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

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Project ID:
ACE077

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Annual Merit Review
June 10, 2015, Arlington, Virginia

U.S. DOE Program Management Team:
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# Overview

## Timeline

- Current SOW started FY13
- SOW extends through FY15
- New 3-year SOW submitted

## Budget

- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2013: $300k
  - FY2014: $283k
  - FY2015: $250k

## Barriers

- *From DOE VT MYPP:*
  - 2.3.1.A: advanced engine combustion knowledge
  - 2.3.1.C: Modeling for combustion control
  - 2.3.1.D: Effective engine controls
- *General*
  - *Engine combustion*
    - Intake-charge uniformity
    - Combustion uniformity & completeness
  - *Engine controls*
    - Variability & diagnostics
    - Lower-penalty control methods
    - Diagnostics for methods demonstrations
  - *Durability*
    - Combustion instabilities
    - Instability induced corrosion, erosion, etc.

## Partners

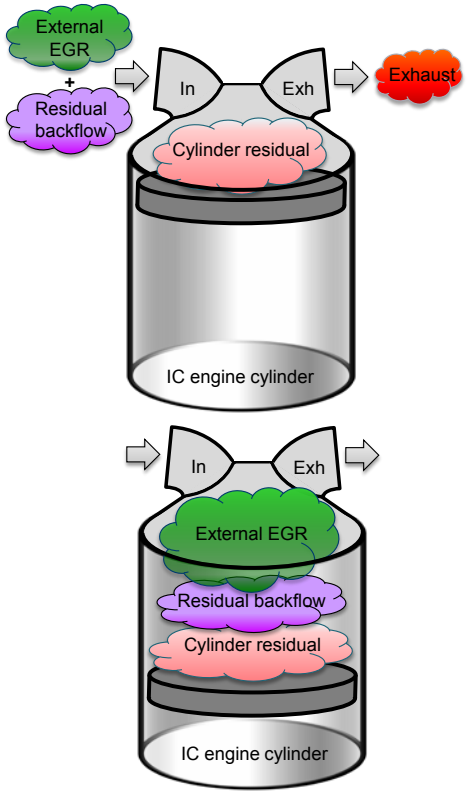
- ORNL & Cummins Inc.
- Cummins HD SuperTruck project

# Objectives & Relevance

***Identify Origins of Multi-Cylinder Engine Fluctuations***
to Accelerate Development
of Advanced Efficiency Engine Systems

## Objectives

- Assess fluctuations in cylinder-charge components
  - External EGR & intake air
  - Internal EGR (residual & rebreathed residual-backflow)
  - Cylinder-to-cylinder & cycle-to-cycle perspective
- 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

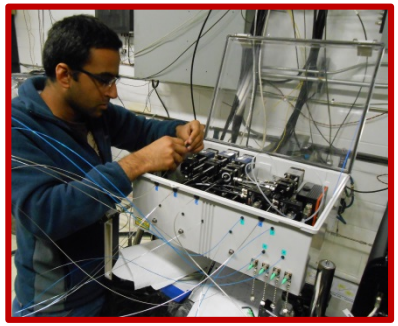
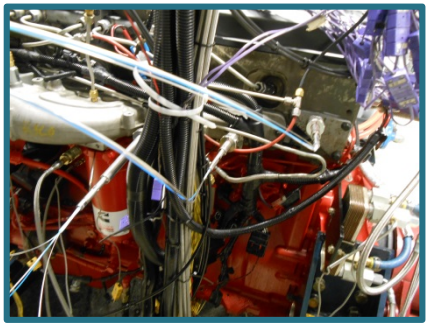
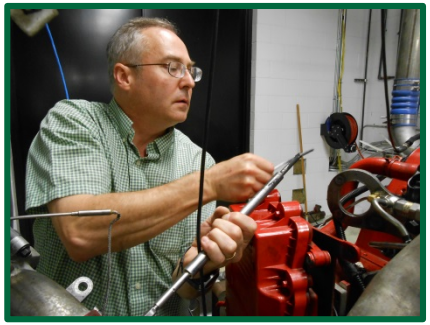
# Milestones

