Efficient Emissions Control for Multi-Mode Lean DI Engines

Presented by Jim Parks

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ACE031

Overview

- Timeline
  - » Start: FY2007
  - » Finish: FY2010
  - » % Complete: ~85%

- Budget
  - » FY08 Funding: $200k
  - » FY09 Funding: $200k
  - » FY10 Funding: $200k

- Barriers
  - » Emissions regulations for advanced lean engine market penetration
    - "An insufficient knowledge base will inhibit the development of advanced LTC or mixed-mode combustion systems…."
    - "Meeting EPA requirements … with little or no fuel economy penalty will be a key factor for market entry …."

- Partners
  - » Catalyst Suppliers
    - Manufacturers of Emissions Controls Association (MECA)
    - AirFlow Catalysts
    - Nanostellar
  - » Filter Sensing Technologies
  - » CLEERS
  - » Other ORNL Projects:
    - Advanced Combustion
    - Joule Milestone
    - Health Impacts

Objectives

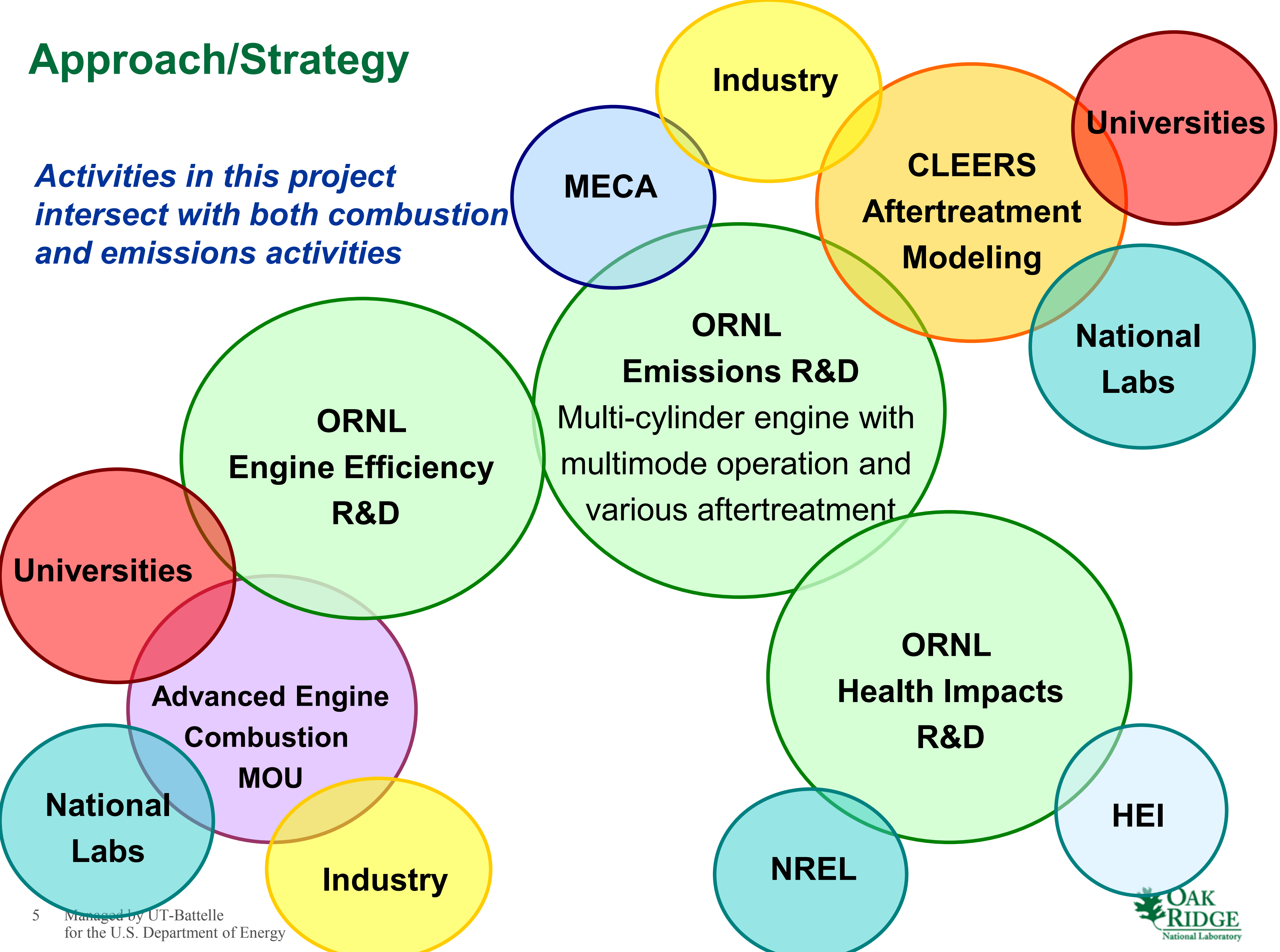
- **Enable efficient lean engine market penetration by meeting emission regulations with efficient, cost effective aftertreatment**
  - » Characterize emissions from ***advanced engine combustion modes*** and define the synergies or incompatibilities with emissions control technologies
    - LNT, Urea SCR, HC-SCR, Lean NOx Catalysis, DPF, Oxidation
  - » Study effect of ***multimode*** operation on system performance
  - » Lower fuel penalty for regeneration
  - » Develop stronger link between bench and full-scale system evaluations
  - » Interact in CLEERS consortium to respond to industry needs and support model development

Milestones

- **FY07:**
  - » Measure the exhaust species including H_2 generated by the indexed cylinder during lean H_2 production and determine the effect on the non-indexed cylinder combustion processes. (September 30, 2007)
- **FY08:**
  - » Couple advanced and conventional (multi-mode) combustion strategies with efficient Lean NOx Trap emission control technologies to estimate FTP emissions from modal points. (September 30, 2008)
- **FY09:**
  - » Exploit synergies of advanced and multi-mode combustion strategies with selective catalytic reduction emission control to estimate FTP efficiency and emissions from modal points in support of emissions part of ACEC goals. (September 30, 2009)
- **FY10:**
  - » Comparison of Cu- and Fe-zeolite Urea-SCR catalyst performance for multimode diesel engine operation. (September 30, 2010)

Approach/Strategy

Activities in this project intersect with both combustion and emissions activities



Technical Accomplishments and Progress

Since last review (May 2009):

