Demonstration/Development of Reactivity Controlled Compression Ignition (RCCI) Combustion for High Efficiency, Low Emissions Vehicle Applications

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Project ID: FT015

Overview

Timeline

- Start – October 1, 2011
- End – September 30, 2014
- 85% Complete

Budget

- Total project funding
  - DOE $1.5M
  - Contractor $0.375M
- Spending FY11 - $42K
- Spending FY12 - $713K
- Spending FY13 - $640K

Barriers

- Barriers addressed
  - LD: Reduced emissions with thermal efficiency comparable to diesel.
  - HD: Extend RCCI operating range to higher engine loads with reduced emissions facilitated by reduced pressure rise rates.

Partners

- Industry, University, Government Lab:
  Caterpillar
  Engine Research Center UW-Madison
  Oak Ridge National Laboratory
- Project lead:
  Wisconsin Engine Research Consultants (WERC)

Objectives/Relevance

Objectives

- Develop combustion systems that facilitate extremely low engine-out nitrogen oxides (NOx) and particulate matter (PM) while maintaining state-of-the-art direct injection diesel engine thermal efficiency or better.

Targets addressed

- LD emissions-regulated drive cycle operation and HD load extension.
- Focus on low emission dual-fuel combustion regime, RCCI.
- Create and apply advanced tools needed for high-efficiency, low-emissions engine design – synergistic use of high fidelity computing and high-resolution engine experiments.
- Peak Pressure Rise Rate: critical parameter for both LD and HD. Focus combustion system development on minimizing PPRR while maintaining low emissions and high thermal efficiency.

Impact

- Novel combustion system analytically designed that greatly reduces PPRR while achieving reduced emissions and comparable thermal efficiency.
- New HD test cell and engine installed for extended load operation.

Project Milestones: 1=WERC, 2=ORNL, 3=UW

Month / Year	Task	Milestone or Go/No-Go Decision	Description	Status
Mar 2012	1.6	Initial HD Model Validation	Validation of CFD model to available HD test results	**Complete**
Mar 2012	2.1	Initial LD RCCI	Demonstrate LD RCCI.	**Complete**
Apr 2012	1.2	Initial LD Model Validation	Validation of CFD model to initial LD test results	**Complete**
Sep 2012	2.2	Initial LD Particulate Characterization	LD particulate characterization with gasoline/diesel.	**Complete**
Dec 2012	3.1	HD Install Complete	Completion of HD engine/dyno install.	**Complete**
Mar 2013	3.2	HD Initial Testing	HD demonstration of conventional diesel combustion.	**Complete**
Dec 2013	2.3	LD RCCI with gasoline/gasoline+cetane	LD demonstration of RCCI combustion with gasoline/gasoline+cetane improver.	**Complete**
Dec 2013	3.3	HD RCCI demonstration	Demonstrate HD RCCI.	**Complete**
Apr 2014	2.5	LD Final RCCI	Demonstrate RCCI with CFD designed combustion system.	**On-going**
Apr 2014	3.4	HD Final RCCI	Demonstrate RCCI with CFD designed combustion system.	**On-going**
Jul 2014	1.10	LD Final Spec.	CFD final update of combustion system.	**On-going**
Jul 2014	1.11	HD Final Spec.	CFD final update of combustion system.	**On-going**
Sep 2014	2.5	Final LD Performance	Final results from LD testing.	**On-going**
Sep 2014	3.4	Final HD Performance	Final results from HD testing.	**On-going**
Sep 2014	2.4	Final Particulate Characterization	Particulate characterization for fuel composition.	**On-going**

Approach

LD Combustion System Development

- Overall Goal
  - Minimize emissions with thermal efficiency similar to state-of-art diesel over emissions-regulated drive cycles.
- LD Simulation (WERC)
  - Optimize combustion system with gasoline/diesel using state-of-the-art CFD models.
- LD Testing (ORNL)
  - Optimize RCCI strategy with gasoline/diesel and gasoline/gasoline+cetane improver.
  - Particulate characterization with both fuel strategies.
  - Experimental engine testing with WERC optimized combustion system.

HD Combustion System Development

- Overall Goal
  - Maximize RCCI load capability while facilitating low NOx and PM emissions.
- HD Simulation (WERC)
  - Optimized piston bowl/nozzle for RCCI with gasoline/diesel.
  - Optimize dual-fuel direct injection strategies.
- HD Testing (UW)
  - Install new high-load capable engine.
  - Optimize dual fuel direct injection strategies.

Task 1.2 –LD Validation/Support Gasoline/Diesel
Task 1.4 –LD Validation/Support Gasoline/Gasoline +Cetane Improver

Approach

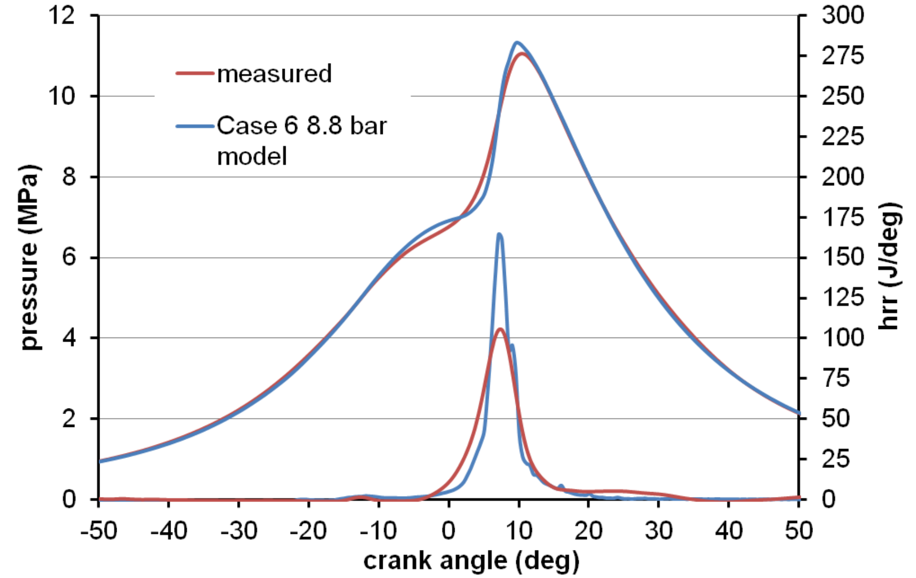
- KIVA3V – WERC
  - Advanced CFD spray and combustion models
  - Detailed chemistry: PRF and EHN mechanisms (47-60 species)
- GM 1.9L 4-cylinder production engine
  - Cylinder pressure and emissions data taken at 6 ‘ad hoc’ steady-state conditions
  - Speed range from 1000 to 2600 rev/min and load range from 1 to 8.8 bar BMEP

