Optimization of Advanced Diesel Engine Combustion Strategies

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Project ID: ACE020

Acknowledgements

DOE University Research Project DE-EE0000202

GM CRL, Woodward Engine Systems

Overview

Timeline

- Start – July 1, 2009
- End – December 31, 2012
- 60% Complete

Budget

- Total project funding
  - DOE $3M
  - Contractor $0.6M
- Received FY10 - $0.64M
- Funding for FY11 - $1.2M

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

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

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

Approach: Use high fidelity computing and high-resolution engine experiments synergistically to create and apply advanced tools needed for high-efficiency, low-emissions engine combustion design

Engine technologies considered include PCCI and lifted flame operation with single and dual fuels (RCCI)

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/Ghandhi*

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 2nd year Milestones

Task	Goals and 2nd 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.

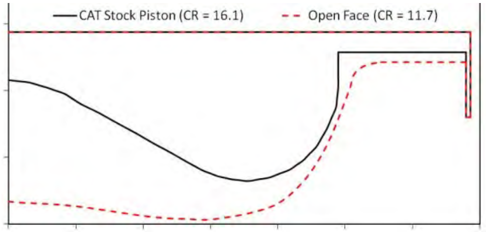
Optimize piston bowl-spray matching for high fuel efficiency, low emissions

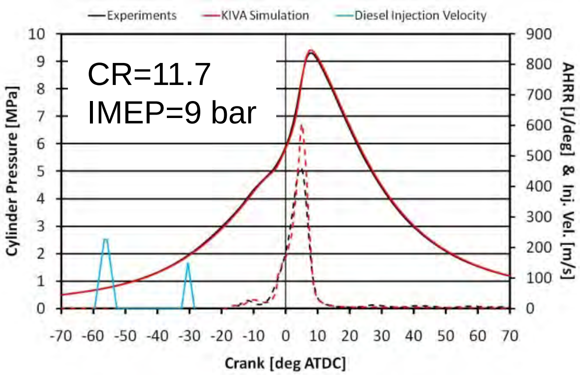
Approach: Apply multi-objective optimization genetic algorithm (MOGA) with KIVA models to Reactivity Controlled Compression Ignition (RCCI).

Accomplishments: Heavy-duty engine optimized with gasoline/diesel dual fuels at low-, mid- and high-load (4, 9, 21 bar), using low CR=11.7 piston. Findings:

- Low- & mid- similar to CR=16.1, but no EGR needed

CR	Objectives					
	Nox [g/kW-hr]	Soot [g/kW-hr]	CO [g/kW-hr]	HC [g/kW-hr]	ISFC [g/kW-hr]	PPRR [bar/deg]
11.7	0.02	0.005	1.1	1.3	159.3	7.0
16.1	0.01	0.008	5.6	1.7	150.0	9.9
CR	**Design Parameters**					
	Gasoline % [-]	SOI #1 [ATDC]	SOI #2 [ATDC]	DI Fuel #1 [-]	Inj Press [bar]	EGR [%]
11.7	0.82	-71.4	-22.8	0.56	862	1.3
16.1	0.89	-58.0	-37.0	0.60	800	43.0





Plans for Next Year: Dual fuel optimization over wide range of speeds and loads with optimized piston bowl geometry/Compression Ratio

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 with multicycle engine simulations for increased accuracy and sensitivity to mixing effects

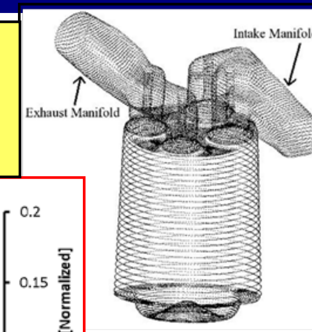
Accomplishments: Injection schedules proposed for controlled mode switching

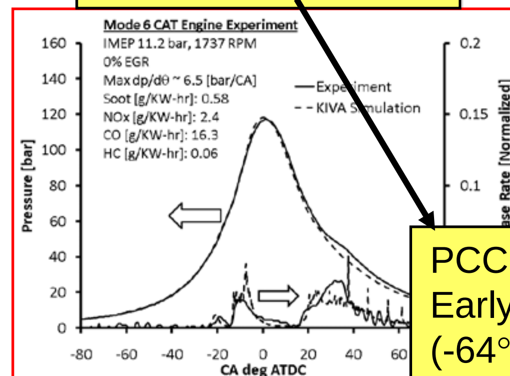
- Original PCCI fuel injection distributes fuel rich regions in the squish area - Switches 2, 3 and 4 distribute fuel evenly between squish and bowl

Plans for Next Year: Further studies to investigate the effect of ramped-up EGR by changing valve timing during mode transition

Effect of 1st cycle after start of mode transition on subsequent cycle

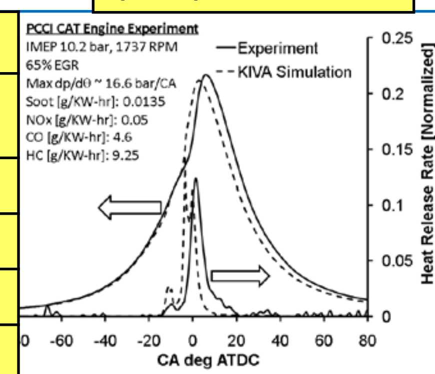
Standard diesel split injection (-57, +12°), 0% EGR

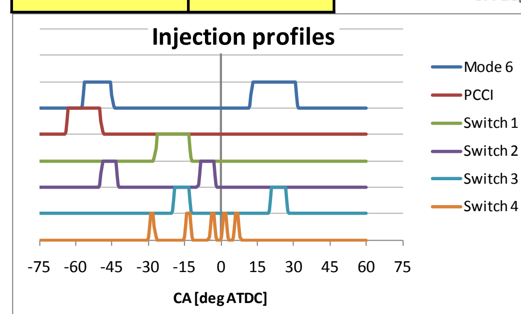




PCCI Early injection (-64°), 65% EGR

PRR	bar/deg
Direct to PCCI	120
Switch 1	26.7
Switch 2	35.1
Switch 4	18.8
PCCI	11.3





Reactivity Controlled Compression Ignition (RCCI) optimizes in-cylinder reactivity gradients to provide high-efficiency, low-emissions operation, with combustion phasing control at both high and low engine loads without high pressure rise rates.

