Cummins-ORNL\FEERC Combustion CRADA: Characterization & Reduction of Combustion Variations

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Overview

Timeline

- Start: FY2010
- Current end date: Sept. 2012
- ~80% Complete

Budget

- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2010: $250k
  - FY2011: $400k
  - FY2012: $300k

Barriers

- *Engine combustion*
  - Intake-charge uniformity
  - Combustion uniformity
  - Incomplete combustion
- *Engine controls*
  - Variability & diagnostics
  - Lower penalty control methods
  - Diagnostics for demonstration of improved efficiency control methods
- *Durability*
  - Knock via EGR nonuniformities
  - Corrosion, erosion etc. from nonuniformity induced condensation

Partners

- ORNL & Cummins Inc.
- Cummins HD SuperTruck project

Objectives & Relevance

- **Assess combustion uniformity**
  - **Non-uniformity origins & results, mitigation hardware and strategies**
- **Develop improved methods & tools for enhanced analysis**

- Quantifying spatial & dynamic variations impacting combustion
- Assessment of CFD models
- Identify origins of combustion uniformity
- Assess strategies improving uniformity
- Improve overall efficiency & durability via better cylinder & cycle uniformity
- Better vehicles for consumers
  - ***Higher Efficiency:*** *no limiting cylinder(s), more stable, better OBD control*
  - ***Improved Durability:*** *knock & EGR-loop condensate mitigation*

Milestones

2011 Milestone:

- ✓ Characterize intake EGR variations on development engine at Cummins Technical Center
  - Proof-of-principle focus
  - Assess & refine analysis techniques

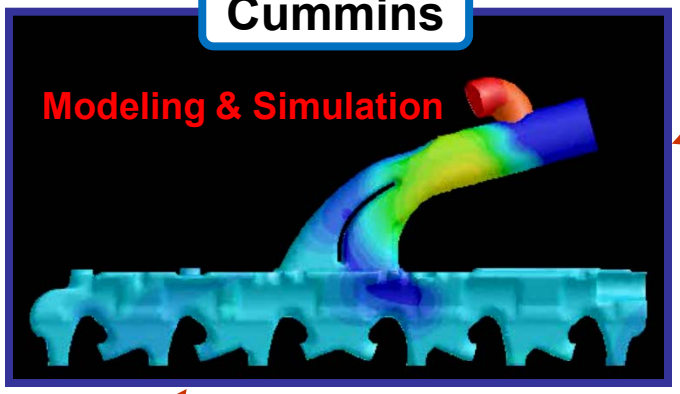
2012 Milestones (on target for Sept. 2012 completion):

- Assess EGR uniformity under typical steady-state & transient conditions
  - Assess specific EGR injection/mixing designs
  - Spatiotemporal variations w/ conditions
  - Correlating EGR uniformity w/ combustion figures of merit

Approach: *Improving Combustion Uniformity Challenges*

Develop & apply advanced diagnostics for engine-system characterization to enable: *model validation, hardware development & controls for fuel efficient engines*

Cummins



Cummins & ORNL

Components, Methods, Systems & Prototypes Assessment

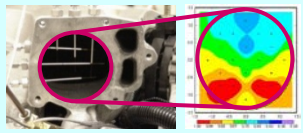
Model Validation

System Studies

ORNL

Diagnostics Development & Applications

- Fast intake & exhaust handling
- In-cylinder residual fraction
- Fueling variations & dilution