## 2014 Milestone (on schedule for timely completion):

- ✓ **Q1:** Specify second laser for quantifying intake & residual-backflow $CO_2$
  - i.e., external & internal EGR
- ✓ **Q2:** Assess methods for differentiating intake and residual-backflow $CO_2$
  - Measure $H_2O$, Temperature & $CO_2$
- ✓ **Q3:** Bench-level demonstration of method for $CO_2$ differentiation
- ✓ **Q4:** Method assessment for measuring cylinder-residual variations

## 2015 Milestone (on schedule for timely completion):

- ✓ **Q1:** Analyze cylinder charge components using advanced EGR Probe
- **Q4:** Compare analysis methods for determining cylinder charge from charge-component measurements


# Approach

## *Develop & Apply Advanced Diagnostics*

for Resolving Multi-Cylinder-Engine Cylinder & Cycle-Uniformity to Improve Models, Design, Control & Enable Advanced Efficiency

***Clean, Fuel-Efficient, Durable***

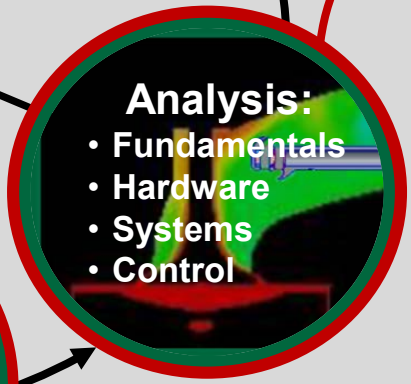