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

Accomplishments: EPA 2010 HD emissions met in-cylinder without after-treatment, with >50% thermal efficiency and PRR < 10 bar/deg. Operation down to IMEPg=2.2 bar achieved.

Plans for Next Year: Further optimization of dual fuel operation over wide speed and load ranges also with low compression ratio piston (Task A.1).

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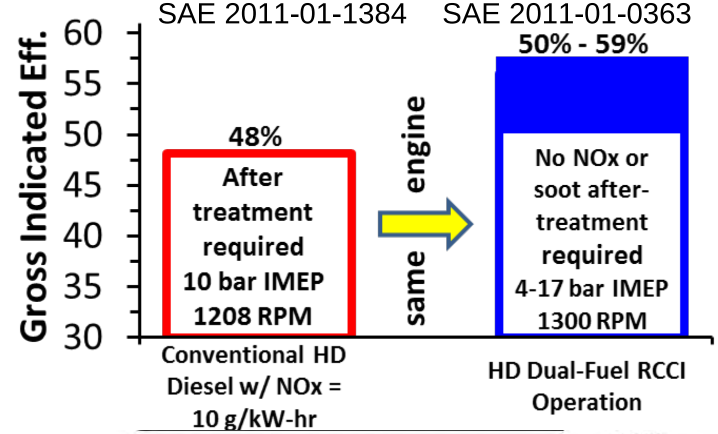

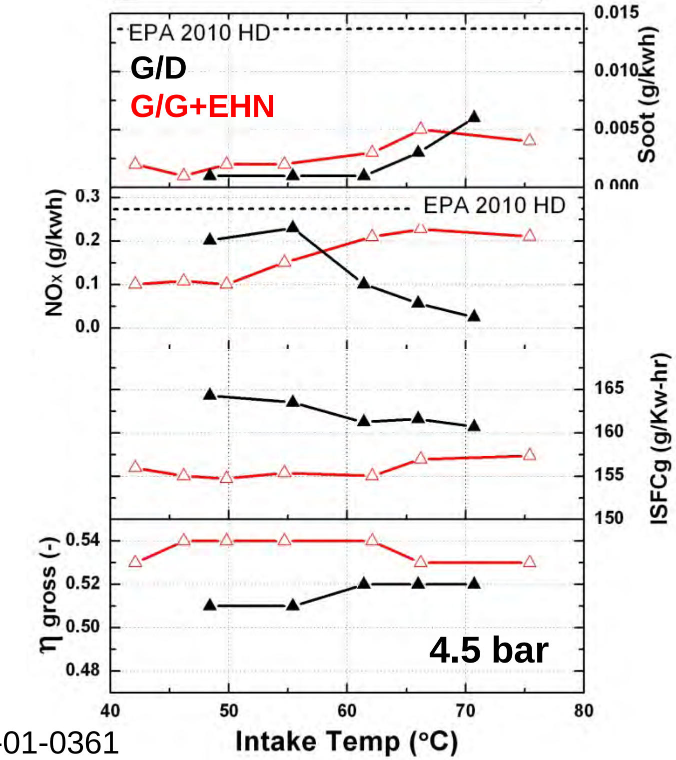

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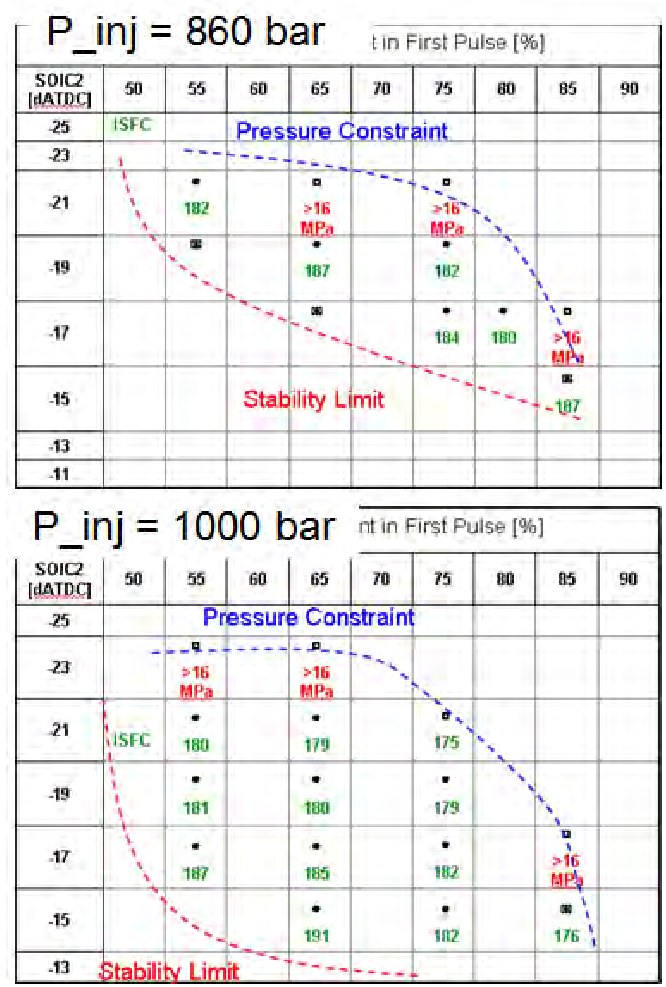
Task A.4: Experimental investigation of chamber design, fuel injection, intake boosting and fuel properties in a LD engine - Foster/Ghandhi

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: Demonstrated LTC with gasoline (GDICI) over load range from 3 bar to 16 bar IMEP. Simulations used to guide choice of multiple injections, fuel partitioning, injection pressure, EGR rate, intake temperature and pressure. Gross indicated efficiencies from 45 to 49% achieved, meeting 2010 emissions in-cylinder (Ra SAE 2011-01-1182)

Plans for Next Year: Use new fundamental understanding of conditions for LTC to assess GDICI load and speed operating ranges.



