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

project ID: ACE077

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Oak Ridge National Laboratory

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Washington, DC

DOE Managers:
Gurpreet Singh, Ken Howden, Leo Breton

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Cummins

OAK RIDGE National Laboratory

Overview

Timeline

- Year 1 of 3-year program
- New 3-year CRADA extension
- Builds on FY13-FY15 R&D

Budget

- 1:1 DOE:Cummins cost share
  - In-kind Cummins contribution
- FY16 DOE Funding: $250k

Partners

- ORNL & Cummins Inc.

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.

Objectives & Relevance

Objectives

- Measure combustion-uniformity parameters & improve related knowledge
  - Develop diagnostics for parameters we can't currently measure
  - Measure both intake & exhaust parameters
  - Develop measurement-based models of cylinder-charge fluctuations
- Apply data & insights to improve engine-system development process
  - Validate & tune Cummins' 1-D & 3-D design models
  - Assess specific hardware, configurations, & control strategies
- Improve inter-cylinder & inter-cycle combustion uniformity
  - Enable advanced powertrain hardware configurations
  - Enable reliable higher-efficiency operation

Relevance

- Improved design models for better analysis-led design
- Increased combustion uniformity has broad performance benefits
  - Lower required engineering margins (efficiency penalty, fuel economy)
  - Improved durability & ultimate efficiency limits across all cylinders
- Advances DOE goals re. combustion knowledge, modeling, & controls

Approach

Develop & Apply Advanced Diagnostics

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

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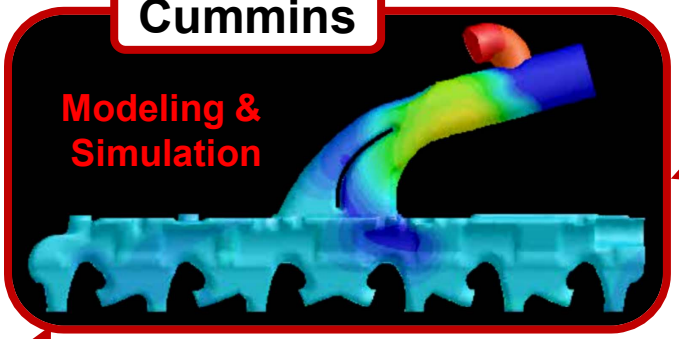

Model Validation

Cummins & ORNL

Components, Methods, Systems & Prototypes Assessment

Diagnostic Specification

Engine Studies

ORNL

Diagnostics Development & Applications

- Combustion uniformity
- EGR, intake & fueling
- Cylinder charge

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Controls, Design, Development

Clean, Fuel-Efficient, Durable

Engines in the Marketplace

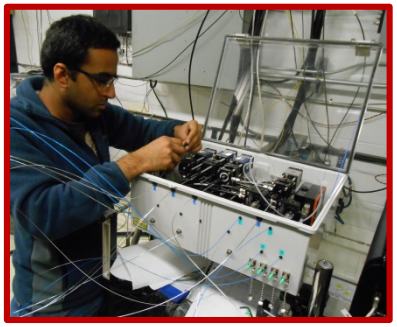
Milestones

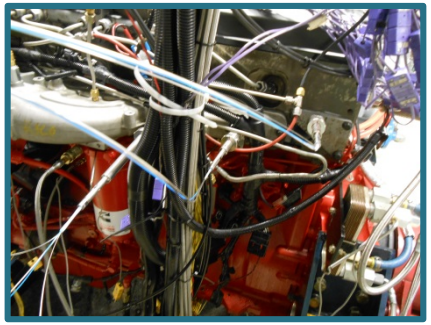
Completed all 2015 Milestones :

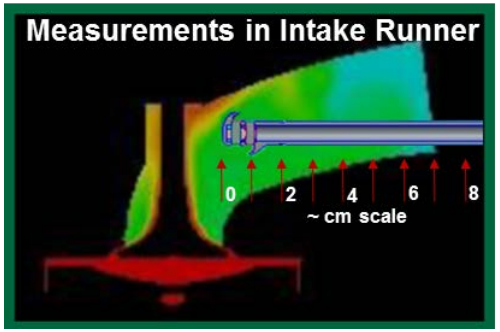
- ✓ **Q1:** Analyze cylinder charge components using advanced EGR Probe
- ✓ **Q4:** Compare analysis methods for determining cylinder charge from charge-component measurements

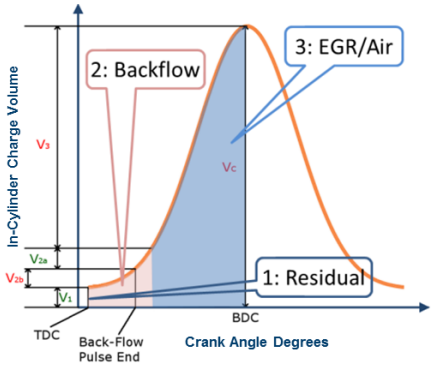
2016 Milestone (on schedule for timely completion):