**Engines in the Marketplace**

**6.7L ISB (Dodge Ram)**
**ISV5.0 (Nissan Titan)**
**SuperTruck Demonstration**

**CRADA**





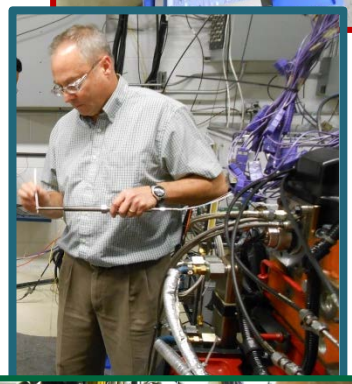


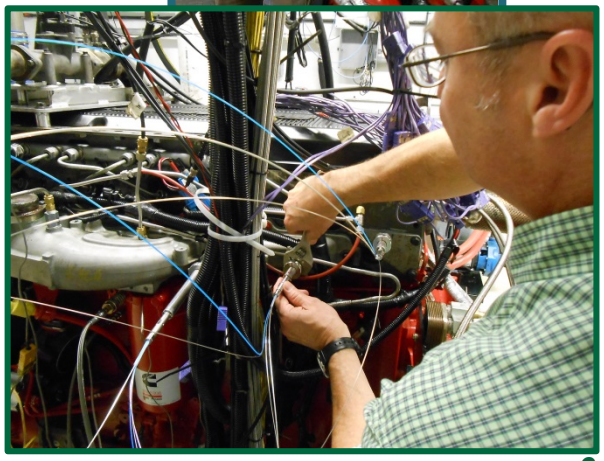



Joint
ORNL Lead
Cummins Lead

# Technical Progress: *Summary*

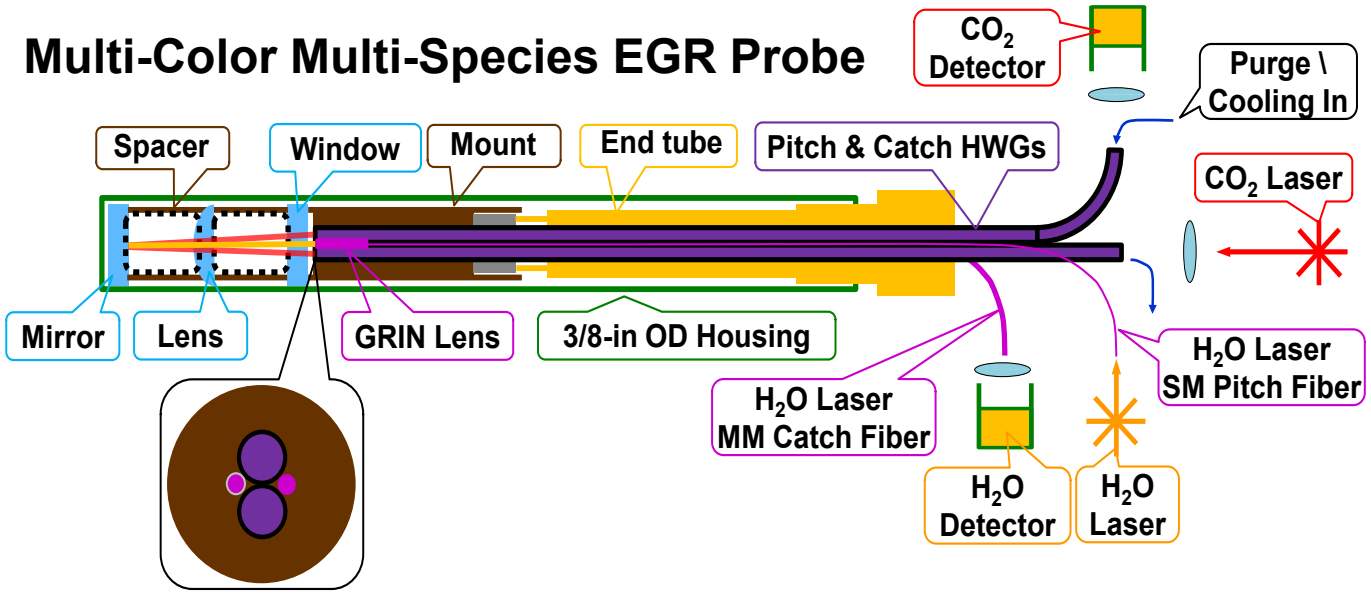
- **Background: Proof-of-principle Backflow Measurements**
  - Resolve Backflow vs. EGR-Air via EGR Probe
  - Proposed: Multi-Color Probe & Charge Prediction Technique
- **Multi-Color EGR Probe**
  - Crank-angle-resolved $CO_2$, $H_2O$, Temperature & Pressure
  - Joint development leveraging CRADA & SuperTruck efforts
- **CRADA Measurement Campaign**
  - Assess Advanced Intake Architectures
  - Spatiotemporal EGR Uniformity
  - Measurements to assess hardware, system & design models
- **SuperTruck Measurement Campaign**
  - Spatiotemporal Backflow Uniformity & Mapping
  - Assess Backflow, Stability and Control
- **Cylinder-Charge Stability**
  - Real-time Composition & Temperature predictions
  - Cylinder- and Cycle-specific uniformity assessment





