Filter Sensing Technologies Inc.

Real-Time Particulate Filter Soot and Ash Measurements, Optimized Control, and Diagnostics via Radio Frequency Sensing

CLEERS Workshop
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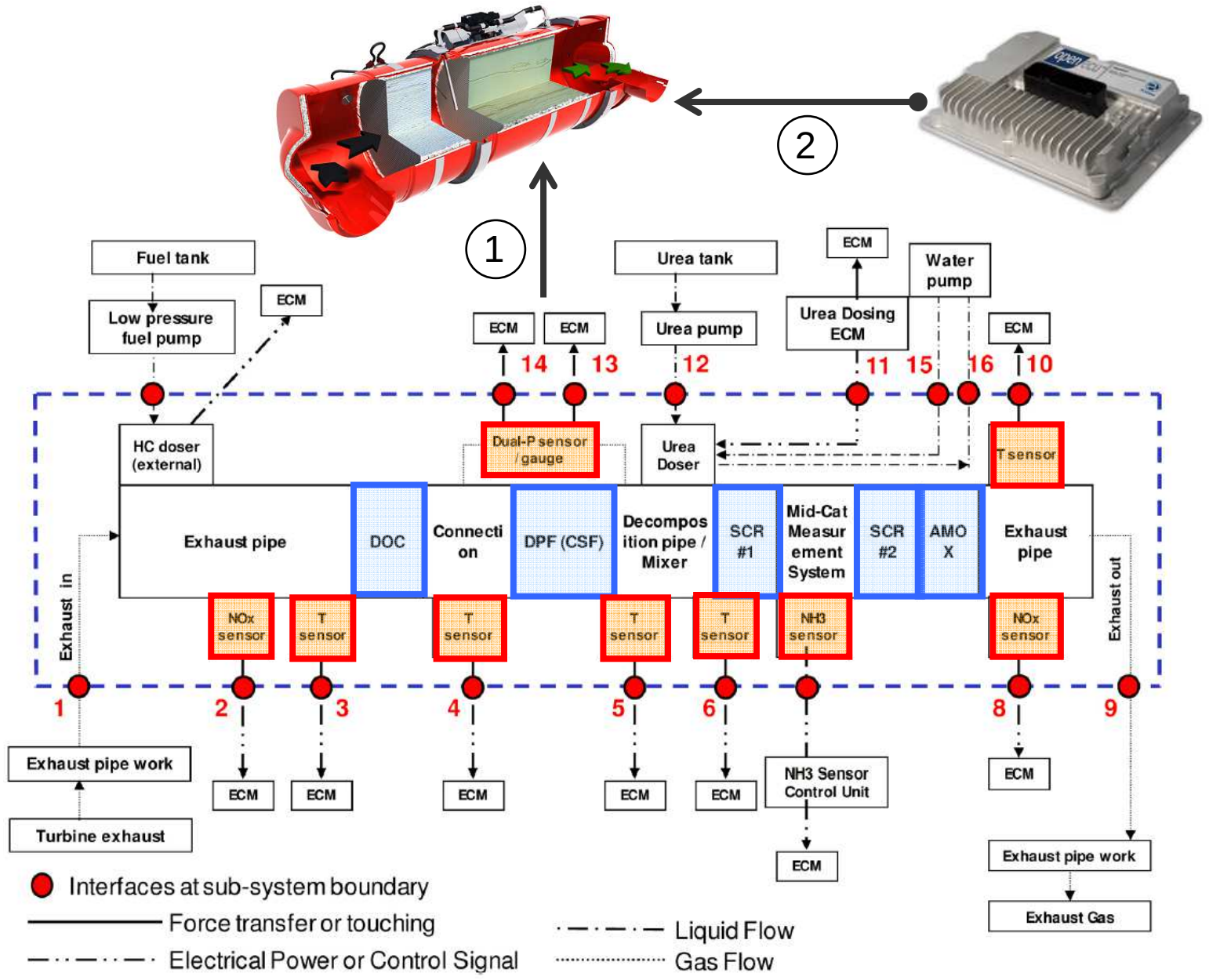
Challenge: Determination of Filter/Catalyst State



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

Measurement of Aftertreatment State Variables

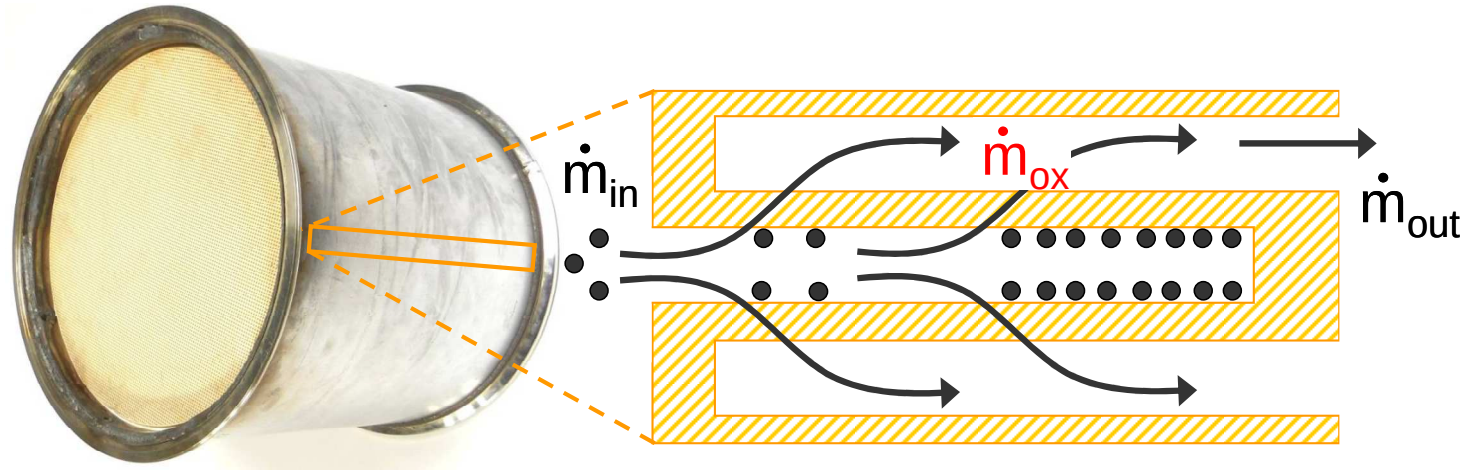
Conventional Exhaust Sensors

- Measure properties of exhaust gas directly
  - *Temperature, Pressure*
  - *Gas Composition, Particle Content*
- Provide only **indirect** indication of DPF state
- Often require complex models or calibration to estimate state of aftertreatment device

RF Based Exhaust Sensing

- RF signal propagates through ceramic media
  - Must be non-conducting
- Responds to changes in dielectric properties of aftertreatment device
- Provides a **direct** measure of the aftertreatment device's loading state

Many Factors Impact DPF Loading State Determination



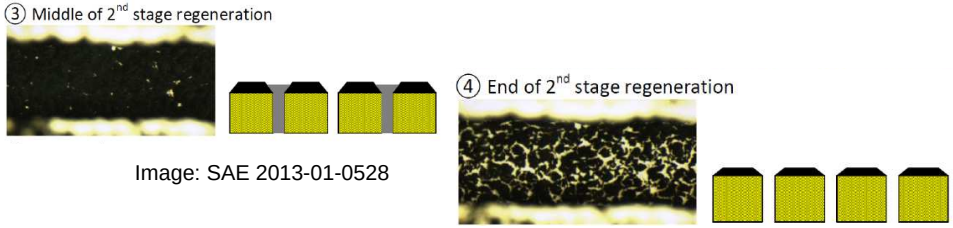
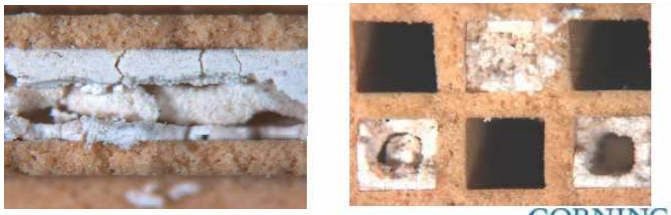