Cummins

Controls Development

Clean, Fuel-Efficient, Durable

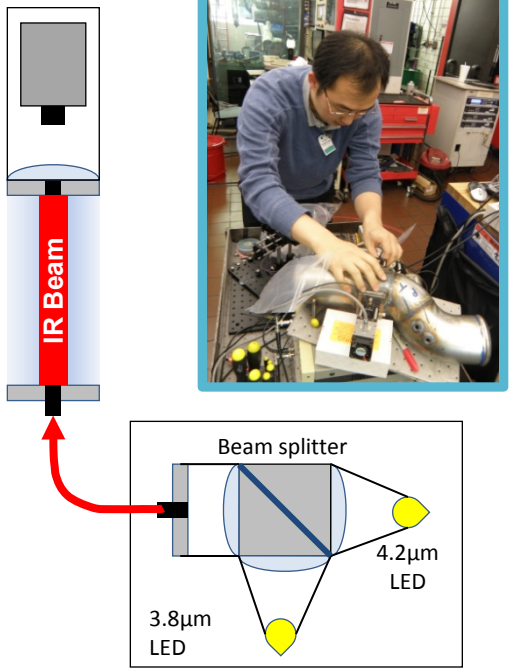
Engines in the Marketplace

Cummins 2007 6.7L ISB

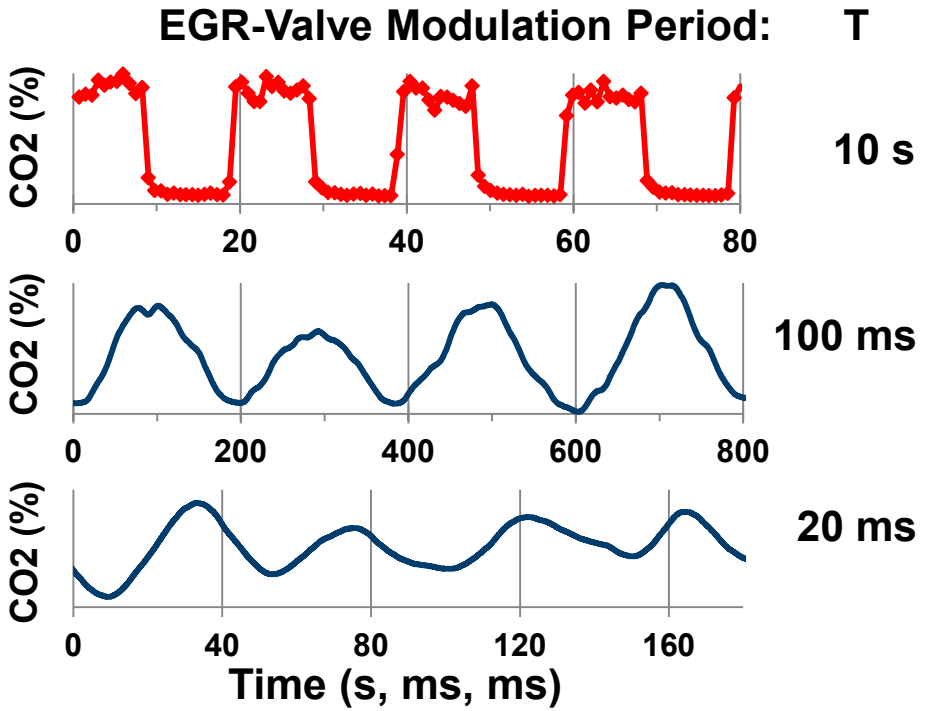
Technical Progress: *Summary*

- **EGR Diagnostic Demonstrated on Engine at Cummins Technical Center**
  - Induced fast (20ms) EGR transients resolved
  - MIR-LED approach applicable to target engine applications
- **Single-Port EGR Probe Developed**
  - Line-of-sight access no longer required
  - Provides for broader engine applications
  - For further-developed & -packaged systems
- **EGR Non-Uniformity & Combustion Variations Resolved at ORNL**
  - Larger Cyl-1 EGR charge; EGR is spatially nonuniform at Cylinder-1 runner
  - Cylinder-specific (~4 ms) EGR events resolved
  - Fast instrument response enables broad development applications
- **Development EGR Hardware & Control Assessed at Cummins**
  - 44% EGR uniformity improvement w/ selected architecture
  - Other results CRADA-protected
  - Data & insights applied to design, control and modeling at Cummins