- ✓ **Q2:** Assess methods for improving EGR Probe signal-to-noise ratio (SNR)
- **Q3:** Specify method for integrating CO measurement in EGR probe







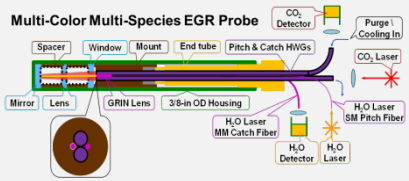


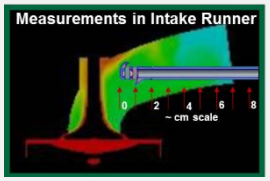
Technical Progress: *Overview*

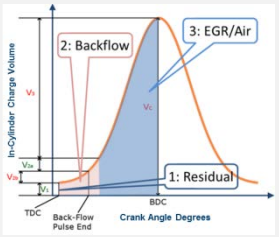
Improving Combustion Uniformity

Multi-Species EGR Probe Measurements

- Crank-angle-resolved CO_2, H_2O, Temperature & Pressure
- CRADA & SuperTruck applications







New Diagnostic Needs/Challenges Identified

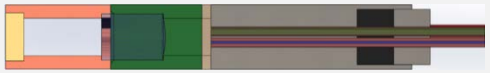
Enable Cylinder-Charge Model

Exhaust-Side Measurements

Exhaust O_2

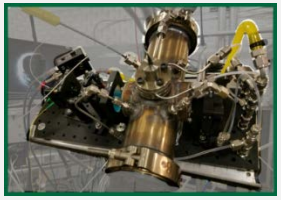
FY 2015

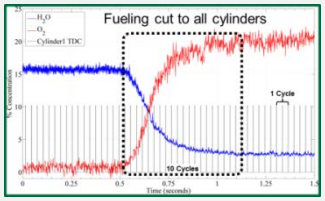
New Probe Design & SNR Analysis



Parameter	WMS	DAS
SNR at low signal	Better	Requires averaging (slow)
Electronic noise & ground loops	Better Native	Comparable if eliminate noise & loops
Absorption baseline measurement required	Not with 2f/1f calculation	Not with iterative baseline fitting (as we use)
Sensitive to background IR	No; can be faster	Account for using shifted-sawtooth
Requires ~100x-fast sine wave	Yes	No; potential for faster measurements

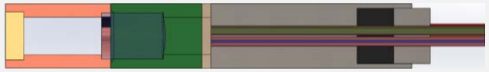
New Diagnostic: Fast Exhaust O_2, H_2O, T & P





FY 2016

New Probe Design & SNR Analysis



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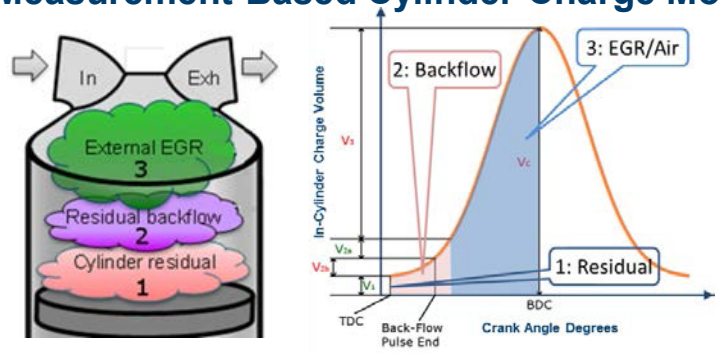
Tech.Prog.: New EGR Probe Design for Better Signal-to-Noise

Measurement-Based Cylinder-Charge Model



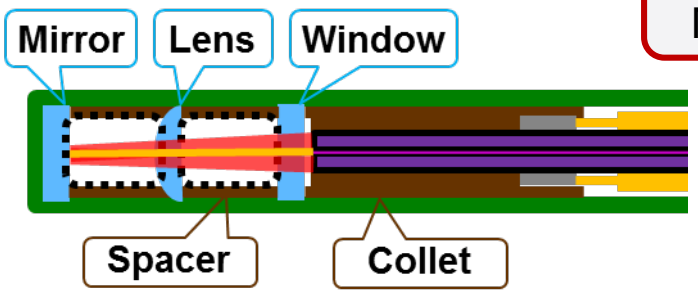
EGR Probe Uncertainty Analysis:

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

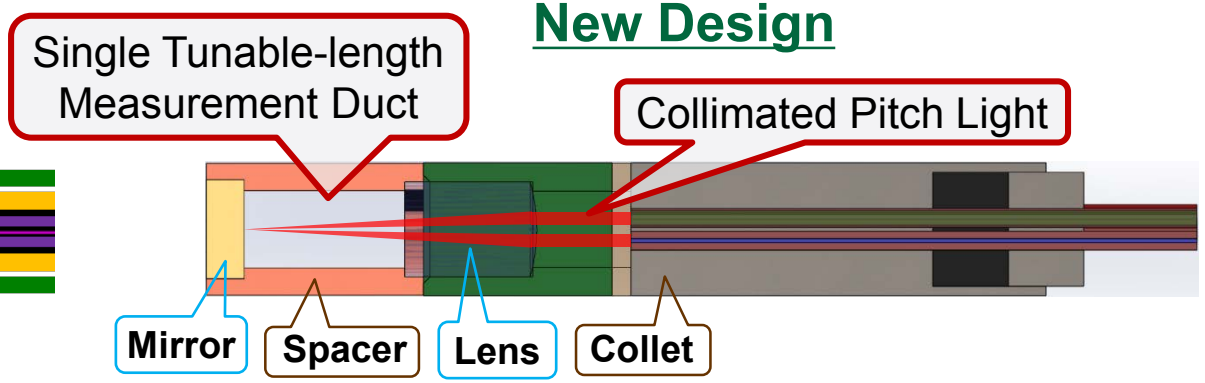
- Need better SNR to enable Cylinder-Charge Model (cf. Tech. Backup slides)
  - Need to resolve 0.5% fluctuations in concentration & temperature
  - Proposed pathway: ***eliminate etalons, increase absorption length, WMS***

Tech.Prog.: New EGR Probe Design for Better Signal-to-Noise

Original Design



New Design



- Need better SNR to enable Cylinder-Charge Model (cf. Tech. Backup slides)
  - Need to resolve 0.5% fluctuations in concentration & temperature
  - Proposed pathway: ***eliminate etalons, increase absorption length, WMS***

New probe design both increases signal & reduces noise

- No parallel optical surfaces – ***eliminates etalon & vibration noise*** *(10% →1.5%)*
- Single tunable-length measurement duct
  - ***50% more signal*** in same housing – longer possible for more signal *(1.5% →1%)*
  - Enables balancing application-specific signal vs. spatial-resolution tradeoff
- Optical fibers replace hollow waveguides – ***eliminates vibration noise***
- Manufacturing of required lensed-fiber currently limiting implementation
  - Other pathways being investigated (e.g., separate micro lenses)

New EGR Probe design could enable Cylinder-Charge Model

Tech.Prog.: Instrument & Method Studies to Improve SNR

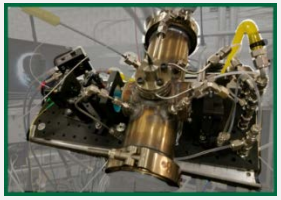
- Focus on Wavelength-Modulation Spectroscopy (WMS)
  - Some practical tradeoffs relative to Direct-Absorption Spectroscopy (DAS)

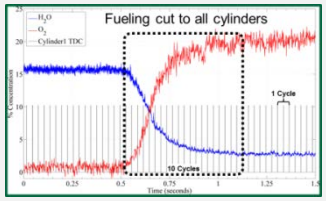
Parameter	WMS	DAS
SNR at low signal	**Better**	Requires averaging (slow)
Electronic noise & ground loops	Better Native	Comparable if eliminate noise & loops
Absorption baseline measurement required	Not with 2f/1f calculation	Not with iterative baseline fitting (as we use)
Sensitive to background IR	**No**; can be faster	Account for using shifted-sawtooth
Requires ~100x-fast sine wave	Yes	**No**; potential for faster measurements

  - WMS-DAS tradeoffs depend on specific application & optical arrangement
  - ***DAS is best for CRADA applications*** - performance equivalent to WMS when electronic noise is minimized & ground loops are eliminated
- Pathways to reduce electronic noise
  - ✓ Operate system on UPS batteries *(>2x SNR gain)*
  -  Optimize driver & laser dynamic ranges (0-0.2 vs 0-1mA) *(5x SNR gain)*
  - Experiment-specific hardware selection *(SNR gain can be significant)*

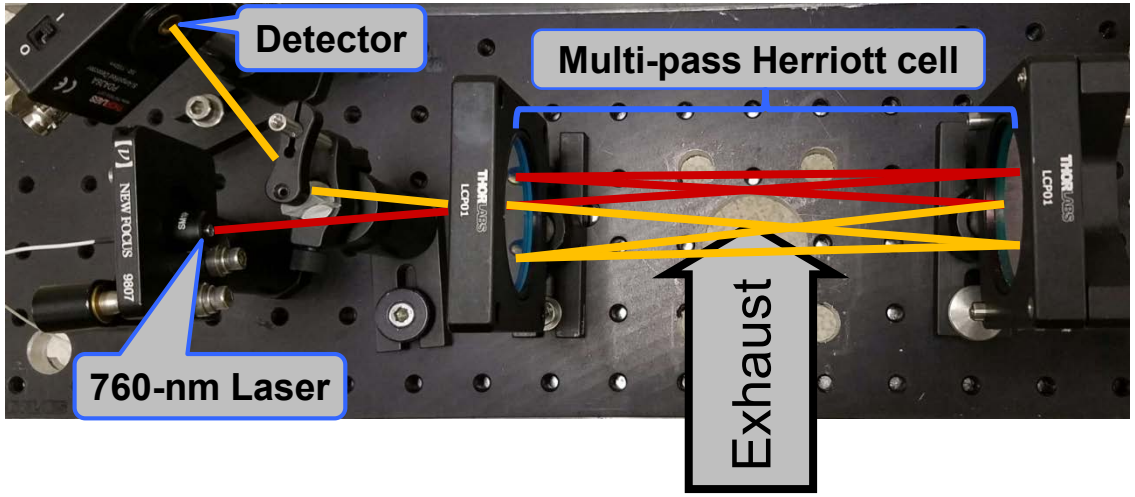
Study provides insights for optimizing existing & future diagnostics

