Filter Sensing Technologies Inc.

Real-Time Particulate Filter Soot and Ash Measurements via Radio Frequency Sensing

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Alexander Sappok, Paul Ragaller, Leslie Bromberg
alexander.sappok@dpfsensor.com
www.dpfsensor.com

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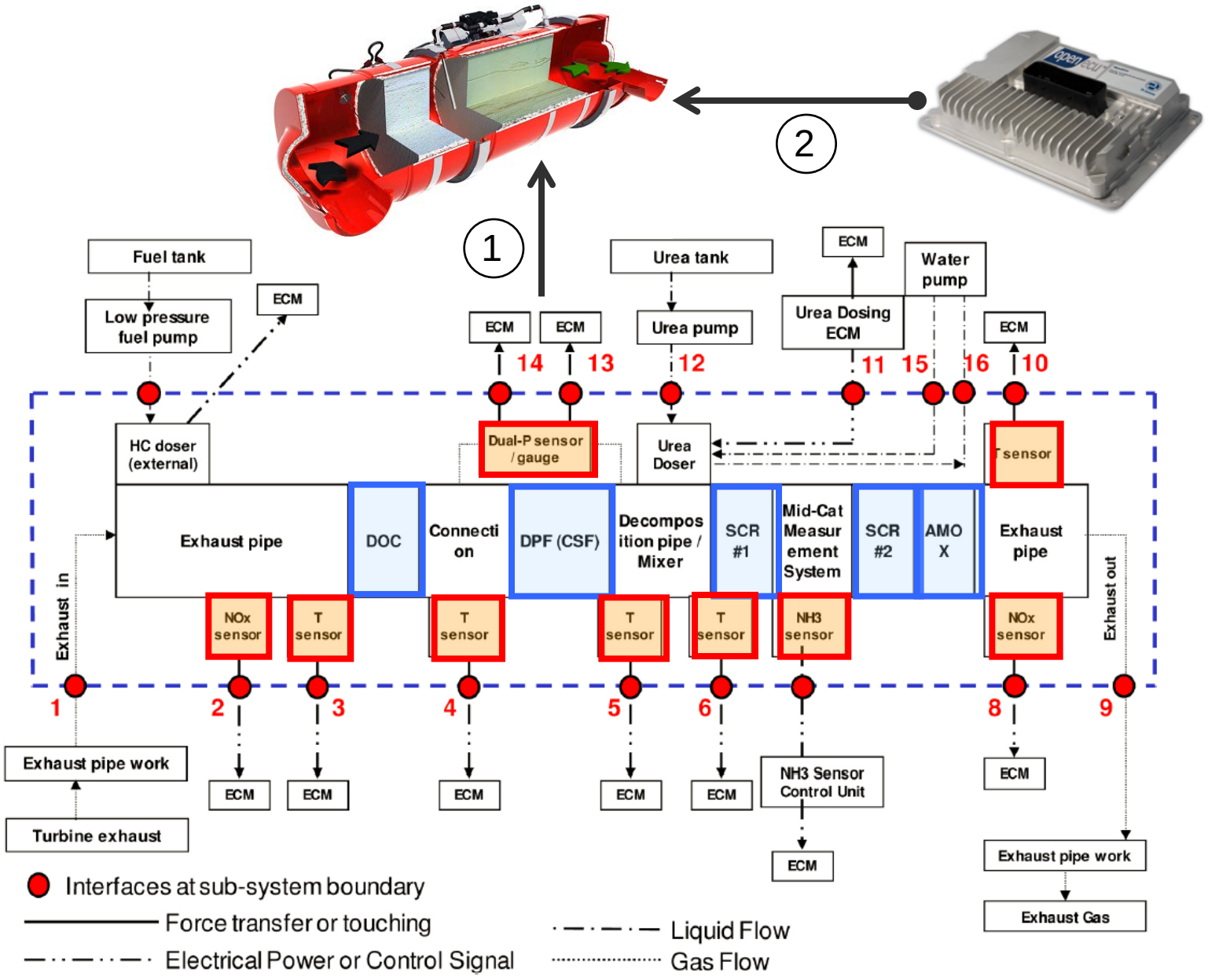
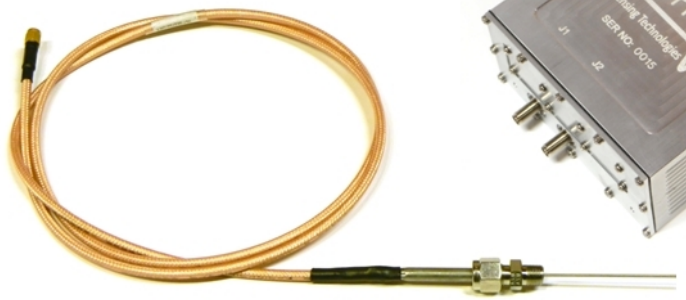
Challenge: Determination of Filter/Catalyst State



