This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline
- Current end date: Sept. 2015
- ~53% Complete

Budget
- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2012: $300k
  - FY2013: $300k
  - FY2014: $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

Understand Nature of Cylinder Charge Fluctuations
to Accelerate Development
of Advanced Efficiency Engine Systems

Objectives

- Assess fluctuations in cylinder-charge components
  - Internal EGR (residual & rebreathed residual-backflow)
  - External EGR & intake air
- Apply insights to advance development
  - Validate & tune 1-D & 3-D design models
  - Assess specific hardware & architectures
  - Assess control strategies

Relevance – Charge Uniformity impacts:

- Combustion uniformity
- Performance of advanced-combustion strategies (RCCI, PPCI)
- Required engineering margins (efficiency penalty, fuel economy)
- Durability & ultimate efficiency limits across all cylinders
Milestones

2013 Milestones:

- 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
  - Canceled due to budget sequester
  - Alternate engine work at ORNL to forward CRADA goals
- Improve EGR Probe based on campaign findings:
  - Resolved probe-to-probe variations

2014 Milestone (on schedule for timely completion):

- Specify second laser for quantifying intake & residual-backflow CO$_2$ (Q1)
  - i.e., external & internal EGR
- Assess methods for differentiating intake and residual-backflow CO$_2$. (Q2)
  - Measure H$_2$O, Temperature & CO$_2$
- Bench-level demonstrate of method for CO$_2$ differentiation. (Q3)
- Method assessment for measuring cylinder-residual variations. (Q4)
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**
Develop diagnostic to directly characterize backflow & external EGR-Air
- CO₂, H₂O, Temperature

Develop procedure to determine net-charge nature from components
- Directly measure residual backflow & external-EGR-Air
- Characterize residual from backflow measurements & models
- Weighted temporal integration to determine net-charge characteristics

Apply at Cummins to characterize cylinder-charge dynamics
- Spatial & temporal backflow mapping
- Assess design tools
- Assess advanced control strategies for viability & efficiency gains

Accelerate development of low-cost Clean, Fuel-Efficient & Durable engines.
Technical Progress: *Summary*

- **Background: Laser-based Multiplex EGR Probe**
  - 4 simultaneous probes – faster & more extensive mapping
  - Improved sensitivity, linearity and temporal resolution

- **Characterizing Charge Components & Fluctuations**
  - Directly measure residual backflow & external EGR
  - Measurements & models to identify cylinder-residual nature
  - Assessing cylinder charge & advanced control strategies

- **Developing Multi-Color Multi-Species EGR Probe**
  - Measures CO₂, H₂O & Temperature of cylinder-charge components
  - Quantifies both hot (backflow) and cool (external EGR) species
  - Improved characterization of cylinder charge

- **New EGR Probe Tip for End-On-Flow Orientations**
  - Enables measurements down intake runner behind intake valve

- **Applications planned for CRADA & SuperTruck projects**
  - July (SuperTruck) & October (CRADA)
Technical Progress: Backflow Proof-of-Principle Measurements

- **Single-cylinder Research Engine**
  - Modified 2.0L gasoline Ecotec engine
  - Three cylinders disabled
  - Laboratory air handling system

- **Fully variable valve actuation**
  - Enables broad residual-backflow variations
  - Excellent demonstration capability

---

**Single-cylinder engine geometry specs**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore (mm)</td>
<td>86.0</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>86.0</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>11.85</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Direct injection, side-mounted</td>
</tr>
</tbody>
</table>
Technical Progress: Backflow & EGR Fluctuations Measured

Valve overlap-timing sweep
- Backflow varies with overlap timing
  - Piston moving up at 40BTDC
  - Piston moving down at 20BTDC
- Cycle-specific backflow events
  - Varies from cycle to cycle
  - Different CO₂ pulse levels

Residual Backflow vs. External EGR
- EGR creates CO₂ baseline
- Backflow creates CO₂ pulse
- Relate backflow to cylinder residual
  - Via heat-transfer & other models
- Integrate Backflow & External EGR
  - Weight by crank-angle displacement

Backflow and External EGR Timing & Magnitude Measured
Technical Progress: Develop Multi-Color Multi-Species EGR Probe

Diagnostic Advances Required
- CO₂ via single P(22) line
  - Absorption ∝ [CO₂] & Temp.
  - External EGR: Cool CO₂
  - Will underestimate Hot CO₂
- Need temperature correction
  - Backflow will be hot
- Add H₂O diagnostic
  - 2nd laser scans over 5 lines
  - Lines varying Temp sensitivity
  - Determine [H₂O] & Temp
  - Use T to correct [CO₂]
- Fast CO₂, H₂O & T diagnostic
  - Redundant EGR measures
- Probe modifications required
- July campaign scheduled
Technical Progress: Develop End-on-Flow EGR Probe Tip

EGR Probe Improvements Required

- EGR Probe designed for cross flow
- Backflow will be end-on flow
  - Probe access is down intake runner
- Modified tip designed
  - Gas cross-flows through probe ducts
- 3D 316SS Metal Printing
  - Enables complex geometry
  - Excellent weld-trial results
- Replaces standard EGR Probe tip
- *Led by SuperTruck Partnership*

Modified Probe Enables Backflow & External EGR Measurement
Responses to 2013 Review Comments