# Tech.Prog.: Leveraged DOE Programs Enables Advanced Diagnostic

## Multi-Color Multi-Species EGR Probe



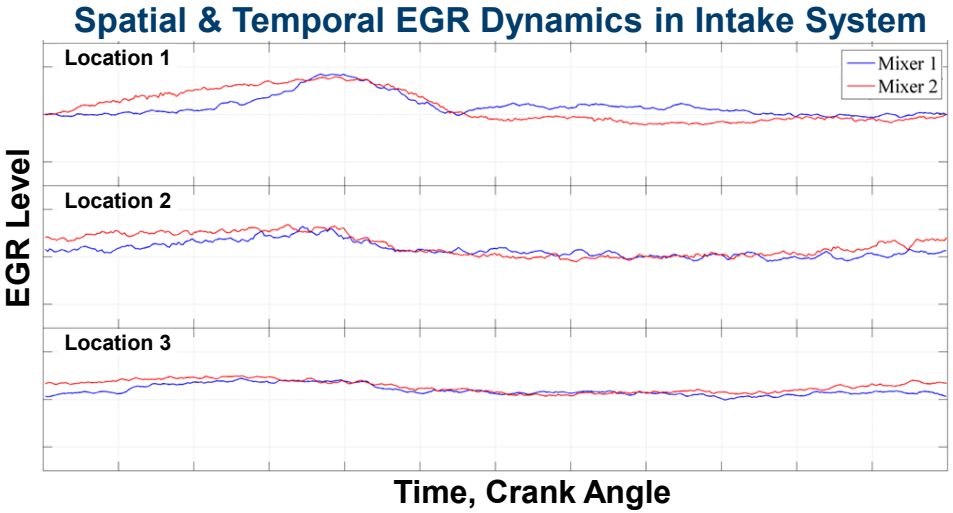

- Measures $CO_2$, $H_2O$, T & P
- Leverages CRADA & SuperTruck
  - CRADA
    - Original EGR Probe development
  - SuperTruck
    - $H_2O$ diagnostic development at Purdue
  - CRADA & SuperTruck
    - 4-probe multi-plex system
    - Combined $CO_2$-$H_2O$ probe instrument
- 4 parallel real-time probes
  - Simultaneous multi-cylinder data
- Improved analysis
  - Iterative baseline fit
  - Absorption profile fit to theory (vs. integration & calibration-factors)
  - Shifted-sawtooth laser ramp for real-time background subtraction
  - Improved wavelength calibration
  - 5kHz rate (200us, 1.2 CAD at 1k RPM)

# Tech.Prog.: ORNL & CMI Jointly Develop Multi-Color EGR Probe


- Extra-long EGR Probe
  - Reaches behind intake valve
  - Non-resonant with engine harmonics
- End-on-flow tip
  - CFD analysis & design at Cummins
  - 3-D 316-SS printed (at MAPI)
- Complex 4-optic collet & key
  - Designed at ORNL
  - Wire-EDM at Cummins
  - Rubber ferrule inserts cast (at MAPI)
- Anti-reflection coated probe optics
  - Reduces etalon noise
  - $CO_2$ purge windows AR coated too
- Enclosure
  - $N_2$ purging to eliminate background
  - Improved protection
- Can add other species
  - e.g., CO, $O_2$, $CH_4$
  - Multiplex on existing infrastructure

# Tech.Prog.: CRADA Campaign Assesses Advanced Intake System

**Multi-Cylinder-Engine Campaign at Cummins Technical Center October 27-31, 2014**




## Studying Intake-EGR Dynamics

- Building on previous campaigns
  - Experimental & Modeling work
- Studying various impacts
  - Mixer hardware (proprietary)
  - Cam profiles
  - Engine conditions
  - Transients & Unsteady operation