Technical Progress: *Proof-of-Principle at CTC (April '11)*



Line-of-Sight
Engine Setup



Measurement Setup

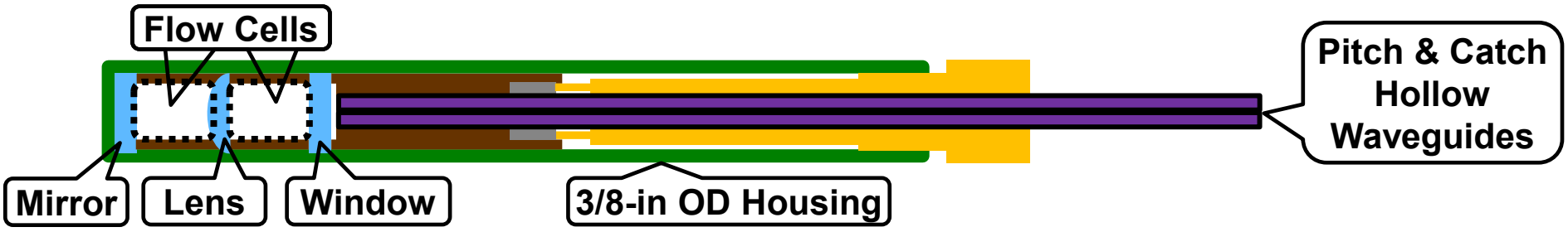
- Filtered Signal & Reference Mid-IR LEDs
- Separate modulation, common detector
- Hollow waveguide delivery
- ***Line-of-sight*** measurement
- Measure adjacent to EGR injection point

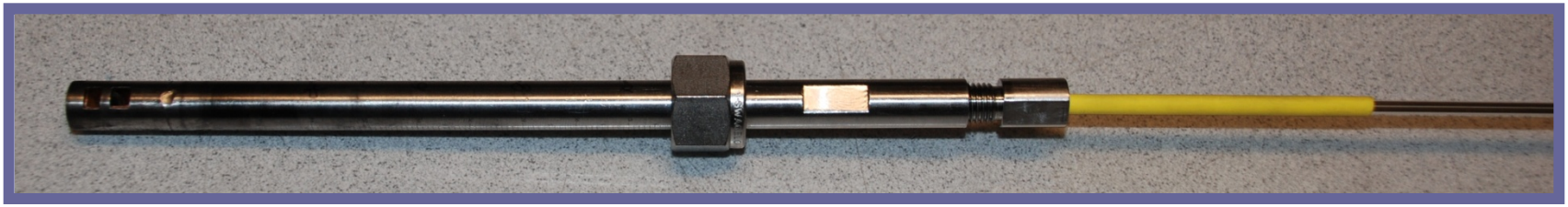
Engine proof-of-principle

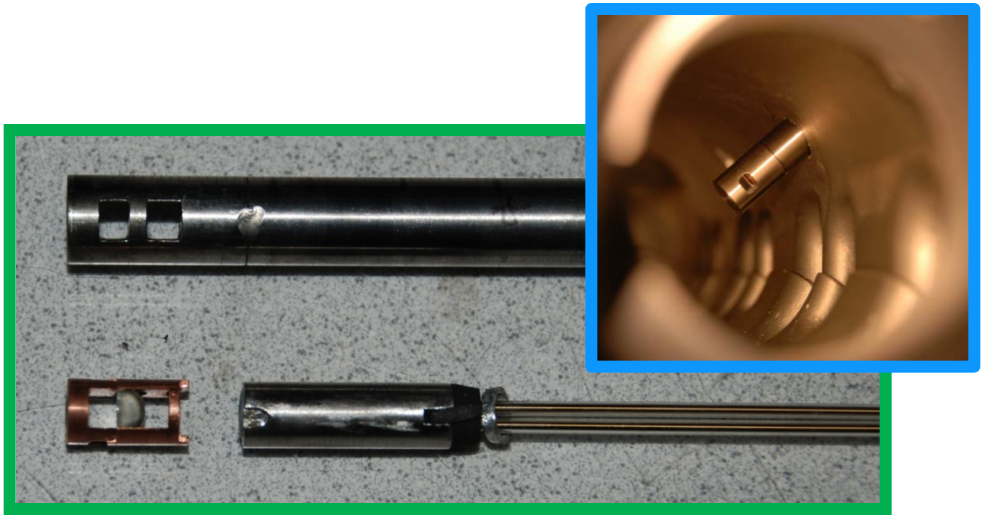
- 20ms EGR fluctuations resolved
- Line-of-sight approach is limiting
  - Developed/packaged engines
  - Resolving spatial gradients