- **4-cylinder GM diesel engine fully operational**
  - » Full control with Drivven system
- ★ **Evaluated Radio Frequency-based technology for DPF analysis on-board vehicle with Filter Sensing Technologies**
  - » Results shared at Diesel Cross-Cut meeting and CLEERS workshop
- ★ **Studying emissions from dual fuel combustion approach (via ORNL combustion team and Reitz etal. at University of Wisconsin)**
  - » Dual fuel combustion demonstrated
  - » Shifting to oxidation catalyst studies
- **Conducting Urea-SCR experiments with Multimode operation including HECC**
  - » Plans for hydrocarbon fouling study with bench flow reactor support

★ ***Details Presented On These Topics***

GM 1.9-l, 4-cyl diesel engine

- *High-pressure common rail*
- *Full-pass Drivven control system (5 event)*
- *Variable geometry turbocharger*
- *Cooled EGR*
- *Swirl actuation*

Technical Results – RF Sensor Experiments

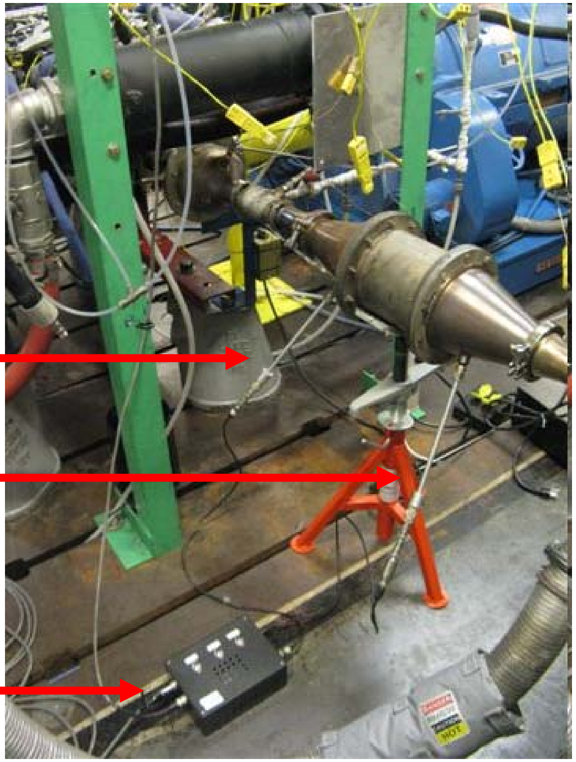
Objective of RF Sensor Studies:

- **Understand DPF diagnostic technology with end goal of better on-board characterization of DPF state to improve DPF regeneration for lower fuel penalty**
- **Characterize features of RF sensor that enable On-Board Diagnostics (OBD) compliance**
  - 2009 CLEERS industry panel discussion:
    - *"Delta P sensors won't cut it."*

Approach of RF Sensor Studies:

- **Partner with Filter Sensing Technologies (FST) to conduct study on ORNL engine platform of FST RF sensor**

RF Sensor and DPF Installed on ORNL engine dyno

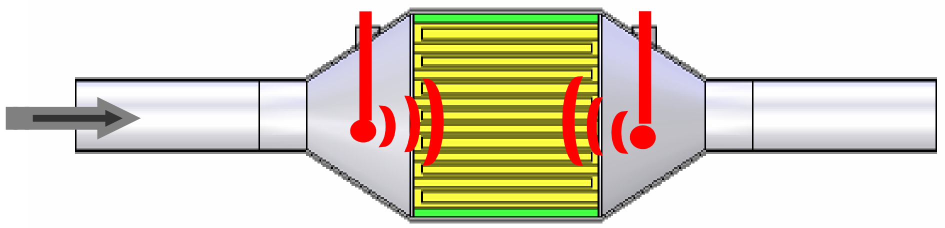


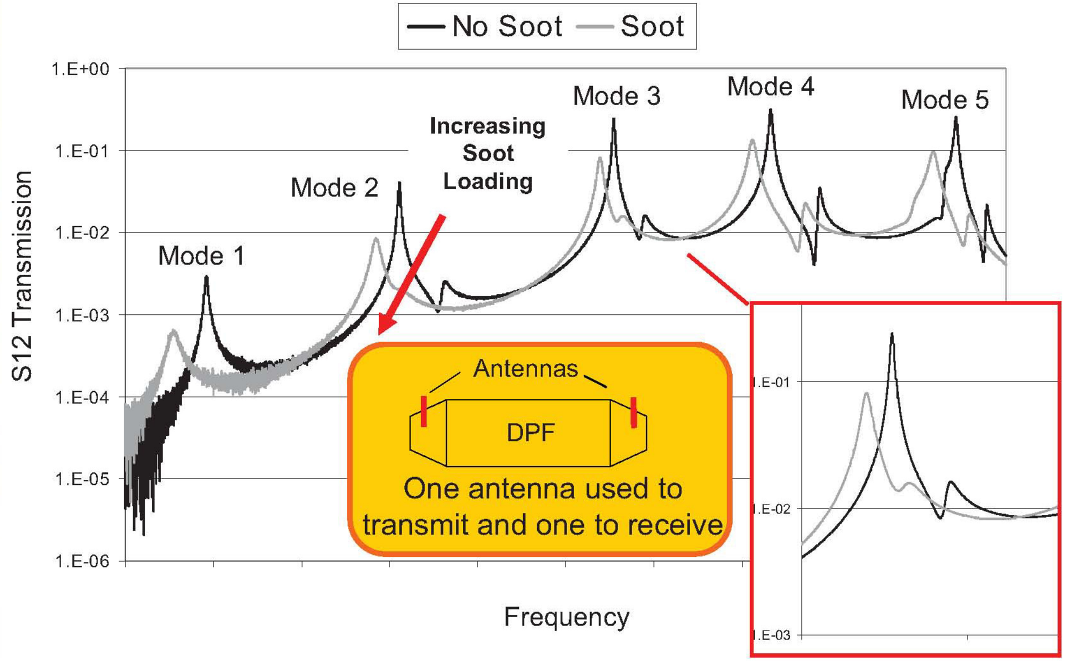
Technical Results – RF Sensor Fundamentals

FST RF Sensor:

- **Antenna placed at DPF inlet and outlet cones for sending and receiving RF signal**
- **Frequency of RF signal scanned**
    - cm-scale wavelengths create localized constructive and destructive zones
    - Resonant modes used to analyze PM loading
    - Modes shift and decrease in intensity with PM/ash loading
    - Multi-frequency approach provides potential for analysis of PM distribution, ash detection, etc.
- **Suitable for variety of DPF substrate materials and geometries**
    - Cordierite studied here

Schematic of RF sensor and DPF





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

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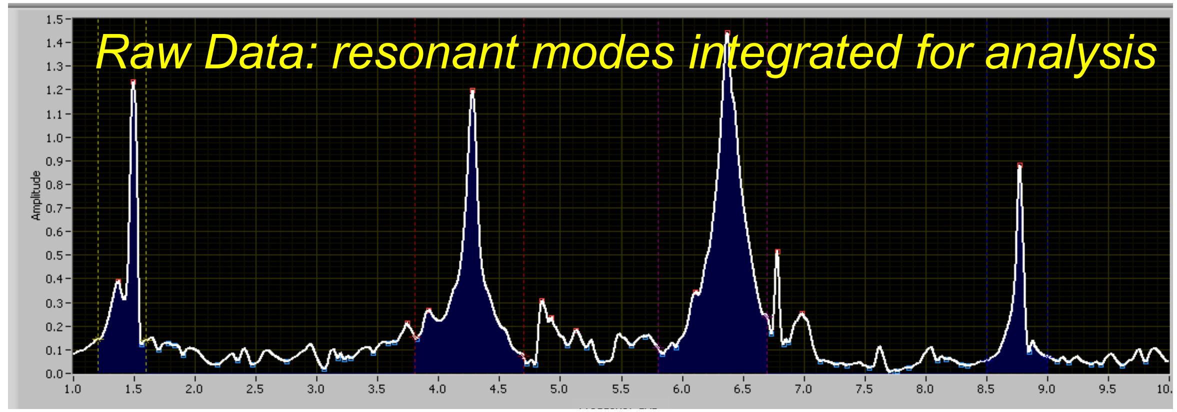
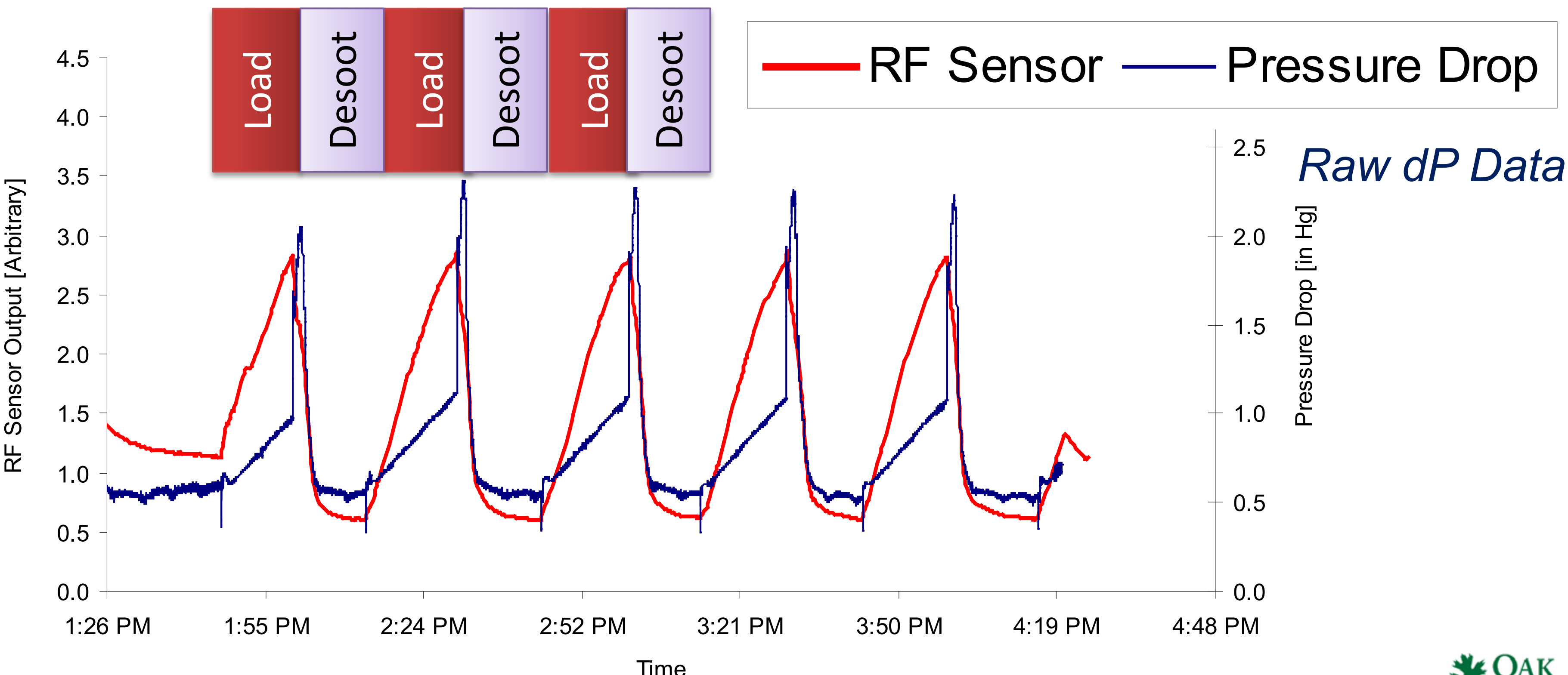
Technical Results – RF Sensor vs. dP Sensor

