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

W.P. Partridge (PI), J. Yoo, R.M. Connatser,
V. Prikhodko, R. S.-Gonzalez, J.E. Parks
Oak Ridge National Laboratory

S. Geckler (PI), A. Perfetto, A. Beck, M. Dane, R. Booth, D. Koeberlein
Cummins Inc.

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Presenter: Bill Partridge
partridgewp@ornl.gov

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U.S. DOE Program Management Team:
Ken Howden, Gurpreet Singh, Steve Goguen

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U.S. DEPARTMENT OF ENERGY

Cummins

OAK RIDGE NATIONAL LABORATORY
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Overview

Timeline

- New SOW start: Sept. 2012
- Current end date: Sept. 2015
- ~13% Complete

Budget

- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2011: $400k
  - FY2012: $300k
  - FY2013: $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*
  - Combustion instabilities
  - Corrosion, erosion etc. from nonuniformity induced condensation

Partners

- ORNL & Cummins Inc.
- Cummins HD SuperTruck project

Objectives & Relevance

Validate Numerical Design Tools
to Accelerate Development
of Efficient EGR-Intake & Engine Systems

Objectives

- Assess EGR uniformity & variations: amplitude, distribution & transients
- Correlate transients with exhaust and intake valve events
- Elucidate physics of EGR mixer performance
- Assess specific intake architectures

Relevance - EGR Performance & Uniformity impacts:

- Charge & combustion uniformity
- Required engineering margins (efficiency penalty, fuel economy)
- Ultimate efficiency limits across all cylinders
- Durability

Milestones

2012 Milestone:

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

2013 Milestones (on target for Sept. 2013 completion):

- Apply EGR Probe to assess:
  - ✓ Spatiotemporal performance of advanced intake architectures,
  - Performance of numerical-simulation design tools used for development
- Follow-on campaign at Cummins to assess design modification
- Improve EGR Probe based on campaign findings:
  - Identify periodic interference
  - Resolved probe-to-probe variations

Global Approach for Improving Energy Security

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

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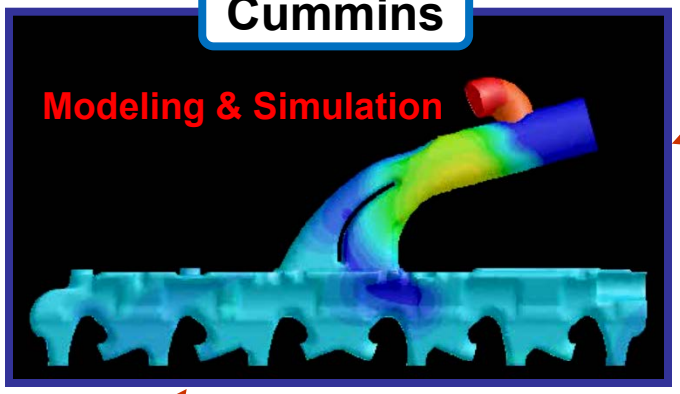