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

RF Sensors for Direct Measurement of DPF Loading

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



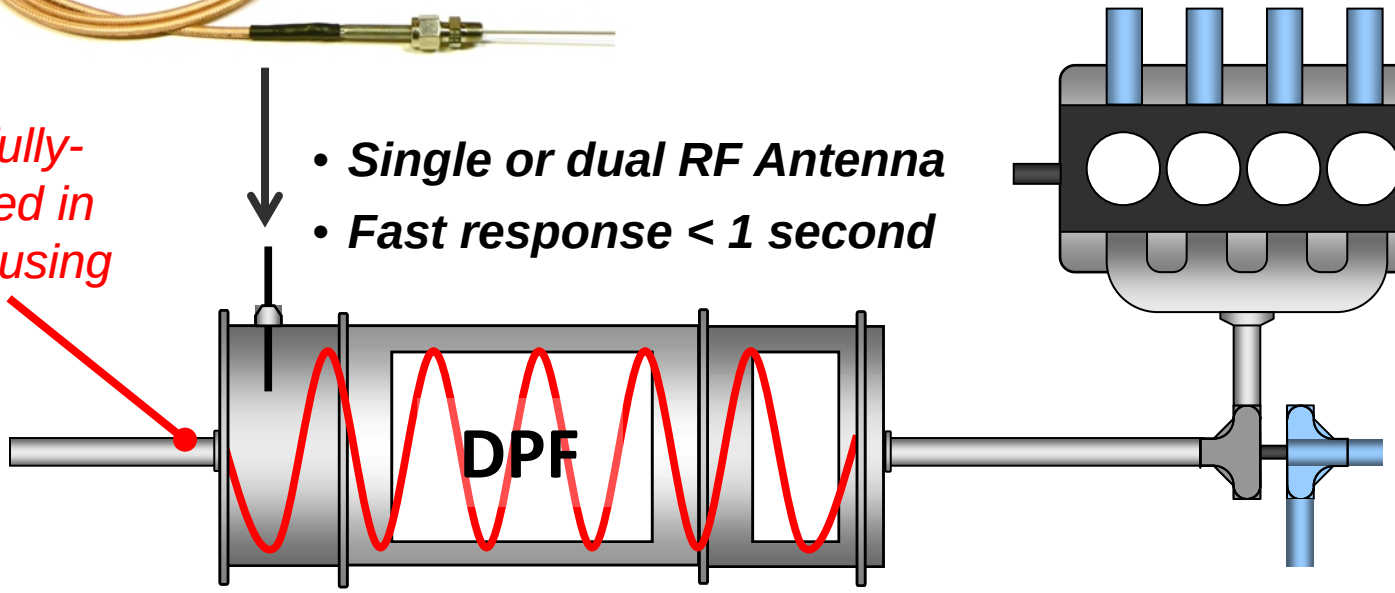
RF Control Unit

DPF Loading

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

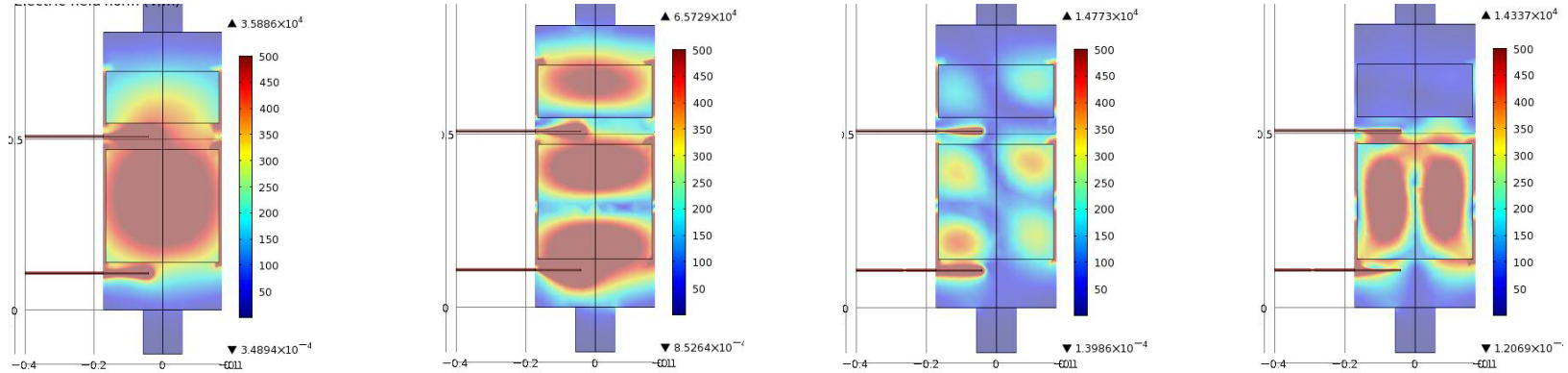
Signal fully-contained in DPF housing

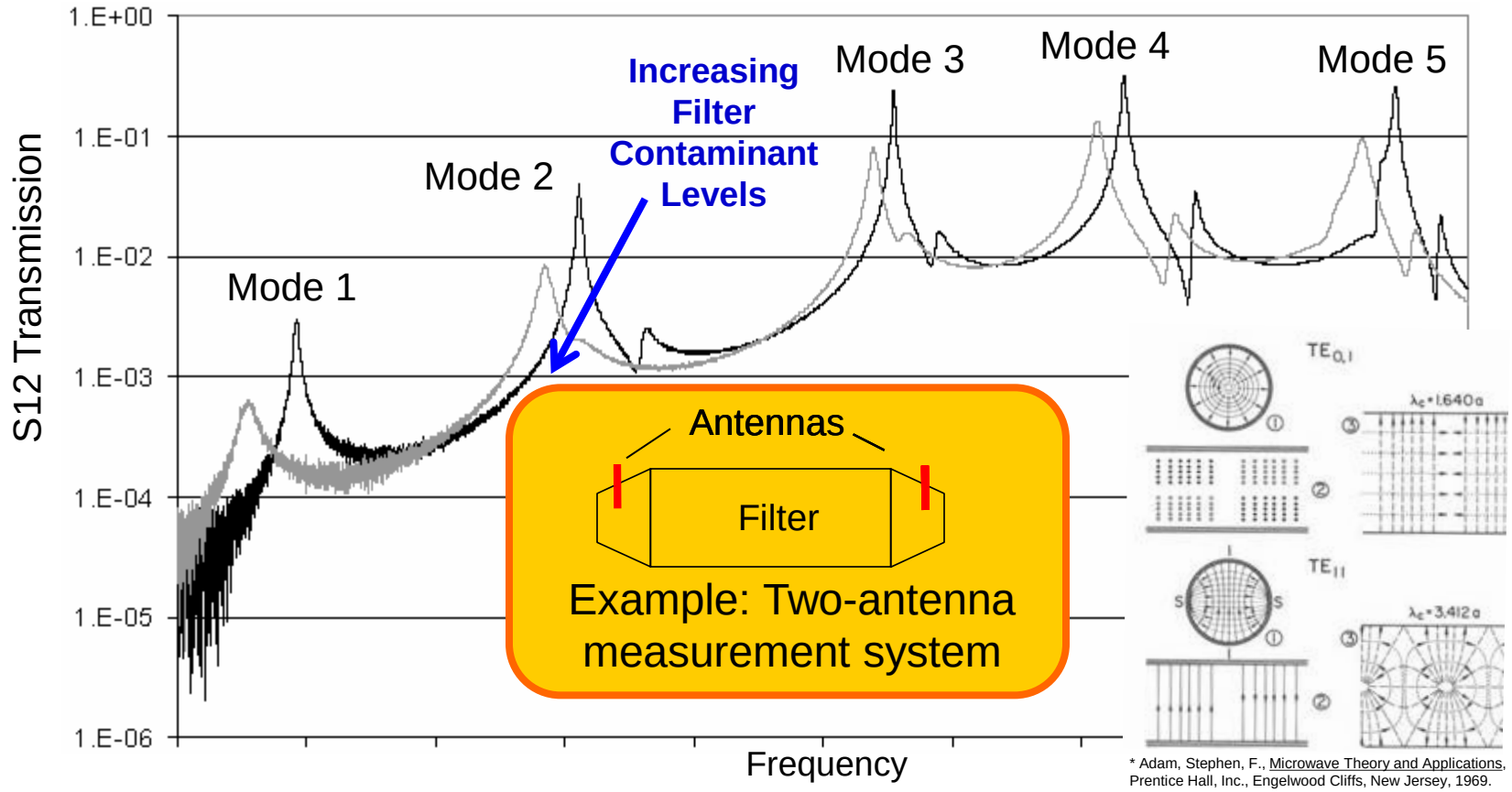
- ***Single or dual RF Antenna***
- ***Fast response < 1 second***