Image: SAE 2013-01-0528



Source: K. Aravelli

DPF Loading State and Current Approach

- Pressure drop (ΔP) and model based controls to estimate loading
- Low-exhaust flow (idle), transients, regeneration, non-uniform soot distribution and oxidation in the wall pores are challenging for ΔP
- Loading state of filter continually changing with ash over lifetime
- Accurate sensing required to **optimize fuel consumption and filter life**

RF Measurement System Configuration and Operation

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

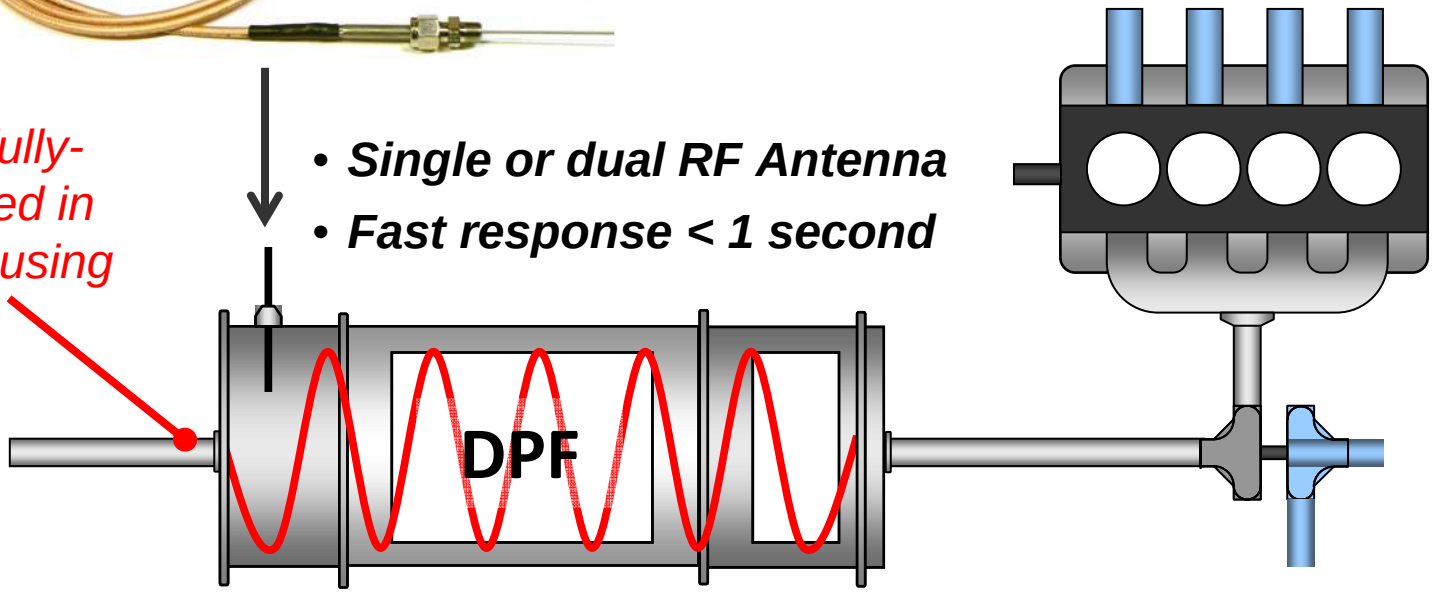
RF Control Unit

DPF Loading

1. **Amount**
2. **Type (PM vs. Ash)**
3. **Distribution**

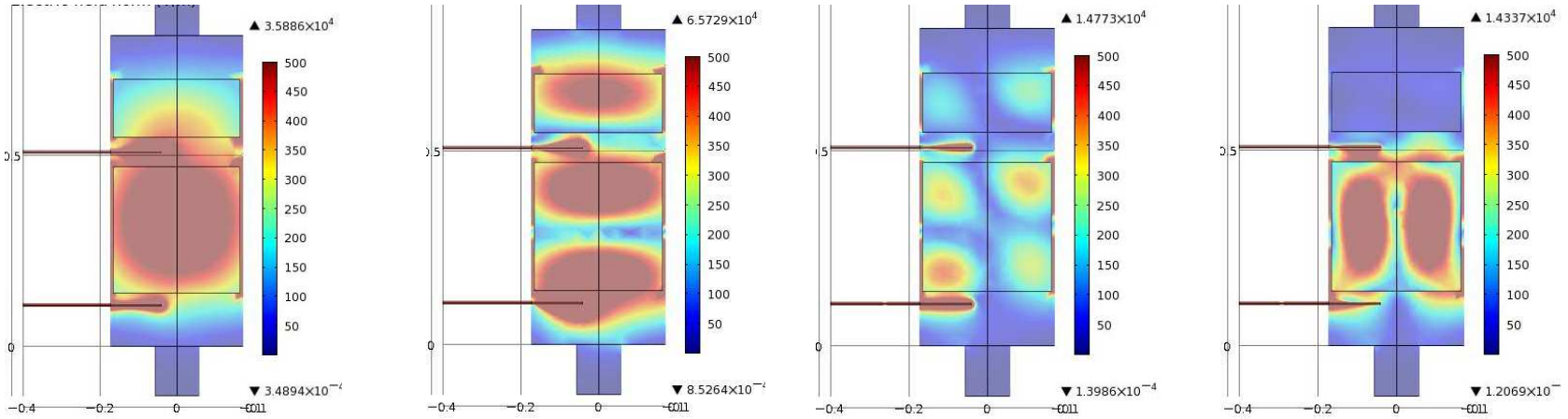
Signal fully-contained in DPF housing

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

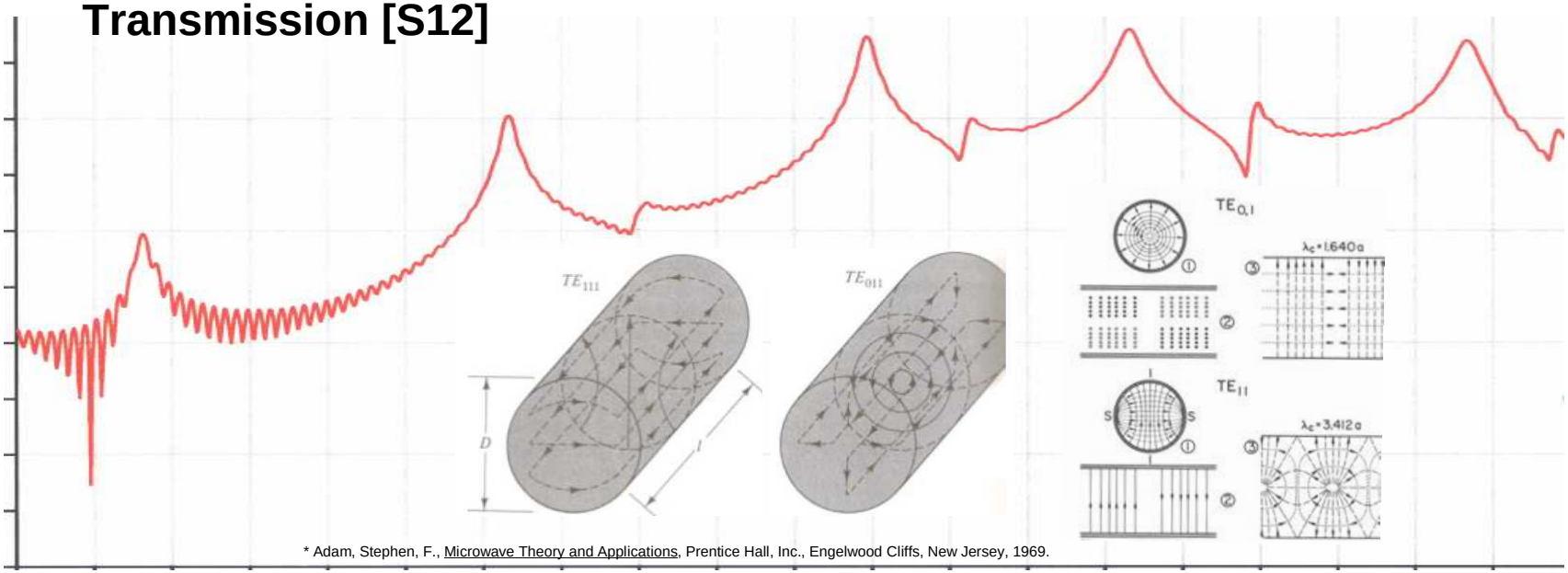


RF sensor responds to changes in DPF dielectric properties

Resonance Measurements and Spatial Sensitivity



Transmission [S12]