Cummins & ORNL

Components, Methods, Systems & Prototypes Assessment

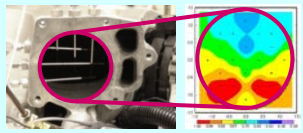
Model Validation

System Studies

ORNL

Diagnostics Development & Applications

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



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Controls Development

Clean, Fuel-Efficient, Durable

Engines in the Marketplace

Cummins 2007 6.7L ISB

Detailed Approach for 2013 Objectives

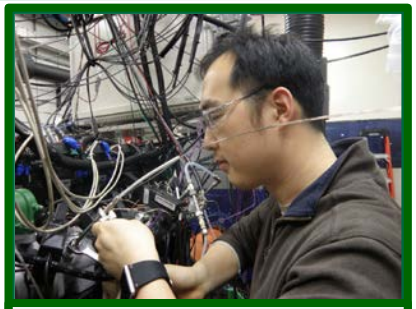
Develop & Apply Advanced Diagnostics

to Enable Next-Generation Engine-Efficiency Advances

- Identify efficiency barrier
  - Robust design tools needed to accelerate efficient engine development
- Apply Numerical Design Tools to:
  - Design intake-EGR architectures that stretch Tool applications
  - Predict characteristic behaviors & performance figures of merit
- Fabricate intake-EGR hardware & implement on engine
- Develop diagnostic to measure predicted performance figures of merit
  - Develop laser-based multiplex EGR Probe
  - Lab & Engine-based development at ORNL
- Apply EGR Probe at Cummins to characterize EGR performance
- Assess Design Tools based on measurements comparisons
- Accelerate development of low-cost Clean, Fuel-Efficient & Durable engines

Technical Progress: *Summary*

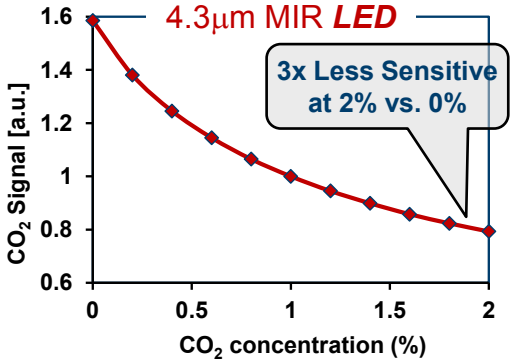
- **Background: EGR Probe based on 4.3μm MIR LED**
  - Robust, agile & spatially resolved measurement w/ EGR Probe
  - Fast measurement resolves cycle, cylinder and valve events
- **Switch to Narrow-Linewidth 2.7μm Laser Source**
  - Greater & linear sensitivity at higher EGR levels
  - Faster temporal resolution
  - Enables multiplexing
  - Allows for simultaneous fast temperature & pressure measurements
- **Multiplex EGR Probes**
  - Multiple probes at different locations
  - More extensive mapping & assessment
- **Map Spatiotemporal Nature of Advanced EGR-Intake Architecture**
  - Detailed results are CRADA protected
  - Crank-angle and ~cm resolutions
- **Assess Numerical Design Tools for Specific Development Application**
  - EGR Probe measured amplitude and temporal variations predicted by model

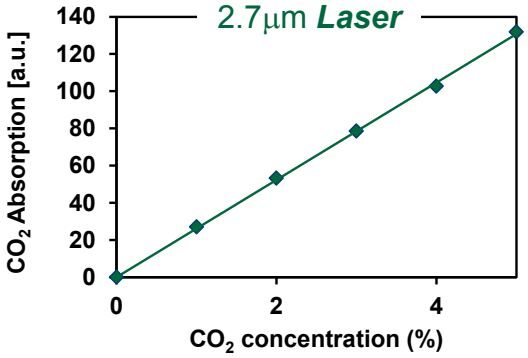


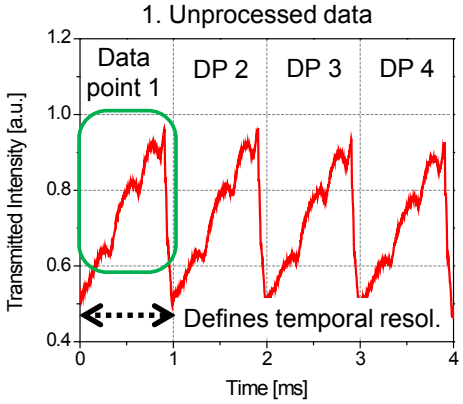
Post Doc Dr. Jon Yoo Adjusting EGR Probe at Cummins