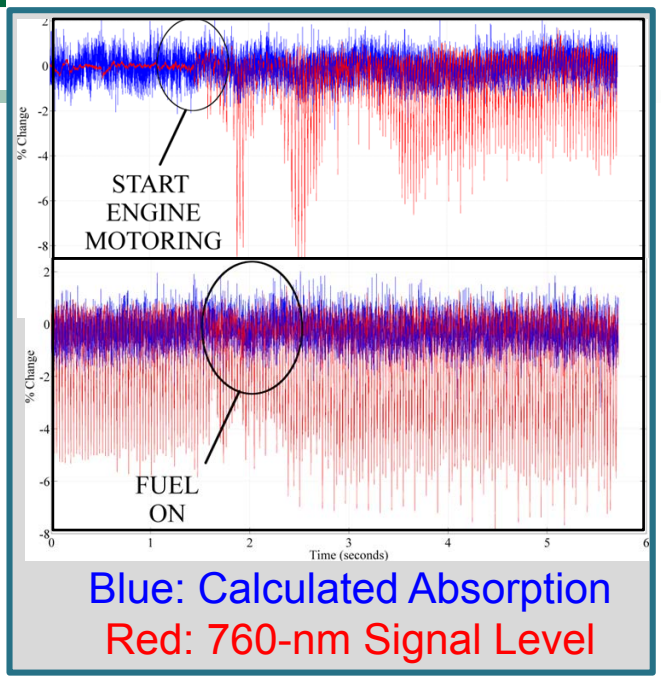
New Diagnostic:
Fast Exhaust O_2, H_2O, T & P





Tech.Prog.: CRADA Delivers on Cummins Request to Measure Fast Exhaust O_2 Fluctuations

