"University Research in Advanced Combustion and Emissions Control"

Optimization of Advanced Diesel Engine Combustion Strategies

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Office of FreedomCAR and Vehicle Technologies Program

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Project ID: ACE020

Acknowledgements

DOE University Research Project DE-EE0000202

DERC, GM CRL, Woodward Engine Systems

"This presentation does not contain any proprietary or confidential information"

Overview

Timeline

- Start – July 1, 2009
- End – September 30, 2012
- 85% Complete

Budget

- Total project funding
  - DOE $3M
  - Contractor $0.6M
- Received FY10 - $0.6M
- Received FY11 - $1.2M
- Received FY12 - $0.8M

Barriers

- Barriers addressed
  - improved fuel economy in light-duty and heavy-duty engines
  - create and apply advanced tools for low-emission, fuel-efficient engine design

Partners

- Industry:

Diesel Engine Research Consortium
General Motors-ERC CRL
Woodward Engine Systems

- Project lead:

Engine Research Center
UW-Madison

Objectives/Relevance

Goals: Development of high efficiency IC engines with goals of improved fuel economy by 20-40% in light-duty and 55% BTE in heavy-duty engines

Approach: Develop methods to further optimize and control in-cylinder combustion process, with emphasis on compression ignition engines

High fidelity computing and high-resolution engine experiments used synergistically to create and apply advanced tools needed for high-efficiency, low-emissions engine design

Engine technologies considered include H/P/RCCI (Reactivity Controlled Compression Ignition) and lifted flame operation with single and dual fuels

Barriers: Optimized combustion phasing and minimized in-cylinder heat transfer losses.
Minimize soot and NOx emissions → reduced fuel for DPF and SCR

Outcomes: Efficient, low-emissions engine concepts proposed, evaluated and understood

Approach – 4 Tasks, 12 Projects

Task A: Combustion strategies for increased thermal efficiency

Team: Reitz, Foster, Ghandhi, Rutland

1 - Optimization of combustion chamber geometry and sprays using advanced CFD - *Reitz*

2 - Modeling combustion control for high power and mode switching - *Rutland*

3 - Experimental investigation of variable injection pressure and dual fuel strategies in a HD engine - *Reitz*

4 - Experimental investigation of chamber design, fuel injection, intake boosting and fuel properties in a LD engine - *Foster*

Task B: Fuels as an enabler for fuel efficiency improvement

Team: Foster, Ghandhi, Reitz, Rothamer

1 - Optical engine in-cylinder investigations of gasoline and gasoline/diesel/other mixtures LTC – *Ghandhi*

2 - In-cylinder optical investigation of soot formation during extended lift-off combustion (ELOC) – *Rothamer*

Task C: Multi-scale predictive tools for combustion & emissions

Team: Ghandhi, Reitz, Sanders, Trujillo

1 - Develop multi-mode combustion models and reduced chemistry mechanisms – *Reitz*

2 - Develop advanced spray and fuel film models for SCR aftertreatment – *Trujillo*

3 - Measurements and control of turbulence mixing in engine flows – *Ghandhi*

4 - Crank-angle-resolved species and temperature measurements for improved understanding of chemistry and mixing – *Sanders*

Task D: System-level engine optimization (including aftertreatment)

Team: Rutland, Foster

1 - Interactions between high and low pressure EGR systems with mixed-mode operation under load and speed transients – *Foster*

2 - Engine and aftertreatment optimization – *Rutland*

Goals and 3rd year Milestones

Task	Goals and 3rd year Milestones
A - **Combustion strategies for increased thermal efficiency**	Optimum spray and combustion chamber design recommendations for improved efficiency of heavy duty (HD) and light duty (LD) diesel engines Milestone: >50% thermal efficiency in HD over extended load range
B - **Fuels for efficiency improvement**	Guidelines for engine control methodologies under light- and high-load operating conditions with consideration of fuel property and mixture preparation effects Milestone: In-cylinder imaging of advanced combustion regimes
C - **Multi-scale predictive tools**	Validated predictive combustion and realistic fuel vaporization submodels for science-based engine analysis and optimization and combustion system concept evaluation Milestone: Develop predictive detailed-chemistry-based models for realistic multi-component fuels, including biofuels.
D - **System-level engine optimization**	Efficient engine system transient control algorithms and strategies appropriate for engine speed/load mode transitions Milestone: Identify important parameters for effective mode transients that have controlled pressure rise rates and minimal emission excursions.

Task A.1: Optimization of combustion chamber geometry and sprays using advanced CFD - Reitz

Optimize combustion system for high efficiency, low emissions

Approach: Use multi-objective genetic algorithm optimization with KIVA for gasoline/diesel and natural gas/diesel RCCI

Accomplishments: HD RCCI optimized with dual fuels over wide load/speed range (4-23 bar, 800-1800 rev/min)

Findings: CH_4 → higher heat loss; Higher boost with CH_4/diesel helps to reduce NOx; no EGR needed up to 14 bar.