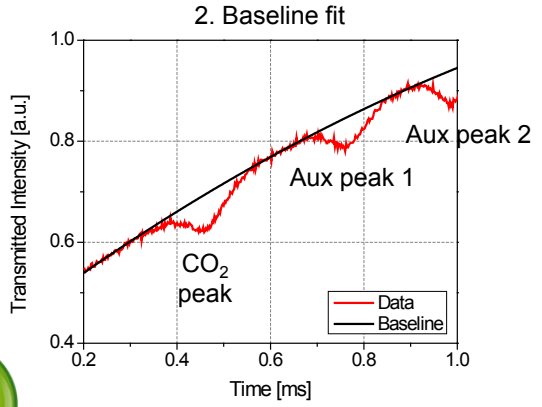
(3 Trips in 2012)

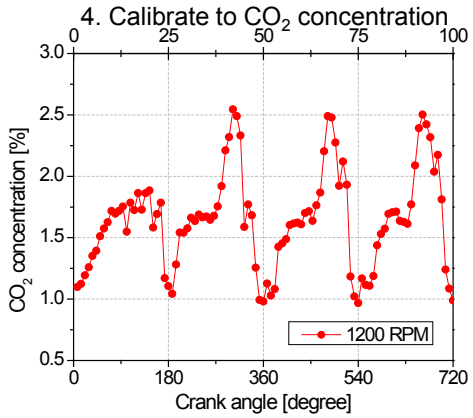
Improve EGR Probe by replacing MIR LEDs with 2.7μm Laser