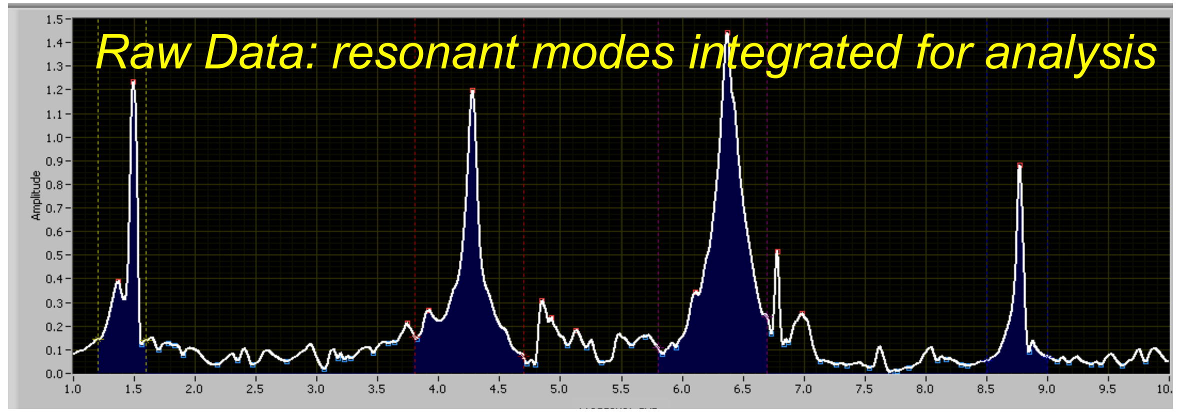
- **DPF load-desoot cycle:**
  - Loading:1500rpm, 50 ft-lb
  - Desoot: 600ºC DPF inlet target
- **Both RF and dP sensors track loading and desoot**
- **dP sensor affected by changes in temperature and flow**

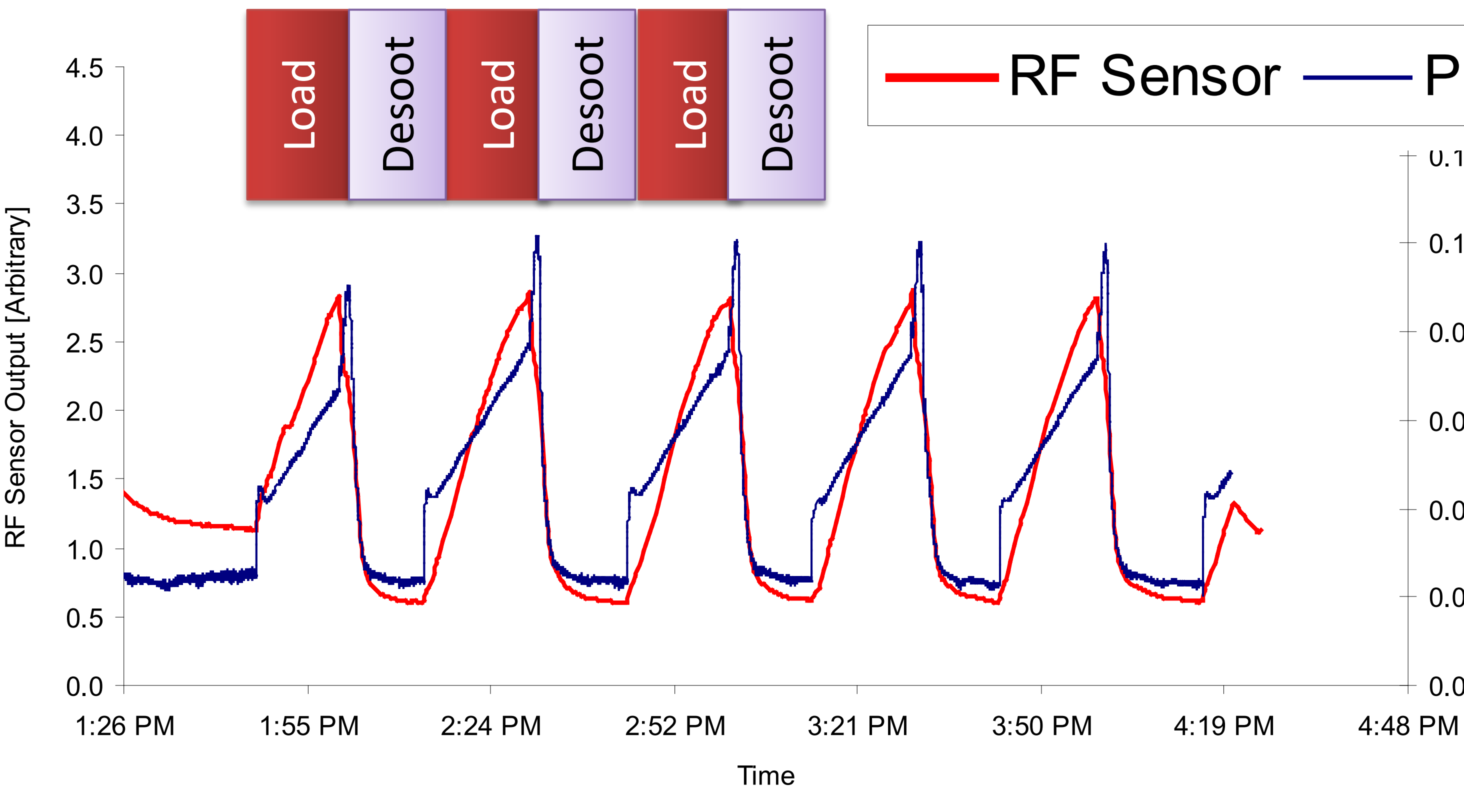




Technical Results – RF Sensor vs. dP Sensor (flow corrected)

- **Both RF and dP sensors track loading and desoot**
- **dP sensor affected by changes in temperature and flow**
  - **correction applied but not perfect**