Plans for wrap-up: Explore triple injection strategies with optimized piston bowl geometry/Compression Ratio

9 bar, 1300 rev/min

Design Parameter	Natural Gas/Diesel		Gasoline/Diesel	
	Low Boost	High Boost	Low Boost	High Boost
Intake Pressure [bar abs.]	1.45	1.75	1.45	1.75
Intake Temperature [C]	60	60	32	32
Total Fuel Mass [mg]	89	89	94	94
Low-Reactivity Fuel (Premixed) [%]	85%	85%	89%	89%
Premixed Fuel Equiv. Ratio [-]	0.35	0.29	0.42	0.35
Diesel SOI 1 [deg ATDC]	-87.3	-87.3	-58.0	-58.0
Diesel SOI 2 [deg ATDC]	-38.3	-38.3	-37.0	-37.0
Diesel in 1st Inj. [%]	40%	40%	60%	60%
EGR [%]	0%	0%	43%	43%
Results				
Soot [g/ikW-hr]	0.002	0.003	0.007	0.014
NOx [g/ikW-hr]	0.25	0.02	0.02	0.01
CO [g/ikW-hr]	0.2	1.8	1.2	3.6
UHC [g/ikW-hr]	0.5	2.5	2.7	4.0
η_{gross} [%]	50.4%	50.4%	52.1%	52.2%
PPRR [bar/deg]	5.1	4.8	10.6	9.9
Ring. Intens. [MW/m^2]	1.5	1.2	5.1	3.7

Nieman et al. SAE 2012-01-0379

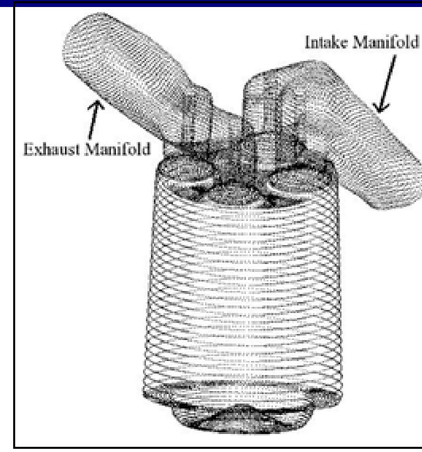
Task A.2: Modeling combustion control for high power and mode switching - Rutland

Improved understanding of primary mixing and combustion processes controlling high power density and mode switching

Approach: Use Large Eddy Simulation (LES) spray and combustion models for increased accuracy and sensitivity to mixing effects

Accomplishments: Examined different strategies to control mode transitions:
(i) various fuel injection schedules, (ii) variable valve timing, (iii) port water injection to compensate for EGR ramp up. Trade-offs among peak-pressure-rise rate, combustion efficiency, and maintaining mean-effective-pressure described.

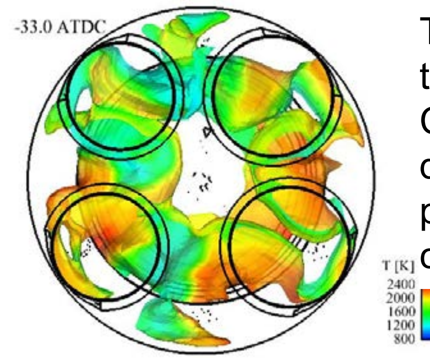
Plans for wrap-up: Correlate mode transition trade-offs with in-cylinder mixing characteristics



Standard diesel split injection (-57, +12°), 0% EGR

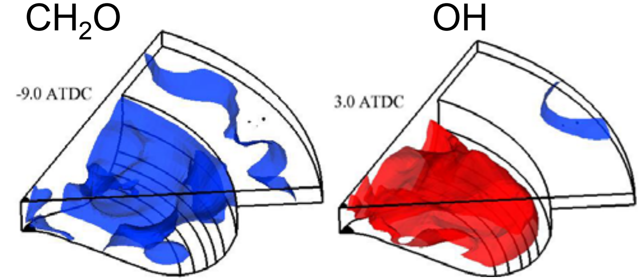
mode transition

PCCI Early injection (-64°), 65% EGR



Temperature during transition using VVA. Combustion is distributed but still partially mixing controlled

CH_2O OH



2-stage combustion with water injection

Task A.3: Experimental investigation of variable injection pressure and dual fuel strategies in a HD engine - Reitz

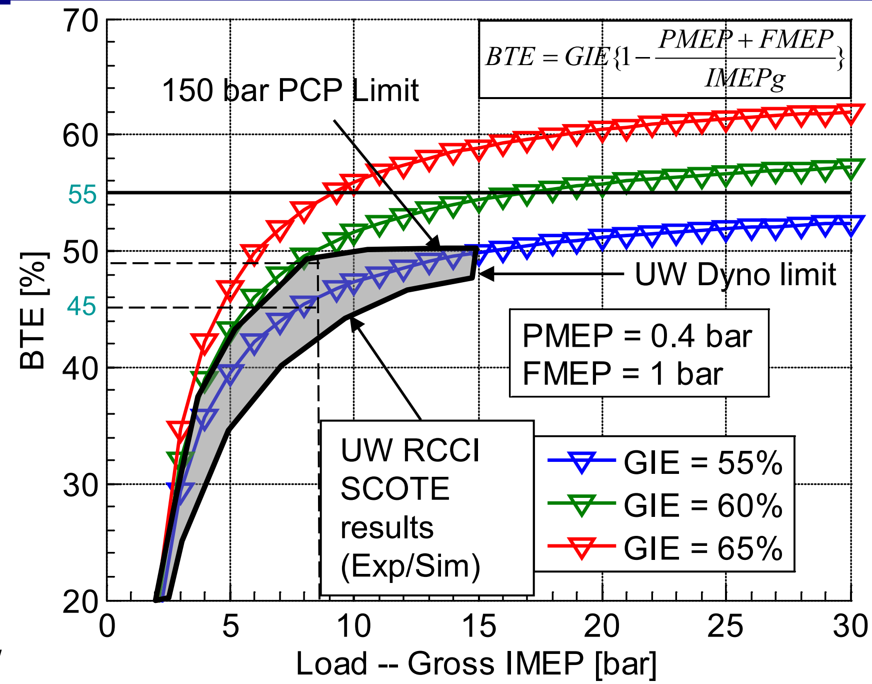
Dual fuel RCCI provides path to high-efficiency, low-emissions operation.

