional Applications



Proposed DIRECT Approach:
Direct Measurement = Filter or Catalyst State

Conventional INDIRECT Approach:
Upstream Sensor + Downstream Sensor + Model → Estimate Filter/Catalyst State

Acknowledgements

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- Roland Gravel, Ken Howden, and Gurpreet Singh from the DOE
- Ralph Nine, Trevelyn Hall, and David Ollett from NETL

Commercial and National Laboratory Project Partners

- Corning Incorporated
- Oak Ridge National Laboratory
- Daimler Trucks NA / Detroit Diesel
- FEV
- DSNY

Relevant Conference and Journal Publications

1. Sappok, A., Ragaller, P., Bromberg, L., Herman, A., Prikhodko, V., Parks, J., and Storey, J., “On-Board Particulate Filter Failure Prevention and Failure Diagnostics using Radio Frequency Sensing,” SAE 2017-01-0950, 2017.
2. Sappok, A., Ragaller, P., Bromberg, L., Prikhodko, V., Storey, J., and Parks, J., “Real-Time Engine and Aftertreatment System Control Using Fast Response Particulate Filter Sensors,” SAE 2016-01-0918, 2016.
3. Ragaller, P., Sappok, A., Bromberg, L., Gunasekaran, N., Warkins, J., and Wilhelm, R., “Lifetime Particulate Filter Soot and Ash Measurements using Radio Frequency Sensors and Potential for Improved Filter Management,” SAE 2016-01-0943, 2016.
4. Sappok, A., Prikhodko, V., Ragaller, P., Bromberg, L., Storey, J., and Parks II, J., “Diesel Particulate Filter-Related Fuel Efficiency Improvements using Biodiesel Blends in Conjunction with Advanced Aftertreatment Sensing and Controls,” ASME ICEF 2015-1146, 2015.
5. Nanjundaswamy, H., Nagaraju, V., Wu, Y., Koehler, E., Sappok, A., Ragaller, P., and Bromberg, L., " Advanced RF Particulate Filter Sensing and Controls for Efficient Aftertreatment Management and Reduced Fuel Consumption," SAE 2015-01-0996, 2015.
6. Sappok, A., Constanzo, V., Bromberg, L., Waldo, C., and Salsgiver, R., "Vibration-Induced Ash Removal from Diesel Particulate Filters," ASME Technical Paper, ICEF2014-5570, 2014.
7. Sappok, A. and Bromberg, L., "Radio Frequency Diesel Particulate Filter Soot and Ash Level Sensors: Enabling Adaptive Controls for Heavy-Duty Diesel Applications," SAE Int. J. Commer. Veh. 7(2):468-477, 2014, doi:10.4271/2014-01-2349.
8. Sappok, A., Bromberg, L., “Development of Radio Frequency Sensing fro In-Situ Diesel Particulate Filter State Monitoring and Aftertreatment System Control,” ASME ICEF2013-19199, ASME ICED Fall Technical Conference, April 2013.
9. Sappok, A., Bromberg, L., Parks, J., and Prikhodko, V., “Loading and Regeneration Analysis of a Diesel Particulate Filter with a Radio Frequency-Based Sensor,” Society of Automotive Engineers, SAE 2010-01-2126, 2010.