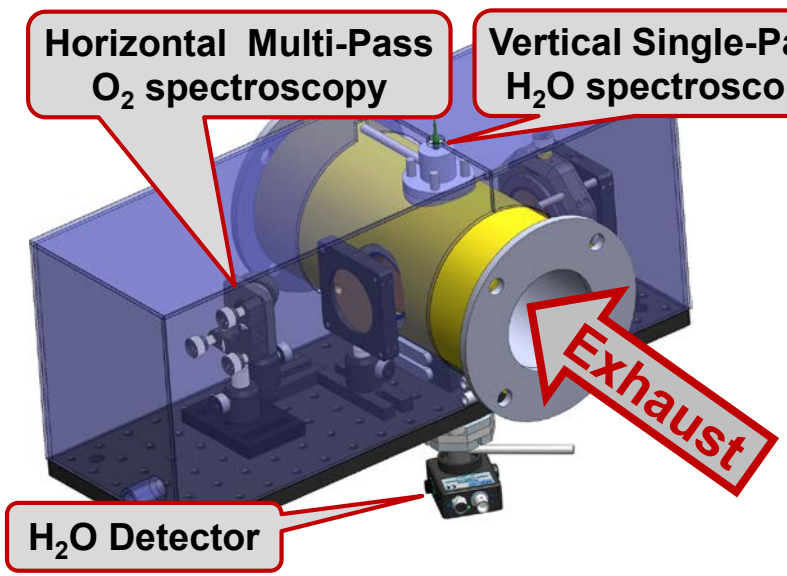


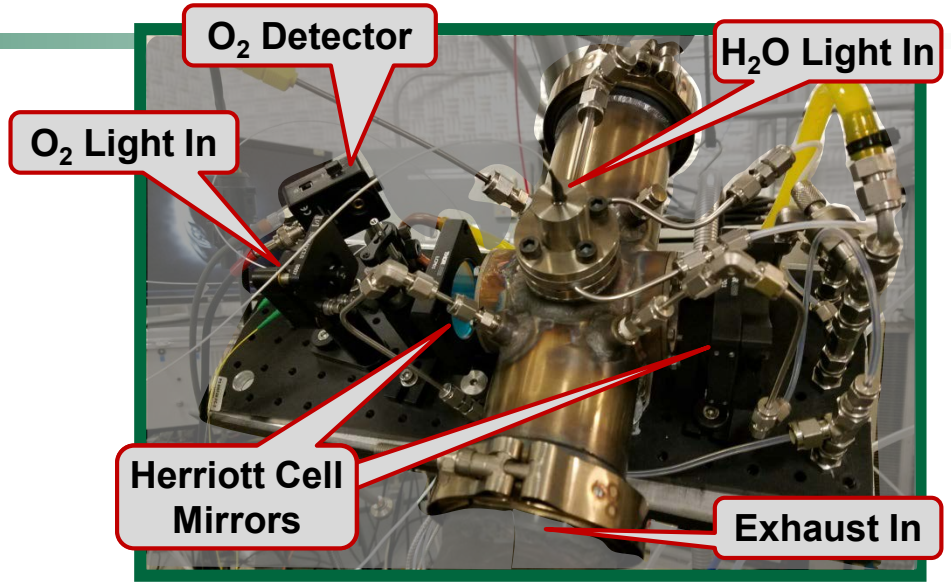


Studying AFR Dynamics in Advanced Spark-Ignited Engines

- Focus on resolving inter-cylinder & inter-cycle exhaust O_2 uniformity
- 760nm O_2 absorption is very weak
  - 100 times less than H_2O line strengths
  - requires ca. 1-m absorption path at exhaust conditions (ca. 1atm, 900K)
- Multi-pass Herriott cell provides measurement solution
  - 4.5-m pathlength across ~76-mm diameter exhaust duct (~30 passes)
  - Stable & robust to engine vibrations (no cell mode hopping)
    - Vibrations impact 760-nm signal level but not calculated absorption

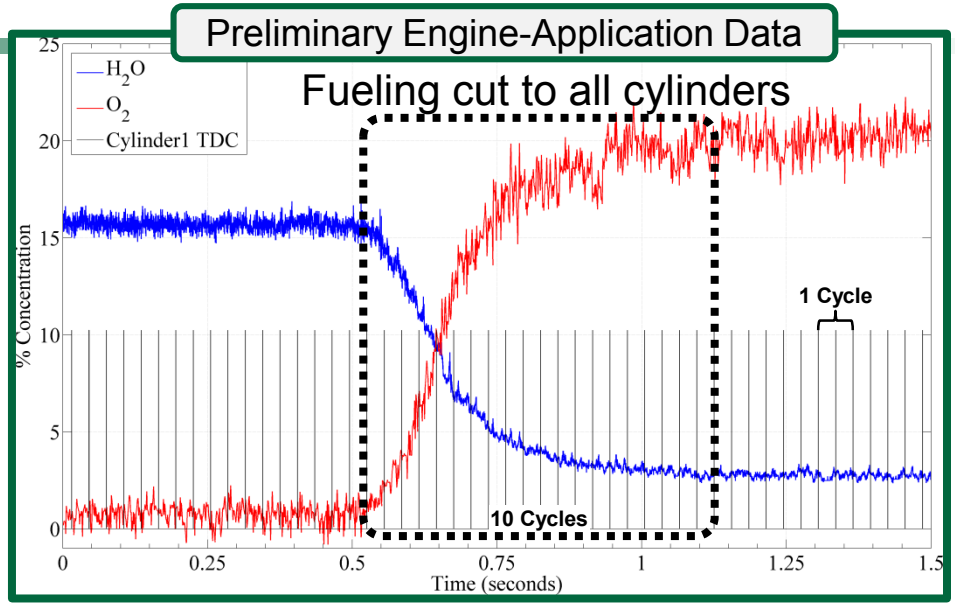
Tech.Prog.: New Diagnostic Measures Fast Exhaust Transients





- Instrumented exhaust section (10-in long x 3-in ID)
  - Optics contained in purged housing (18-in long x 6-in wide x 6-in tall)
    - Includes various cooling, purge and guard flows
  - Lasers, drivers, data-acquisition remotely located
- Measures exhaust O_2 & H_2O concentration, Temperature, Pressure
  - Single-pass H_2O, T & P measurement based on EGR Probe technology
  - Other species can be added; e.g., CO_2, CO, PM
- Capable of resolving intra-cycle transients (5kHz rate: 200us, 1.2 CAD at 1k RPM)
- 0.4% O_2 detection limit
  - Quantifies residual O_2 (catalyst applications) & combustion uniformity

Tech.Prog.: On-Engine Exhaust Transient Measurements



Diagnostic demonstrated on engine to resolve exhaust transients

- GM LNF 2.0L gasoline engine (as used by Kaul, ACE090)
- Not limited to demonstration position shown in picture
  - Applicable upstream of turbocharger
- Fueling-cut transient significantly broadened by exhaust hardware
  - Native instrument response can resolve 1.2CAD transients (at 1k RPM)
- Multi-pass sensitivity to window deposits limit experiments to ~20min
  - Need in-situ cleaning (e.g., liquid spray, wiper), and/or guard flow
  - Can tune Herriott-cell mode for best signal vs. PM-sensitivity tradeoff
- ***SI-engine uniformity application at Cummins Technical Center in May***

Responses to 2015 Review Comments

FY2015 AMR Review
(4 Reviewers; max score: 4)

Category	Score
Approach	3.50
Tech Progress	2.90
Collaboration	3.30
Future Research	3.00
Weighted Average	**3.11**

Numerous Positive Comments:

- "key linkage between project and goals to reduce petroleum usage"
- "practical applications tied to real product improvements"
- "very good work, enhancing understanding"
- "a well-run CRADA," "quite well coordinated"