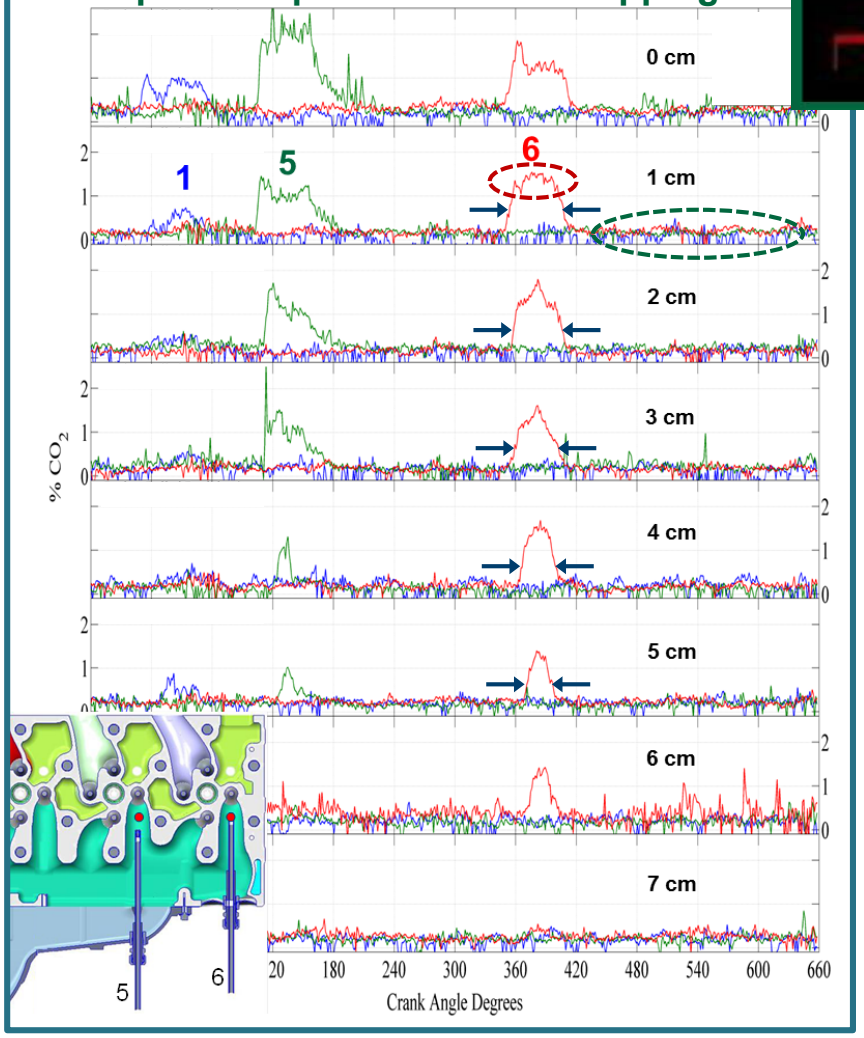
## Spatiotemporal EGR Mapping

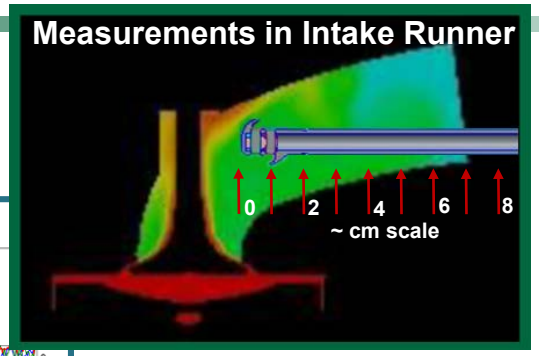
- Origin of temporal dynamics varies
  - Pressure vs. flow induced
- Dynamics vary through the system
- Current focus is data application
  - Validating CFD design models
  - Understanding design tradeoffs
  - Optimizing system performance

# Tech.Prog.: SuperTruck Campaign Assesses Backflow & Uniformity

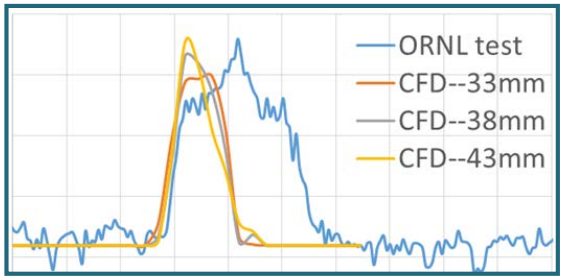
## Multi-Cylinder-Engine Campaign at CMI Development Facility September 22-26, 2014