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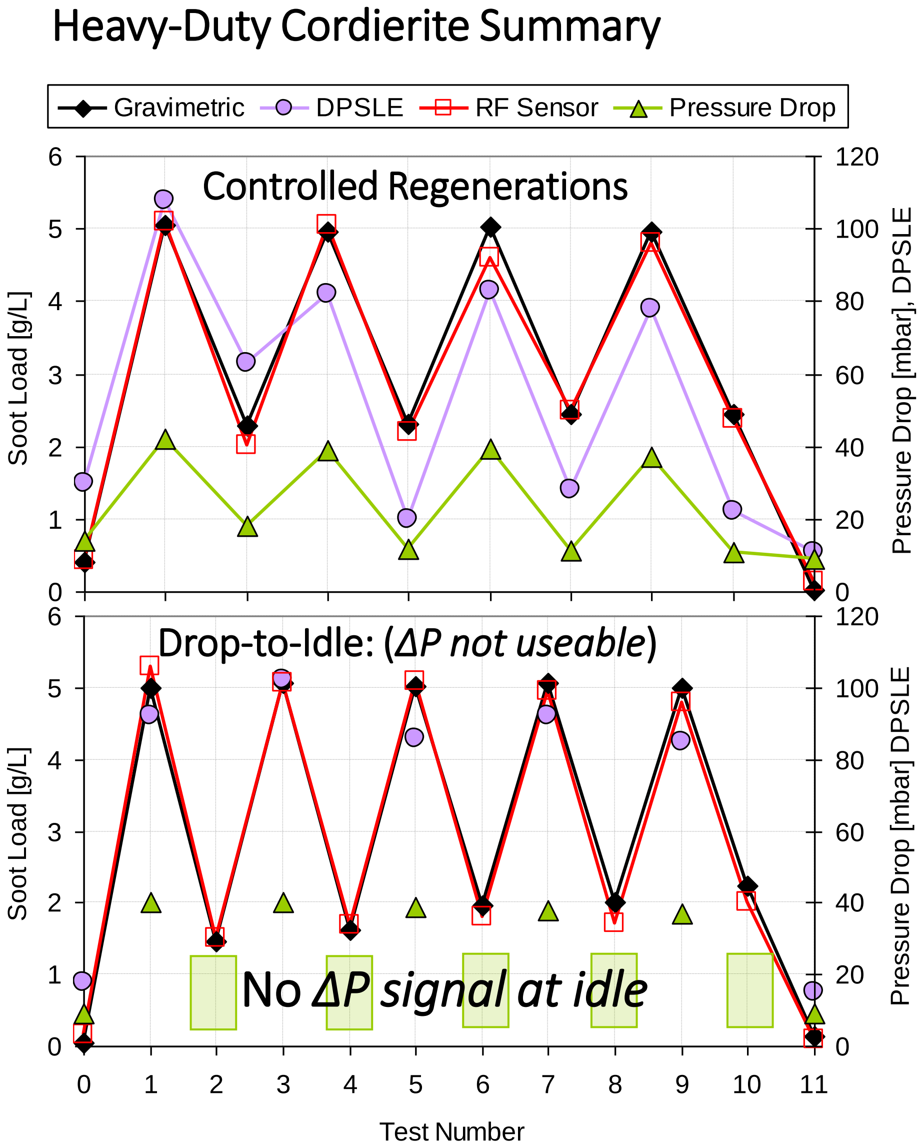
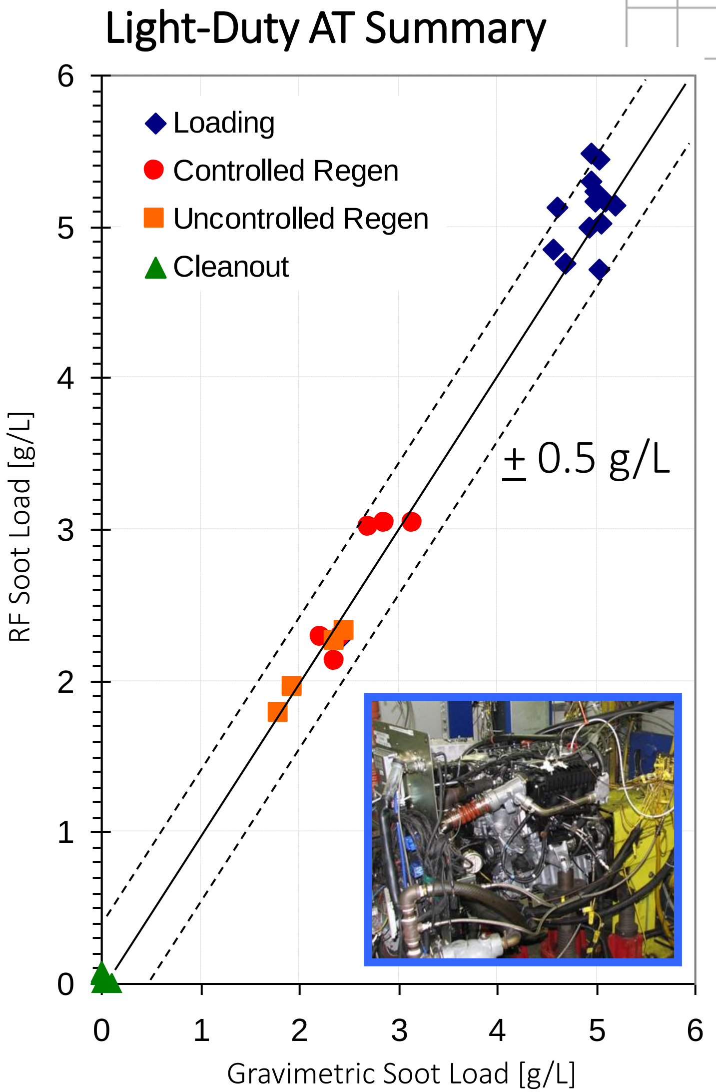
RF Accuracy over Wide Range of Operating Conditions