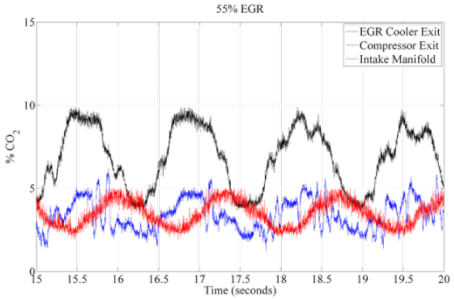
Recommendations:

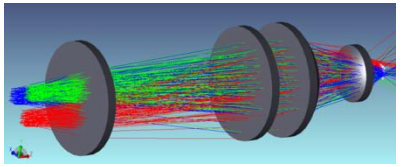
- ✓ Questions re. sufficiency of the EGR Probe vis-à-vis 'noninvasive' diagnostics for spatial mapping
  - ***Both the measurement method and access methodology impact a diagnostic's invasive nature***
  - ***Many light-based diagnostics have invasive access, or access is not practically possible (2012 AMR)***
  - ***A probe was developed to access points not practically accessible via other methods, and to require minimal modification of the base engine hardware (2012 AMR)***
  - ***Impact of the probe on proximal flow filed has been discussed in past AMR presentations (2014 AMR)***
  - ***Uncertainty analysis was presented, and used to define required measurement SNR (2015 AMR)***
  - ***Spatial mapping was realized by probe translation and orientation (2015 AMR)***
- ✓ Desire to see expansion of the CRADA diagnostics to other DOE projects and national labs
  - ***EGR Probe applied to Brian Kaul's High-Dilution SGDI (ACE090) & SuperTruck***
  - ***CRADA-developed SpaciMS is broadly applied for catalysis, combustion & engine development***
  - ***Other applications across DOE, national labs and industry are welcome***
- ✓ Desire to see more development of new diagnostics
  - ***The Multi-Species EGR Probe was a major effort that significantly expanded capabilities, and resulted in new capabilities; (CO_2, H_2O, T & P, vs. CO_2 at ambient temperature only)***
  - ***A new diagnostic for resolving inter-cylinder & -cycle exhaust variations was developed***
- Suggest including engine OEM's in the CRADA
  - ✓ ***Such valuable broader input is received and incorporated via the AMR and ACEC Tech Team***
  - ***The CRADA is s formal partnership between ORNL and Cummins***

Collaborations & Coordination with Other Institutions

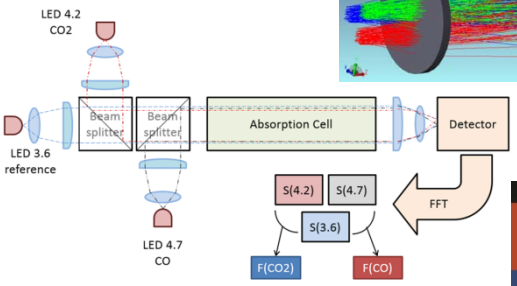
- **Cummins**
  - CRADA Partner, Sam Geckler (Co-PI)

- **High-Dilution SGDI (ACE090, Tue 1:45-2:15pm)**
  - Brian Kaul, ORNL (PI)
    - Applying EGR Probe to monitor cyclic-dispersion
    - Publications

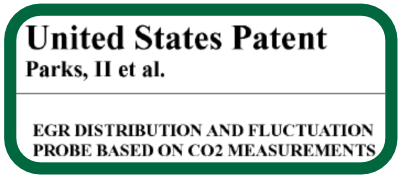


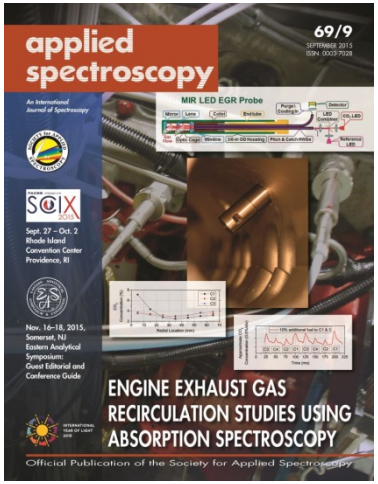


- **University of Central Florida**
  - Professor Subith S. Vasu & students
    - Advancing MIR LED CRADA technology
    - New light sources for advanced diagnostics
    - Joint presentations & publications



- **Publications, Presentations and Patents**
  - Patent: Laser-based Multiplex EGR Probe
  - Archival journal publication & presentations
  - EGR Probe highlighted on Sept. 2015 Applied Spectroscopy cover





Remaining Challenges & Barriers, and Proposed Future Work

Major Challenge: Improved combustion uniformity, configurations & design models
Solution: Develop & apply diagnostics to resolve what we can't currently measure

- Measurement campaigns at Cummins
- Assess performance of hardware, systems, control & design models