RF sensor responds to changes in DPF dielectric properties

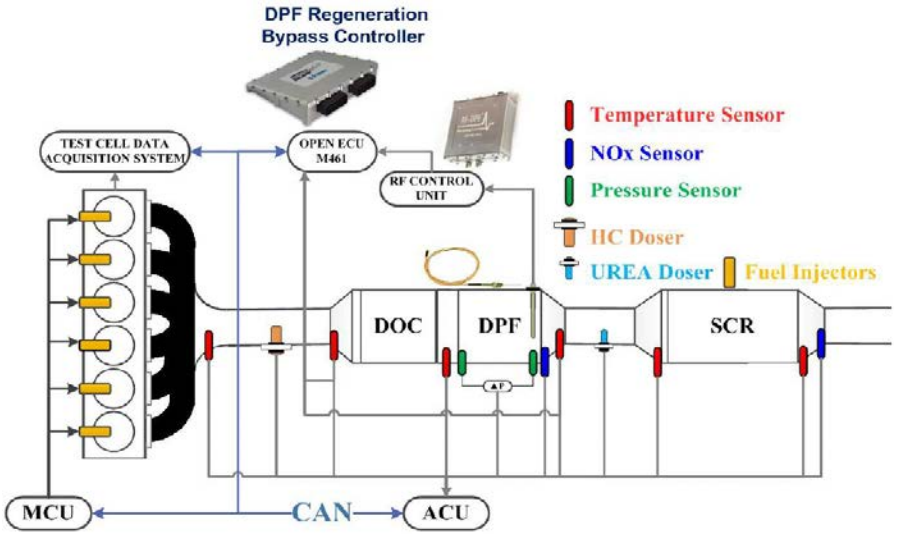
RF System Measurement Methodology





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

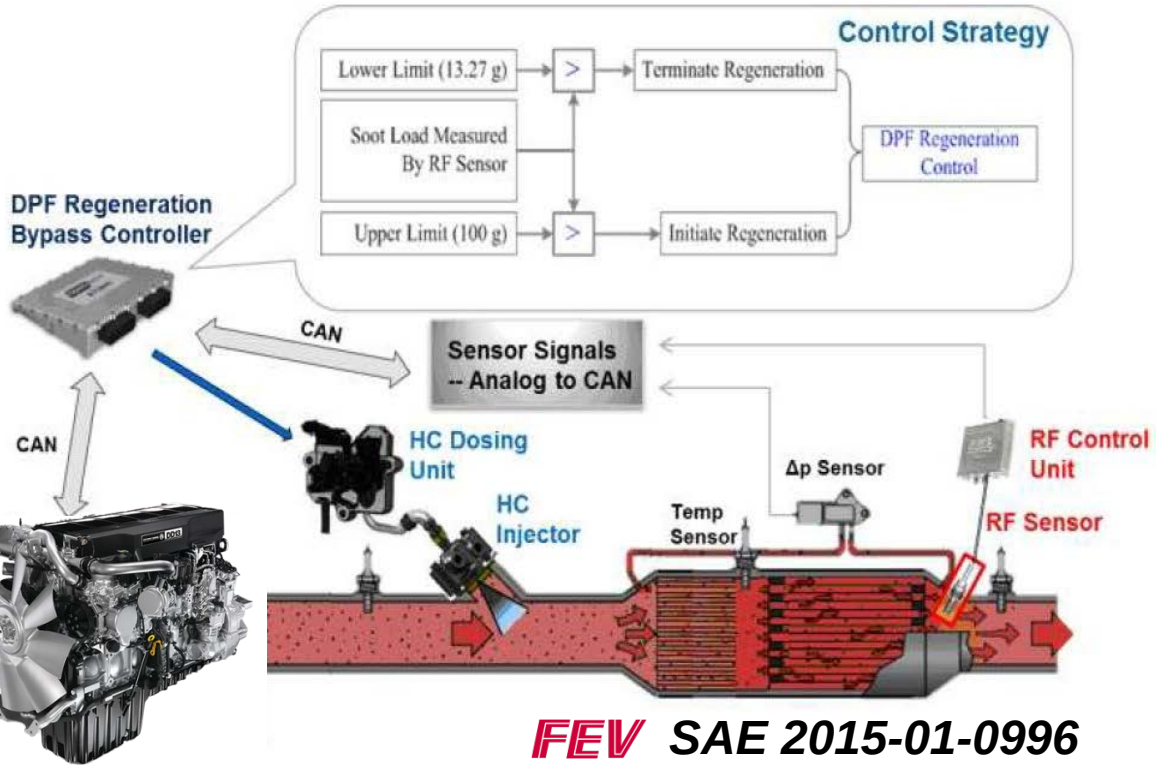
Single Probe RF Sensor Integration for DPF Control



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



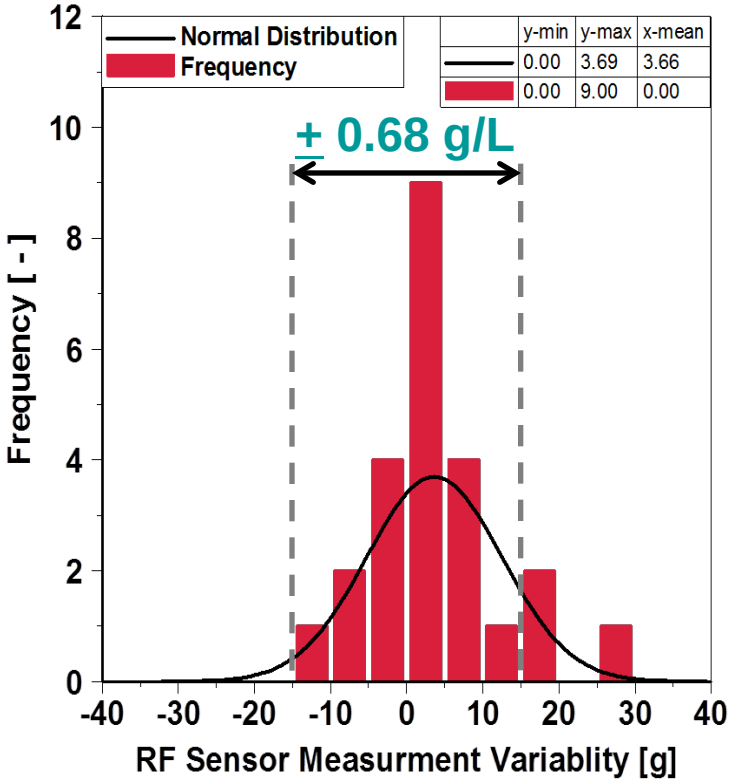
Single Probe RF Sensor Integration for DPF Control