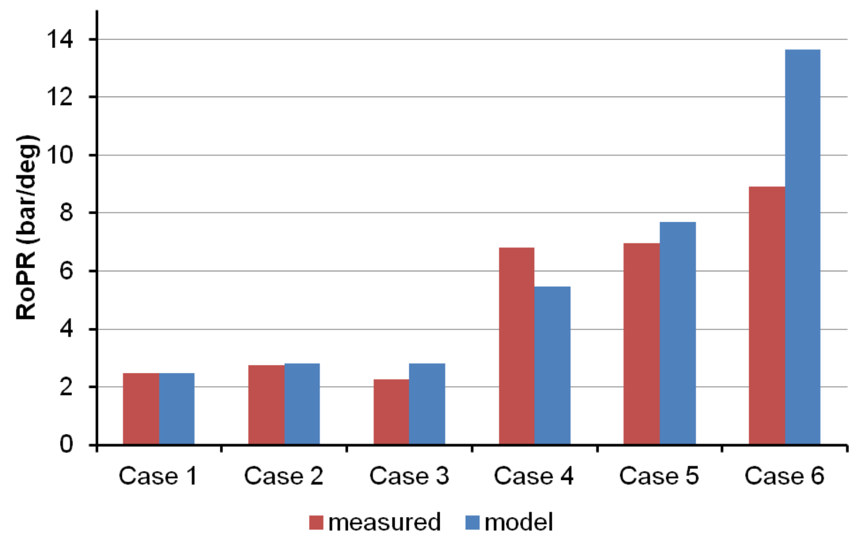
Accomplishments

- Validated model with measured results
  - Predicted measured trends
  - Cylinder pressure and HRR
  - Soot, NOx and CO emissions

Plans for Wrap-Up

- Task 1.2 Complete
- Task 1.4 Finish gasoline+EHN validation





Approach

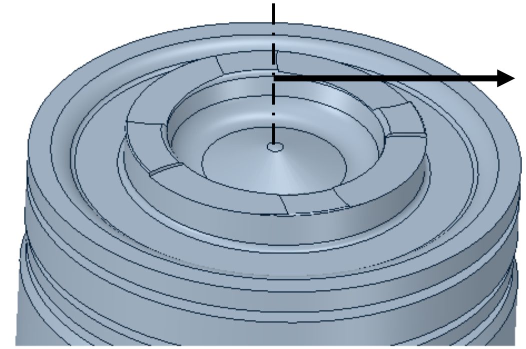
- CFD-designed combustion system
  - Based on validated engine model, an exploration of novel bowl designs suited to pre-mixed combustion was performed.

Accomplishments

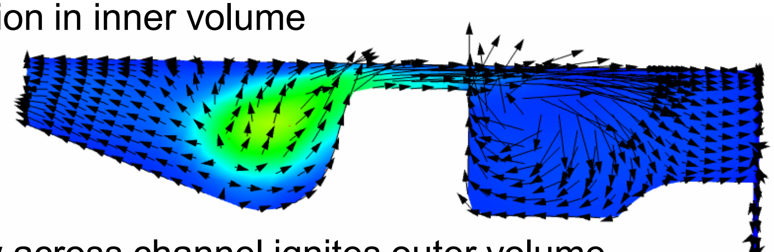
- Development of 2-zone combustion system (patent pending)
  - Features separated inner and larger outer volumes to stage combustion event
  - As in RCCI, premixed gasoline at IVC, optimized direct injection(s) of reactive fuel (diesel) during compression
  - Combustion sequence begins with ignition in inner volume
  - Combustion products from inner volume jet across channel to ignite outer volume
  - Combustion products from outer volume flow back to inner volume to cool and oxidize any remaining fuel

Plans for Wrap-Up

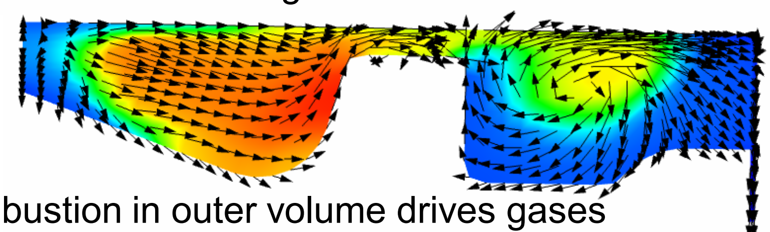
- Task Complete



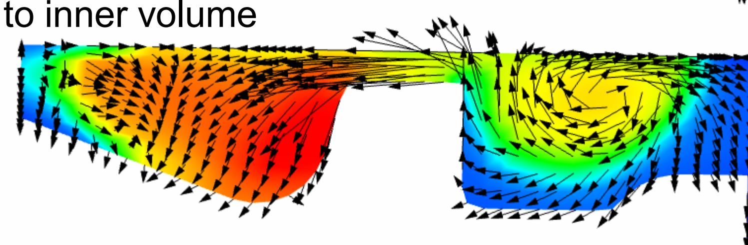
Ignition in inner volume



Flow across channel ignites outer volume.



Combustion in outer volume drives gases back to inner volume



Task 1.3 – LD Gasoline/Diesel CFD (cont.)