### Spatiotemporal Backflow Mapping



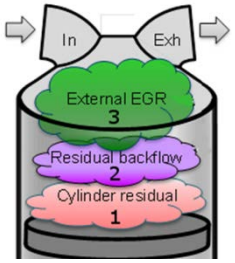

### CFD EGR Probe Comparison

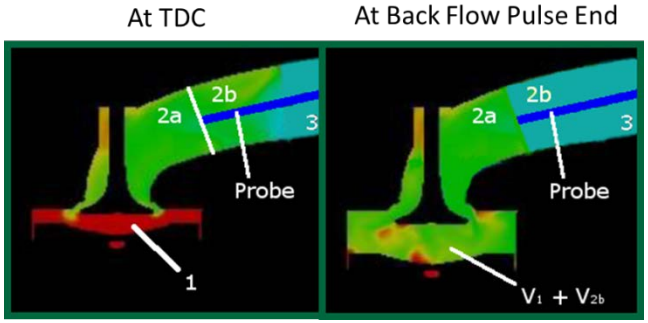


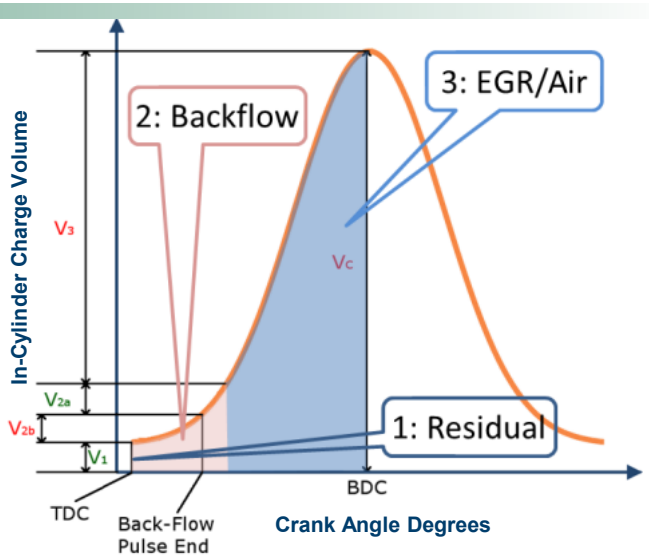

- 2 Charge components directly measured
  - EGR-Air (baseline)
  - Combustion-residual backflow (pulse)
- EGR-Air uniform temporally & cyl-to-cyl
- Flat pulse indicates uniform backflow dilution
  - Dilution factor relates backflow to cylinder residual
  - Backflow ≈ 20.8% residual + 79.2% fresh EGR-air
- Width indicates backflow penetration depth
  - Use in Cylinder-Charge model
- Measured backflow wider than CFD
  - Flow in probed port much slower than modeled
- Many details & insights for assessing
  - Hardware, system, models, control

# Tech.Prog.: Real-Time Predictions of Cylinder-Charge Parameters

Measurements & Modeling to predict Cylinder Charge
- Composition & Temperature
- Fluctuations (cycle- & cylinder-specific)




**Model Results:**

| Charge @ IVC | 30% EGR w/ Backflow | 30% EGR w/o Backflow |
|---|---|---|
| $\%CO_2$ | 2 | 1.8 |
| T (K) | 370 | 362 |

**EGR Probe Uncertainty Analysis:**

| Charge @ IVC | Uncertainty Analysis | | Measured Charge Noise |
|---|---|---|---|
| | w/ Etalons | w/o Etalons | |
| $\%CO_2$ | 10% | 1.5% | 9% |
| T (K) | 10% | 1% | 3% |

- ***Backflow variations reflect system stability***
  - Use backflow as a direct uniformity indicator
  - Backflow accounts for 10% of Charge $CO_2$
- Currently limited by sensor uncertainty
  - 0.5% fluctuations impact engine performance
  - Varying etalons are a major noise source
  - Sensor noise dominates measurements
- Pathway to resolving 0.5% fluctuations:
  - Eliminate etalons
  - Increase absorption length
  - Modulation spectroscopy

# Responses to 2014 Review Comments

FY2014 AMR Review
(5 Reviewers; max score: 4)

| Category | Score |
|---|---|
| Approach | 3.40 |
| Tech Progress | 3.50 |
| Collaboration | 3.20 |
| Future Research | 3.30 |
| **Weighted Average** | **3.41** |

## Numerous Positive Comments:

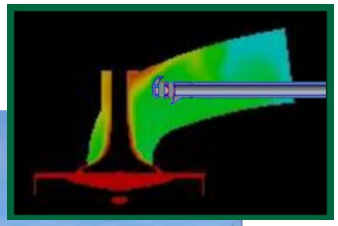
- "unique approach via smart way of monitoring EGR variations"
- "creative approach," "holy grail of tracking gas distribution"
- "demonstrated solid achievement for last few years"
- "innovative," "good teamwork," "future work well planned"
- Support DOE objectives "for both fuel economy and in-cylinder emissions"