- 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

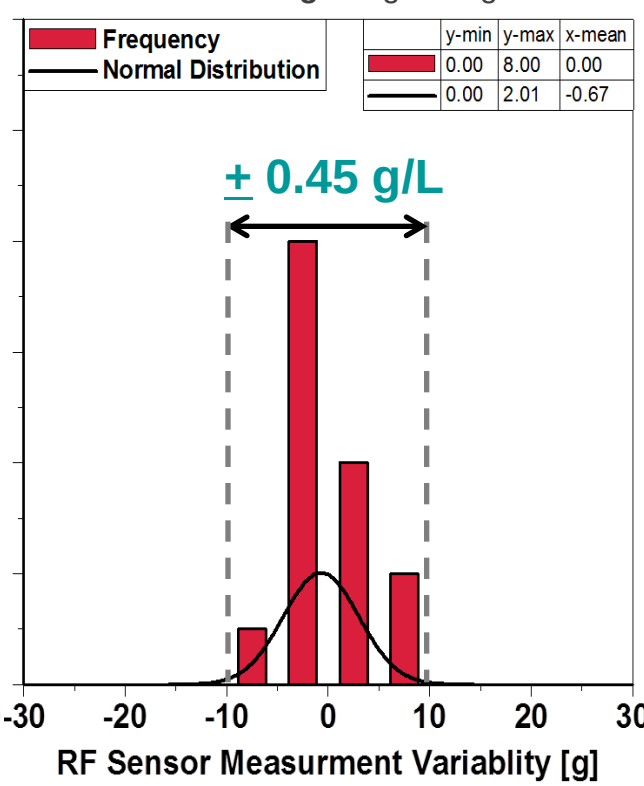
Aftertreatment

DPF and SCR

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

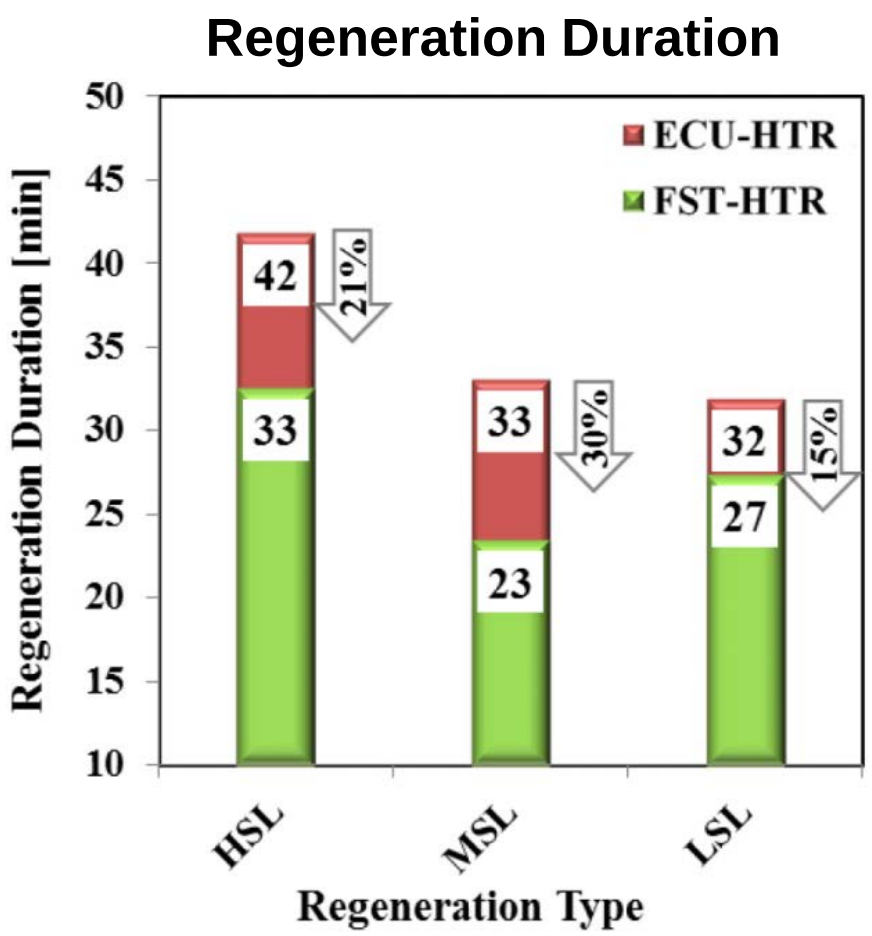


Regen Sample Set: 15 DPF cycles
PM Load Range: 1 g – 18 g



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

RF-Based Regeneration Management

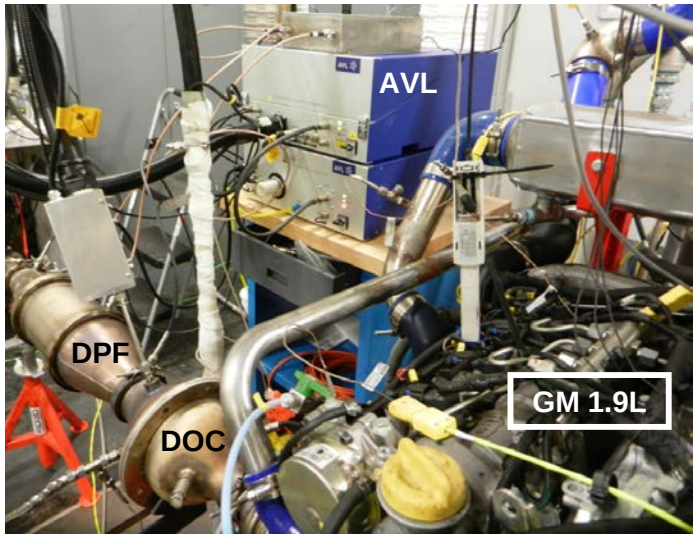


Test Procedure

- 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

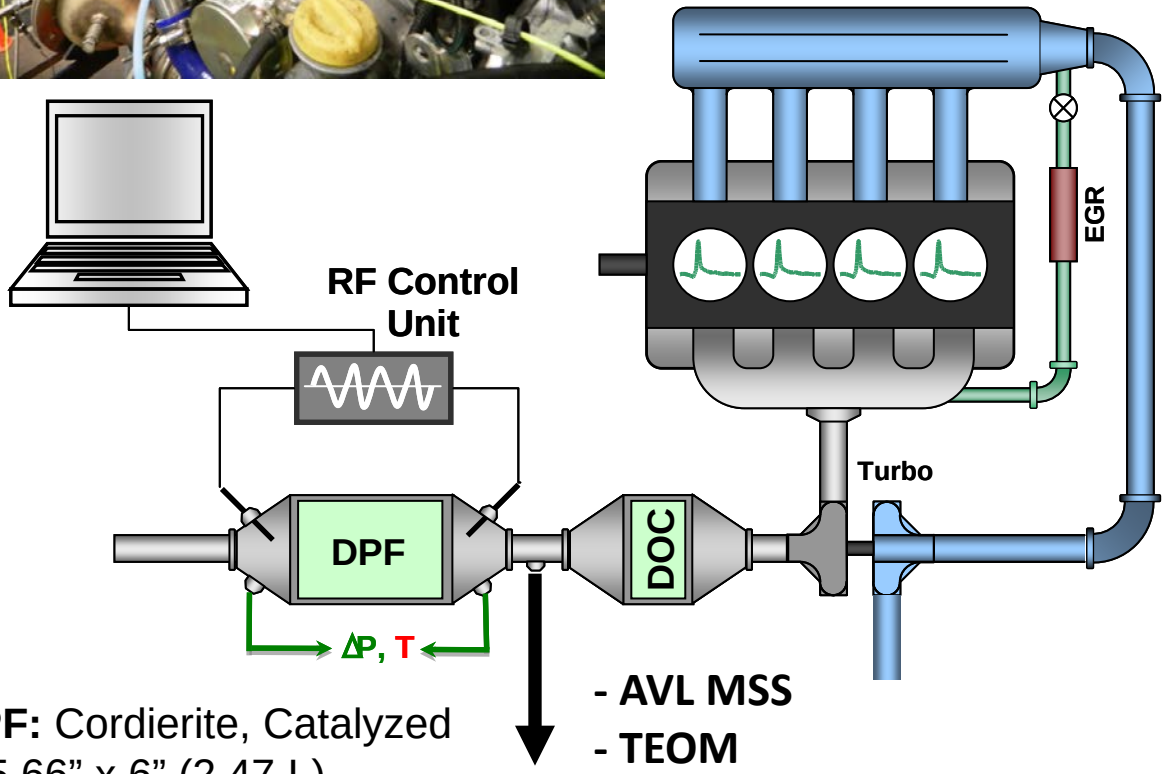