Effects of injection pressure @ 14 bar IMEPn, 860- vs. 1000-bar injection pressure operating maps

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

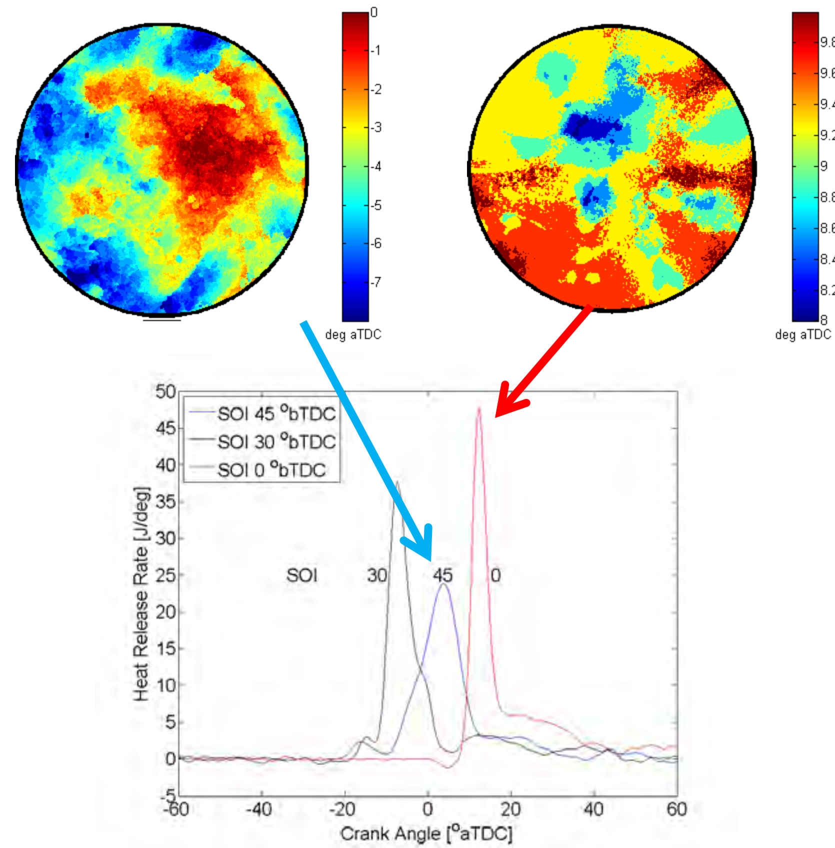
Understanding the mode of combustion progression is important to properly model RCCI combustion

Approach: Acquire high speed chemiluminescence movies to determine ignition location, spatial progression of combustion, and the mode of reaction front propagation.

Accomplishments: Dual fuel combustion has been visualized in the optical engine over a range of operating conditions using high speed chemiluminescence. Different optical filters have been employed to assess behavior relative to standard diesel combustion.

Plans for Next Year: Continue optical engine testing at other operating points; characterize the fuel distribution.

Ignition maps showing when (in the bowl) ignition takes place. For optimized case (45 SOI) ignition starts in the squish region.



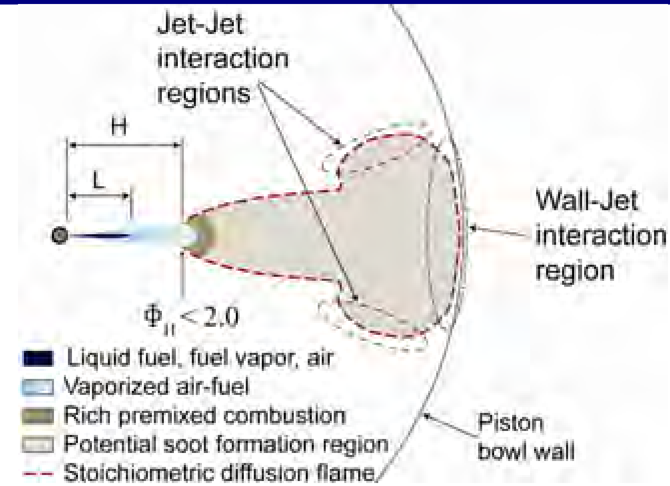
Task B.2: In-cylinder optical investigation of soot formation during extended lift-off combustion (ELOC) – *Rothamer*

Diesel soot formation reduced or even eliminated with increased premixing prior to lift-off length.