Supporting Diagnostic Tools

Challenges	Approach\Future Work (FY16-18):
Implement cylinder-charge model – Resolve 0.5% cylinder-charge fluctuations	Implement new EGR Probe design – Develop solution for collimated fiber output
High-temperature exhaust measurements – Faster & direct vs. via EGR loop – More complete cylinder uniformity assessment	Improve line-of-sight exhaust instrument – Develop in-operation cleaning of multi-pass windows Develop high-temperature probe – Modify cooling, surface contacts & coatings
CO combustion uniformity measure	Modify instruments to incorporate CO – EGR Probe & line-of-sight exhaust instrument – FY16-17 milestones
Measure other significant parameters influencing combustion uniformity	Develop stretch diagnostic technologies – Candidates: mass flux & cylinder-head temperature

Work supports improving combustion uniformity to allow advanced powertrain arrangements, which can reliably deliver higher-efficiency operation

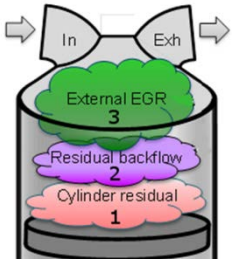
Summary

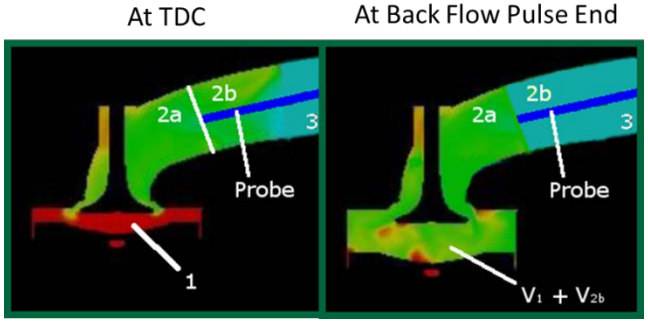
- **Relevance**
  - CRADA work enables improved cylinder-to-cylinder & cycle-to-cycle uniformity
  - Enables DOE goals for improved combustion knowledge, modeling, efficiency and durability
- **Approach**
  - Develop diagnostics to measure multi-cylinder-engine spatial & temporal uniformity
  - Apply diagnostics to advance engine technology
    - Assess specific hardware configurations
    - Tune, validate & improve design simulation tools (models)
- **Technical Accomplishments**
  - New EGR Probe design for improved signal-to-noise performance
    - Provides pathway to implementing measurement-based cylinder-charge model
  - Identified additional SNR improvements via instrument & methods studies
  - New diagnostic for crank-angle-resolved exhaust O_2, H_2O, T & P measurements
- **Collaborations**
  - EGR Probe application to DOE High-Dilution SGDI project & U. Central Florida partnership
  - Archival publication, patent, publication, & cover feature of Applied Spectroscopy journal
  - CRADA-developed diagnostics available to users outside the CRADA
- **Future Work**
  - Application campaigns at CTC on advanced development engine platforms
    - Assess hardware, design models and advanced closed-loop control strategies
  - Improve SNR and applicability of diagnostics
  - Add CO measurement capability in intake and exhaust diagnostics
  - Develop new measurements for parameters relevant to combustion uniformity

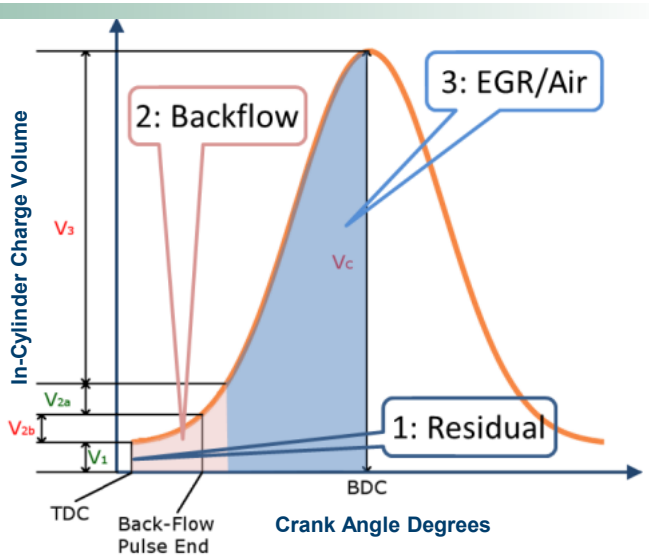
Technical Back-Up Slides

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

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







Model Results:

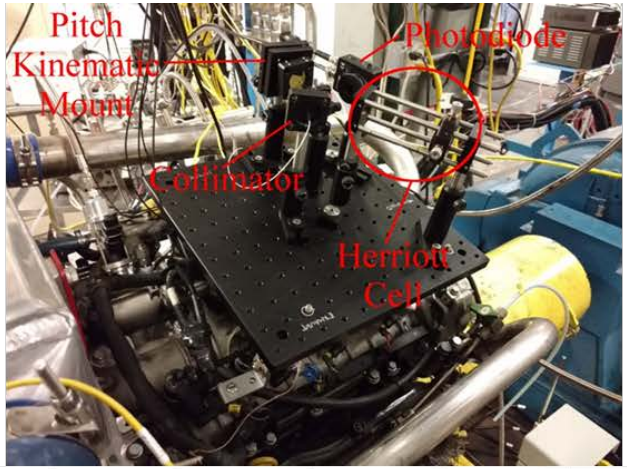
Charge @ IVC	30% EGR w/ Backflow	30% EGR w/o Backflow
$\%CO_2$	2	1.8
T (K)	370	362