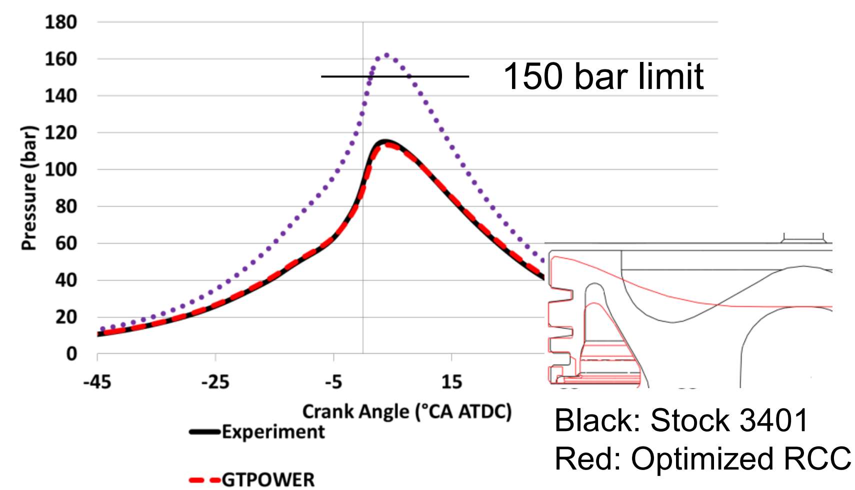
Approach: Use Caterpillar 3401 HD diesel engine with dual-fuel (port injection of gasoline/E85 and optimized early-cycle, direct multiple injections of diesel or gasoline + 3.5% 2-EHN).

Accomplishments: RCCI demonstrated to provide high-efficiency (GIE ~ 53-58%), low-emissions (EPA-2010) in cylinder w/ combustion phasing control and PRR < 10 bar/deg.

Plans for wrap-up: Explore increased CR=18.6 (1 pt), Optimized piston/crevice (0.5 pt), Thermal Barrier Coating for reduced heat transfer (1.5 pt) to reach GIE~ 60%.

Splitter SAE 2012-01-0383.





Task A.4: Experimental investigation of chamber design, fuel injection, intake boosting and fuel properties in a LD engine - Foster

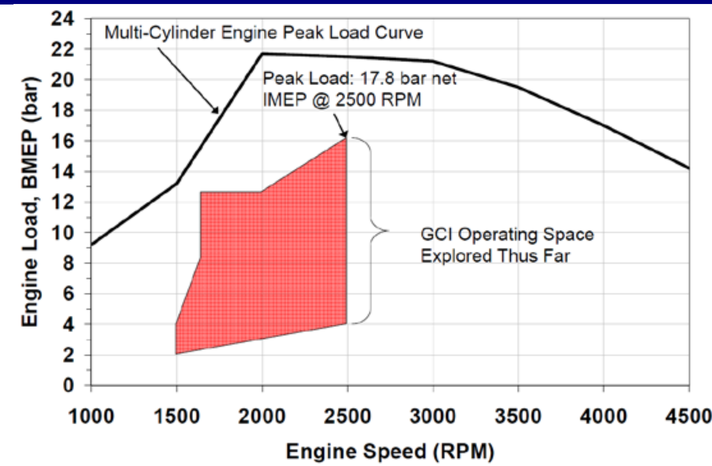
Investigate potential of achieving LTC operation with a range of fuels in LD engine.

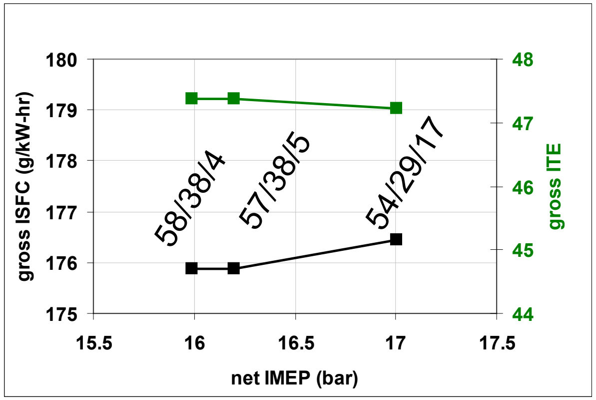
Approach: Use advanced multiple injection strategies and fuel partitioning to evaluate LTC operation on a research GM 1.9L diesel engine using only gasoline fuel

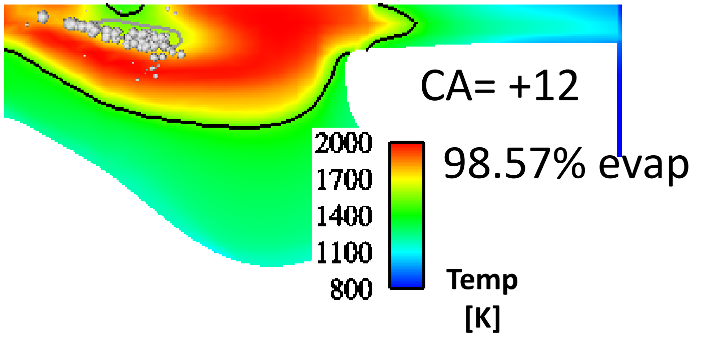
Accomplishments: GCI combustion w/ triple injection has been demonstrated in a LD diesel engine over a large load/speed operating range, (2 – 17 bar), with low emissions and high efficiency. Developed a combustion index (CI) to assess potential of successful operating parameters

$$CI = \frac{t_{c,res}}{M_t} \sum \frac{m_{ijk}}{\tau_{ig,ijk}}$$

Plans for wrap-up : Use new fundamental understanding of conditions for LTC to extend GCI load and speed operating ranges.