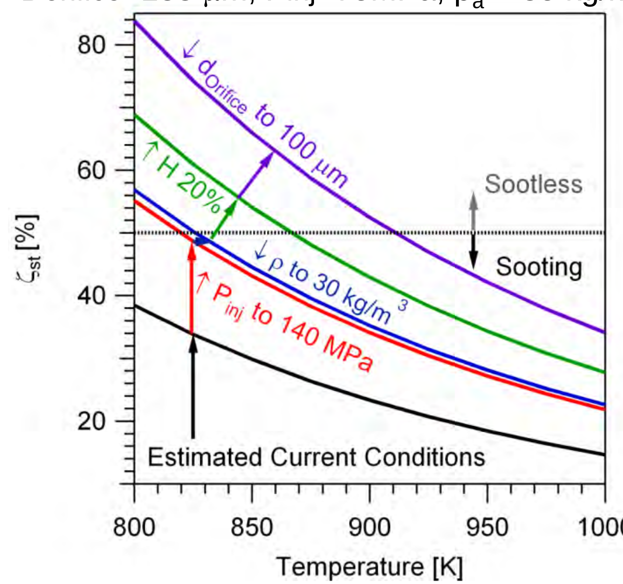
Approach: Explore sootless diesel combustion with extended lift-off in LD optical engine. Key parameters to explore include: fuel ignition properties, swirl, rate-of-injection details.

Accomplishments: New optical piston, head, and liner plate completed. Natural luminosity and chemiluminescence images acquired at baseline operating condition. Currently establishing conditions for achieving ELOC combustion during mixing controlled period of heat release.

Plans for Next Year: Use simultaneous natural luminosity and OH chemiluminescence to investigate effect of ignition properties by sweeping fuel PRF number. Investigate effect of swirl on lift-off.



Dorifice=133 μm, Pinj=75MPa, ρ_a = 35 kg/m^3



Dependence of % stoichiometric air on engine parameters

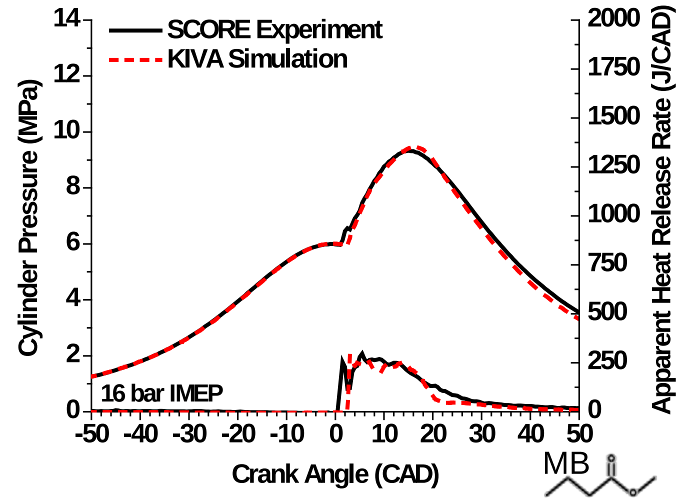
Task C.1: Develop multi-mode combustion models and reduced chemistry mechanisms – *Reitz*

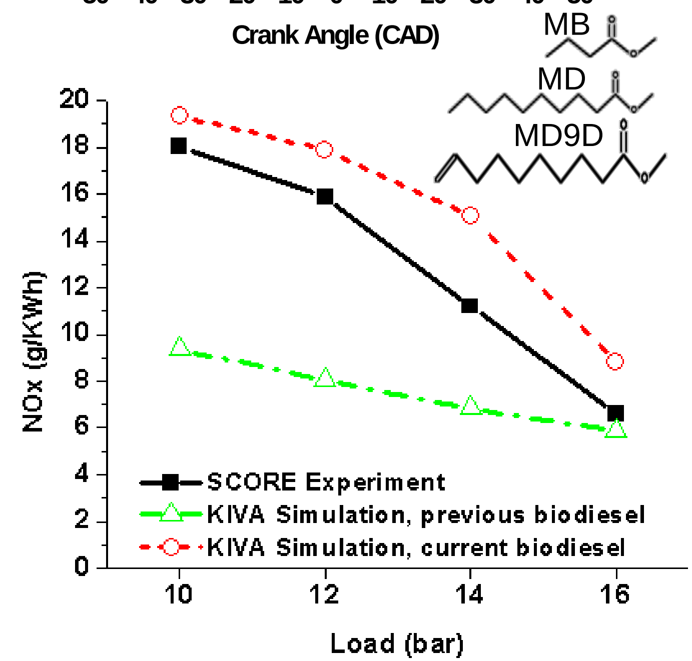
CFD combustion predictions are an essential tool for exploring new combustion regimes.

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: Previously reduced methyl butanoate biodiesel surrogate replaced with methyl decanoate + methyl-9-decenoate mechanism (77 species, 216 reactions) reduced from LLNL 3,299 species, 10,806 reactions. Improved agreement using KIVA with Sandia SCORE experiments for load sweep.

Plans for Next Year: Further bio- and other fuel mechanism development; Application to RCCI.





Brakora SAE 2011-01-0831

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

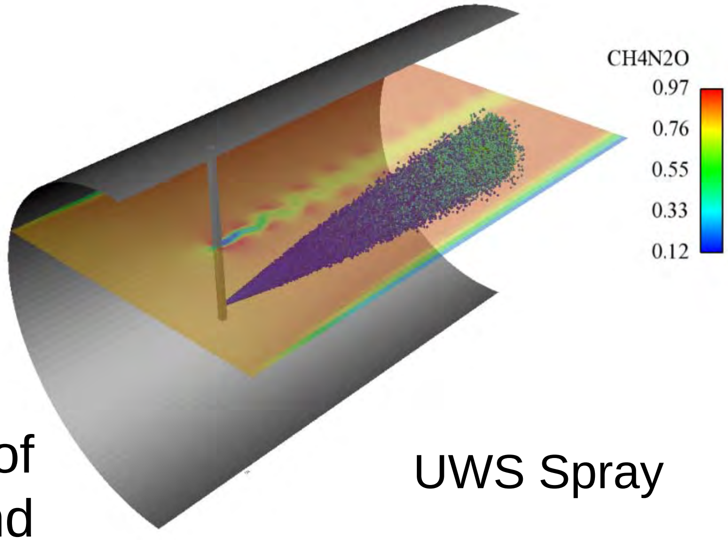
Provide better control/understanding of the Urea-SCR NO_x process through modeling and simulation to allow engine to be optimized for low fuel consumption.