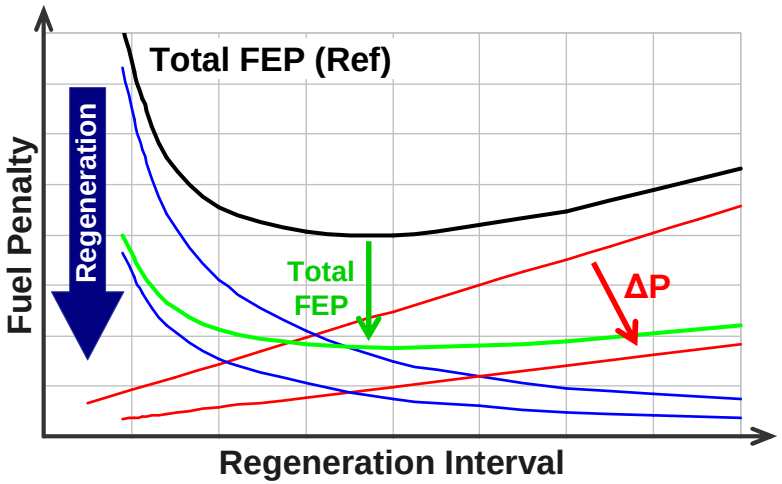


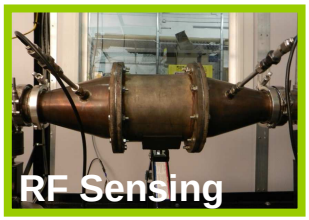
* Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

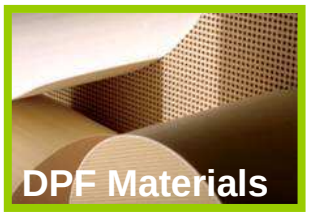
Frequency

Motivation: Aftertreatment Controls Optimization

Motivation: Enable reduced energy consumption, cost, and increased durability of particulate filter systems through improved sensing and controls.



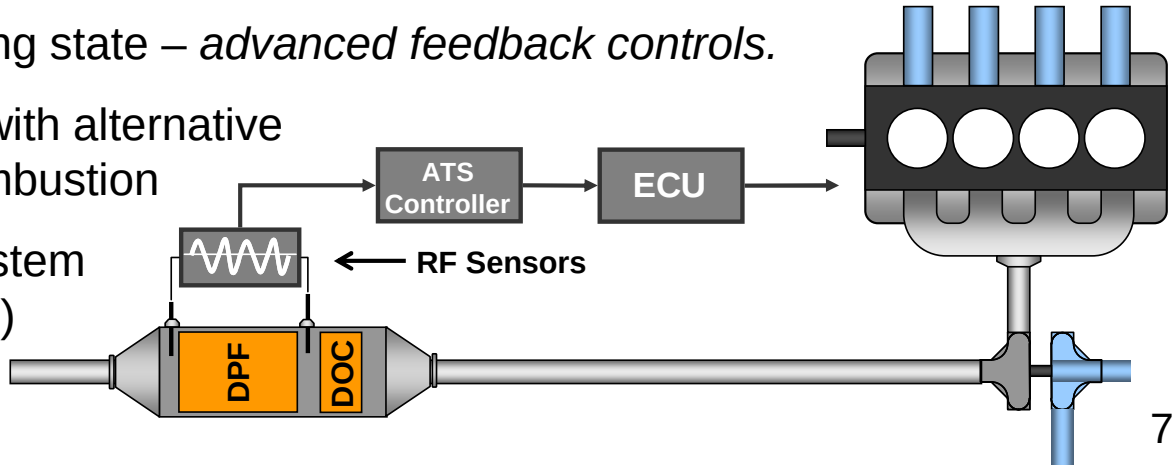




Advanced Controls

Concept: Apply inexpensive radio frequency (RF) technologies to directly monitor DPF soot and ash levels and distribution with low-ΔP DPF materials.

- Direct measure of loading state – *advanced feedback controls.*
- Additional advantages with alternative fuels and advanced combustion
- Adaptive controls as system ages (ash accumulation)
- Applications for OBD



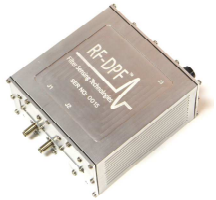
Technical Highlights: Parallel Testing Activities

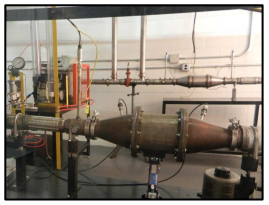
Technical Focus Areas

Performance Metrics

FST Inc.

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

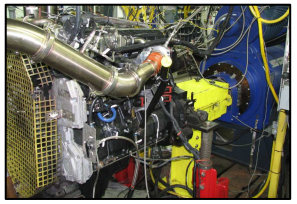




- Pressure drop (OE)
- Gravimetric PM
- Gravimetric Ash

CORNING

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



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

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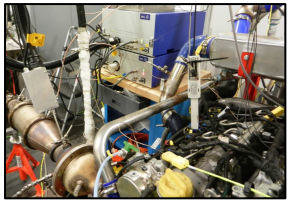
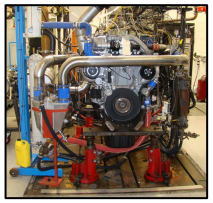
- **AVL benchmarking**
- **TEOM benchmarking**
- **Fuels & adv. combustion**



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

FEV

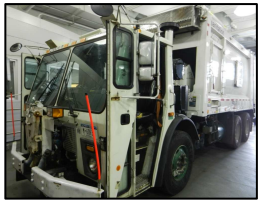
- **Controls development**
- **DDC engine platform**
- **2013+ aftertreatment**