Task B.1: Optical engine in-cylinder investigations of gasoline and diesel/other mixtures LTC – *Ghandhi*

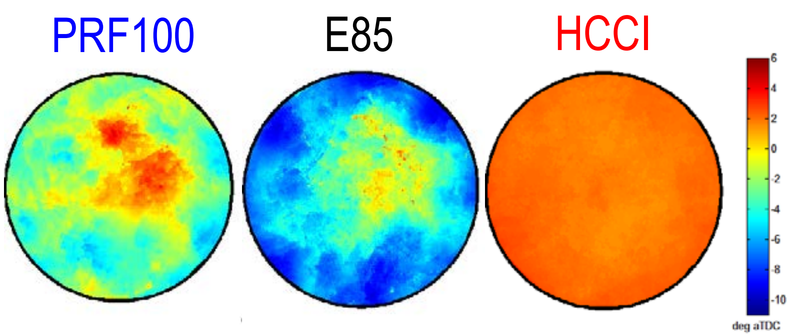
Understanding the mode of combustion progression is important to properly model advanced combustion regimes

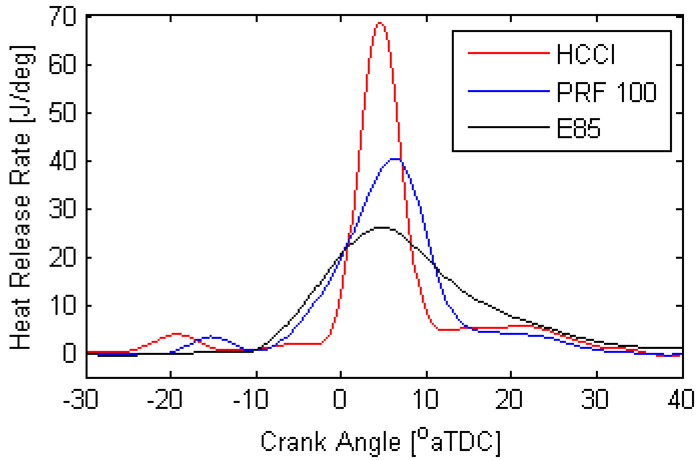
Approach: Acquire high speed chemi-luminescence movies to understand spatial progression of combustion and the mode of reaction front propagation.

Accomplishments: Optimized RCCI combustion using fuel pairs (PRF100/diesel; E85/diesel) with varying level of reactivity difference has been visualized. Reactivity difference seen to control heat release duration. Comparisons made to pure HCCI at a similar phasing.

Plans for wrap-up: Pursue optical method for determining the mode of combustion front propagation under low temperature combustion.

Ignition maps showing when ignition takes place (in the bowl) .





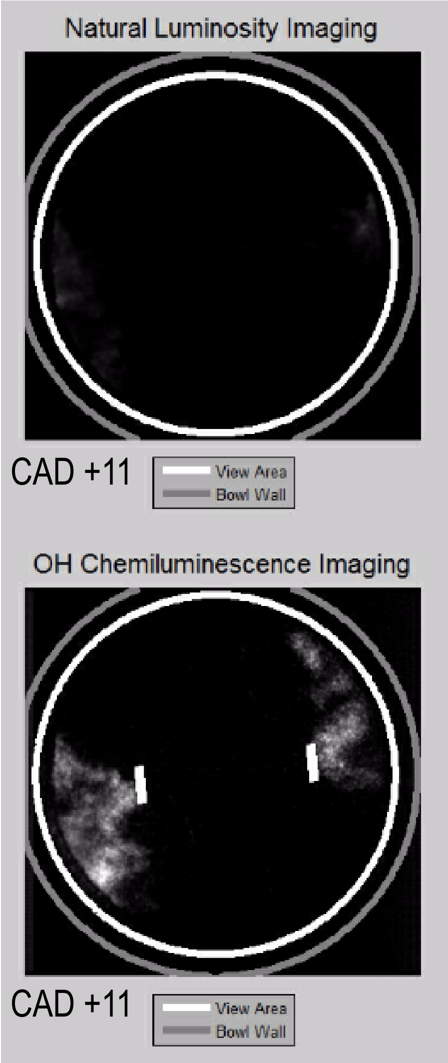
Task B.2: In-cylinder optical investigation of soot formation during extended lift-off combustion (ELOC) – *Rothamer*

Soot formation from diesel flames reduced/eliminated with increased premixing prior to lift-off length.

Approach: Explore sootless diesel combustion with extended lift-off in automotive-size optical engine. Parameters explored include: fuel ignition properties, swirl, rate-of-injection, in-cylinder T/V distributions.

Accomplishments: Demonstrated strong influence of swirl on soot formation and premixing using high-speed in-cylinder imaging of OH^* chemi-luminescence and soot natural luminosity. Begun probing in-cylinder temperature (T) and velocity (V) distributions using phosphor based simultaneous PIV+T diagnostic.

Plans for wrap-up: Study in-cylinder T and V regions where gases are entrained into fuel jet. Results will provide important information on temperature of entrained gases during combustion which has been previously unobtainable.