Approach: CFD spray modeling with RANS turbulence models in combination with Volume-of-Fluid spray/wall impingement simulations for deposition modeling.

Accomplishments: i) Performed first set of calculations with UWS spray vaporization and thermal decomposition; ii) Executed detailed VoF simulations of multiple droplet impingement on a heated surface; iii) In the process of developing calculations with full spatial resolution of urea decomposition.

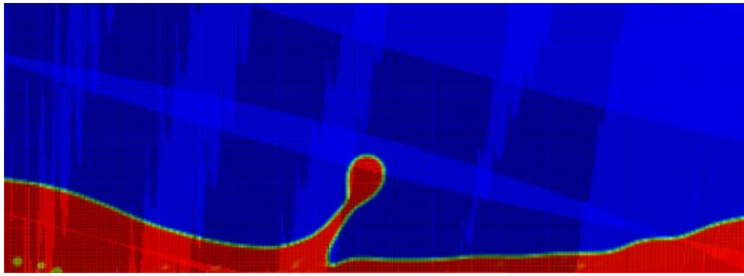
Plans for Next Year: UWS wall impingement and particle decomposition treatment added to spray model; integrate results with Task D.2.

Participation in CLEERS 2011



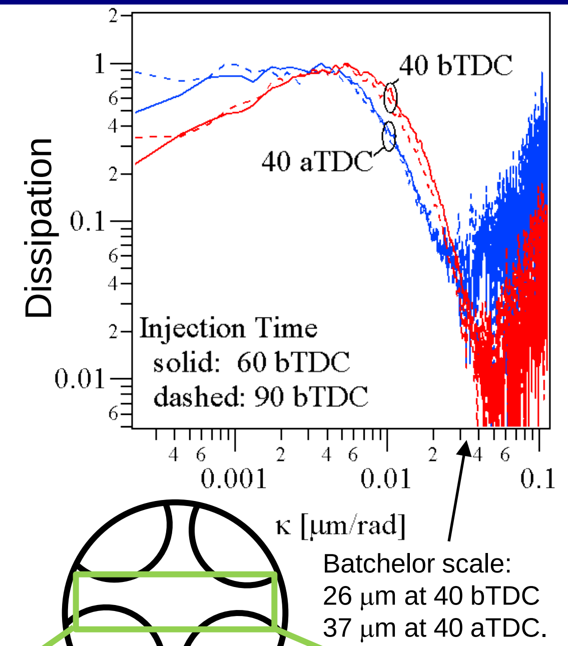
UWS Spray

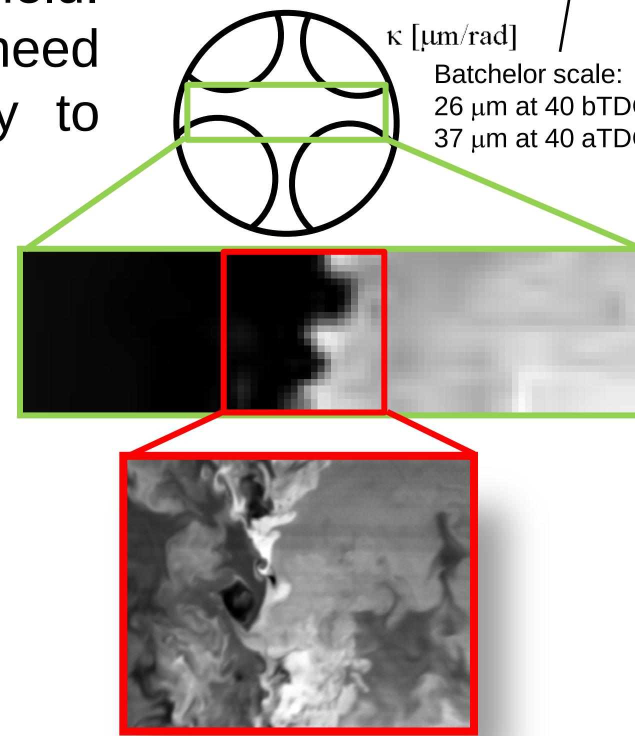
Full resolution of wall film droplet impingement and phase change with heat transfer



High-efficiency, low-emission combustion requires precise control of mixing - RCCI requires controlled spatial stratification of ignitability - HCCI combustion rate influenced by small-scale temperature (scalar field) inhomogeneities

Approach: High resolution measurements of scalar field to characterize the full turbulent engine flow field. Chemistry occurs at molecular mixing scale, thus need high spatial resolution and good model fidelity to capture small-scale phenomena.





Accomplishments: Demonstrated use of tracer gas injection to extend scalar measurements to late in the cycle.

Plans for Next Year: Perform measurements through entire stroke for a range of operating conditions. Collaborate with LES model development Task A.2.