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

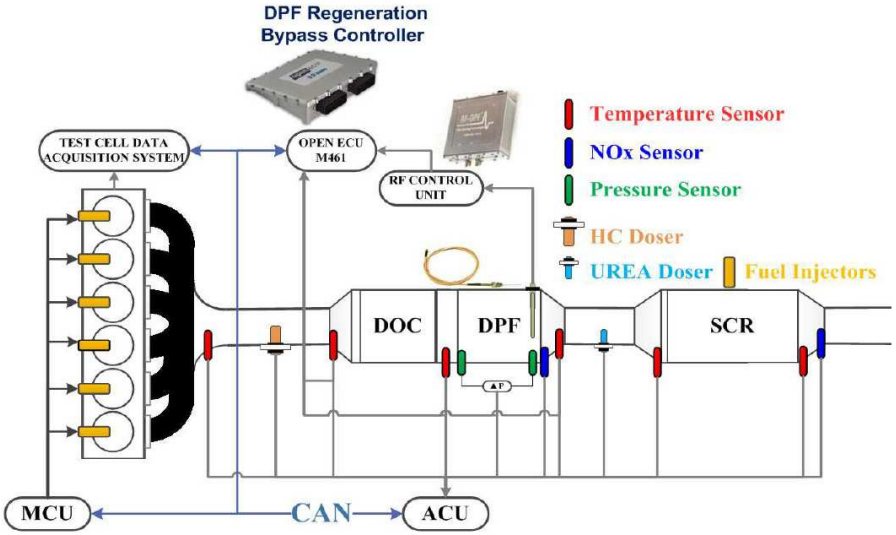
THE CITY OF NEW YORK DEPARTMENT OF SANITATION

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



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

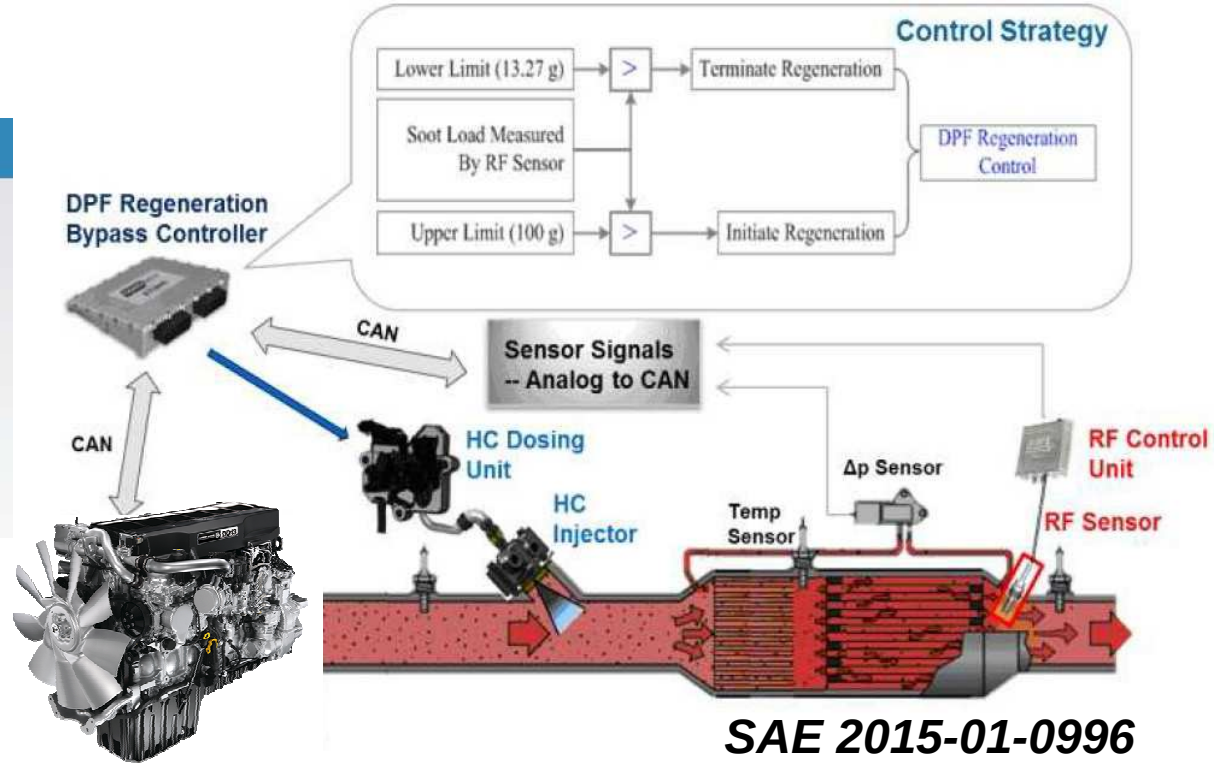
Single Probe RF Sensor Integration for DPF Control



Hardware and System Setup

- MY 2013 DD-13 diesel engine
- Stock controls and aftertreatment
- Open ECU M461 for RF-based control of regeneration
- HC dosing system upstream of DPF
- **Single antenna** RF sensor

DD13 SPECIFICATIONS	
Configuration	Inline 6 Cylinder
Displacement	781 cu. in. (12.8 L)
Compression Ratio	17.3:1
Bore	5.20 in. (132 mm)
Stroke	6.15 in. (156 mm)
Weight (Dry)	2540 lb. (1152 kg)
Electronics	DDEC®
Oil Capacity	40 qt. (38 L)
Horsepower Range	350-470



SAE 2015-01-0996

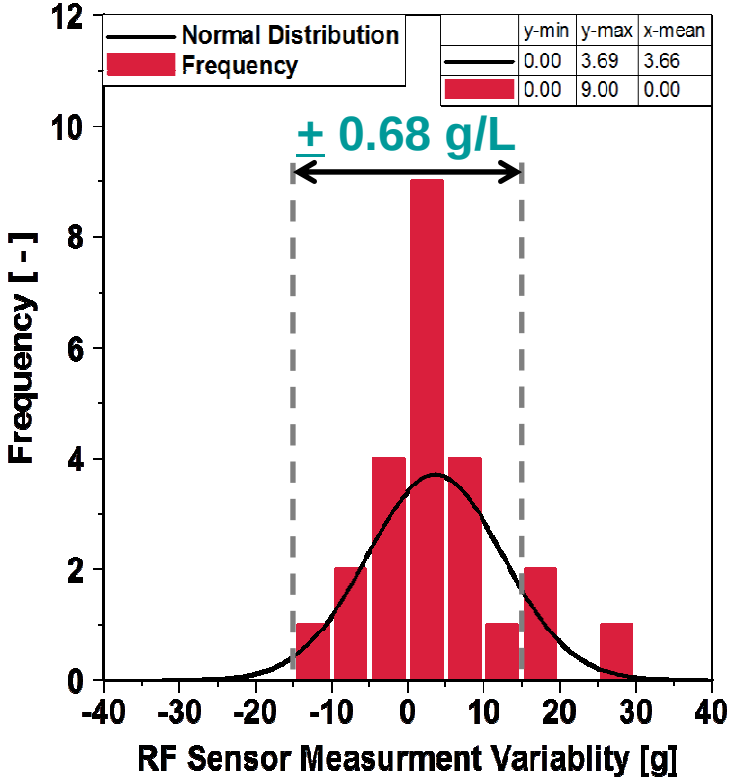
Single Probe RF Sensor Integration for DPF Control

- Stock aftertreatment system with 22.03 L DPF (27.73 kg base weight)
- DOC upstream of DPF (same can) and RF antenna mounted at DPF outlet