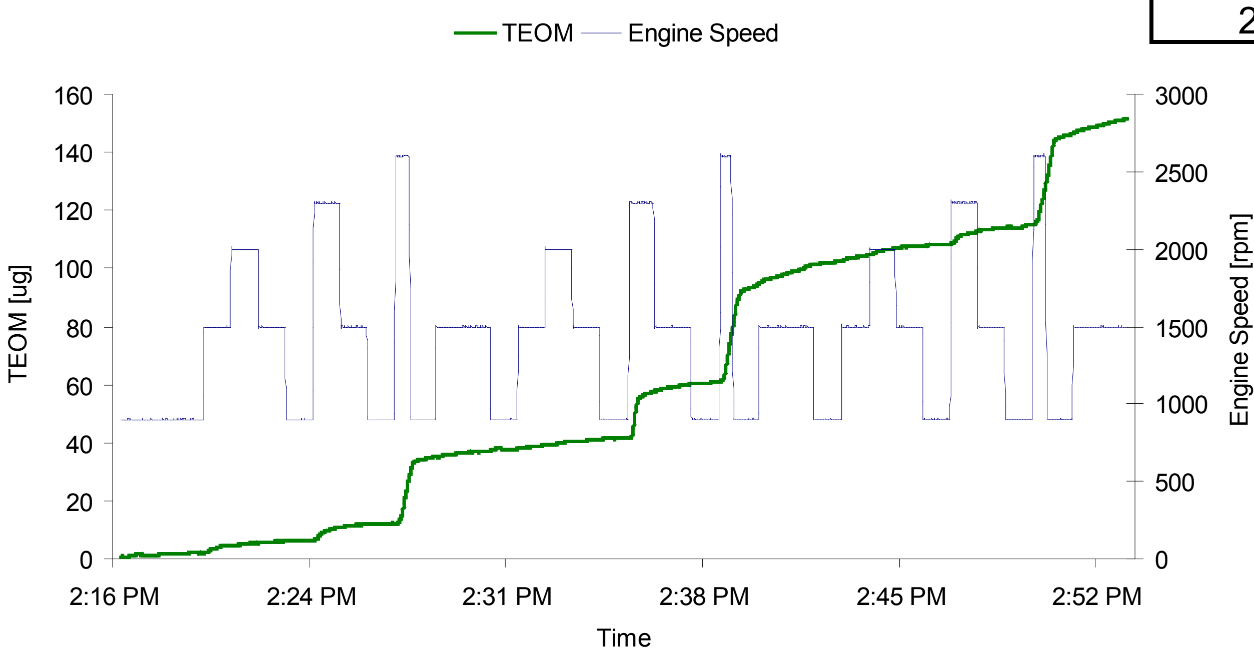
*Flow Corrected dP Data**

**dP/flow rate*

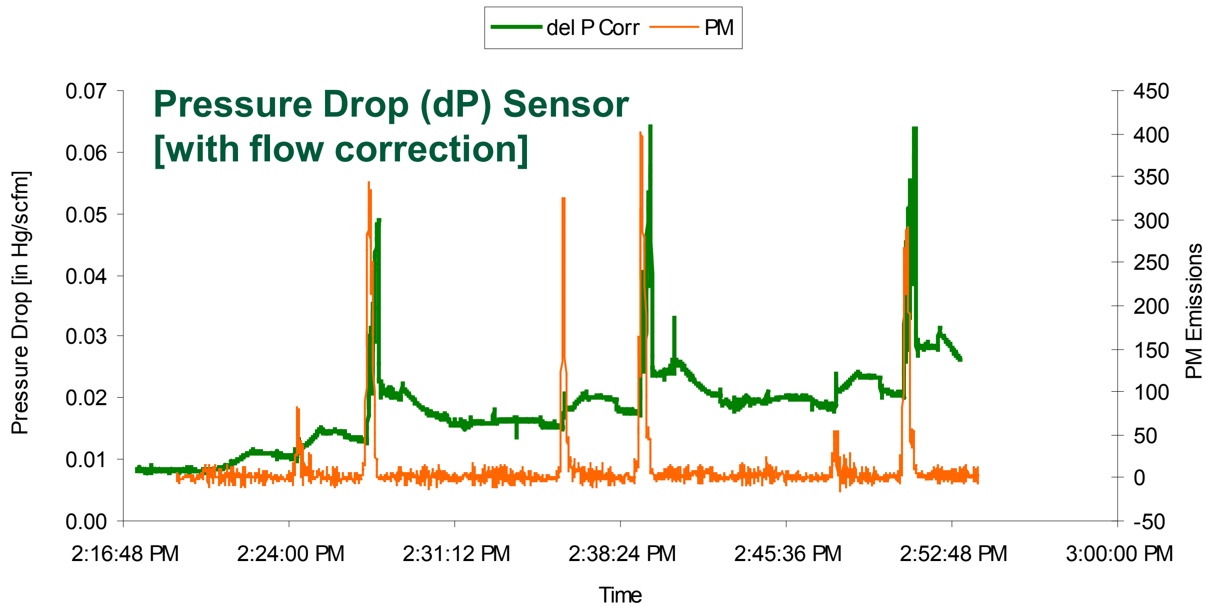
Technical Results – Modal Cycle for Study

- **Modal points from AdHoc working group (as used in past) used to generate step-wise simulation of transient conditions**
- **Highest loads and transitions cause greatest short-term rise in PM emissions**

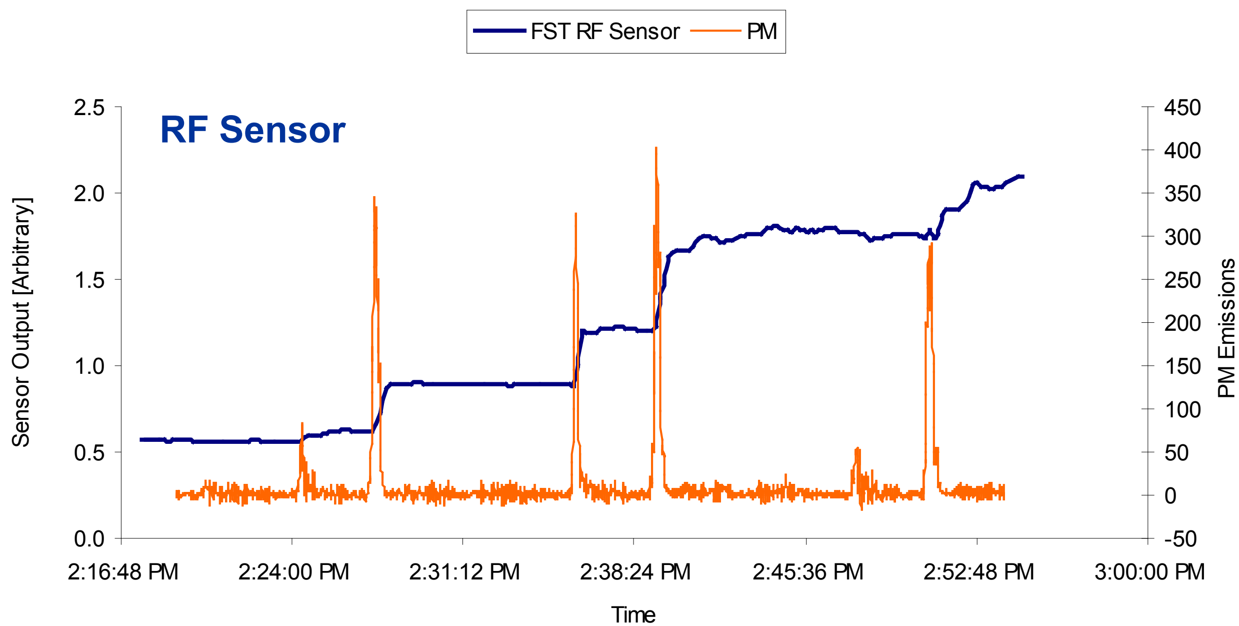
Mode	Speed [rpm]	Load [ft-lb]
0	900	10
2	1500	29.2
3	2000	22.4
1	1500	14.5
0	900	10
4	2300	47.1
2	1500	29.2
0	900	10
5	2600	98.7
0	900	10
1	1500	14.5
2	1500	29.2