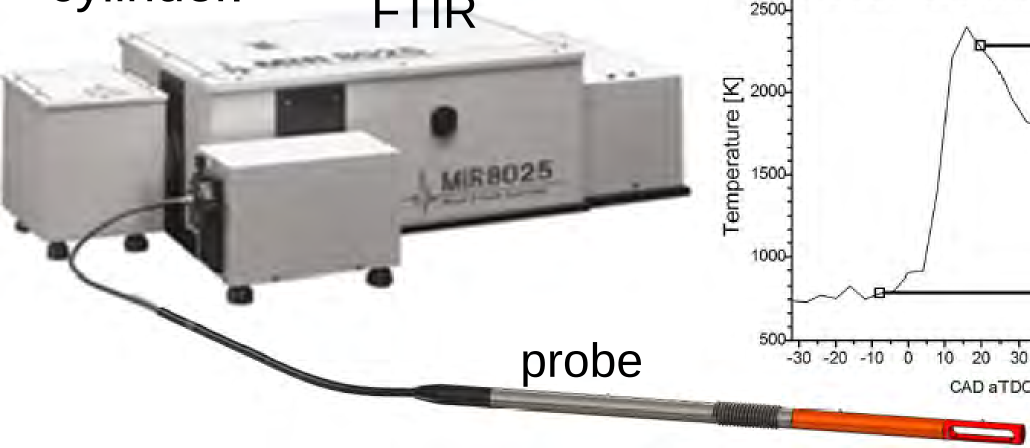
Task C.4: Crank-angle-resolved species and temperature measurements for improved understanding of chemistry and mixing – *Sanders*

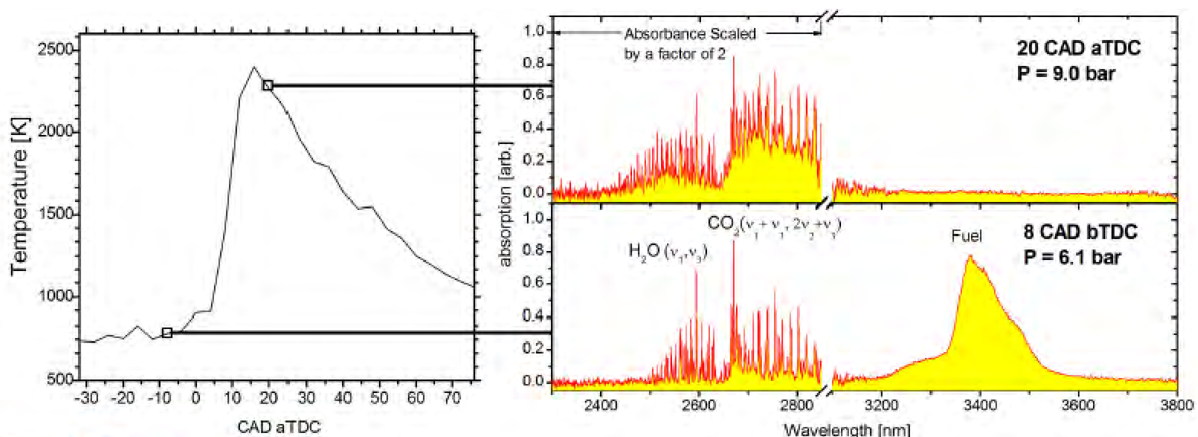
Comparison of measured and simulated in-cylinder species composition histories will help optimize low-temperature combustion processes.

Approach: Couple laser sensors, new implementations of traditional optical instruments to in-cylinder gases using advanced fiber-optic probes.

Accomplishments: 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. Designed probe providing 220 nm – 4800 nm fiber-optic access. Identified key molecules absorbing in this range (NO, OH, H_2O, CO_2, CH_4, CO) and associated state-of-the-art spectroscopic databases.

Plans for Next Year: Build probe, use it to monitor important species in-cylinder.

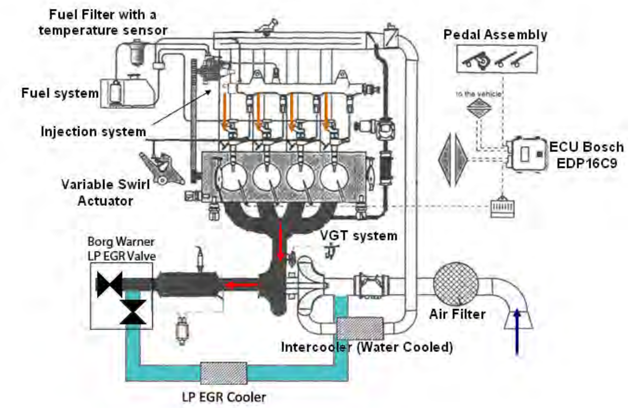




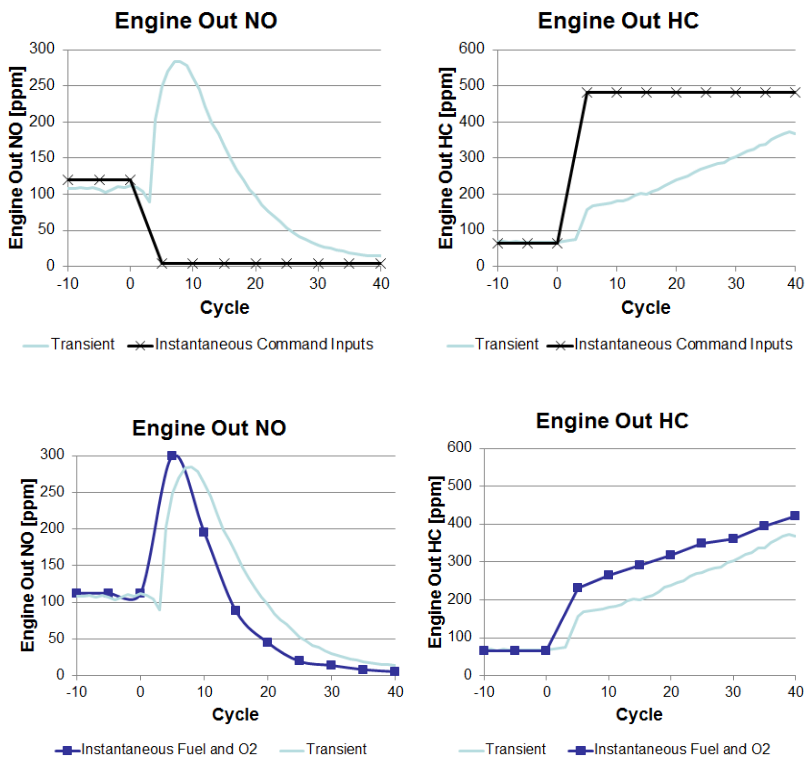
Task D.1: Interactions between high and low pressure EGR systems with mixed-mode operation under load and speed transients – *Foster*

Evaluate steady state and transient LTC operation to understand requirements for combustion phasing control.