Approach

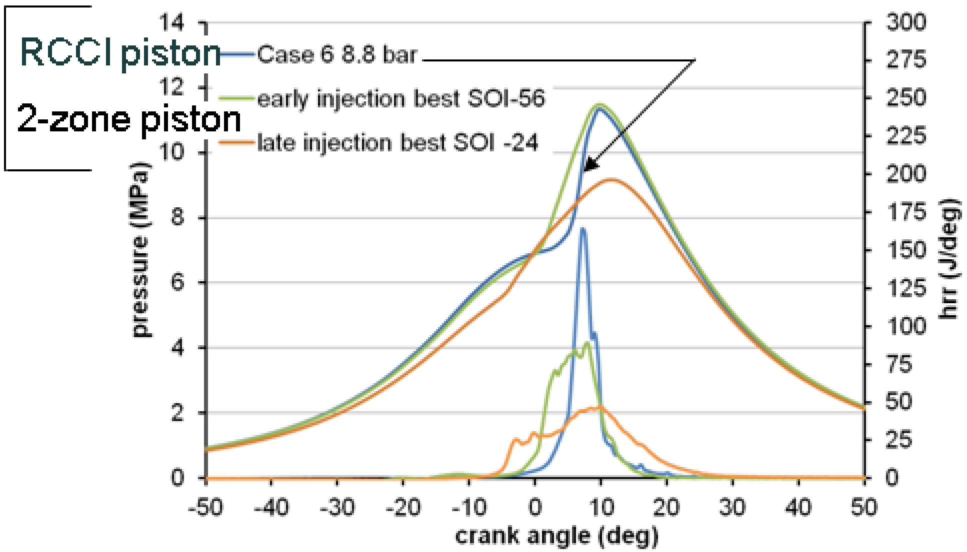
- CFD-designed combustion system
  - Based on validated engine model, an exploration of novel bowl designs suited to pre-mixed combustion was performed.

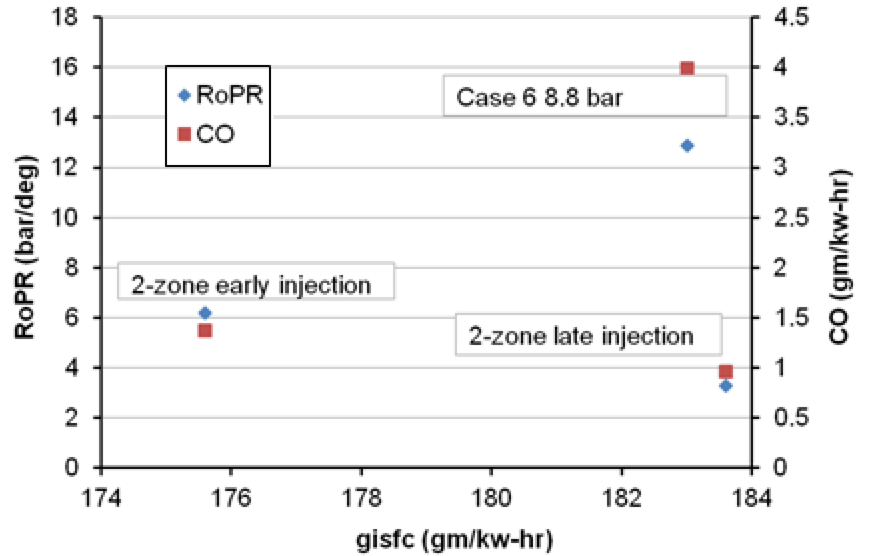
Accomplishments

- Development of 2-zone combustion system (patent pending)
  - Optimization of separated inner and larger outer volumes and DI injection timings
  - Decreases peak pressure and RoPR
  - Decreases UHC and CO emissions
  - NOx/PM levels within regulated targets
- Prototype piston designed and delivered to ORNL for testing
  - 3d cad model used directly to CNC machine piston blanks

Plans for Wrap-Up

- Task Complete





Task 1.6 – HD Validation Conventional and RCCI

Approach

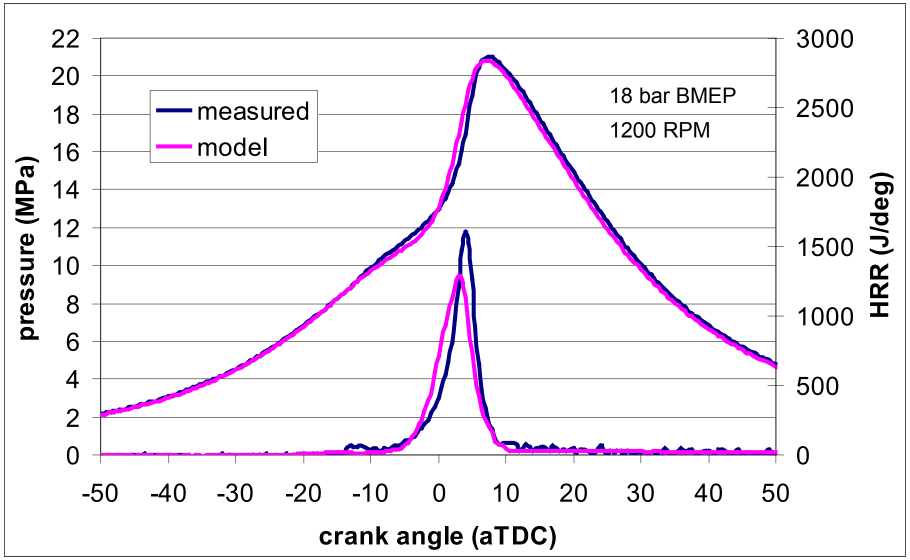
- KIVA3V – WERC
  - Advanced CFD spray and combustion models
  - Detailed chemistry: PRF mechanism (47 species, 74 reactions)
- C15 RCCI engine data (Caterpillar)
  - Load sweeps at 1200 and 1800 rpm
  - BMEP 8 -18 bar
  - Geometric CR 12
  - Port injection gasoline, DI diesel
  - Near zero soot and NOx emissions