## Recommendations:

- Some questions re. how EGR Probe would be implemented in a practical & cost-effective way
  - ***The EGR Probe is a research tool and not intended for on-vehicle implementation***
- Suggestion that other combustion parameters be studied in addition to EGR
  - ***This has been proposed in our Future Work (e.g., AFR, mass flux, cylinder-head temperatures)***
- Several comments re. Cummins' contribution & benefits, and contributions of the informal collaborators
  - ***This has been highlighted in the presentation***
  - ***A summary of contributions is provided in the Technical Backup Slides***
- Interesting to compare measured data to model predictions
  - ***This is a CRADA priority; we have presented such here & in previous AMR presentations***
- Question re. if Cummins would apply the diagnostic to one of their multi-cylinder engines in the future
  - ***cf. campaigns at CTC, which have occurred throughout CRADA ; two were highlighted here***
- Several comments re. adding non-CRADA participants to broaden project impact
  - ***The CRADA strives to broadly benefit DOE and the Vehicle Technologies community***
  - ***The formal (ACED Tech Team & AMR Reviewers) & informal (UCF) partnerships strengthen the project***
  - ***CRADA is a formal CMI-ORNL agreement***
- Questions re. residual measurement, the EGR Probe's invasive nature, and soot impact on quantification
  - ***The CRADA team has performed experimental and numerical studies of these topics.***

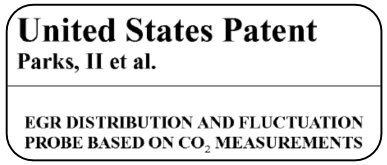
# Collaborations & Coordination with Other Institutions

- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)
- **Cummins SuperTruck Program (ACE057, Friday 10-10:30am)**
  - David Koeberlein (PI), Rick Booth, Lyle Kocher
  - ***Combustion-Residual Backflow Campaign***
    - Cooperative development of Multi-Color Multi-Species EGR Probe
    - Compared measurement to 3D-CFD model results
    - Used backflow data with Cylinder-Charge model




- **High-Dilution SGDI (ACE090, Wed 2:15-2:45pm)**
  - Brian Kaul, ORNL (PI)
    - Applying EGR Probe to monitor cyclic-dispersion
- **University of Central Florida**
  - Professor Subith S. Vasu & Students
    - Advancing MIR LED CRADA technology
    - Joint presentations and invention disclosures

- **Publications, Presentations and Patents**
  - Patent: re. MIR LED EGR Probe
  - Invention Disclosure: re. Fast CO-$CO_2$ probe
  - Poster presentation
  - ORNL-Cummins partnership recognized by Dr. Danielson, DOE EERE Assistant Secretary, for enabling clean & efficient engines for current & future vehicles



# Remaining Challenges & Barriers, and Proposed Future Work

| Remaining Challenges: | Future Work (FY16-18): |
|---|---|
| • Engine-system design models | • Compare models to measurements<br>– *Ongoing throughout CRADA* |
| • Developing advanced intake architectures for enabling improved efficiency | • Measurement campaigns at CTC<br>– *Assess hardware, system and control*<br>– *Compare results to model-based expectations*<br>– *Ongoing throughout CRADA* |
| • Pathway to resolving 0.5% cylinder-charge fluctuations | • EGR Probe modifications<br>– *Eliminate etalons*<br>– *Increase absorption pathlength*<br>– *Modulation spectroscopy* |
| • High-temperature exhaust measurements<br>– *Direct exhaust measurements*<br>▪ *vs. via EGR loop*<br>– *More direct cylinder-balance assessment* | • Probe modifications<br>– *Reduce component contact , thermal-barrier coatings, and internal forced cooling*<br>• Line-of-sight hardware |
| • CO-based combustion uniformity measure<br>– *Relevant to transient & high-EGR diesel, and stoichiometric combustion applications* | • Modify instrument to incorporate CO<br>– Implement on existing HWG optics<br>– Multiplex with existing $CO_2$ measurements |
| • Measure other significant parameters influencing combustion uniformity | • Develop stretch technologies<br>– *Candidates include cylinder- & cycle-resolved:*<br>▪ *AFR, mass flux, & cylinder-head temperature* |