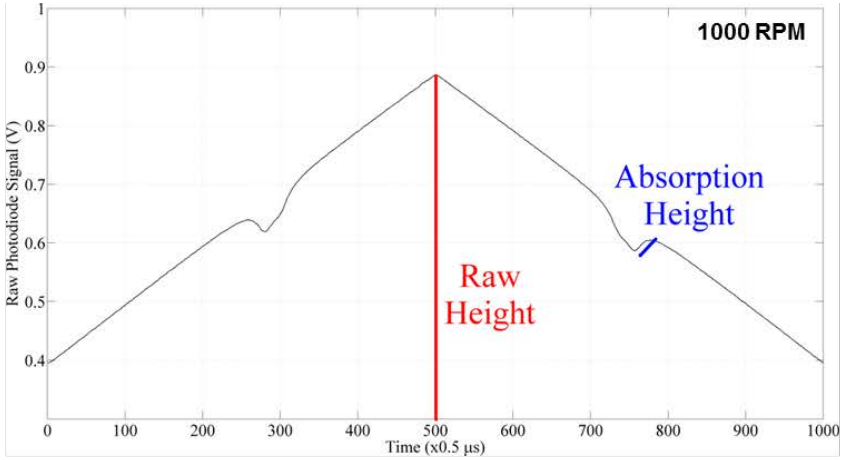
EGR Probe Uncertainty Analysis:

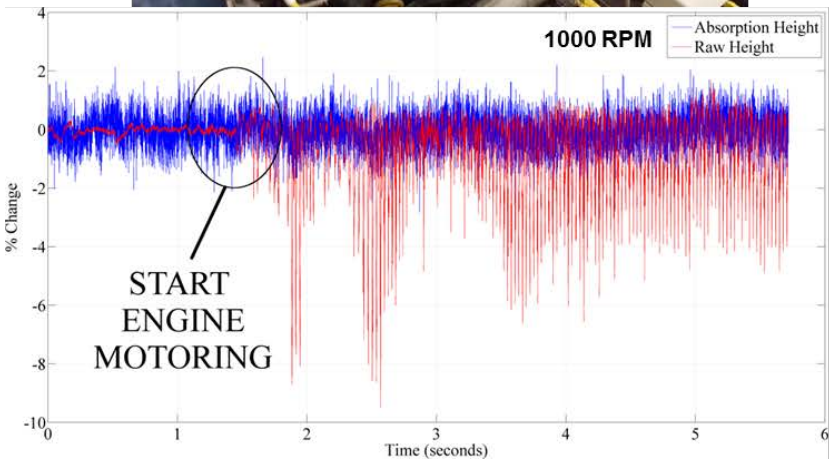
Charge @ IVC	Uncertainty Analysis		Measured Charge Noise
	w/ Etalons	w/o Etalons	
$\%CO_2$	10%	1.5%	9%
T (K)	10%	1%	3%

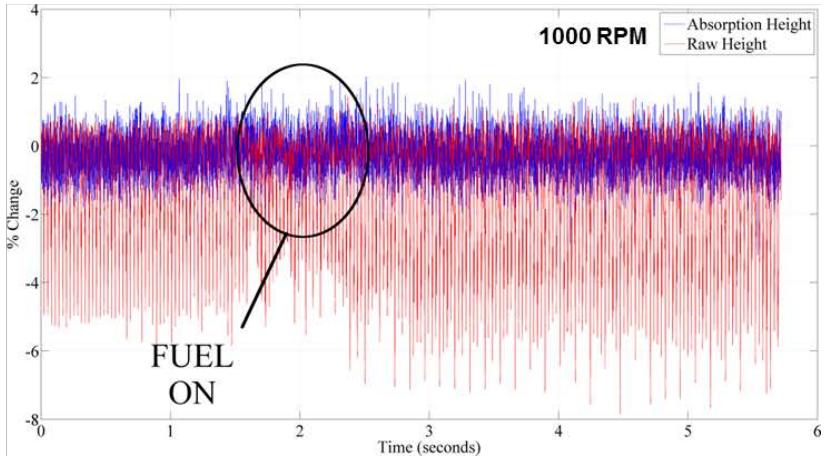
- ***Backflow variations reflect system stability***
  - Use backflow as a direct uniformity indicator
  - Backflow accounts for 10% of Charge CO_2
- Currently limited by sensor uncertainty
  - 0.5% fluctuations impact engine performance
  - Varying etalons are a major noise source
  - Sensor noise dominates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

Tech.Prog.: Herriott Cell Robust to Engine Vibrations









- Stable Herriott-cell operation
  - Mounted on motoring & running diesel engine
  - No cell mode hopping
  - Absolute height varies, but not absorbance