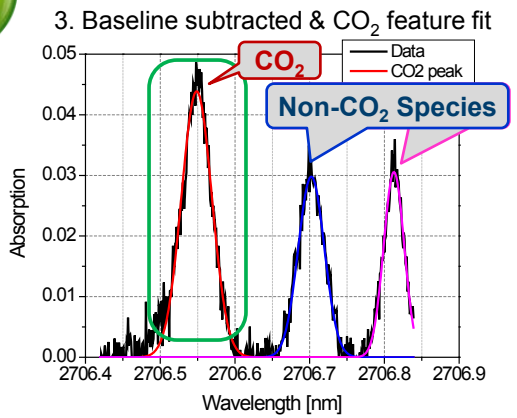








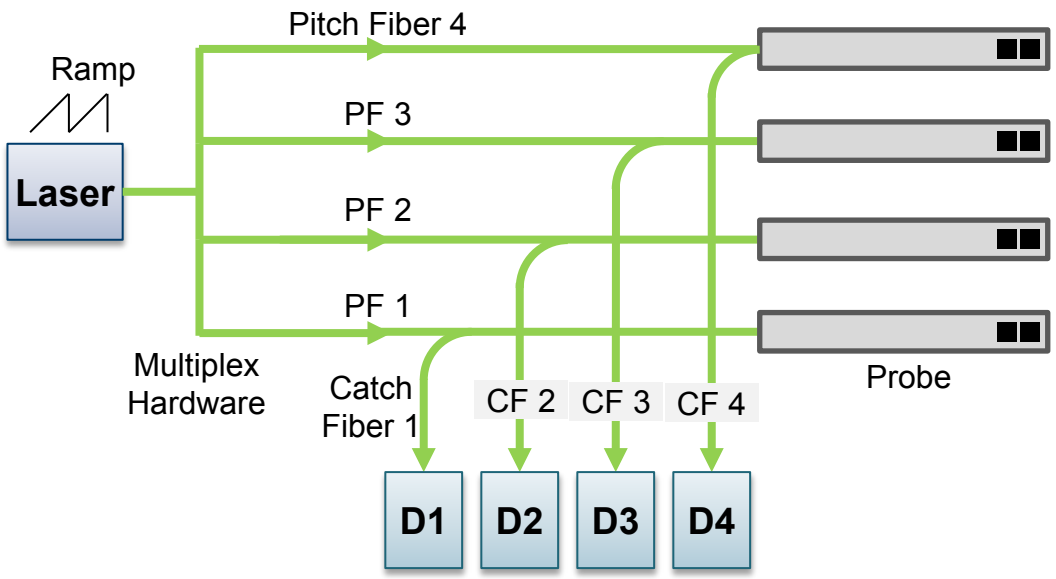


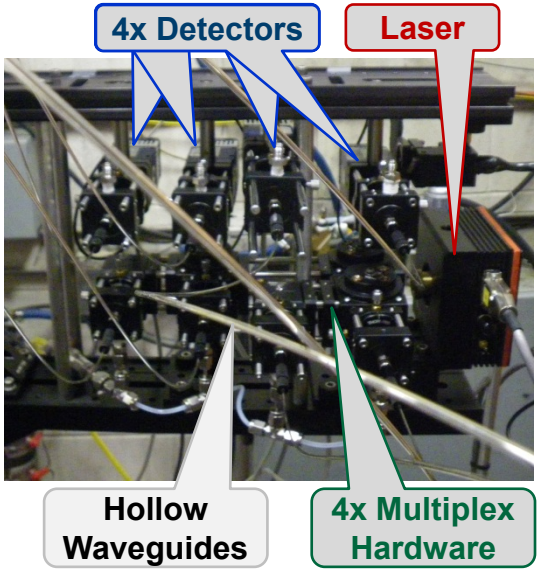


Laser Benefits:

- Linear sensitivity over wide CO_2 range
- More power, ca. 400x:
  - Better signal-to-noise
  - Faster measurements (~20-50X @ 100kHz)
  - Enables multi-probe multiplexing
- Narrow linewidth
  - Spectrally discriminate interfering species
  - Detect CO_2 line broadening w/ Δ pressure
- Wavelength-Modulation Spectroscopy
  - Better SNR & less low-*f* interferences
- Simultaneous P & T measurements

Multiplex EGR Probes Accelerate Engine Design Advances





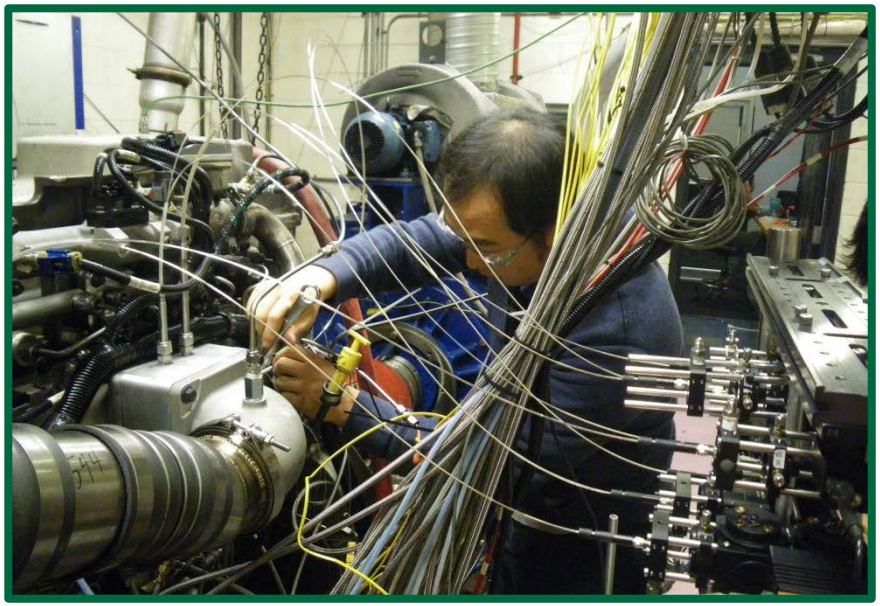
Multiplex Approach:

- Laser divided into 4 beams
- Each beam routed to an EGR Probe
- Dedicated detectors for each probe
- Simultaneous 4x measurements