Numerous Positive Comments:

- “very unique and systematic approach”
- “good approach supporting work to achieve SuperTruck’s 55% BTE target”
- “making very good progress”
- “making these measurements in real engine situations is a major accomplishment”
- “very strong collaborative relationship with Cummins”
- “project is very well-defined and planned”
- “This project makes fuel-economy advances via engine-intake improvements a refined engineering possibility”
- “project work supports overall DOE objective on developing advanced fuel efficient engines”

Recommendation:

- “apparently not making this technology available to the other participants in the SuperTruck program”
- “would like to see this project technology be rolled out to other HD engine manufactures”
  - All of the CRADA-developed technologies are available to any organization
    - These include the EGR Probe, SpaciMS, Fuel-in-Oil
    - The CRADA has always shared the diagnostics while keeping certain applications protected
    - Each of these diagnostics has been applied outside the CRADA via funds-in projects
    - The ORNL team is very interested in working with any interested customer
  - This broad availability was specifically mentioned in the 2013AMR presentation
  - Moreover, we have presented EGR Probe applications to the Advanced Combustion and Emission Control (ACEC) Tech Team (1-10-2013), where we communicated the availability of this and other CRADA-developed diagnostics to participating OEMs
  - We will take additional measures to make this broad availability more clear
Collaborations & Coordination with Other Institutions

- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)
- **Cummins SuperTruck Program** (ACE057, Friday 11-11:30am)
  - David Koeberlein (PI), Rick Booth
  - ORNL is subcontractor on Cummins’ VT SuperTruck project
  - *Multi-Color EGR Probe scheduled for SuperTruck July 2014*
  - Cooperative development of Multi-Color Multi-Species EGR Probe
    - End-on-flow tip
    - Harmonic analysis & stiffening of long EGR Probes
  - Coordination of common development interests
  - Use of CRADA-developed technologies
- **University of Central Florida**
  - Professor Subith S. Vasu & Students
    - Informal collaboration outside VT Program
    - Combined CO-CO₂ probe (*see Thurmond presentation*)
- **Publications, Presentations and Patents**
  - 2013 R&D100 Award: Fuel-in-Oil technology
  - 2 Patents: re. oil dilution & particulate sensing
  - 1 Invention Disclosure: re. Multi-Color EGR Probe
  - 6 oral presentations (3 invited)
### Remaining Challenges & Barriers, and Proposed Future Work

#### Remaining Challenges:

- **EGR Probe hardware modifications**
  - Incorporating optics for H$_2$O spectroscopy
  - Avoiding resonance with engine harmonics

- **Instrument modifications for Multi-Color Multi-Species EGR Probe measurements**

- **Modify instrument for closed-loop control studies**

- **Applications for advancing engine efficiency**
  - EGR & charge uniformity, combustion uniformity
  - Tuning and validating design models
  - Two campaigns at Cummins Technical Center

- **Determining net cylinder charge from component measurements**

#### Future Work:

- **Modify probe to incorporate H$_2$O & T optics**

- **Stiffen Long EGR Probe to avoid vibration**
  - *In collaboration with SuperTruck team*

- **Modify instrument to incorporate H$_2$O & Temp.**
  - Hardware: laser, multiplex unit, detection
  - Software: control, data acquisition & analysis

- **CO$_2$ temperature-compensation methods**

- **Determine analysis speed & accuracy tradeoffs**
  - Real-time analysis for control assessment
  - Slower post-analysis for improved accuracy
  - Requirements & tradeoffs to be defined by team

- **Assess nature of cylinder-charge components**
  - Spatial, cyl-to-cyl. & cyc.-to-cyc. uniformity
  - Calibrate simple scavenging model in GTPower
  - Campaigns in July (SuperTruck) & Oct. (CRADA)

- **Apply campaign insights to initial development**

- **Further development**
  - Models linking backflow to cylinder-residual nature
  - Weight factors for backflow & intake charge
  - Temporal (crank angle) integration methods
Summary

• Relevance
  – CRADA work enables improved cylinder-to-cylinder & cycle-to-cycle combustion uniformity
  – This in turn enables DOE goals for improved fuel efficiency and durability

• Approach
  – Develop diagnostic to measure spatial & temporal uniformity of cylinder-charge components
  – Apply diagnostic to advance engine technology
    – Assess specific hardware architectures
    – Tune, validate & improve design simulation tools (models)
    – Assess closed-loop control strategies & associated efficiency gains

• Technical Accomplishments
  – Residual-backflow and external EGR measurements demonstrated
  – Advanced EGR Probe designed & specified for quantifying backflow & external EGR
  – End-on-flow EGR Probe tip designed (in collaboration with SuperTruck project)

• Collaborations
  – Application of EGR Probe to Cummins’ SuperTruck 55% BTE Goals
  – EGR Probe design & development work outside VT program with U. Central Florida
  – R&D100 Award, numerous presentations and two patents
  – EGR Probe available to users outside the CRADA

• Future Work
  – Modify EGR Probe for quantifying backflow and external-EGR charge components
  – Apply modified probe in CRADA & SuperTruck campaigns to characterize charge uniformity
    – Assess hardware, design models and advanced closed-loop control strategies
  – Develop methods for determining net charge nature from backflow & EGR measurements