Soot natural luminosity and OH chemi-luminescence images during ELOC

Task C.1: Develop multi-mode combustion models and reduced chemistry mechanisms – *Reitz*

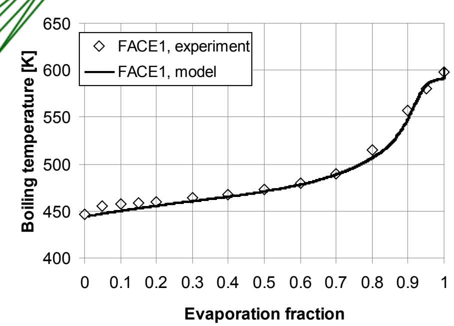
CFD combustion predictions are an essential tool for exploring new combustion regimes.

Approach: Multi-component fuel vaporization and reduced chemistry models developed and applied to study combustion regimes, including dual-fuel, gasoline, biodiesel CI combustion under a range of multiple injection, injection pressure, EGR, and conditions.

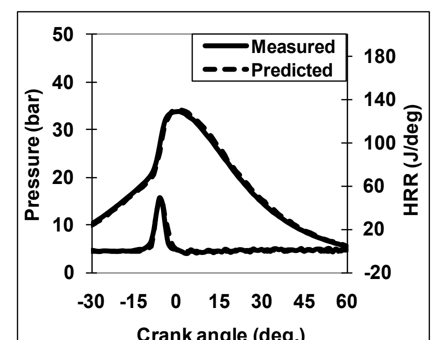
Accomplishments: Physical Surrogate Group Chemistry Representation developed using generic reaction paths.

Spray compo	Mass_frac
c14h30(alkane)	0.12004
chx(naphthene)	0.08000
c10h18(naphthene)	0.26000
c10h22(alkane)	0.05000
c16h34(alkane)	0.12137
c20h42(alkane)	0.05091
c14h10(poly-aromatic)	0.05500
mxylene(aromatic)	0.01000
mcymene(aromatic)	0.02000
c11h16(aromatic)	0.04000
tetralin(aromatic)	0.06900
c13h20(aromatic)	0.12368

Chemistry compo	Mass_frac
c14h30	0.292
nc7h16	0.050
cyclo-hexane	0.340
toluene	0.318



Realistic multi-component fuels modeled with 35 surrogate component data base (194 species, 877 reactions).



Plans for wrap-up: Further bio- and other mechanism development; Application to RCCI.

Task C.2: Develop advanced spray and fuel film models for SCR aftertreatment – *Trujillo*

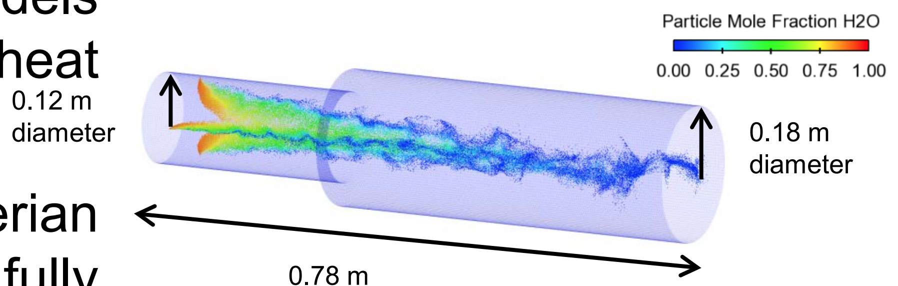
State-of-the-art Urea-Water-Solution (UWS) spray models make assumptions regarding gasification process. Improved models implemented for thermodynamic and heat transfer processes.

Approach: Arbitrary-Lagrangian-Eulerian method with explicit interface tracking to fully resolve urea droplet spatially and temporally. CFD spray modeling with RANS turbulence model.

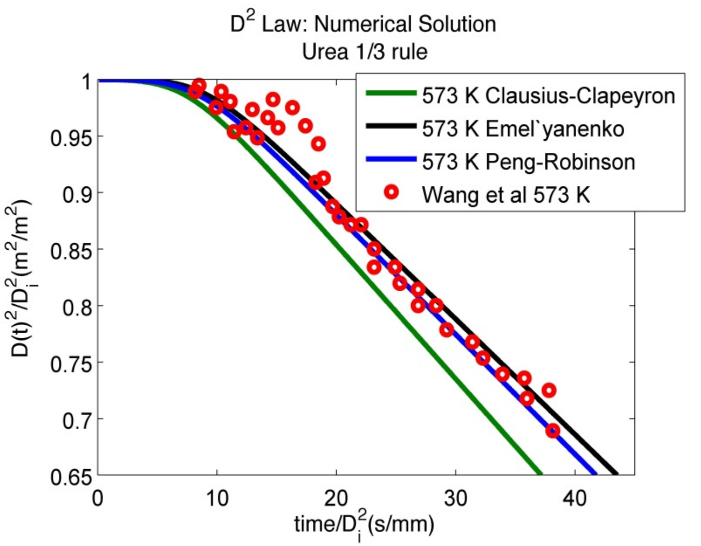
Accomplishments: Good agreement with 2-phase heat transfer solutions and vaporization of UWS droplets. Excellent agreement with n-heptane, water & urea drop experimental data.

Plans for wrap-up: Finalization of results and documentation for submission to journals and workshop/meetings.