20ms Fluctuations Resolved….Need Single-Port Probe

Technical Progress: *Developing Single-Port EGR Probe*







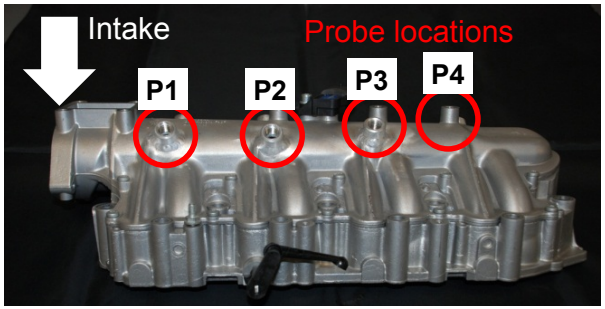
- 3/8-in OD tube housing
- 2x flow cells for improved detection
- Mount via Swagelok Union
  - NPT-3/8” Swage BoreThru
- Non-swaging ferrule for translation

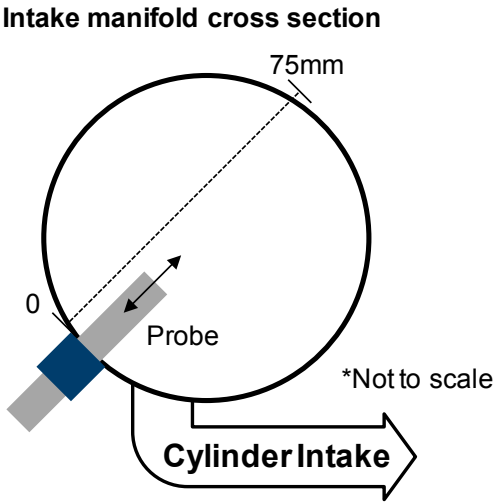
EGR Probe Enables Ready Application to Packaged Engines

Technical Progress: *EGR Probe Assessment at ORNL*

Engine Platform

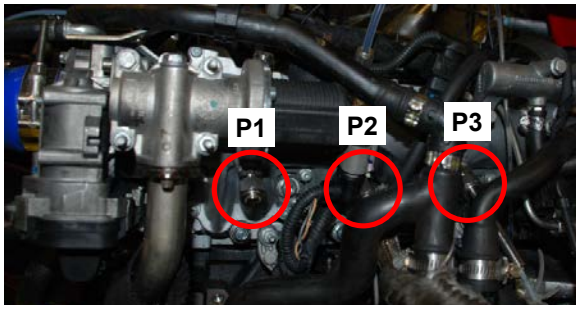
- 4-Cyl, GM 1.9L, DI Diesel
- High pressure cooled EGR