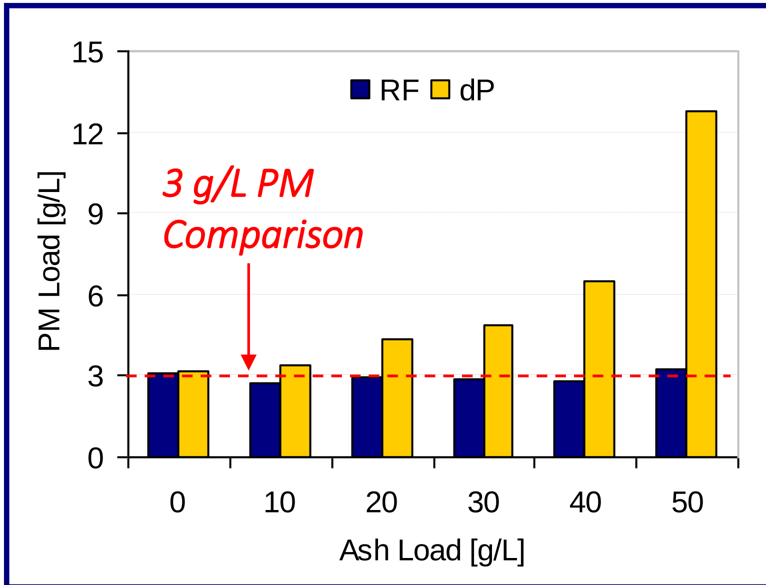


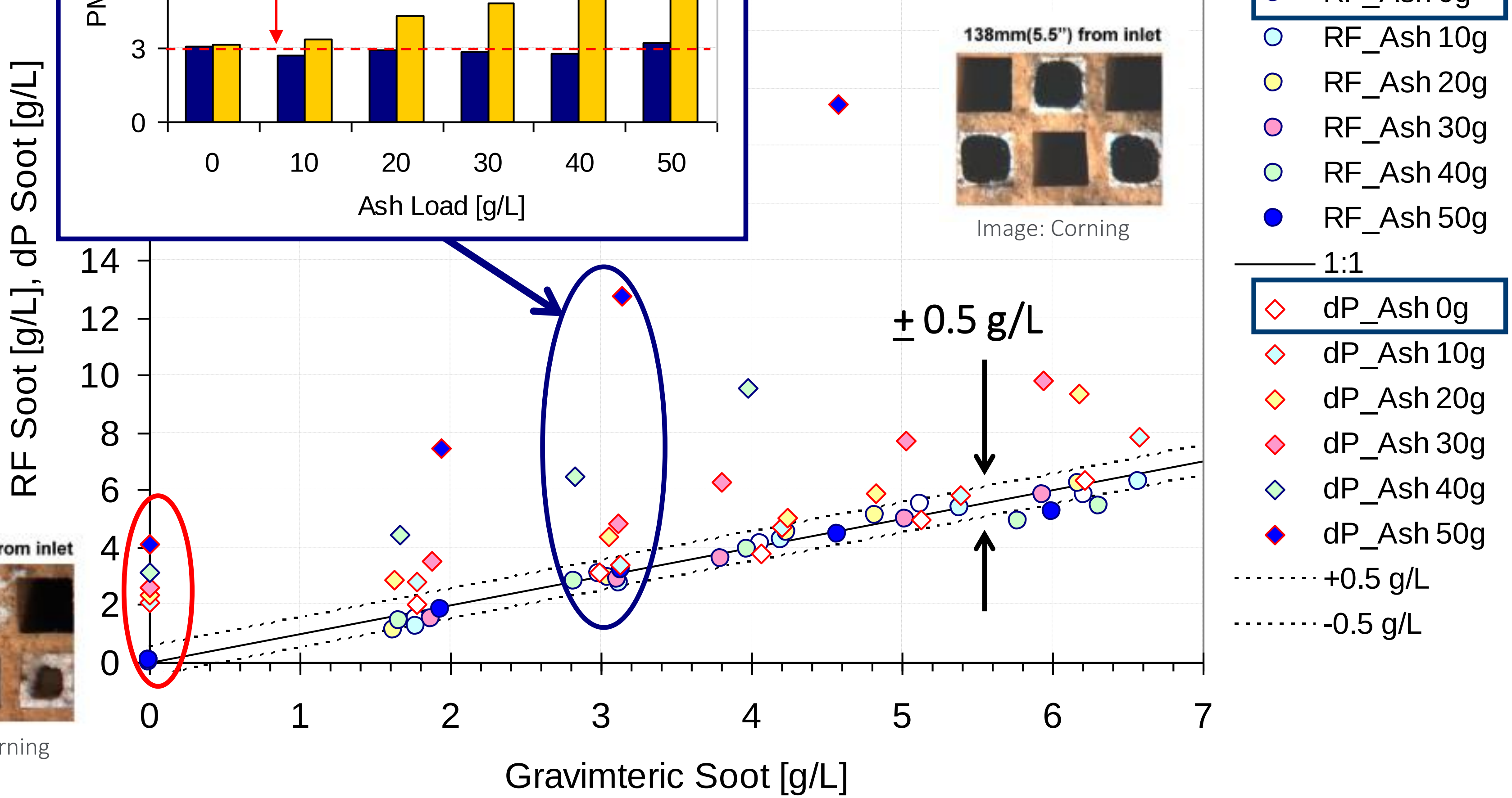


- **HD** tests on **Navistar** engine and **LD** tests on **Mercedes** engine at Corning
- RF accurately measures PM levels after partial regenerations

Accurate RF Soot Load Measurements Even with Ash

RF and dP (ΔP) measurements both scaled to **0 g/L ash case** to develop simple calibration function





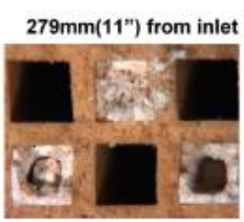


Image: Corning

RF soot load measurements unaffected by ash unlike current approaches