Participation in CLEERS

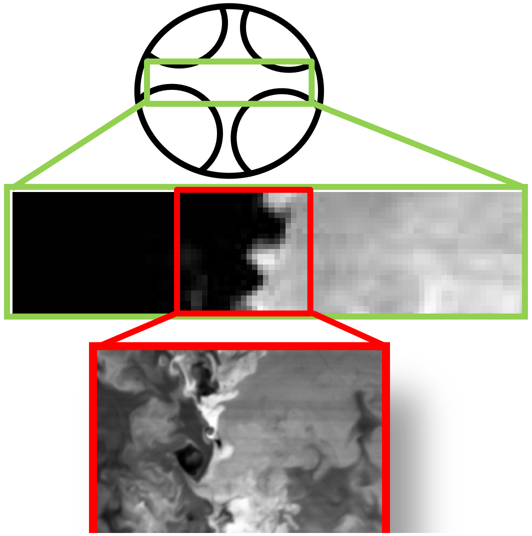


UWS Spray

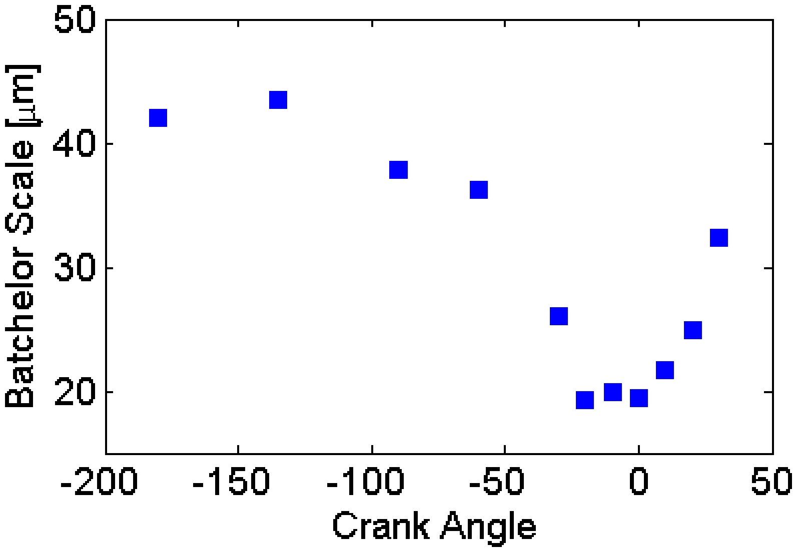


To correctly model mixing requires an understanding of turbulent flow field at smallest length scales where mixing takes place.

Approach: Use high-resolution scalar field measurements to characterize the full turbulent engine flow field.



Accomplishments: Used gas injection technique to perform measurements over entire cycle. Able to detect reduction in Batchelor scale due to piston compression. Updated hardware to a well-characterized (with PIV) cylinder geometry.

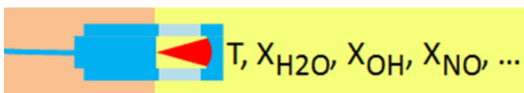


Plans for wrap-up: Use PIV and PLIF data to complete analysis of length scales. Collaborate with model development in project A.2.

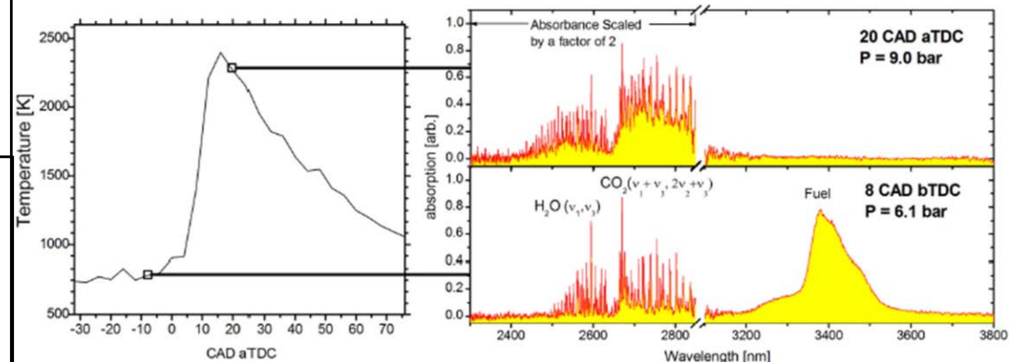
Task C.4: Crank-angle-resolved species and temperature measurements for improved understanding of chemistry and mixing – *Sanders*

In-cylinder measurements, together with simulations, will lead to optimized low-temperature combustion.

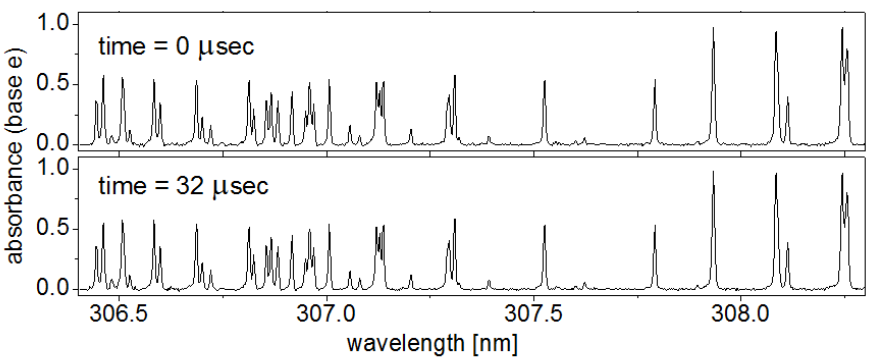
<u>Accomplishments:</u>



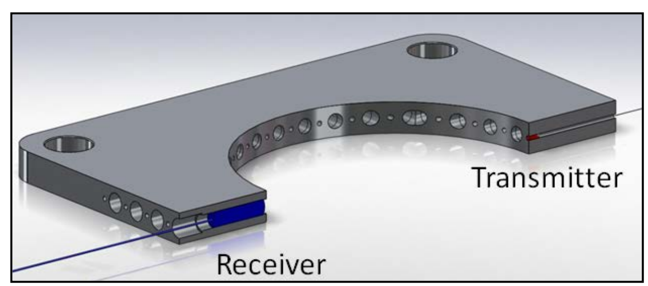
Developed fiber-optic probes to simplify access to in-cylinder gases.