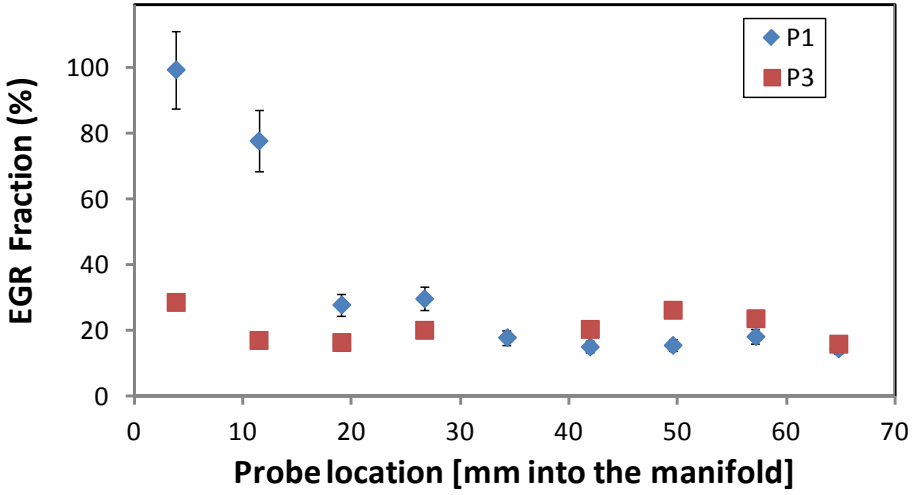
General Observations

- Withstand window fouling
  - Several hrs at dirtiest location (P1)
  - Entire day at cleaner locations (P3)
- Withstand vibrations



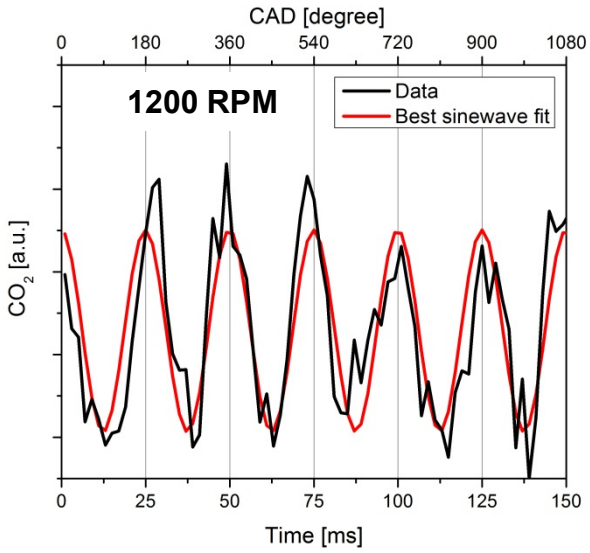
EGR Non-Uniformities Resolved

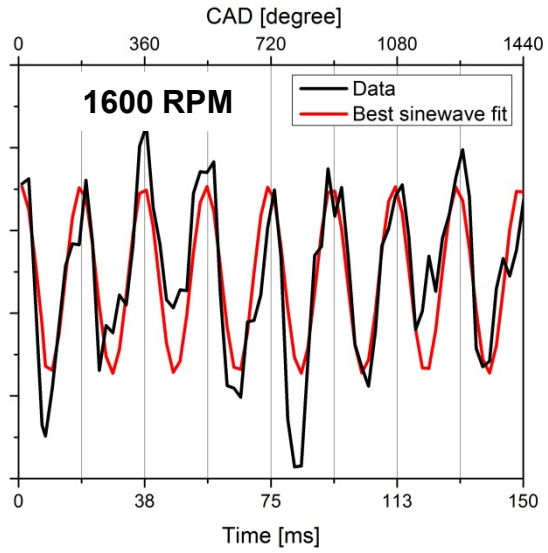
- Dramatic EGR spatial gradient at P1
  - EGR varies 20 to 100% !
  - EGR Highest at intake runner inlet
- EGR fully mixed by P3
- Cylinder 1 likely has higher EGR
  - Correlate w/ combustion merit in future work
- Particulate distribution mirrors EGR