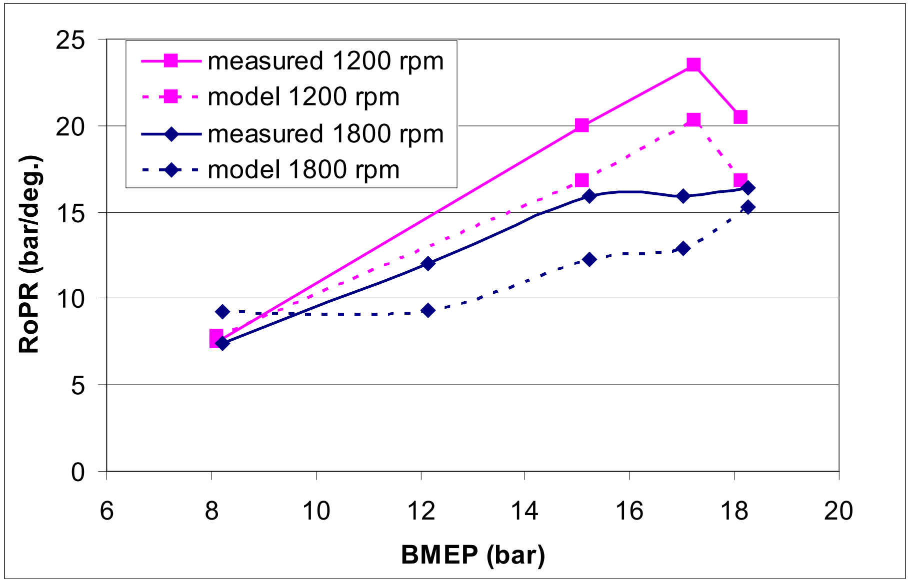
Accomplishments

- Validated ability to predict RCCI over load and speed ranges
  - Predicted measured trends
  - Cylinder pressure, HRR and RoPR
  - Soot, NOx and CO emissions

Plans for Wrap-Up

- Task completed

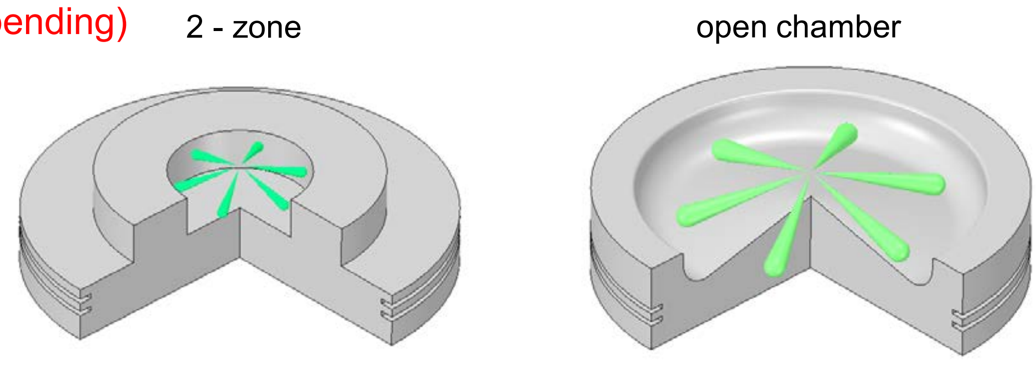




Task 1.7 – HD CFD DoE Studies

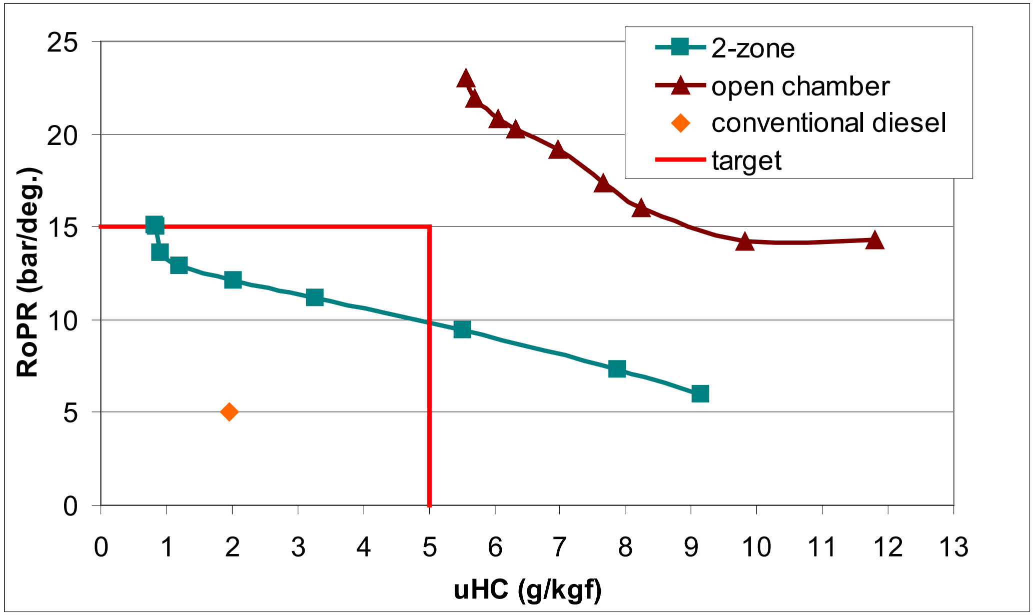
Approach

- Novel 2-zone piston geometry (patent pending)
  - Optimize volume split between two combustion zones and clearance height
  - 18 bar BMEP, 1200 rev/min



Accomplishments

- Developed strategies for RCCI load extension
  - Open chamber has excessive peak RoPR and / or excessive uHC emissions at high load.
  - 2-zone piston greatly improves RoPR vs. uHC emissions trade-off. Enables mandated emissions targets to be met with acceptable peak RoPR.
  - Strong jet flows between 2 zones enhance mixing → significant reduction in uHC and CO emissions.
  - 2-zone combustion system is potential breakthrough technology for enabling practical implementation of RCCI combustion in HD engines.