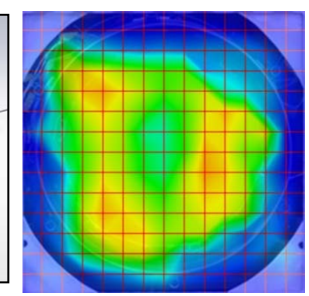


Recorded quantitative in-cylinder absorption spectra of fuel, H_2O and CO_2 with crank angle resolution over the 2.4 - 3.7 μm range.



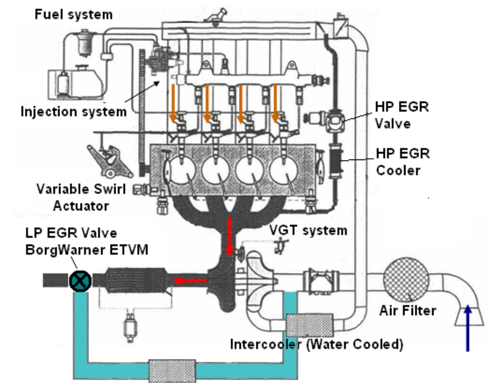
Developed 30 kHz spectrometer for in-cylinder measurements in the 220 – 380 nm range, demonstrated OH measurements near 308 nm.





Built many-beam fiber-optic access spacer rings; demonstrated 50 kHz, 2-D gas temperature imaging using H_2O absorption near 1350 nm.

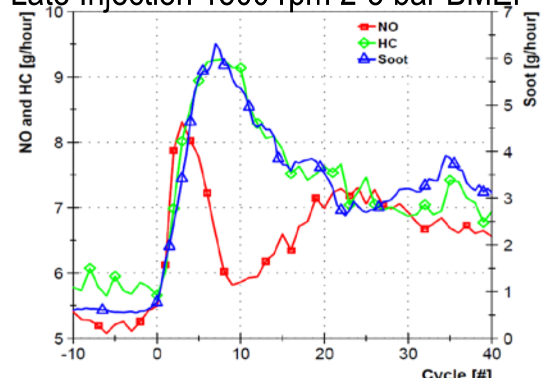
Task D.1: Interactions between high and low pressure EGR systems with mixed-mode operation under load and speed transients – *Foster*



Develop fundamental level understanding of transient combustion processes by studying transient diesel LTC.

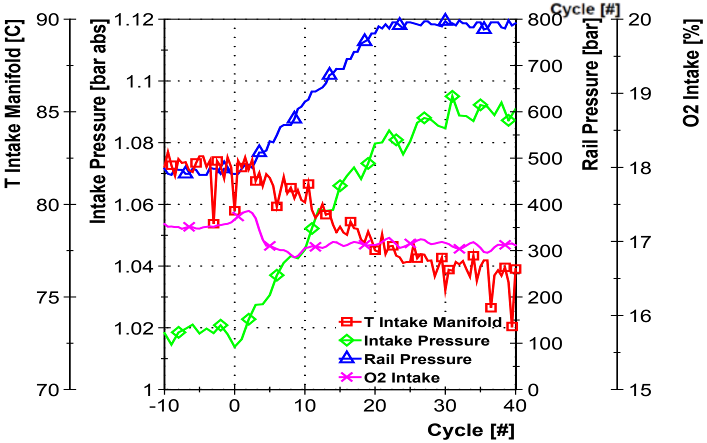
Approach: Use coordinated engine experiments and system simulations to identify fundamental variables that cause differences between actual transient performance and quasi-steady approximations of the transient.

Late Injection 1500 rpm 2-5 bar BMEP



Accomplishments: Deviations in MAF and MAP during mode change transients do not fully account for transient behavior of LTC. Instead, deviations in intake charge temperature and oxygen concentration have much greater impact on transient performance.

Plans for wrap-up: Further analysis of effect of exhaust manifold pressure variations on transient performance. Study of sensitivity of emissions and performance to transient behavior of EGR fraction, boost pressure, common rail pressure, swirl, etc.



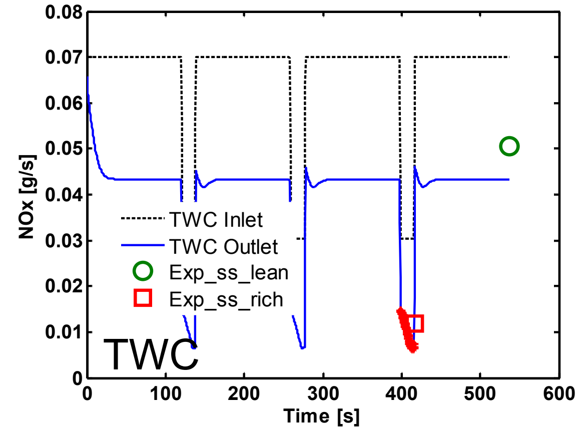
Task D.2: Engine and after-treatment optimization-Rutland

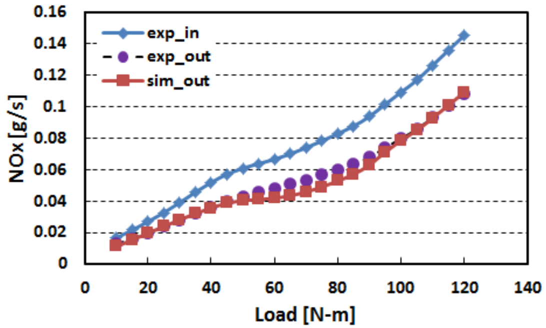
Explore strategies for engine optimization including aftertreatment during transients.