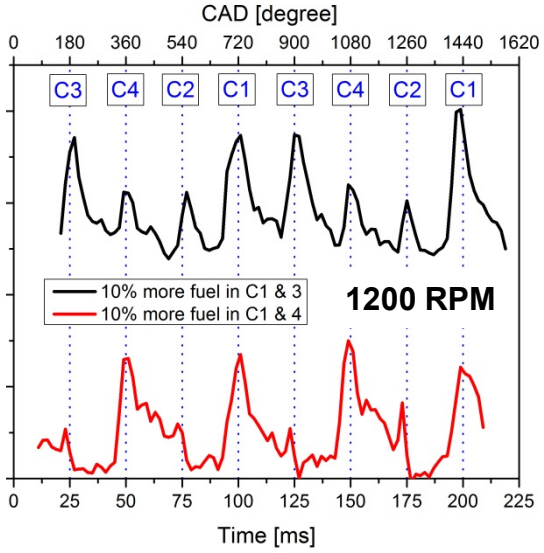


Steady-State Spatial EGR Non-Uniformities Resolved

Technical Progress: *Cylinder-Specific Dynamics Resolved*







Fast fluctuations at constant EGR

- Synchronous w/ engine timing

Cylinder-selective fuel addition

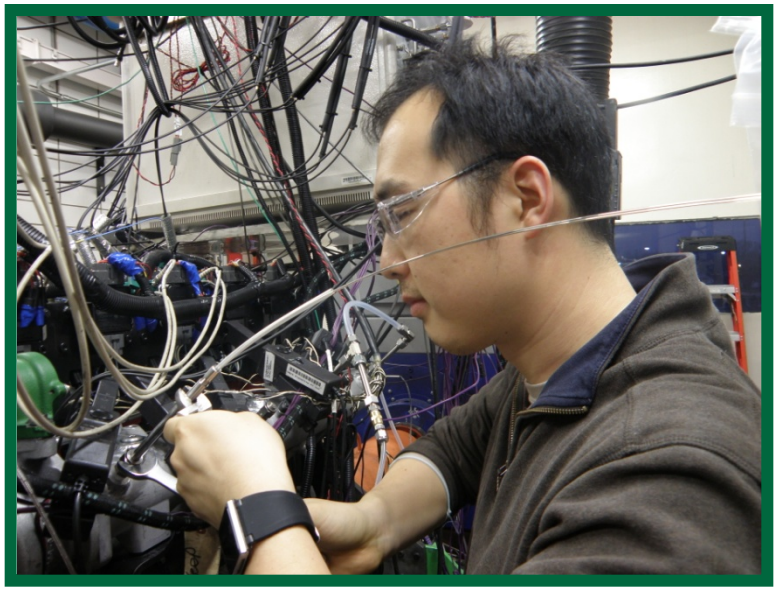
- Cylinder firing order: 1-3-4-2
- Cylinder-specific CO_2 dynamics apparent
  - ca. 4-8 ms $t_{10\text{-}90}$ response

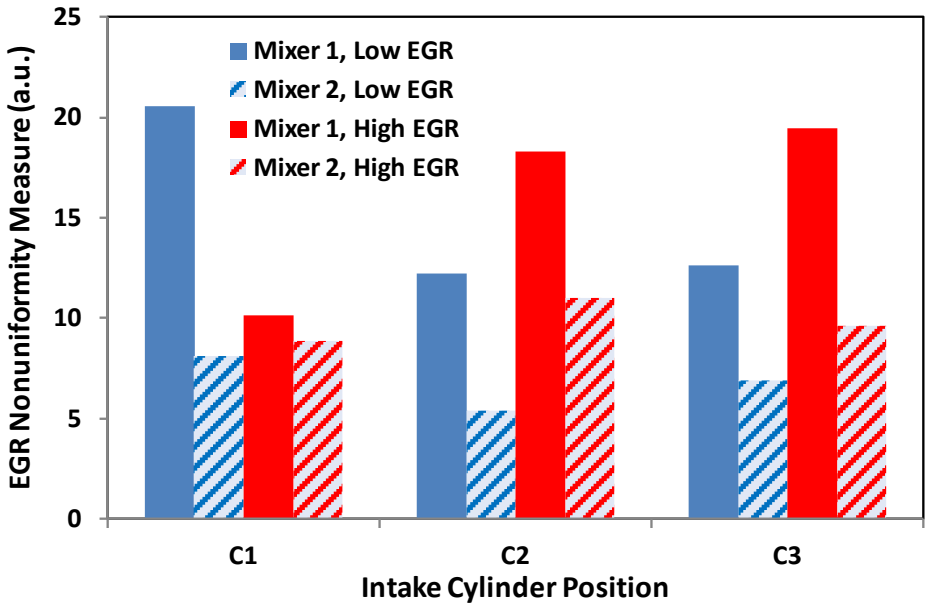
Fast response has broad development applications