# Summary

- **Relevance**
  - CRADA work enables improved cylinder-to-cylinder & cycle-to-cycle uniformity
  - This in turn enables DOE goals for improved fuel efficiency and durability
- **Approach**
  - Develop diagnostics to measure multi-cylinder-engine spatial & temporal uniformity
  - Apply diagnostics to advance engine technology
    - Assess specific hardware architectures
    - Tune, validate & improve design simulation tools (models)
- **Technical Accomplishments**
  - Developed Multi-Color EGR Probe for crank-angle-resolved $CO_2$, $H_2O$, T & P measurements
  - CRADA campaign measurement of advanced-intake architectures to assess CFD models
  - SuperTruck campaign: assess 3D CFD models & measure charge-component fluctuations
  - Developed measurement-based real-time model for predicting cylinder-charge parameters
- **Collaborations**
  - Application of EGR Probe to Cummins' SuperTruck 55% BTE Goals
  - EGR Probe application to DOE High-Dilution SGDI project & U. Central Florida partnership
  - 1 patent, presentations & recognition by Dr. Danielson DOE Assistant Secretary for EERE
  - EGR Probe available to users outside the CRADA
- **Future Work**
  - Improve signal-to-noise & harden diagnostics for exhaust measurements
  - Application campaigns at CTC on advanced development engine platforms
    - Assess hardware, design models and advanced closed-loop control strategies
  - Develop new measurements for parameters relevant to combustion uniformity

# ***Technical Back-Up Slides***

# Remaining Challenges & Barriers, and Proposed Future Work

| Remaining Challenges: | Future Work (FY2015; i.e., from 2014 AMR): |
|---|---|
| • EGR Probe hardware modifications<br>- Incorporating optics for $H_2O$ spectroscopy<br>- Avoiding resonance with engine harmonics | Completed<br>• Modify probe to incorporate $H_2O$ & T optics<br>• Stiffen Long EGR Probe to avoid vibration<br>- *In collaboration with SuperTruck team* |
| • Instrument modifications for Multi-Color Multi-Species EGR Probe measurements | Completed<br>• Modify instrument to incorporate $H_2O$ & Temp.<br>- Hardware: laser, multiplex unit, detection<br>- Software: control, data acquisition & analysis<br>• $CO_2$ temperature-compensation methods |
| • Modify instrument for closed-loop control studies | Completed<br>• Determine analysis speed & accuracy tradeoffs<br>- Real-time analysis for control assessment<br>- Slower post-analysis for improved accuracy<br>- Requirements & tradeoffs to be defined by team |
| • Applications for advancing engine efficiency<br>- EGR & charge uniformity, combustion uniformity<br>- Tuning and validating design models<br>- Two campaigns at Cummins Technical Center | Completed<br>• Assess nature of cylinder-charge components<br>- Spatial, cyl-to-cyl. & cyc.-to-cyc. uniformity<br>- Calibrate simple scavenging model in GTPower<br>- Campaigns in July (SuperTruck) & Oct. (CRADA) |
| • Determining net cylinder charge from component measurements | Initial Work & Model Completed<br>• Apply campaign insights to initial development<br>• Further development<br>- Models linking backflow to cylinder-residual nature<br>- Weight factors for backflow & intake charge<br>- Temporal (crank angle) integration methods |

# Technical Progress: *Summary of Participant Actions*

- **Summary of FY15 CRADA Participant Contributions**
  - ***Responding to AMR Reviewer request***
  - 1:1 DOE:Cummins cost share; i.e., Cummins matches DOE investment 1:1
  - Near and long-term research planning(Joint ORNL & CMI)
  - Diagnostics development, bench & mule-engine proof (ORNL lead)
    - Field-proofs at CTC (Joint ORNL & CMI)
  - Development engine & CTC resources (CMI lead)
  - Measurement campaigns (Joint ORNL & CMI)
  - Data analysis (ORNL lead for diagnostic, CMI for CTC sensors)
  - Interpretation (Joint ORNL & CMI)
  - Model comparison, assessment and modifications (CMI lead)
  - Next-steps and future-work planning (Joint ORNL & CMI)