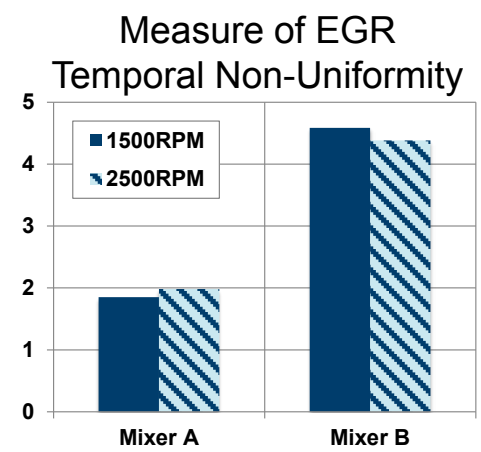
Multiplex Benefits:

- Multiple probes at different locations
- More extensive uniformity mapping
- Accelerated validation & development

Map Spatiotemporal Nature of Advanced EGR-Intake Architecture



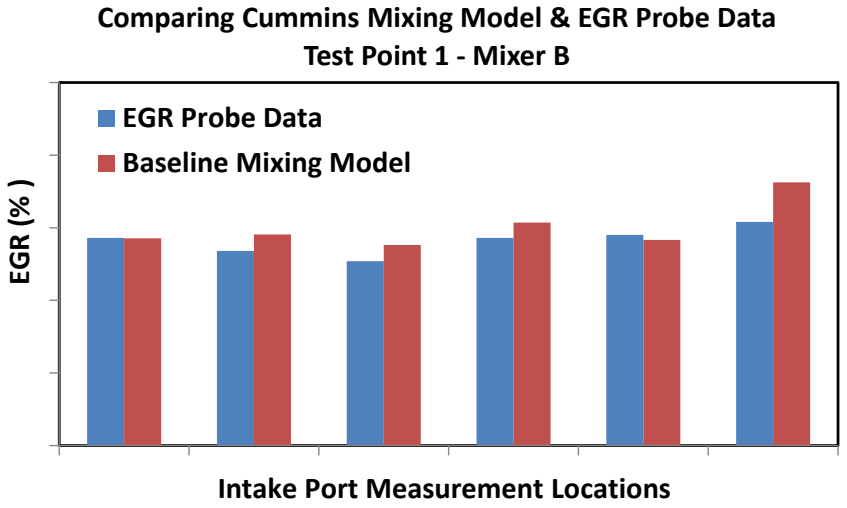
EGR Probe Measurements at Cummins

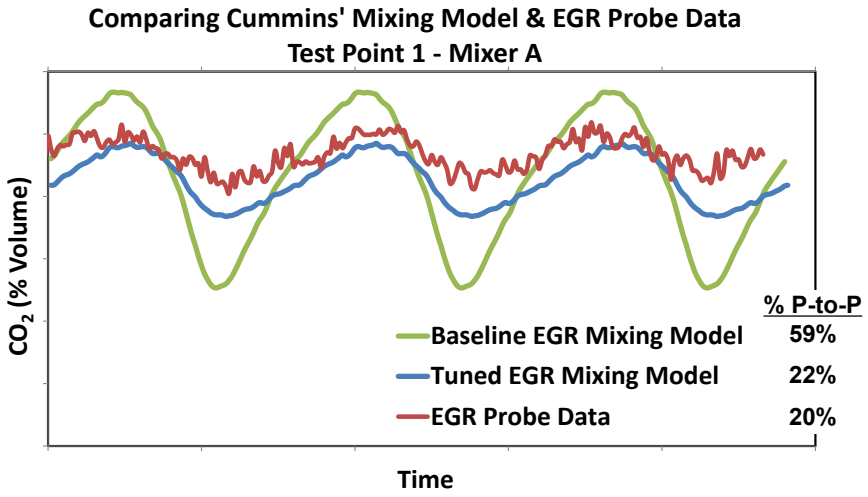


- Measurements at Cummins Oct., 2012
  - Next-generation efficiency platform
  - 2nd SuperTruck campaign in December
    - 55% Break Thermal Efficiency
    - See Koeberlein ACE057, Thursday 1:45pm
- Focus on spatial & temporal EGR mixing
  - Magnitude & frequency of dynamics
  - Timing vs. intake & exhaust valve events
- Numerical models used for design
  - Predicts EGR uniformity performance
  - Compare predictions to measurements