Technical Results – Modal Cycle: RF vs. dP



- Although flow correction applied, transient response complicated by exhaust flow rate influence
- Spikes in pressure drop correspond to high exhaust flow rates and elevated soot emissions

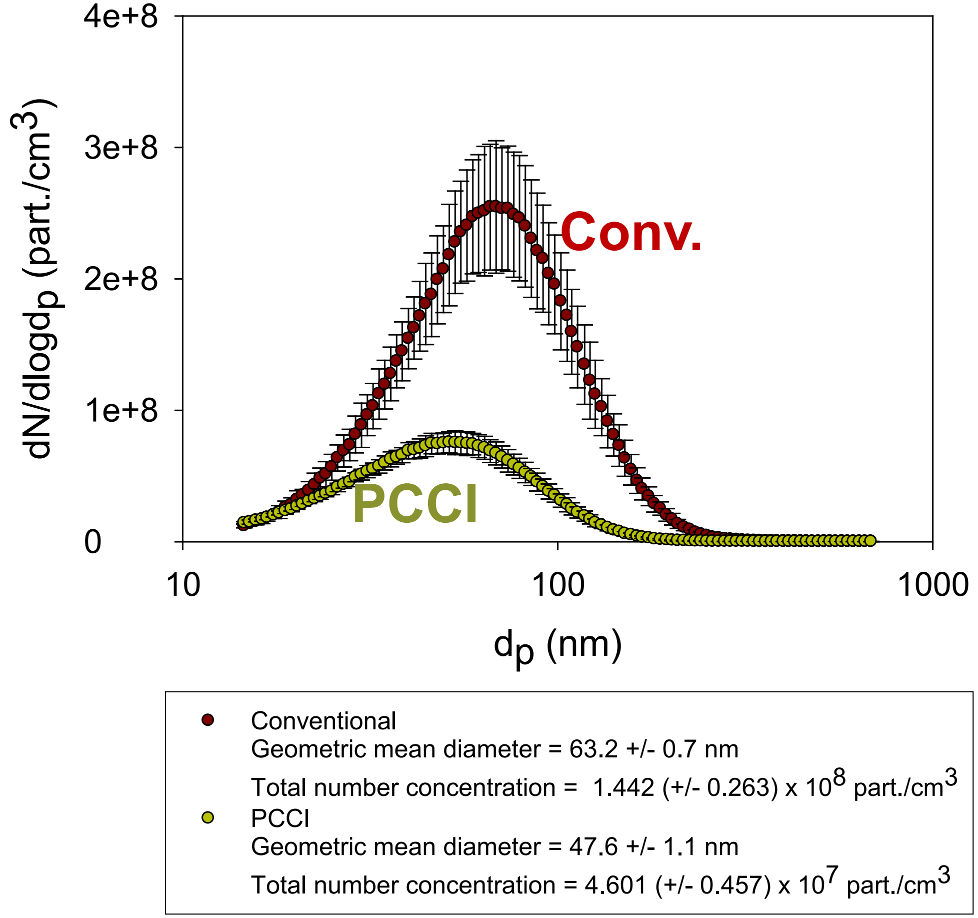


- Good transient response and repeatability
- Not affected by exhaust flow rate variations

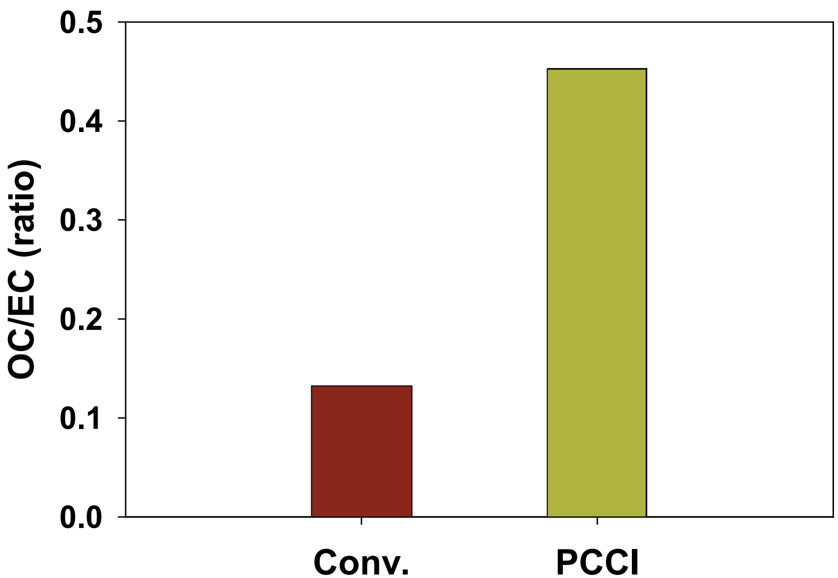
Technical Results – HECC/PCCI PM vs. Conventional(OEM) PM

- **PM from HECC/PCCI (as compared with conventional OEM combustion):**
  - **Lower concentration**
  - **Smaller diameter**
  - **Higher organic content**
- **Note: GM engine shows less PM overall than previous experience with HECC (on older Mercedes engine)**