Note: uHC emissions target assumes use of DOC

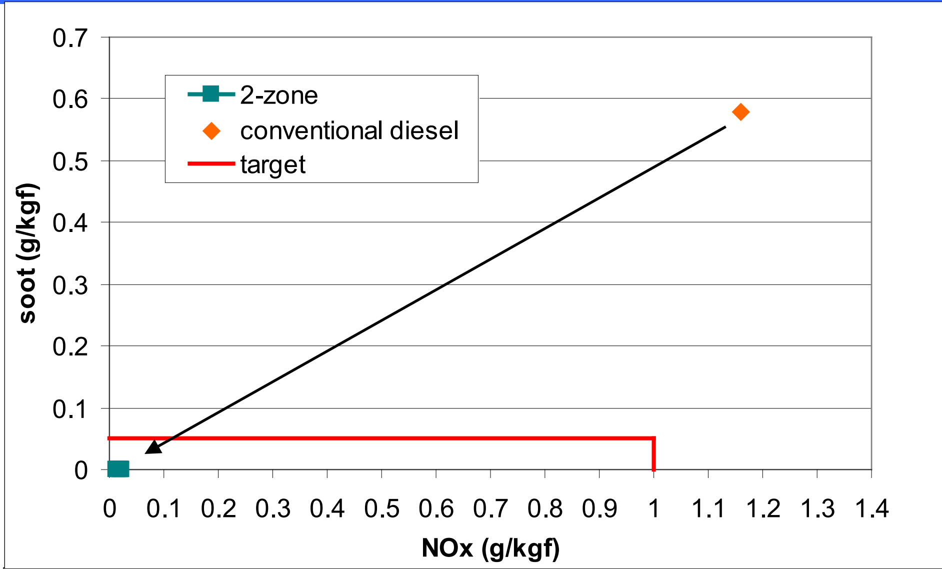
Task 1.7 – HD CFD DoE Studies

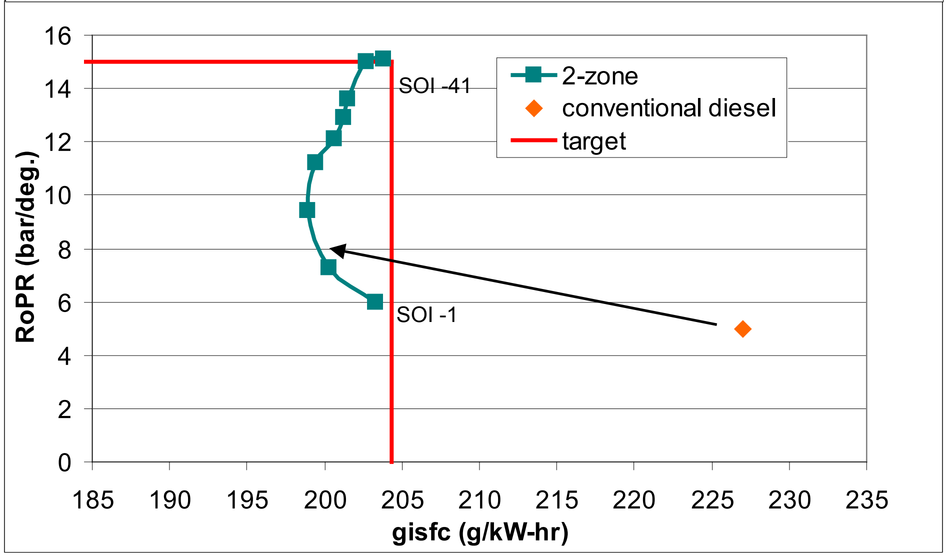
Accomplishments (cont.)

- Developed strategies for RCCI load extension
  - Soot and NOx targets based HD on-highway engine-out mandates.
  - RCCI combustion has near zero soot and NOX emissions.
  - Fuel consumption target met based on 10% reduction from conventional diesel.
  - New combustion system reduces fuel consumption (gisfc) up to 12% compared to conventional diesel combustion while maintaining control over RoPR.
  - Near optimal results with 60/40 volume split (outer/inner) and ~1mm clearance height (squish).

Plans for Wrap-Up

- Further exploration of 2-zone concept
  - 18 bar BMEP, 1800 rev/min





Note: gisfc for valves-closed portion of cycle

Task 2.1 – LD Gasoline/Diesel Experiments

Approach

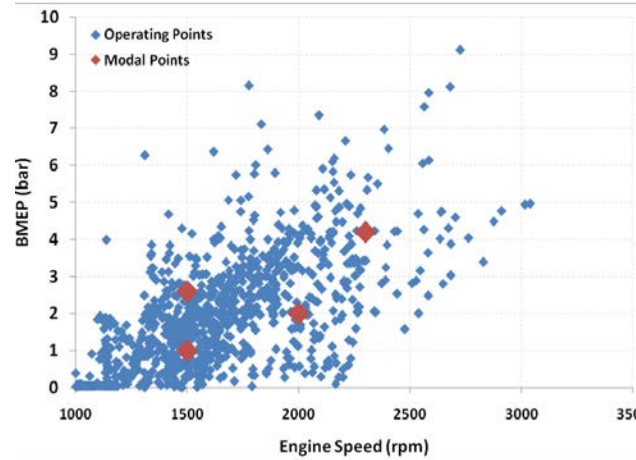
- Ad-hoc modal points used to prescribe engine speed and load conditions for LD RCCI experiments with gasoline/diesel fuel
- Key engine parameter sweeps performed for model validation and for engine performance and emissions characterization