Cummins using data to assess design models & decisions

EGR Probe Improves Spatial-Temporal Mixing Model





Intake Runner-to-Runner variations:

- Ideally all bars are the same height
  - i.e., same R-to-R EGR charge
- Model & Measurement comparison
  - Same Max & Min cylinder predicted
  - Different R-to-R patterns
  - But differences are usually < 3-8%
- Certain ports have regularly greater variations

Temporal variations:

- Shows need to resolved EGR dynamics
  - e.g., vs. intake-valve timing
- Model & Measurement comparison
  - Same phase, frequency & shape
- Model tuned based on measurements
  - Improves amplitude & shape match
  - Tuning requirements give model insights
- Analysis ongoing for other conditions

EGR Probe Enables Design Model Improvement for Accelerating Development of Fuel-Efficient Engine systems

Collaborations & Coordination

- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)
- **Cummins SuperTruck Program (ACE057, Thursday 1:45pm)**
  - David Koeberlein (PI), Rick Booth
  - ***Multiplex EGR Probe applied to SuperTruck December 2012***
  - Cooperative development of Multiplex EGR Probe
  - CRADA & SuperTruck projects share monthly telecons
  - Coordination of common development interests
  - Use of CRADA-developed technologies
- **Dissemination via Publications, Presentations and Patents**
  - **1 Patent allowed:** re. transient particulate sensing
  - **1 Invention Disclosure filed:** re. multiplex laser-based EGR Probe
  - 5 oral presentations (3 invited)
  - 2 Invited Presentations of EGR Probe diagnostic & applications
    - **CLEERS Teleconference, June 2012**
    - **ACEC & Diesel Crosscut Team meeting, January 2013**
  - 2 poster presentations
    - DEER, International Symposium on Combustion

Future Work

2013 Work:

- Assess performance numerical design tools
  - Finalize comparisons between measurement & models
- Assess detailed physics driving observed performance
  - Investigate EGR-Probe insights to enable further performance enhancement
- Assess EGR Probe interferences & probe-to-probe variations
- Study & downselect next major CRADA research thrust technology
  - Characterizing cylinder residual (ex- & in-cylinder methods)
  - In-cylinder temperatures
  - Ignition visualization
  - H_2 & HC characterization
- Initial development of down-selected technology

2014 Work:

- Develop down-selected technology
  - Iterating between lab & engine cell at ORNL
- Proof of principal demonstration at Cummins
  - Further refinement at ORNL as necessary
- Applications at Cummins for engine-technology development

Summary

- **Relevance**
  - CRADA work enables improved cylinder-to-cylinder & cycle-to-cycle combustion uniformity
  - This in turn enables improved fuel efficiency and durability
- **Approach**
  - Develop diagnostic to characterize EGR spatial & temporal uniformity
  - Apply EGR Probe to assess specific hardware architectures
  - Apply EGR Probe data to validate and improve design models
- **Technical Accomplishments**
  - EGR Probe improved for more sensitive, accurate, interference free measurements
  - 3 EGR Probe measurement campaigns at Cummins in 2012
  - Data used to improve design models & accelerate development of efficient engine systems
- **Collaborations**
  - Application of EGR Probe to Cummins' SuperTruck 55% BTE Goals
  - Presentations to CLEERS and ACEC Technical Team, Patents & Invention disclosures
  - EGR Probe available to users outside the CRADA
- **Future Work**
  - Analysis & tuning of EGR mixing model – identify mixing and model-data difference origins
  - EGR Probe Improvements : interference identification & probe-to-probe variations
  - Diagnostic identification & development for addressing next-generation efficiency barriers