SMPS Characterization of PM

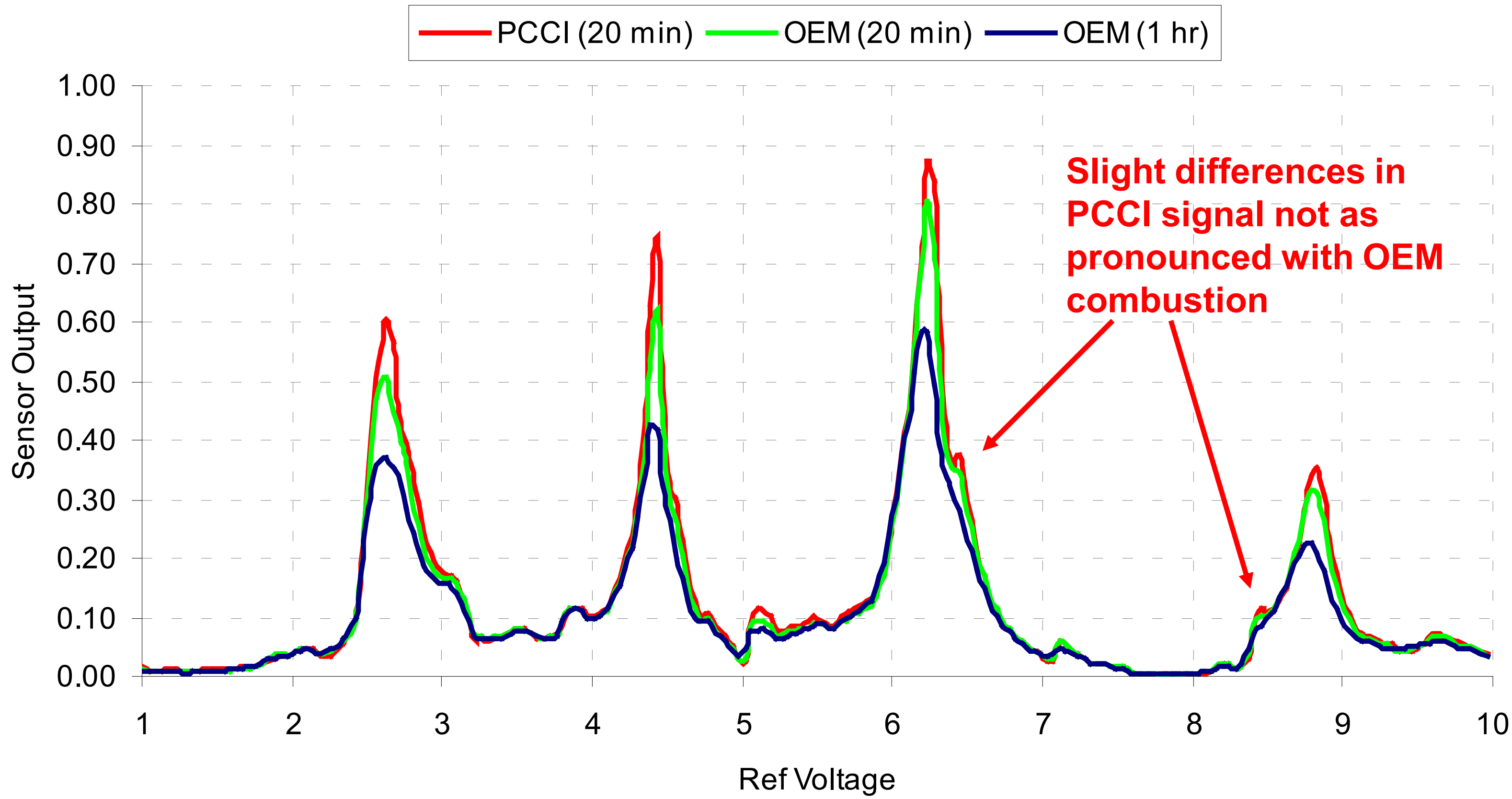


PM Organic Carbon:Elemental Carbon



Technical Results – HECC/PCCI affect on RF signal

- **PCCI and OEM PM stored on DPF showed similar quality for resonant modes indicating filling of DPF similar**
- **Note that Soluble Organic Fraction of PM from PCCI may desorb or oxidize from PM while trapped on DPF**



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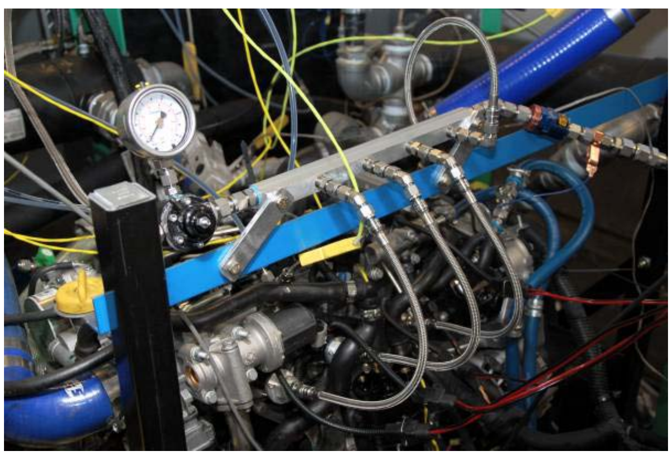
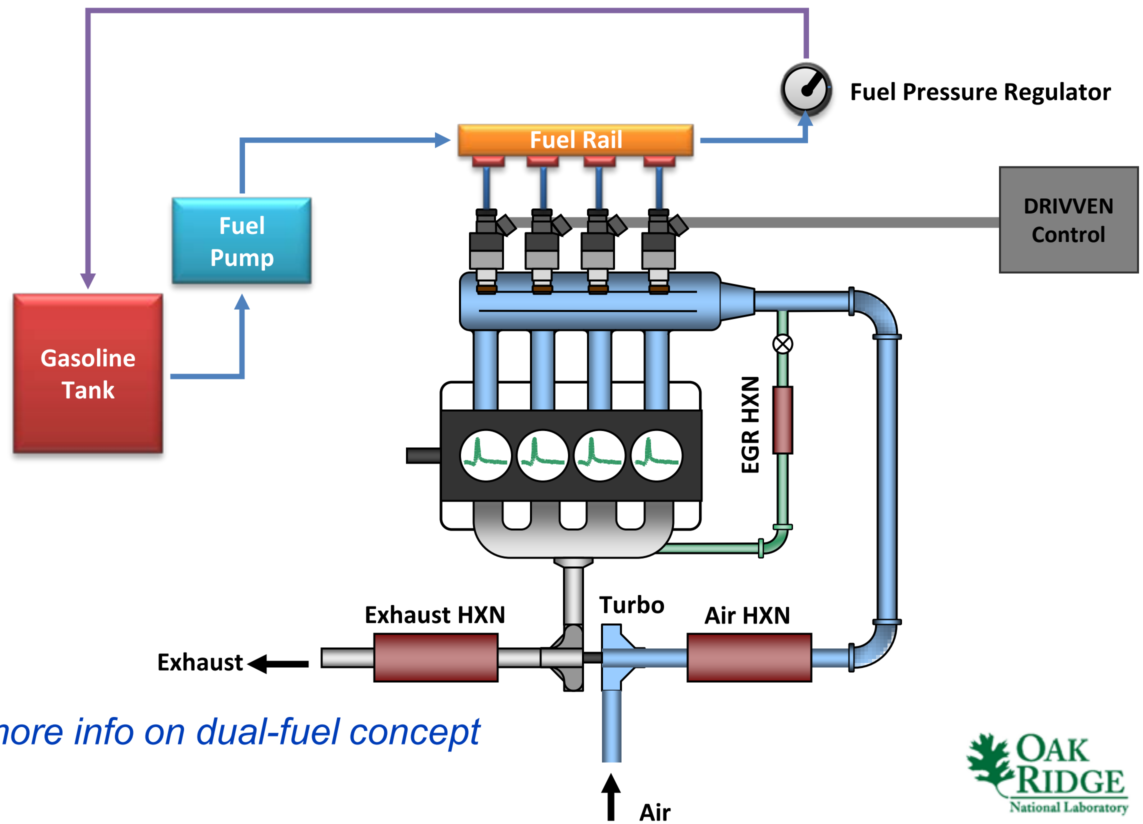
Technical Results – Interim Summary on RF Sensor