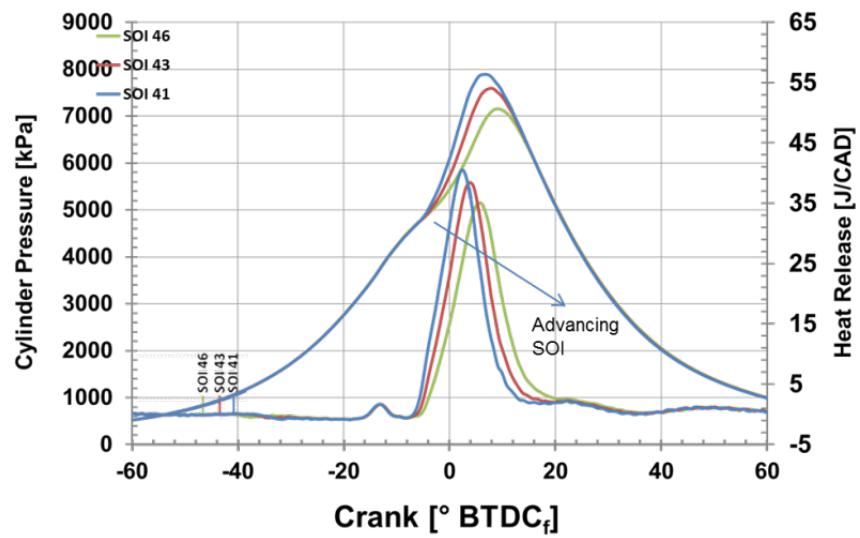
Accomplishments

- Provided detailed data sets for model validation
- Baseline data obtained for WERC piston bowl development

Plans for Wrap-Up

- Compare open bowl results to WERC 2-zone piston results





Cylinder pressure and heat release traces for diesel SOI sweep at 70% gas/diesel ratio for 2300 RPM, 4.2bar BMEP.

Task 2.2 – LD Gasoline/Diesel PM Characterization

Approach

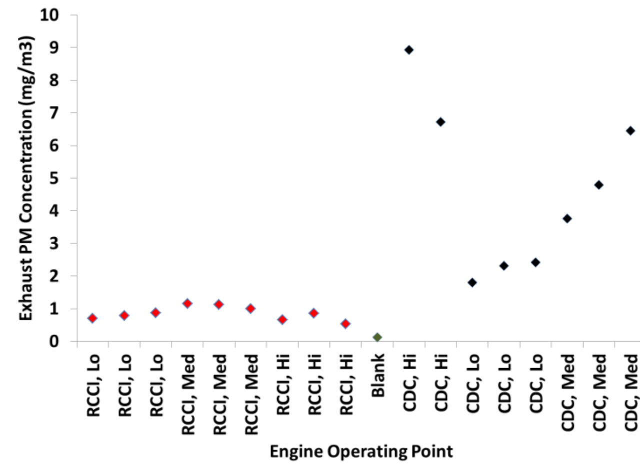
- Examined RCCI and CDC with PRF fuels and known lube oil
  - Low (froth point), medium and high load
  - Look for metals that present in lube oil and lube oil components
- Several techniques used
  - X-ray fluorescence (XRF) elemental composition
  - Filters for mass measurement
  - Filters for pyrolysis GC-MS – composition

Accomplishments

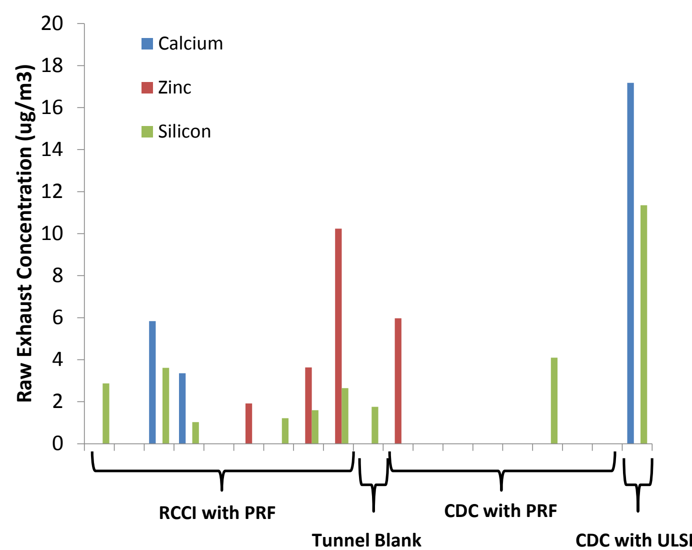
- XRF results show that RCCI does not have significant contribution of lube oil to PM
- RCCI resulted in much lower PM than CDC

Plans for Wrap-Up

- Completed task, followed up with MCE piston study with EHN (see backup slides)
  - Follow-up studies with WERC 2-zone piston will be compared to RCCI piston



PM Mass Concentration much higher for CDC



Lube Metals Higher with CDC and ULSD

Task 2.3 – LD Gasoline/Gasoline+Cetane Improver Experiments

Approach

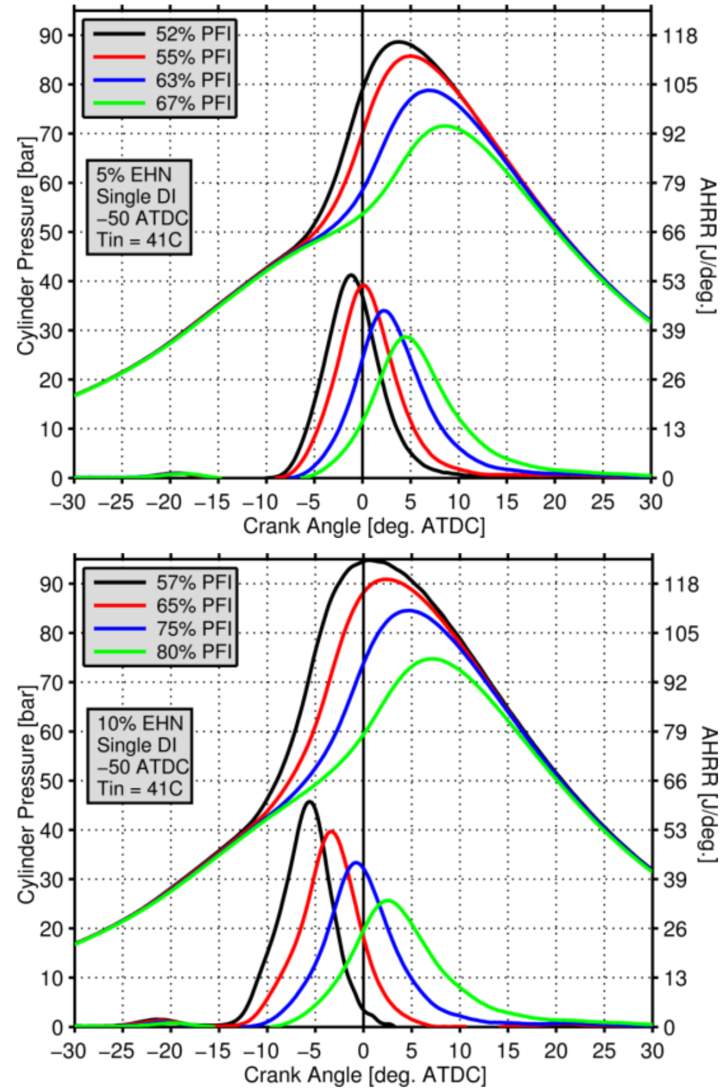
- Validation data obtained on ORNL MCE for RCCI with PFI gasoline and DI gasoline+cetane improver (EHN)
- 2.5%, 5%, and 10% EHN by volume added to the gasoline. Infinium lubricity additive used at a rate of 0.3 mL/L