Approach: Use coordinated engine experiments and system simulations to study LTC load and mode transients.



Accomplishments: Used new LP – HP hybrid EGR system and enhanced instrumentation to identify and map critical parameters controlling the cycle-to-cycle combustion and emissions during LTC and combustion mode change transients.



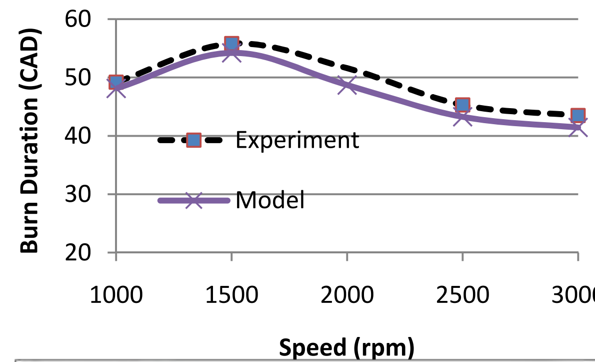
Plans for Next Year: Study transient operation over wider load range and develop requisite information for model based control development in Task D.2.

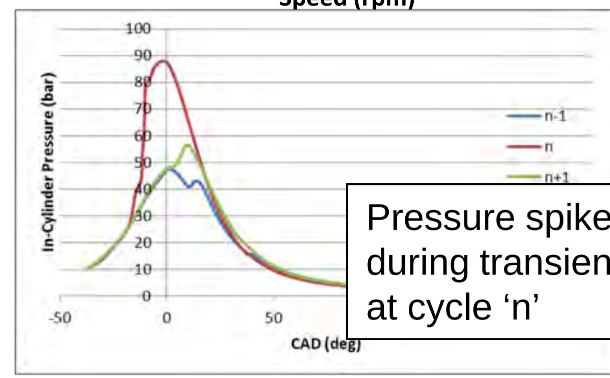
Study mode transients using system level models. Explore impact of different strategies for injection timing, intake valve activation, and high-low pressure EGR switching to minimize transient emissions.

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

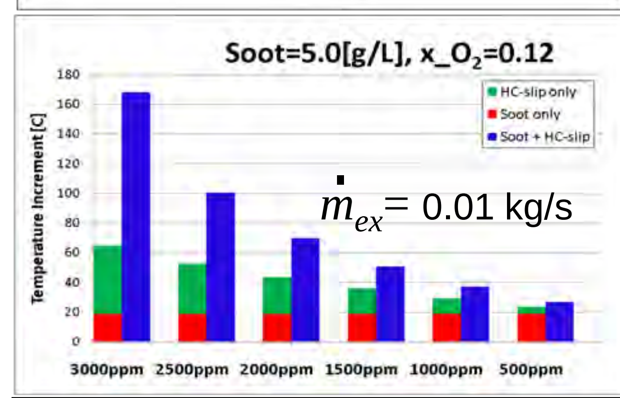
Accomplishments: Combustion duration model developed for CA50 control; Mode transient cycles simulated; HC slip model developed and impact on DPF regeneration explored.

Plans for Next Year: Explore combined effects of injection timing and EGR high-low pressure switching to improve transition from conventional diesel to PCCI operation. Integrate with Task C.2.





Pressure spike during transient at cycle 'n'



Impact of HC slip on DPF regeneration temperatures

Tech. Transfer & Collaborations/Interactions

DOE LTC Consortium project DE-EE0000202

Collaborators:

General Motors CRL, Sandia Labs, Woodward Engine Systems
Diesel Emissions Reduction Consortium (DERC) 24 members

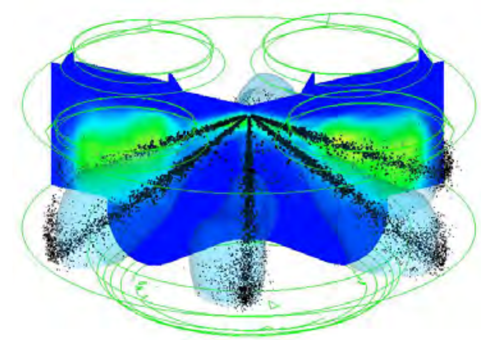
Argonne National Laboratory
Caterpillar
Chevron Companies
Chrysler
Corning Incorporated
Cummins
Daimler NA
Faurecia
Ford Motor Company
GE Global Research
General Motors
John Deere Company

Navistar
Nippon Soken
Oak Ridge National Laboratory
PACCAR
Renault
Robert Bosch
Thomas Magnete USA
Toyota Motor Engr & Manf NA,
US Army RDECOM-TARDEC
Volvo Powertrain (Mack Trucks)
Woodward
Yanmar