- **Observations on RF sensor for DPF diagnostics**
  - » Excellent sensitivity to PM loading
    - best sensitivity at cleanest DPF state
  - » Not sensitive to exhaust flow rate variation (as opposed to DP sensor)
    - Some sensitivity to temperature, but correction possible
  - » Resonant modes observed by scanning RF signal give potential for more detailed analysis of DPF failure/status; details important to capability
    - HECC vs. conventional PM loading did not show appreciable difference in RF sweep at condition studied

Technical Accomplishments: Dual-fuel study

- **Dual-fuel approach shown at Univ. of Wisconsin (UW) to have high indicated thermal efficiency with very low emissions.**
  - » Modeling ~49% Net ITE.
  - » Single-cylinder experiments ~45% Net ITE.
- **ORNL collaborating with UW to compare UW model to ORNL multi-cylinder experimental results** ***[See Wagner talk ACE016 for more info]***
- **This project will focus on emissions control from dual-fuel combustion**





See Kokjohn et al. SAE 2009-01-2647 for more info on dual-fuel concept

Technical Accomplishments: Dual-fuel emissions

- **Experimental observations at ORNL mirrored model predictions by Univ. of Wisconsin**
- **Dramatic reductions in PM and NOx with increasing BTE**
- **High efficiency enabled by Drivven control of gasoline PFI injection timing, advanced diesel timing, cylinder-to-cylinder balancing, swirl valve control, etc.**
- **Ongoing plans for emissions research:**
  - » Characterize hydrocarbon and PM emissions
  - » Study oxidation catalyst control of CO and hydrocarbons (with model and Nanostellar* catalysts)
    - ***See SAE 2008-01-0070 for more info on Nanostellar work***

2300 rpm, 4.2 bar BMEP condition (no EGR)

	Diesel	Dual-Fuel	
Gasoline (%)	0	81	77
Boost (bar)	1.18	1.30	1.20
Swirl DC (%)	32.1	32.2	33.6
BTE (%)	32.1	32.2	33.6
NOx (ppm)	94	5.4	7.5
FSN	1.78	0.02	0.02
CO (ppm)	423	1988	1512
HC (ppm)	296	2669	2581
Exhaust T (C)	412	247	260

Summary of "best case" results seen to date on multi-cylinder engine

Work in progress to characterize these emissions and study oxidation catalyst control

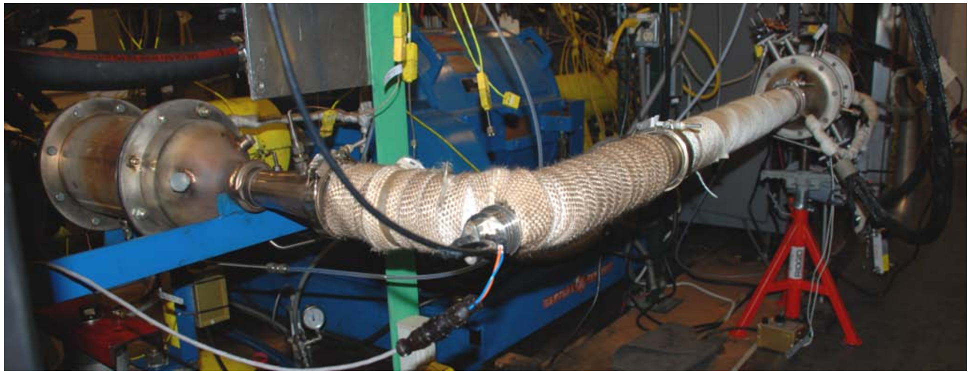
Collaborations

- **Engine/Combustion**
  - » Working internally with ORNL combustion team which in turn works externally with Combustion MOU and Univ. of Wisconsin
  - » GM 1.9-liter platform used widely in research community
- **Emissions and Catalysts**
  - » CLEERS
  - » Catalyst suppliers: MECA, AirFlow Catalysts, Nanostellar
  - » Filter Sensing Technologies (RF sensor)
  - » Thanks to Ford for helping with urea injector (Mike Levin, Zafar Shaikh)

Future Work

- **Remainder of FY2010**
  - » Continue work in progress to characterize dual fuel emissions and oxidation catalyst control
  - » Examine affect of hydrocarbons from HECC on urea-SCR catalyst
    - Planned bench flow reactor analysis of cores exposed to hydrocarbons from HECC

Urea-SCR System



- **Beyond**
  - » Further investigation of emission control for dual fuel combustion approach (other load and speed points)

Summary

- **Focus of project on emissions control from multi-cylinder engine with advanced combustion or multi-modes of combustion**
  - » GM 1.9-liter engine with Drivven controller operational for conventional (OEM), HECC/PCCI, and dual fuel combustion
- **RF sensor evaluated shows promise for better on-board diagnostics**
  - » Technology relevant to industry for OBD (fuel efficient engine enabler) and for lowering fuel penalty (better controls)
- **Dual fuel combustion achieved on multi-cylinder engine; emissions control studies in progress**
- **Plans for rest of FY10 involve examining effects of hydrocarbons from HECC on urea-SCR catalyst**

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