- Reduction in regeneration duration **15% - 30%** relative to stock ECU control
- RF system directly monitors PM levels in DPF during regeneration and terminates HC dosing once oxidation is complete (vs. time-based ECU approach)

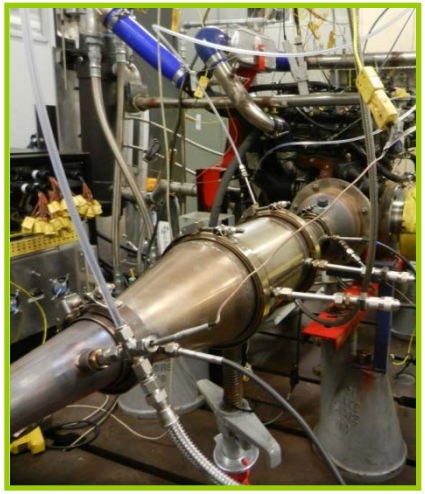
RF System Transient Response Evaluation



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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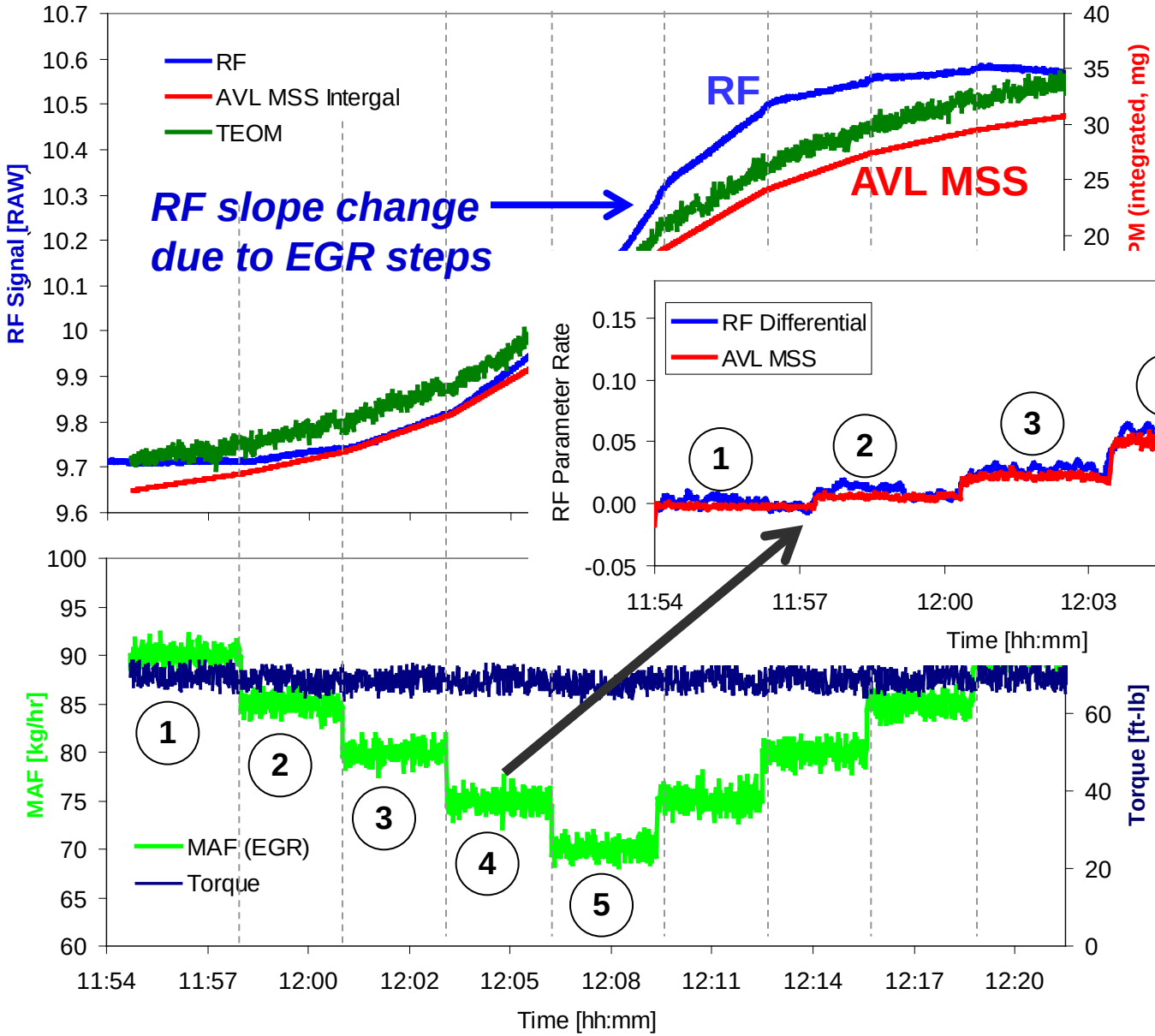
Transient Response Well-Correlated with AVL MSS