Accomplishments

- Detailed sweeps of premixed-DI fuel ratios, DI SOI timings, boost pressures and intake temperatures for multiple EHN levels
- Results: High BTE, low NOx and Soot possible with low total additive quantities

Plans for Wrap-Up

- Additional analysis on organo-nitrates sampling
- Publish paper on findings from single-cylinder and multi-cylinder experiments



Experimental PFI-DI ratio sweep for 5 and 10% EHN DI fuel

Task 2.5 – LD Experiments with WERC Bowl/Nozzle

Approach

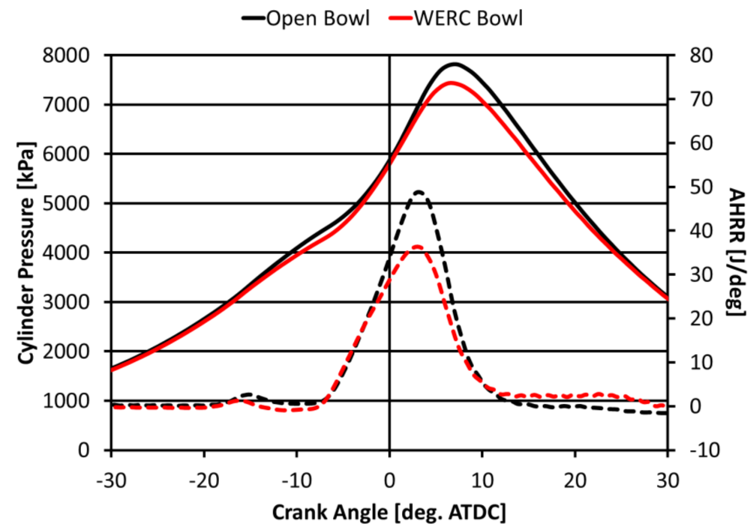
- Comparison against detailed data with open-bowl design and CDC
  - Detailed sweeps comparing at multiple operating conditions
  - Compare to CDC with base OEM engine too

Accomplishments

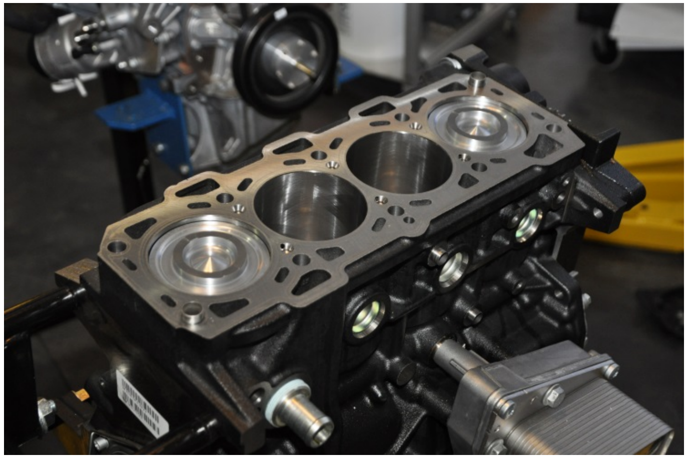
- Installation of WERC pistons in multi-cylinder engine
  - Installed pistons in new short block - top end same as for baseline data
- Initial comparison underway
  - Preliminary results show lower PPRR with 2-zone piston design

Plans for Wrap-Up

- Complete experiments
- Noise investigation
  - AVL combustion noise & microphone noise if needed
- Joint paper on experimental findings and model validation covering entire project



Preliminary pressure and heat release rate comparisons of WERC 2-zone and RCCI open-bowl pistons at 2000 rev/min/4 bar BMEP



2-zone pistons Installed in MCE Engine

Task 3.1 – HD Test Cell Setup/C15 Engine Install
Task 3.2 – HD Break-in/Baseline Experiments

Approach

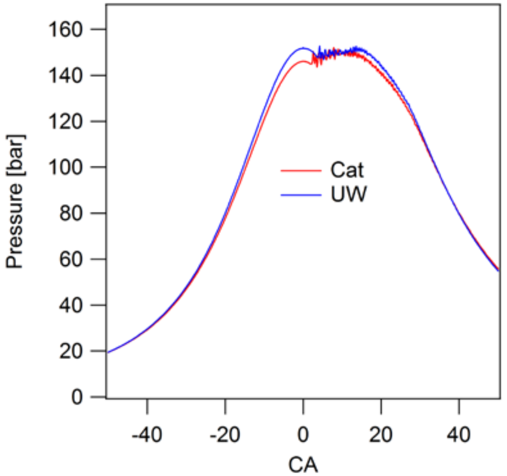
- Develop test cell capable of high-load RCCI testing with facilities for complete thermodynamic analysis
  - Single-cylinder version of Caterpillar C-15 engine installed; capable of 25 bar BMEP load and 23 MPa peak cylinder pressure; dyno capable for full operation range of engine
  - Air handling system developed for 4 bar intake MAP and 5 bar exhaust pressure and high levels of EGR
  - Two fuel systems developed: high pressure common rail for diesel, low pressure PFI system for gasoline