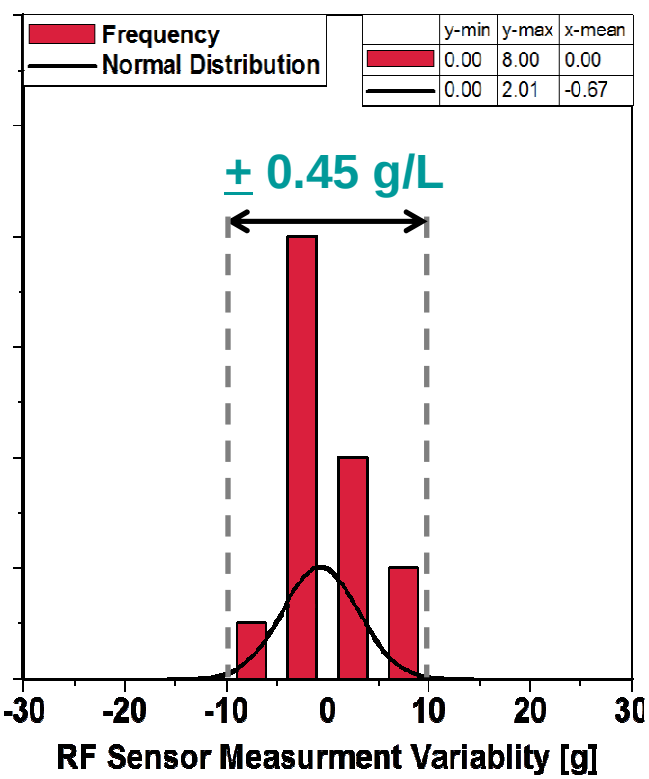
Aftertreatment

DPF and SCR

Loading Sample Set: 24 cycles
PM Load Range: 6 g – 126 g

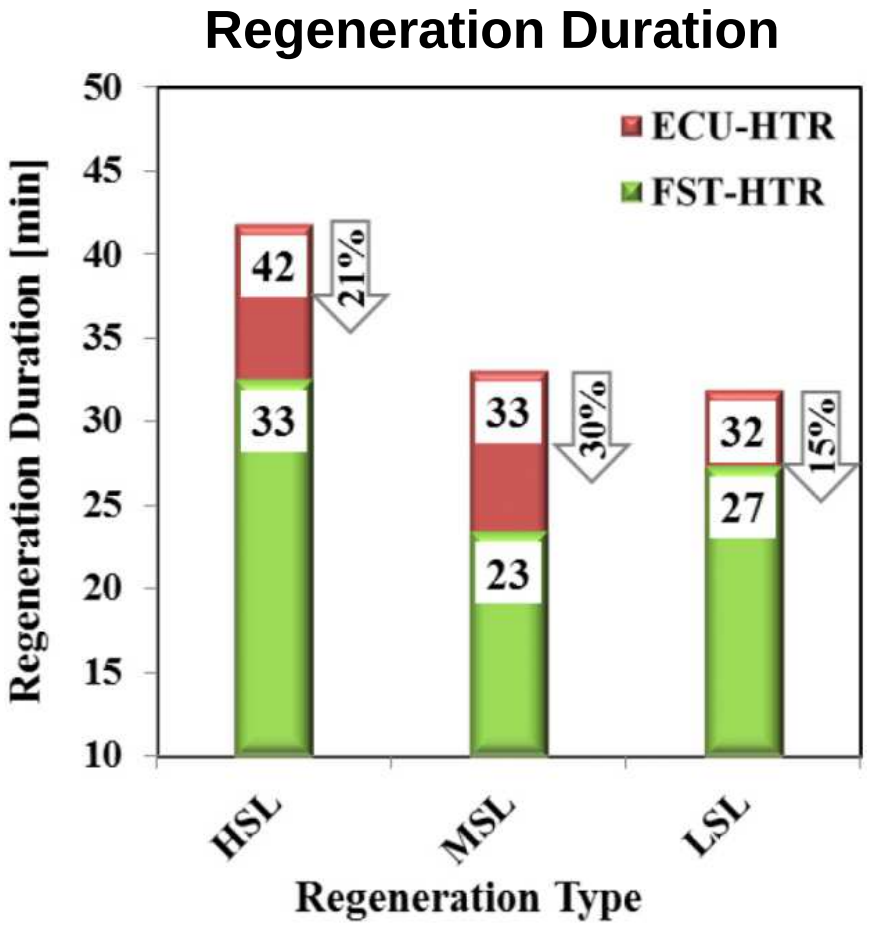


Regen Sample Set: 15 DPF cycles
PM Load Range: 1 g – 18 g



- RF sensor validation over multiple loading and regeneration cycles
- Comparison with gravimetric, AVL MSS, BG3, and smoke meter measurements

RF-Based Regeneration Management

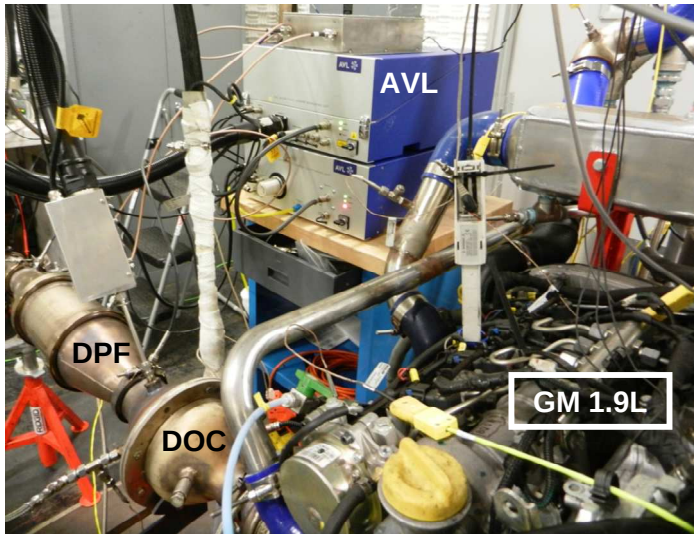


Test Procedure

- DPF loaded to three different levels of PM
  - *High, medium, low load*
- **Stock ECU** controlled regenerations carried out
- **RF-controlled** regenerations repeated at similar conditions
- Duration normalized to account for small differences in PM load and temperature

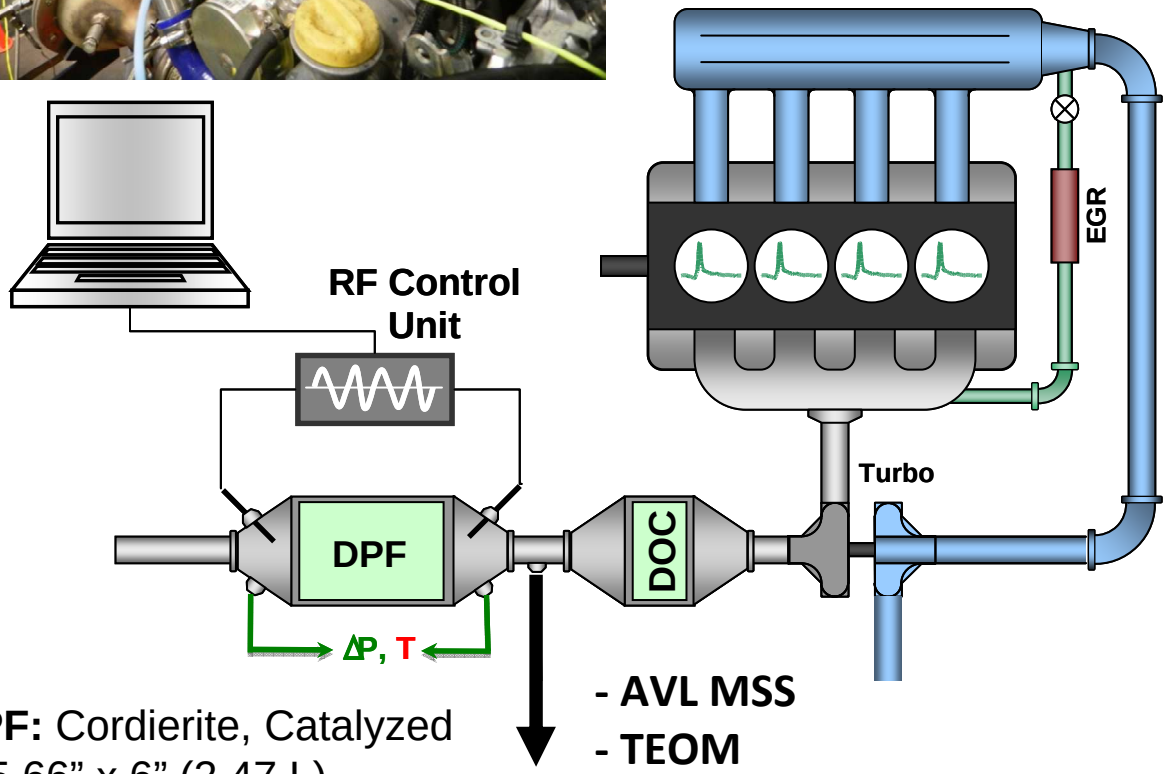
- Reduction in regeneration duration **15% - 30%** relative to stock ECU control
- RF system directly monitors PM levels in DPF during regeneration and terminates HC dosing once oxidation is complete (vs. time-based ECU approach)

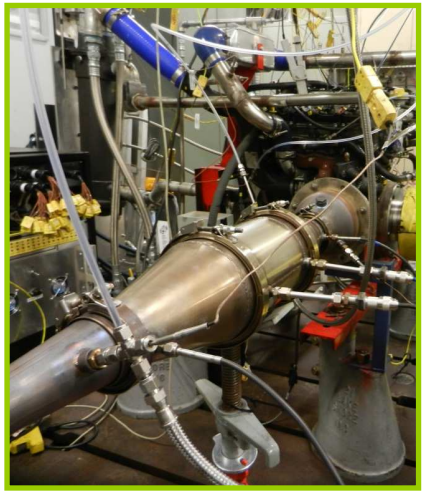
RF System Transient Response Evaluation



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)