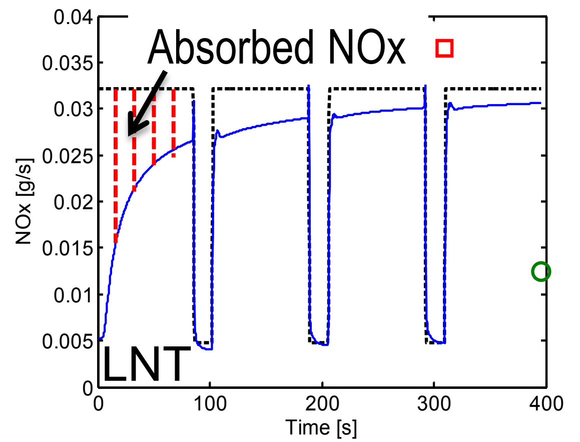
Approach: Integrate engine, combustion, emissions, and aftertreatment models into Simulink. Use multi-cycle simulations with controllers to simulate transients.

Accomplishments: Fuel injection strategies for light duty mode transients explored. Aftertreatment models developed, tested, and validated with ORNL data during transients. Tests under a wide range of loads show good comparison.

Plans for wrap-up: Additional validation with more detailed data; explore emissions during load transient.







Tech. Transfer & Collaborations/Interactions

DOE LTC Consortium project DE-EE0000202

Collaborators:

General Motors CRL, Sandia Labs, Woodward Engine Systems
Diesel Emissions Reduction Consortium (DERC) ~30 members

Argonne National Laboratory
Caterpillar
Chevron Companies
Chrysler
Corning Incorporated
Cummins
Daimler NA
Eaton Corp.
Ford Motor Company
GE Global Research
GM R&D Powertrain
Isuzu AEC.
John Deere Company
Mahle Powertrain
Magneti Marelli Powertrain
Mitsubishi Heavy Industry
NI/Drivven
Navistar
Nippon Soken Inc.
Oak Ridge National Lab
PACCAR
Renault
Robert Bosch
Thomas Magnete USA
Toyota NA
US Army TARDEC
Volvo Powertrain
Weichai
Woodward Governor Co.
Wuxi Fuel Injection
Yanmar

Tech transfer: GM/Sandia monthly teleconference and face-to-face meetings, DERC members receive quarterly reports and annual meeting.

Optimization of Advanced Diesel Engine Combustion Strategies – Summary

4 Tasks, 12 projects integrated to optimize and control diesel combustion for maximum fuel efficiency with minimum penalty to meet emissions mandates.

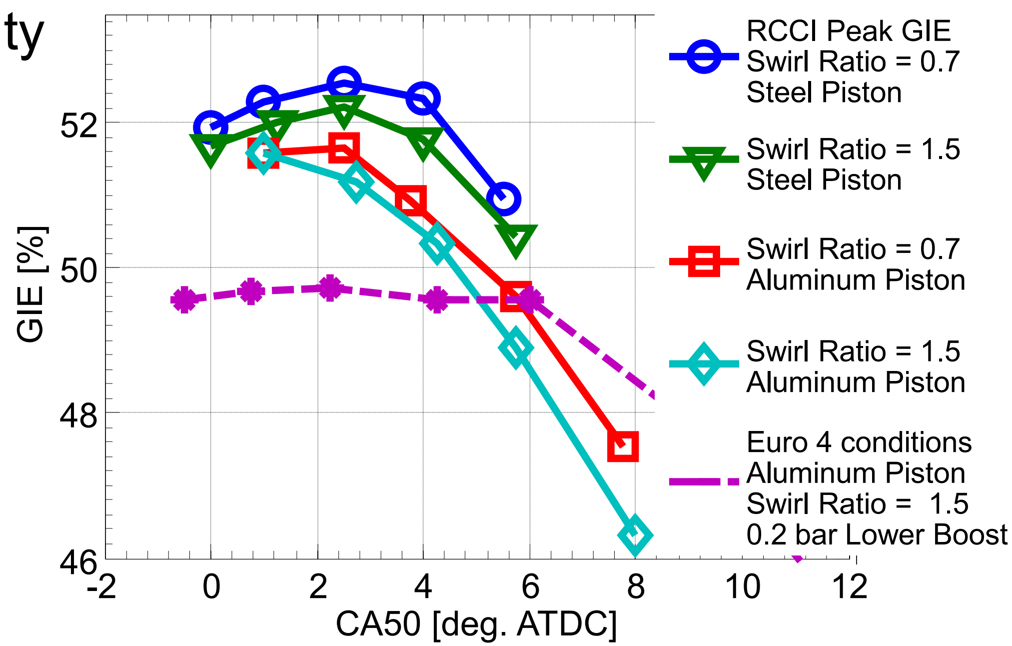
Approach: Use novel diagnostics, fuel-types, injection concepts, optimized piston geometries with advanced CFD models and coordinated engine experiments.

Accomplishments: Optimization of mixture preparation and fuel reactivity demonstrated to offer significant improvements in engine efficiency (GIE >50%) without need for NOx or PM aftertreatment.

Plans for Next Year: Continue to explore further increases efficiency on HD and LD engines

- Optimize injection strategies and piston geometry and CR.
- Explore transient control strategies

RCCI in Light-Duty GM 1.9L engine



S. Kokjohn, PhD thesis 2012