- Closed-loop control implementation & evaluation
- Dynamic EGR charge impacts
  - Misfire & incomplete combustion
  - Knock
- Temporal EGR mixing

***Fast* EGR-Probe Enables Efficiency & Durability Advances**

Technical Progress: *EGR Assessment at CTC (Jan.'12)*





- 2 EGR Mixer Designs assessed
- High & low EGR
- Uniformity & Design impact vary w/ location
- Mixer 2 ca. 44% more uniform overall
  - 54% \ 34% better at Low \ High EGR
- Other results CRADA protected
- Applied to design & modeling at Cummins

More 2012 Work Using Simultaneous Multi-EGR Probes

Collaborations & Coordination

- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)
- **Cummins SuperTruck Program**
  - David Koeberlein (Director Advanced Engineering), Rick Booth (Technical Advisor, Gator/Natural Gas Controls Leader)
  - CRADA & SuperTruck projects share monthly telecons
  - Coordination of common development interests
  - Use of CRADA-developed technologies
  - Cooperative development of simultaneous multi-point EGR Probe diagnostic
    - Similar for in-cylinder measurements
  - Adapt EGR-probe to fast AFR\O_2 measurements for closed-loop control application
- **WFO Development Application at Cummins Engine Plant**
  - Ryo Fuchinoue (Technical Specialist, Performance & Emissions Development)
  - Joint application of CRADA-developed technology to meet development milestone on 5.0L V8 engine platform
- **Dissemination via Publications, Presentations and Patents**
  - 4 presentations accepted at CLEERS, ISA and CAPoC9
    - 3 others planned for DEER and ICEC
  - 2 invention disclosures filed based on CRADA technologies

Future Work

2012 Work:

- Analysis of high-speed EGR data from work at Cummins
  - Mine for correlations w/ engine events
- Develop Simultaneous Multi-Point EGR Probe diagnostic
  - Laser based alternative to MIR-LED….for better sensitivity
  - Faster & higher-spatial-density EGR mapping
- Multiplexed EGR-Probe Application at Cummins
  - Assessment of stretch Air/EGR handling hardware
  - Validation and assessment of GTPower development models

2013 Work:

- Development of stretch Air/EGR handling hardware
  - Design and model development
  - Evaluation of spatial and temporal mixing
  - Assessment of control diagnostics and strategies for efficiency gains
- Diagnostic advancement and development
  - Intake charge flow, misfire (not-speed-based detection), O_2, internal residuals

Summary

- CRADA approach effectively addresses major DOE & Cummins goals
  - Improved hardware, modeling & controls for reducing intake-system penalties
  - Improved EGR spatial & temporal uniformity to enable efficiency gains
  - Advanced diagnostics to elucidate the same
  - Enabling improved engine ***efficiency, cost and durability***
- Analytical methods improved to allow broader development applications
  - Single-port EGR Probe
  - Spatial and temporal resolution
  - Enables demonstration and assessment of ***efficiency improving*** closed-loop control strategies
- Quantified effectiveness of intake hardware in new development application
  - Specific architecture provides ~35-55% better performance
  - Other CRADA-protected insights valuable to Cummins' development
- Leveraging collaborations to strengthen CRADA & enhance value
  - Coordination with Cummins' SuperTruck project
  - CRADA technologies used in development outside CRADA to ***realize efficiency improvements***
- Future work focuses on:
  - EGR-Probe improvement for simultaneous multi-point measurement & higher temperature applications
  - Applications to develop stretch air-handling hardware
  - Assessment of models, spatial & temporal mixing, and control diagnostics and strategies
  - Developing diagnostics for addressing the next barriers to ***efficiency improvements***