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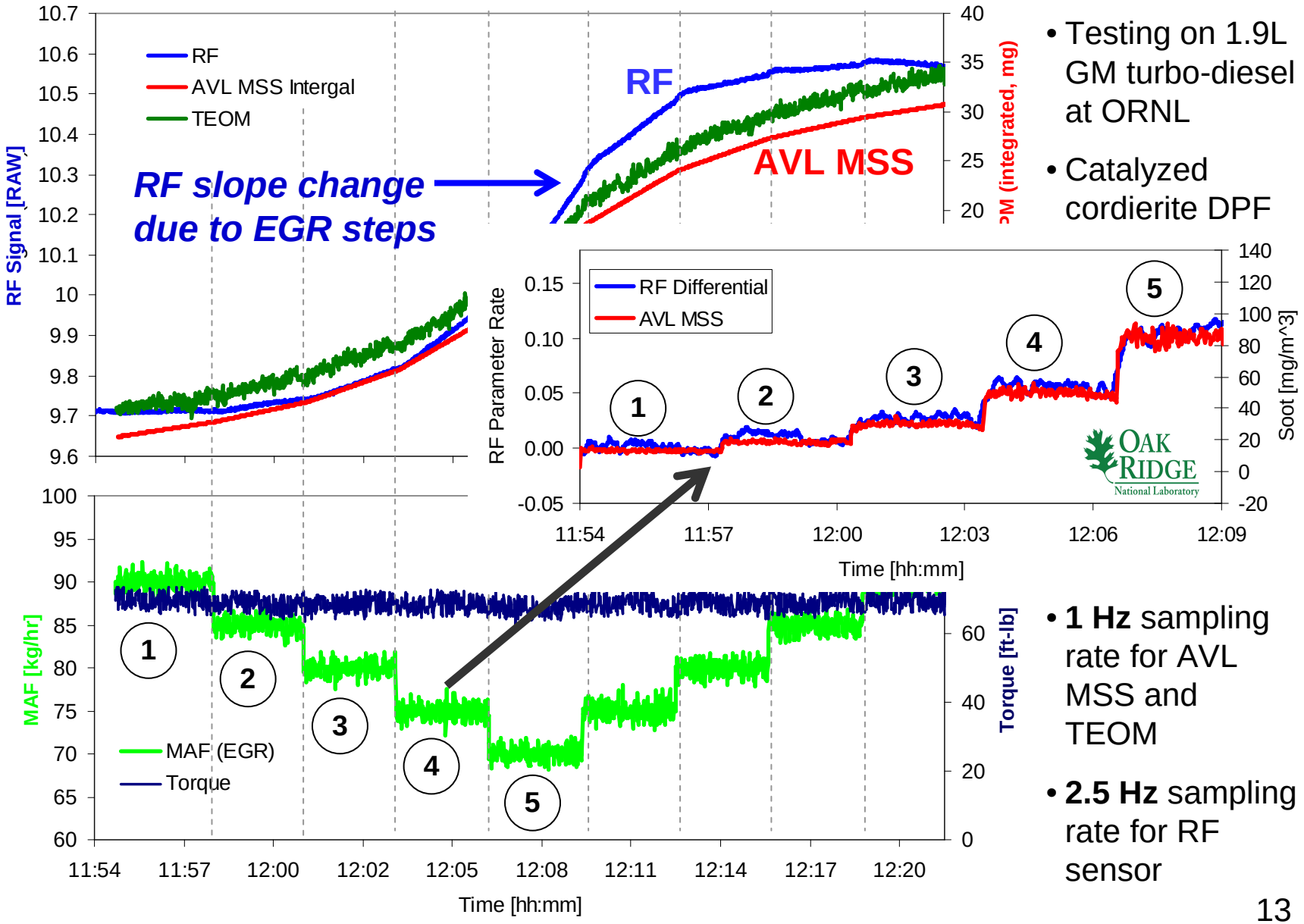
Transient Response Well-Correlated with AVL MSS

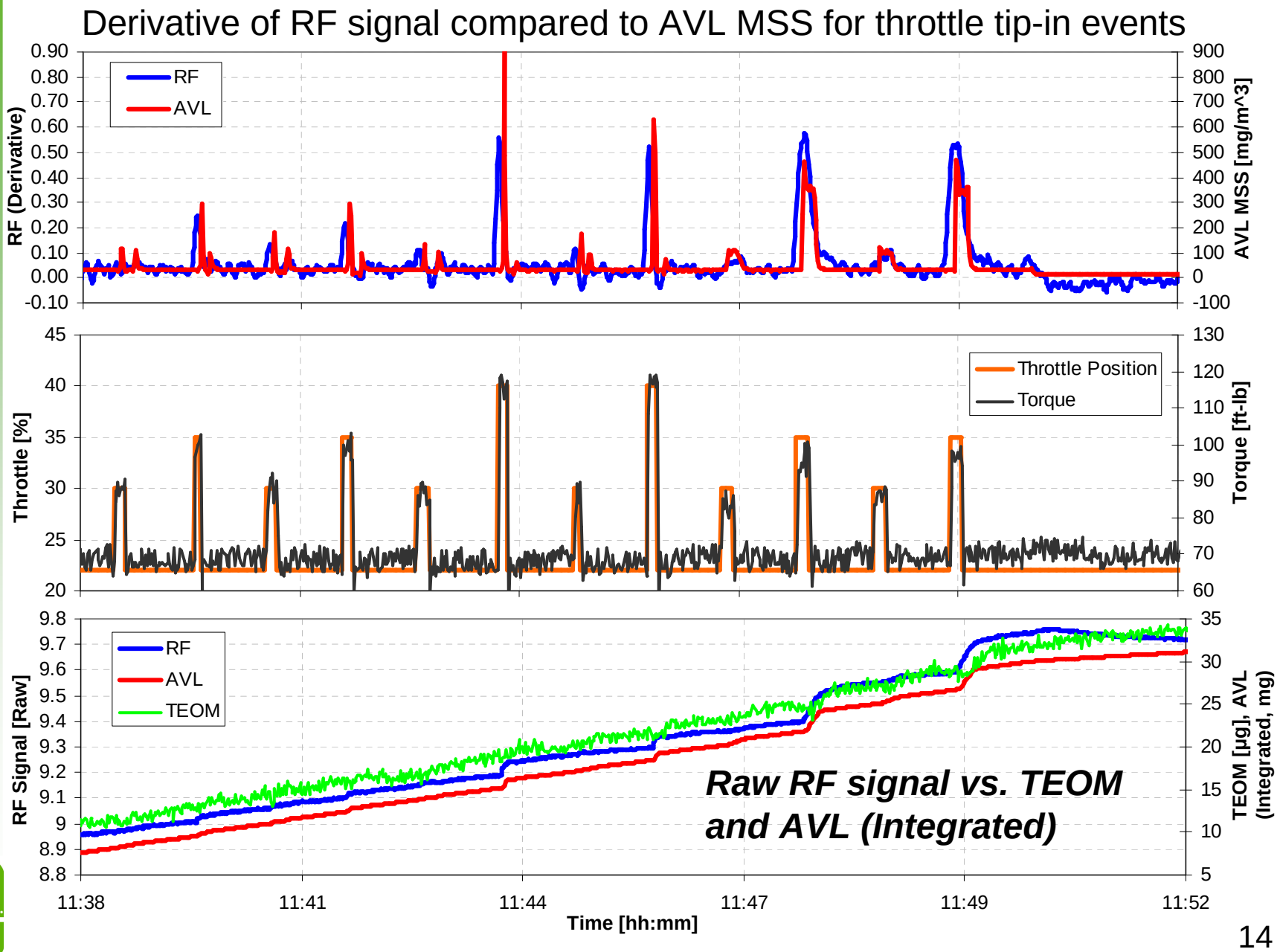
Fast transient response to small changes in engine-out PM