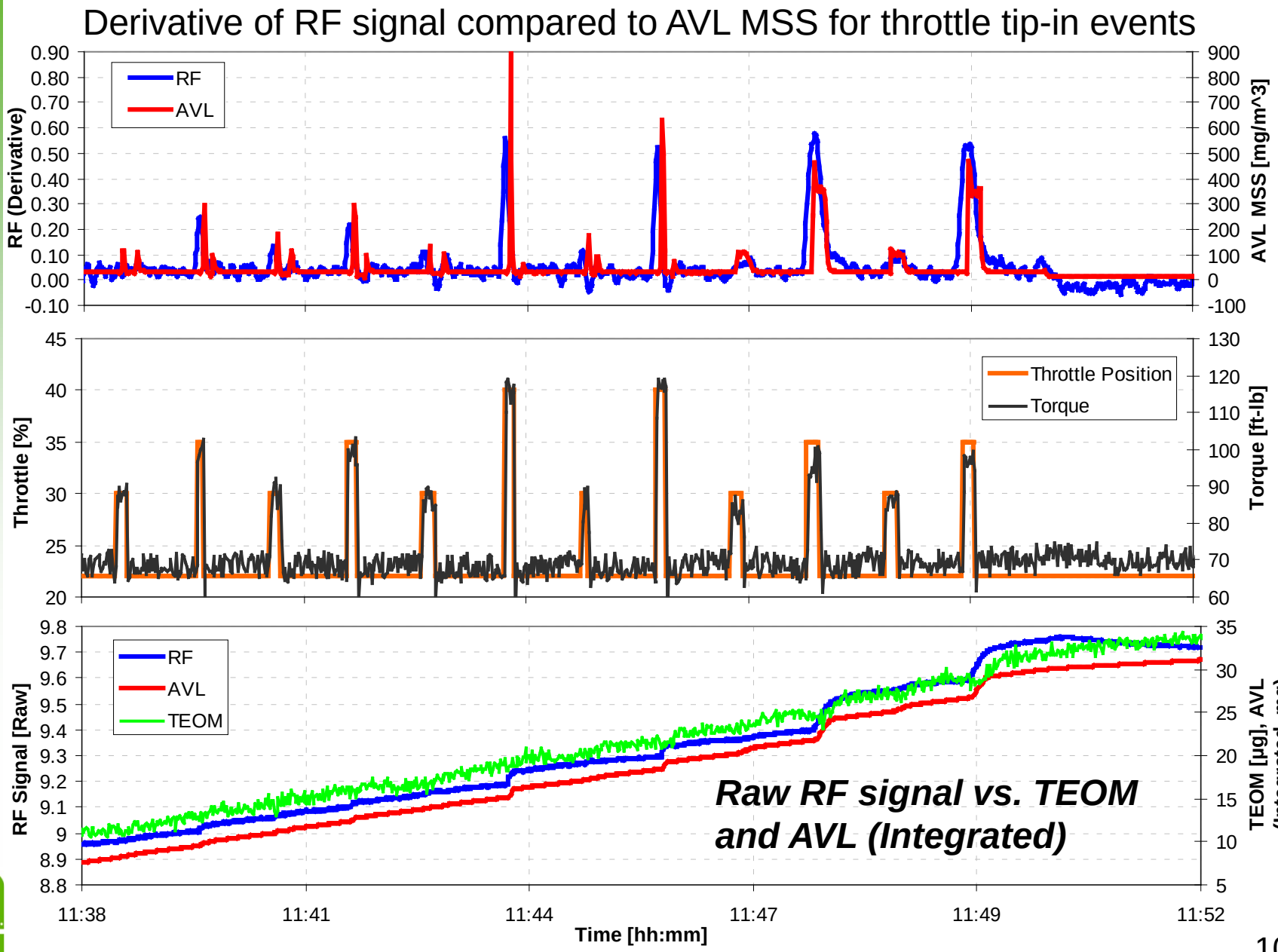
EGR steps result in variation in engine-out PM measured by RF sensor



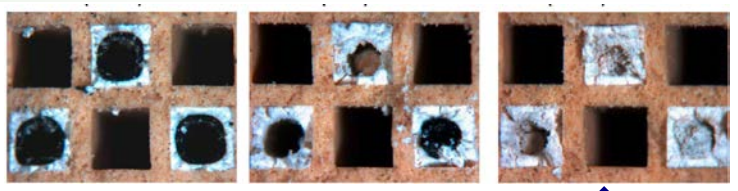
- Testing on 1.9L GM turbo-diesel at ORNL
- Catalyzed cordierite DPF