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

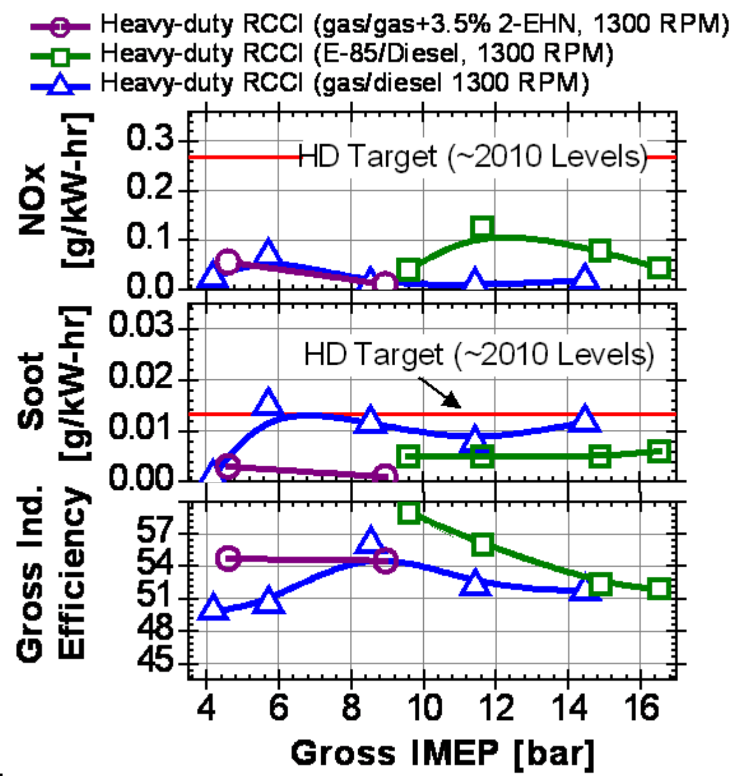
Optimization of Advanced Diesel Engine Combustion Strategies – Summary

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: Advanced combustion regimes with optimized control of mixture preparation and fuel reactivity distribution offer significant improvements in engine efficiency (>50% Thermal Efficiency over wide ranges).



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Plans for Next Year: Continue to develop methods to further increase fuel efficiency

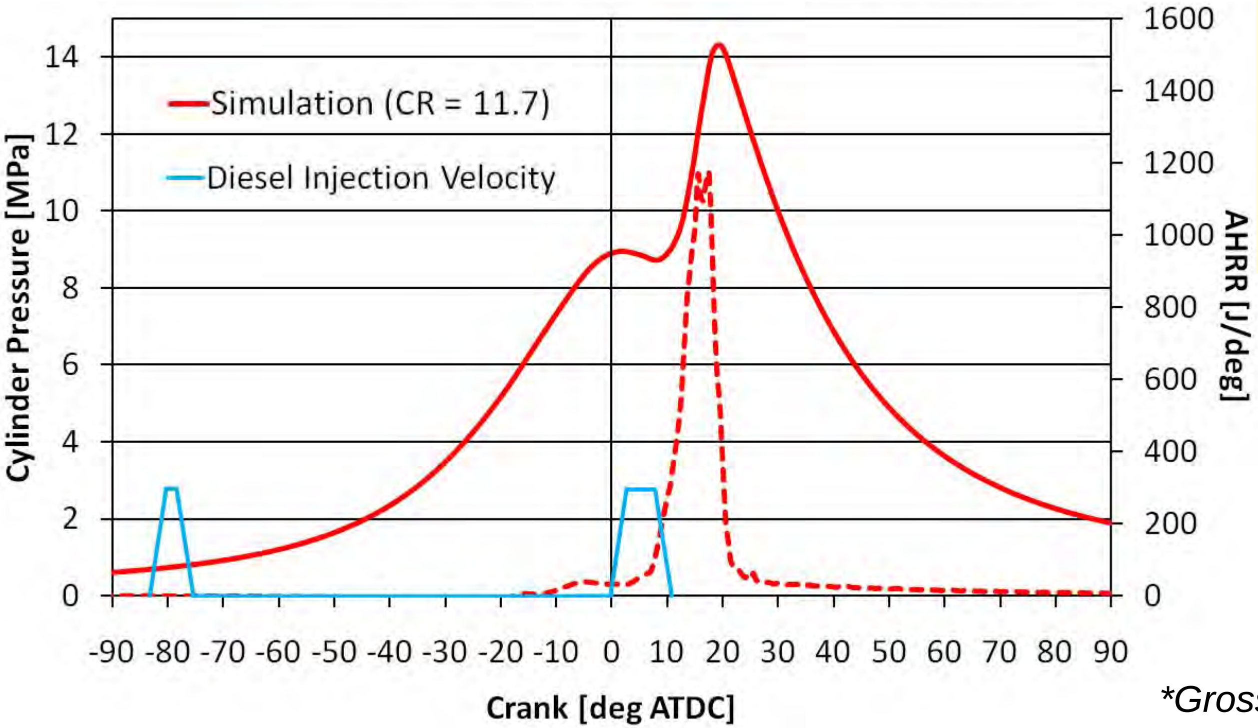
- Explore LTC concepts on HD and LD engines
- Optimize injection strategies, matched with piston geometry and compression ratio.
- Demonstrate and test transient control strategies

Technical Back-Up Slide

Preliminary RCCI Optimization at 21 bar IMEP

Objectives*					
Nox [g/kW-hr]	Soot [g/kW-hr]	CO [g/kW-hr]	HC [g/kW-hr]	ISFC [g/kW-hr]	PPRR [bar/deg]
0.22	0.103	0.9	0.9	175.1	10.1

Design Parameters					
Gasoline % [-]	SOI #1 [ATDC]	SOI #2 [ATDC]	DI Fuel #1 [-]	Inj Press [bar]	EGR [%]
0.82	-83.3	-0.3	0.38	850.0	38.9



Computational Optimization (CR = 11.7)

- Relatively low EGR
- High soot from near TDC injection
- Overall equivalence ratio ~ 0.85
- Effect of increased boost currently being explored (simulations used 3 bar → TC effic ~50%)

Gross Indicated Results (-180^{o} to 180^{o})