- Testing on 1.9L GM turbo-diesel at ORNL
- Catalyzed cordierite DPF

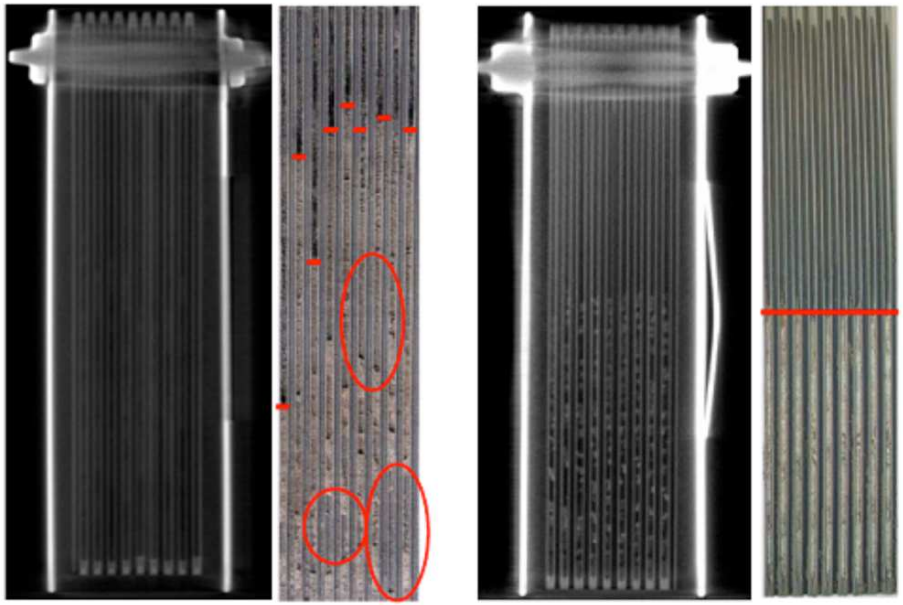
- **1 Hz** sampling rate for AVL MSS and TEOM
- **2.5 Hz** sampling rate for RF sensor

Transient Response Details of Throttle Tip-In Events

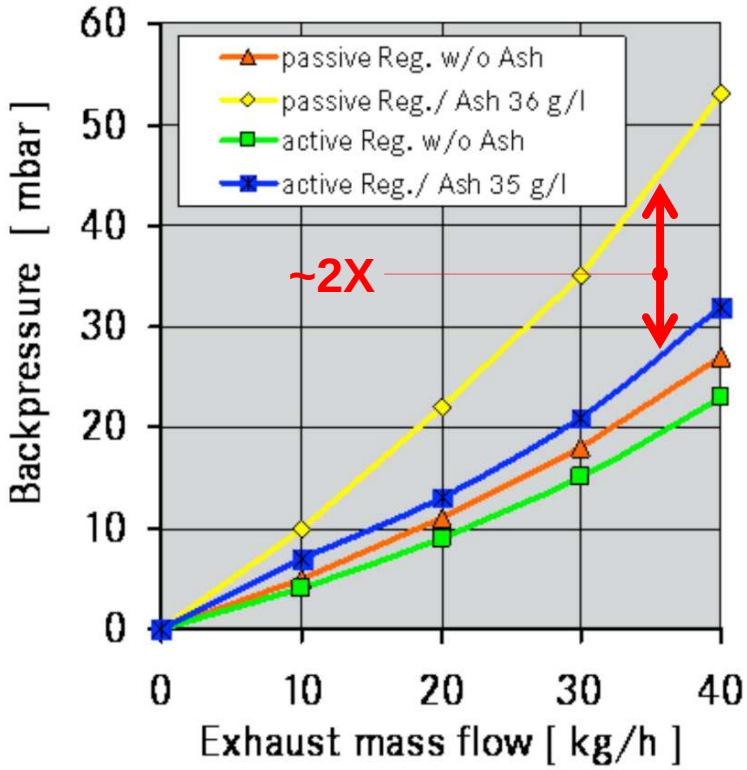


Ash Distribution Impacts Performance Over DPF Life

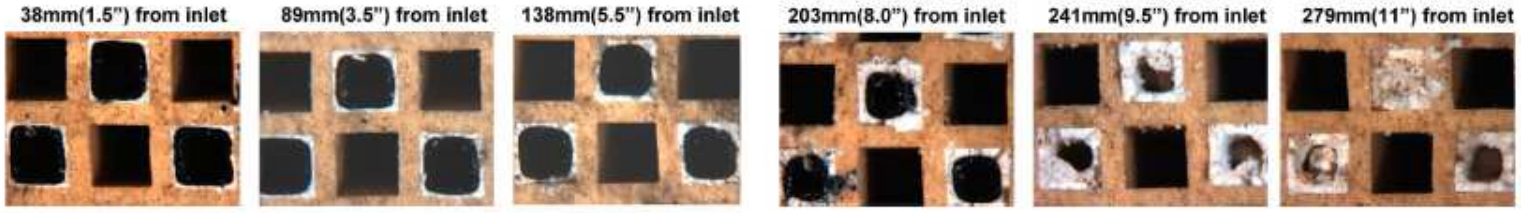
Ash distribution and deposit characteristics may result in very different ΔP measurements for same ash level in DPF.