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

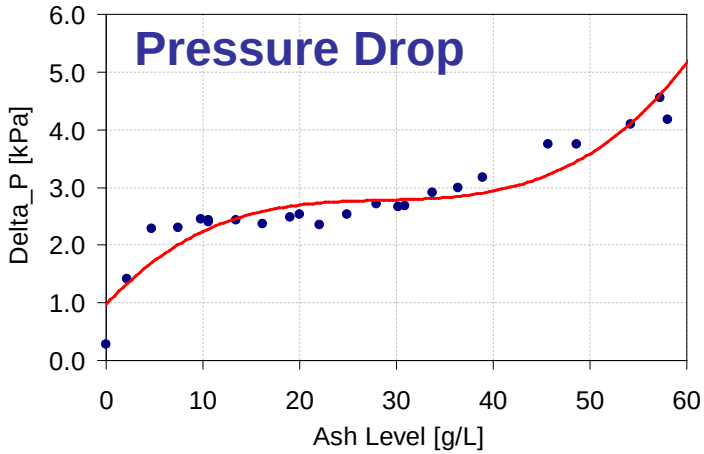
Transient Response Details of Throttle Tip-In Events



Frequency Shift Well-Correlated to DPF Ash Levels



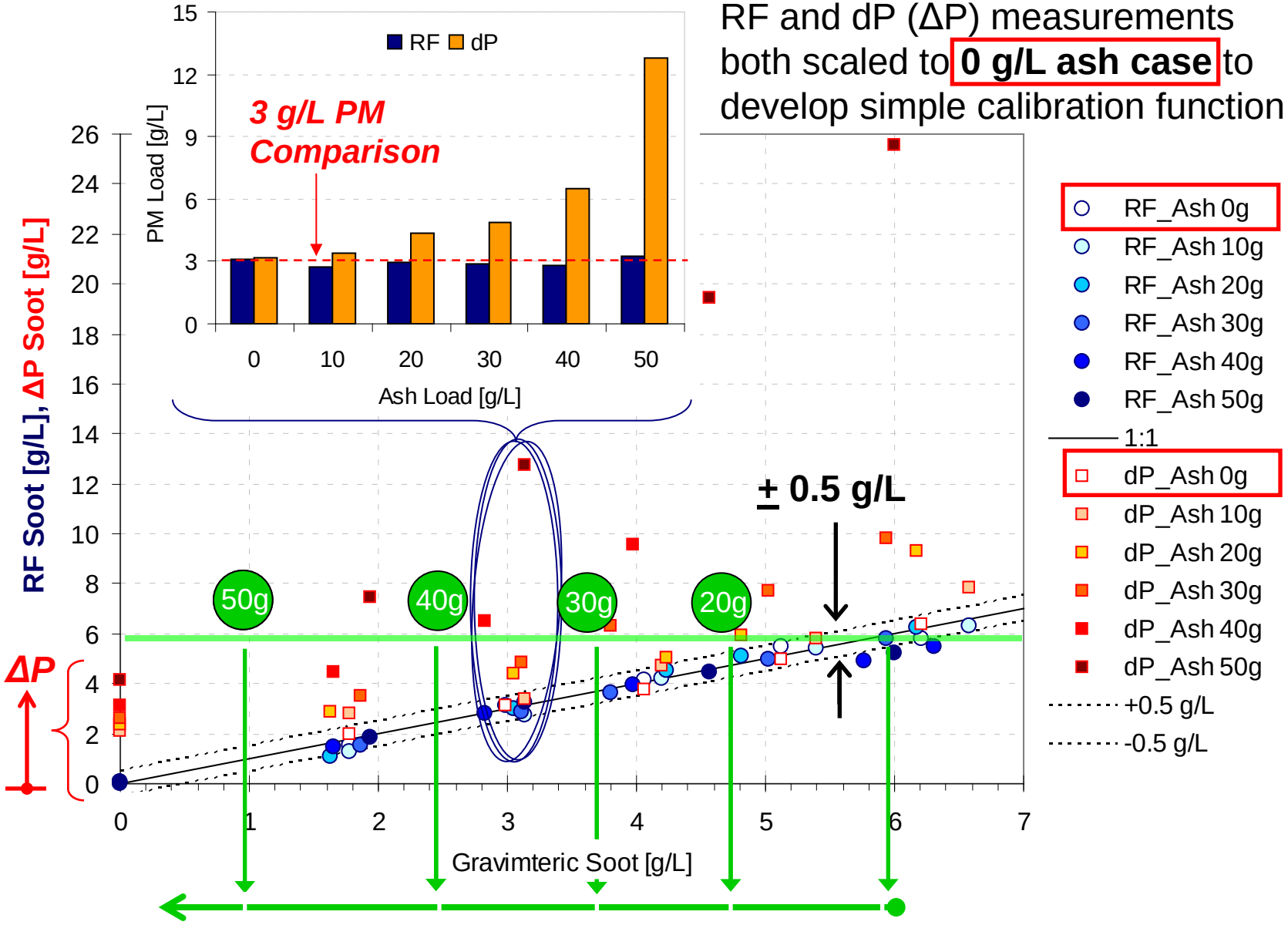
Images: SAE 2007-01-0920



- Ash loading level equivalent to **~ 380,000** miles of on-road accumulation
- Frequency shift at resonance well-correlated to ash level in DPF

DPF Soot Load Measurements with Ash

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



ΔP regeneration frequency increases with ash (over-estimate PM load)