Passive **Active**

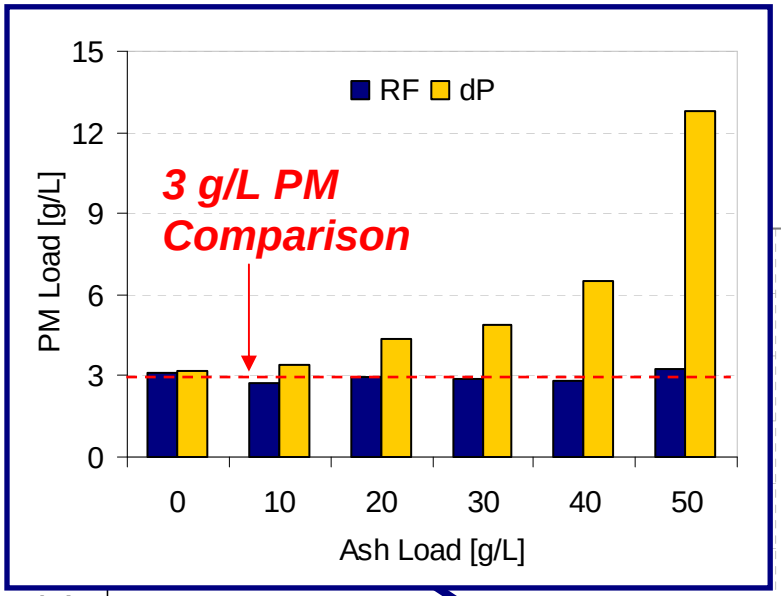


Source: SAE 2012-01-1732



Source: SAE 2007-01-0920

DPF Soot Load Measurements with Ash



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

RF soot load measurements unaffected by ash unlike ΔP

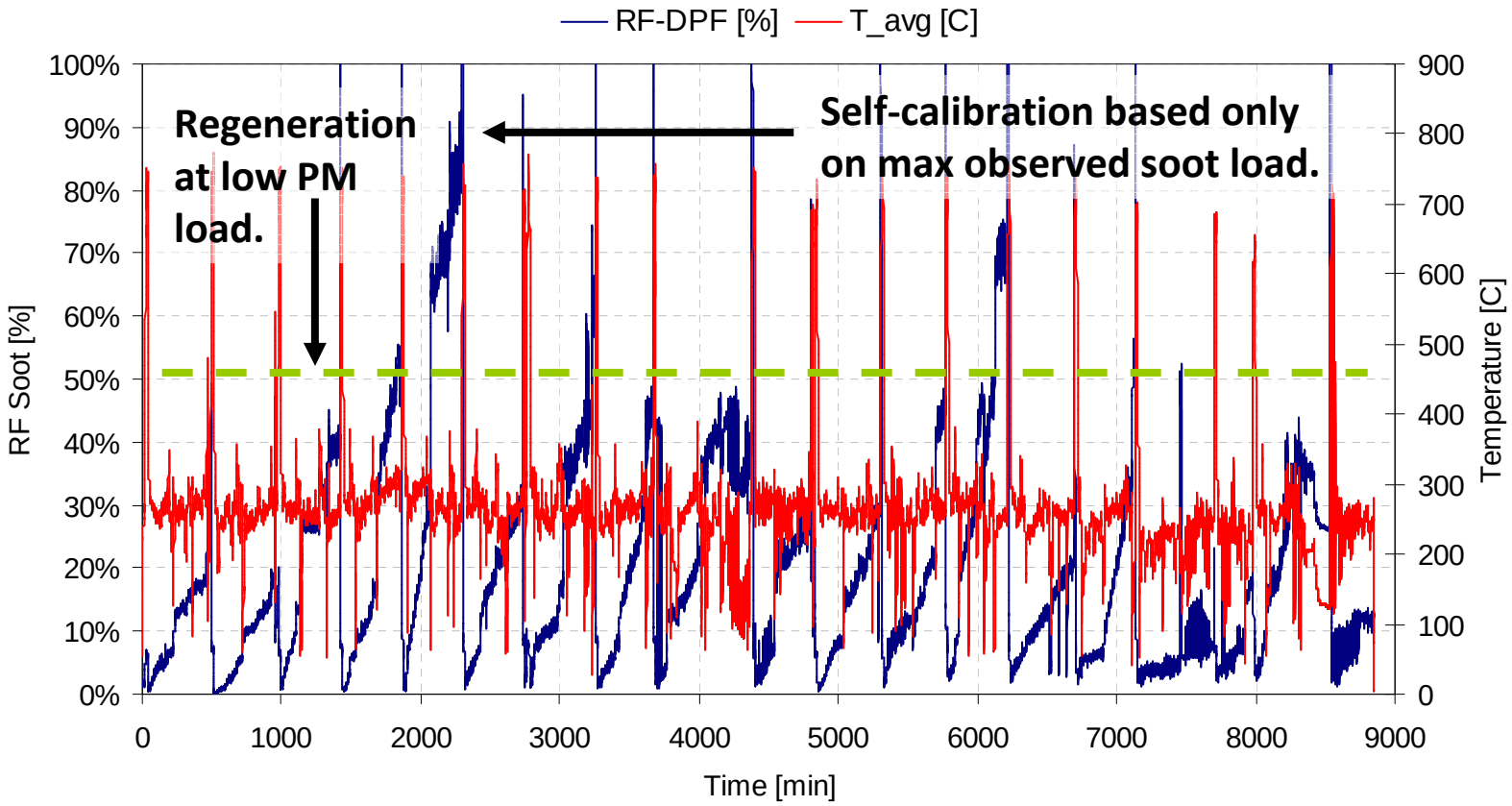
Sensing System Fleet Testing on Urban Cycles (NYC)

RF System Configuration (Mack MP-7) DSNY Fleet

- MY 2009 and MY 2010+ vehicles over two year (24 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

Fleet Vehicle Data Shows Frequent Regenerations

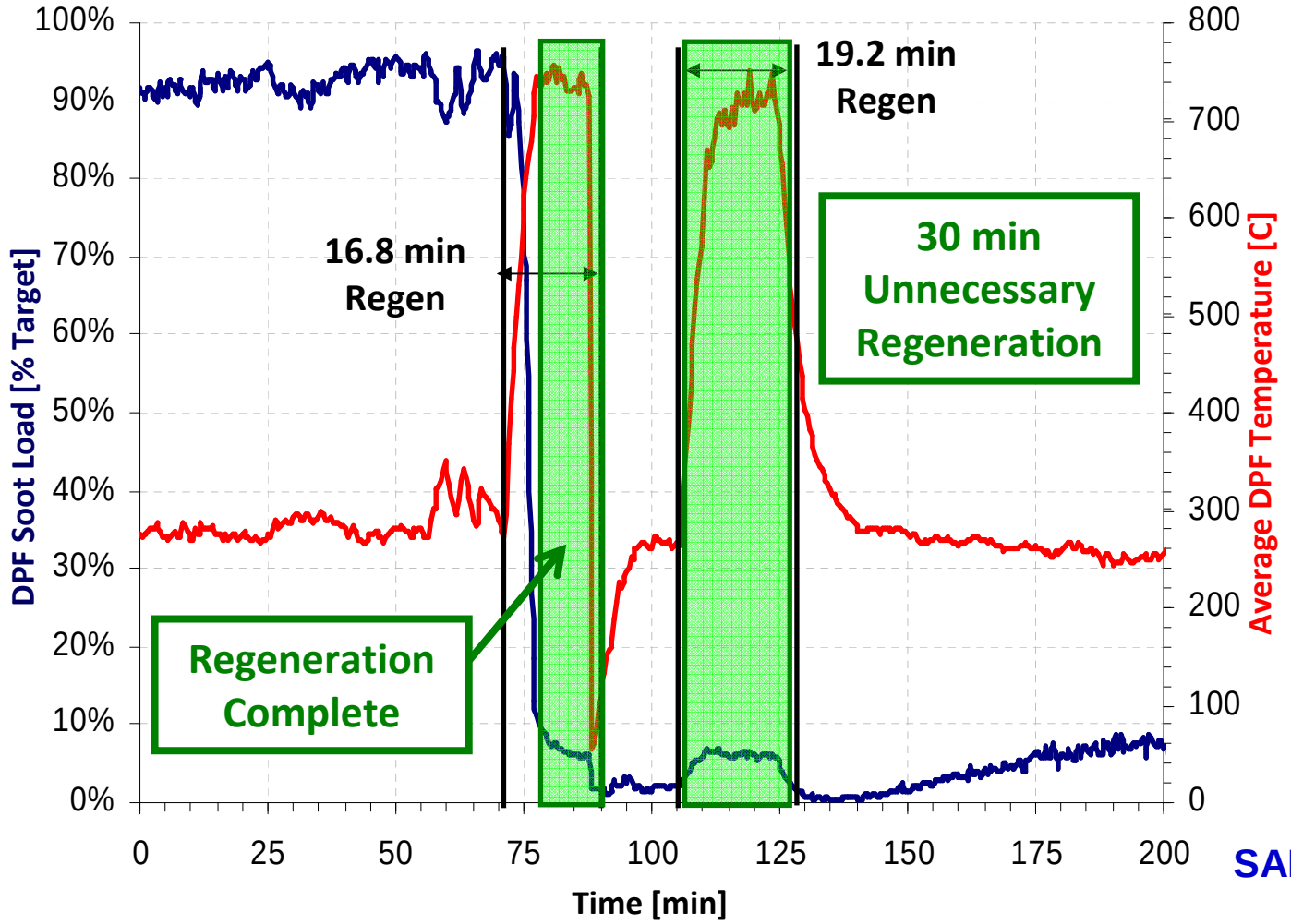
RF sensor measurement data for 150 hr period with stock 2009 Volvo/Mack DPF regeneration control system.



- Data from 150 hours with 21 regenerations, avg. 18 min per regeneration
- OEM control triggers regenerations (~ every 7.1 hrs) at low soot loads
- Vehicles spends **4% - 5%** of operating time in regeneration

RF Measured Soot Oxidation to End Regeneration

RF measurements can provide direct feedback control to end regeneration.



SAE 2014-01-2349

- Back-to-back regenerations occasionally observed due to vehicle shut-down
- Real-time measurement of soot load can end regeneration when complete

Summary and Technical Highlights

Demonstrated direct measurement of DPF soot and ash levels via RF sensing in test cell and vehicle applications.

Technical Highlights

- Developed single antenna RF system and demonstrated high level of accuracy for DPF soot level measurements
- Demonstrated combined DPF **soot AND ash** measurements
- RF transient response well-correlated with AVL micro-soot sensor
- Demonstrated fast sensor response < 1 second
- Evaluated RF performance over **380,000 mile equivalent** DPF aging
- **Fuel savings** potential via extend regeneration interval and reduced regeneration duration relative to stock OEM controls

Outlook and Additional Applications

- Current work focused on controls optimization and sensor validation in a range of light-duty and heavy-duty applications with project partners.
- Additional opportunities for GPF and catalyst applications to monitor gas species adsorbed on catalysts

Acknowledgements

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Commercial and National Laboratory Project Partners

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