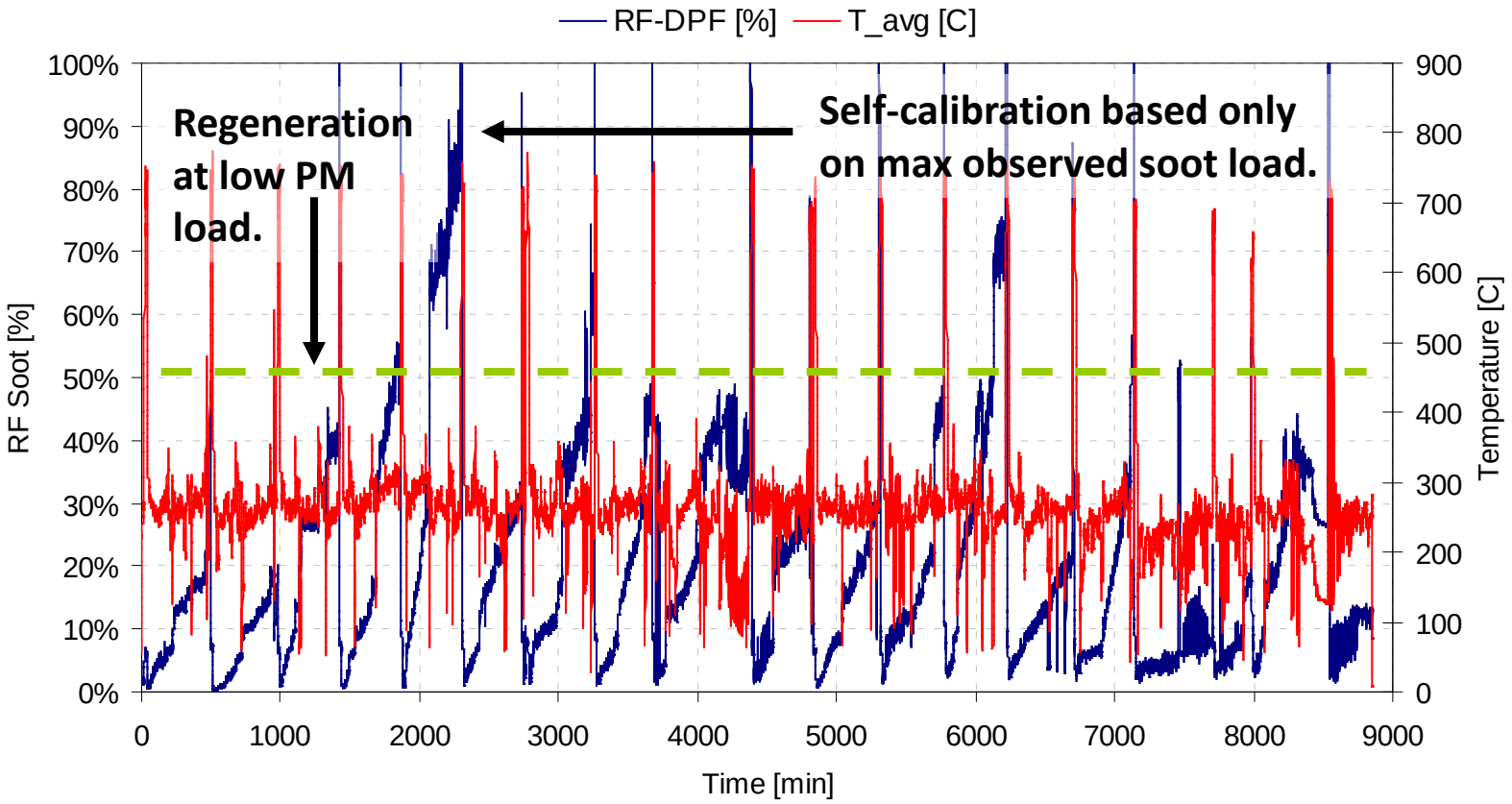
Sensing System Fleet Testing on Urban Cycles (NYC)

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

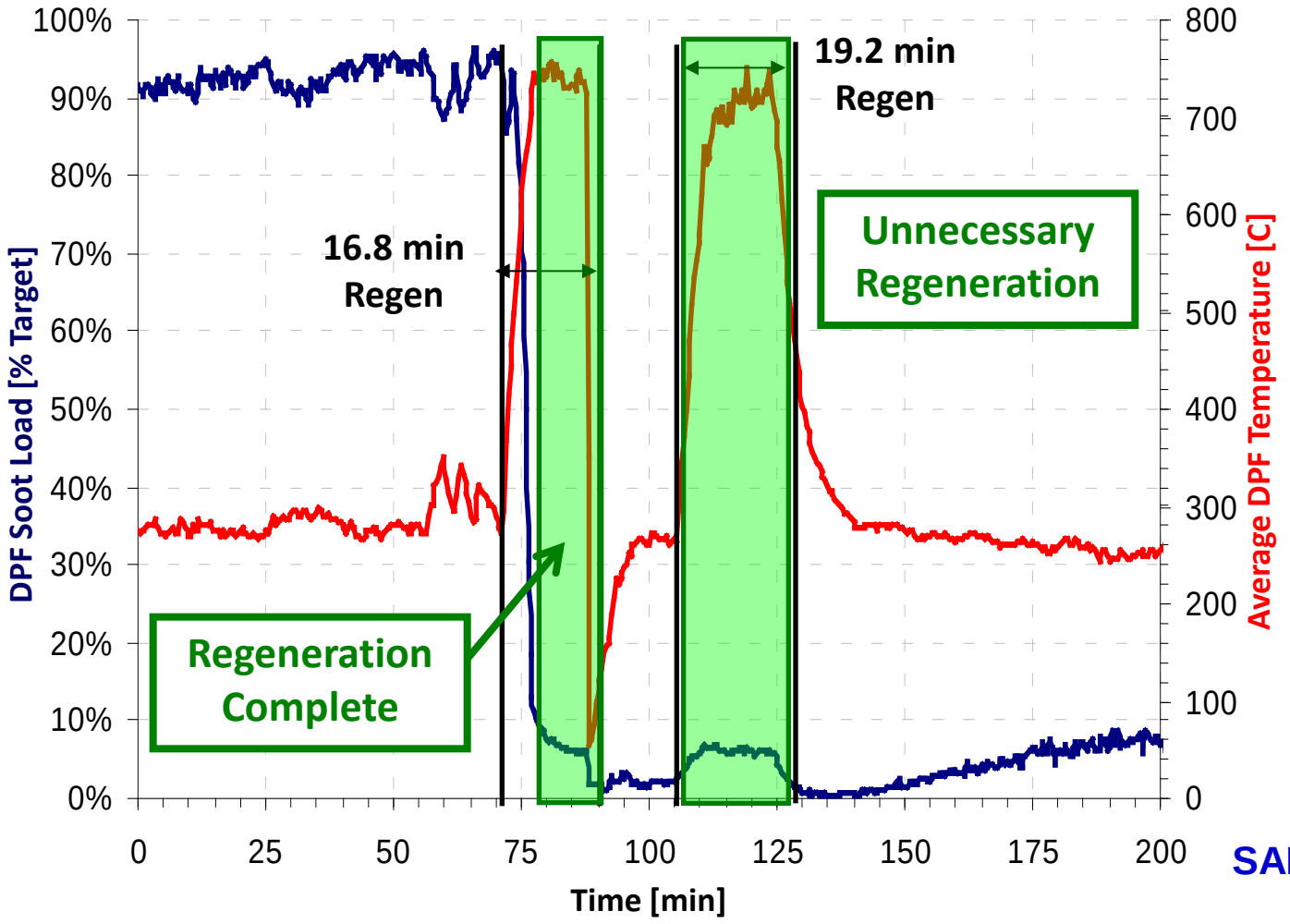
RF sensor measurement data for 150 hr period with stock 2009 Volvo/Mack DPF regeneration control system.



- 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.

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Acknowledgements

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