Accomplishments

- Engine installed and test cell demonstrated over the full load / speed range of the engine
- Baseline comparisons to data provided by Caterpillar
- Heat release analysis, fuel and emission systems verified - carbon balance calculated using both systems is within acceptable range

Plans for Wrap-Up

- All major systems have been verified, data acquisition in progress



Task 3.3 – HD Gasoline/Diesel Experiments

Approach

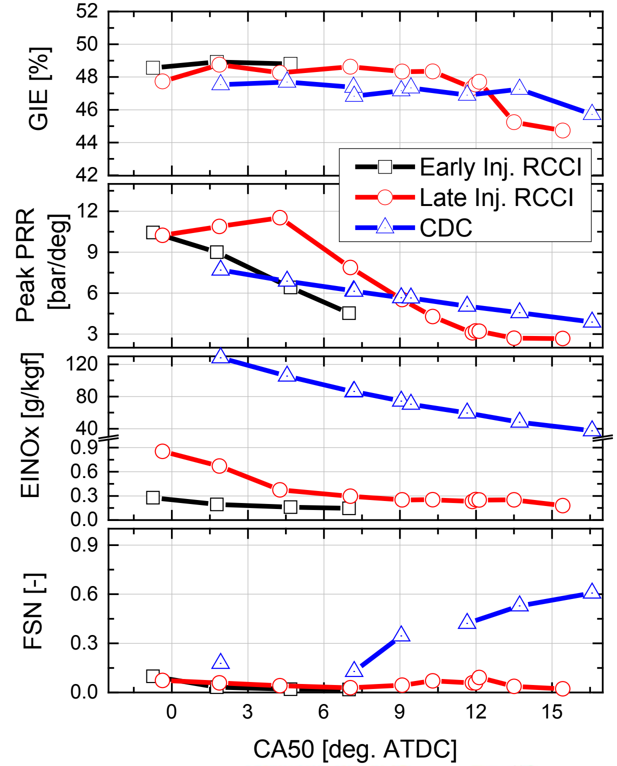
- Compare conventional diesel combustion (CDC), early- and late-injection RCCI
  - 1300 rev/min / 8 bar IMEPg
  - Intake conditions constant: 1.75 bar (abs) and 25 °C
  - EGR rate: CDC – 0%; RCCI (both) – 60%

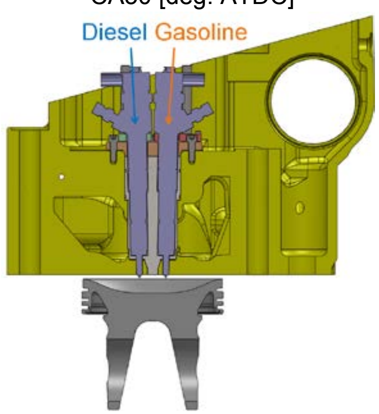
Accomplishments

- Testing performed for range of combustion CA50 by varying injection timing (CDC, late-injection RCCI) or fuel split (early-injection RCCI)
  - NOx emissions for both RCCI conditions significantly below the CDC data (note scale break)
  - RCCI and CDC peak pressure rise rates comparable
  - Early-injection RCCI heat release profile smooth; late-RCCI heat release shows characteristics of diesel combustion at early times, then homogeneous ignition

Plans for Wrap-Up

- Explore load range of engine with standard fuels
  - Dual-injector (allowing gasoline and diesel direct injection) head designed - being machined by Caterpillar





Tech. Transfer & Collaborations/Interactions

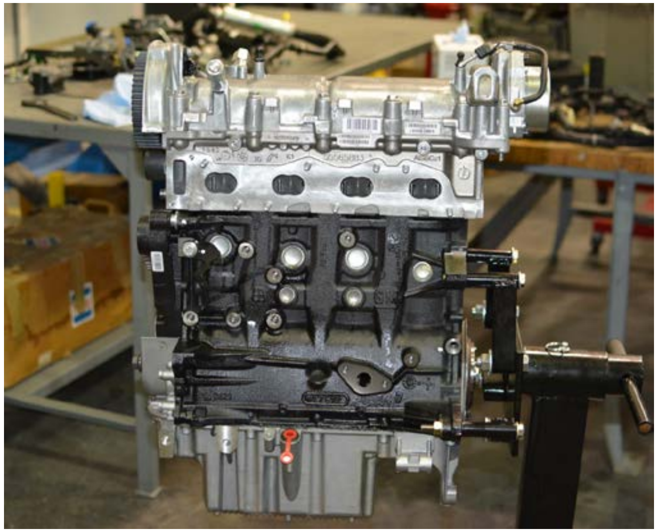
U. S. Department of Energy National Energy Technology Laboratory
FY 2011 Vehicle Technologies Project DE-EE0005423

Collaborators:
Wisconsin Engine Research Consultants
Engine Research Center UW-Madison
Oak Ridge National Laboratory
Caterpillar

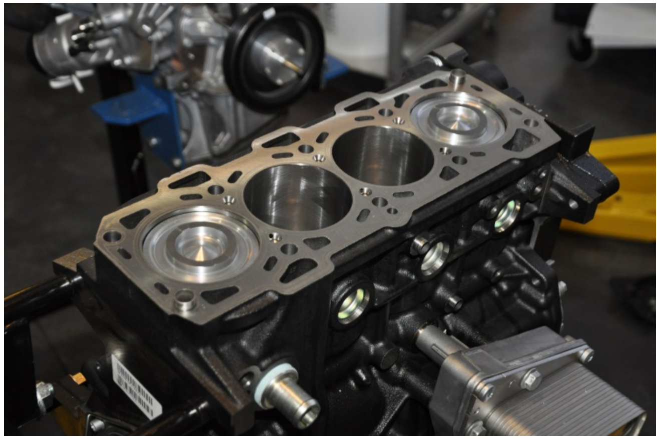
Tech transfer:
- Teleconference and face-to-face meetings.
- Department of Energy quarterly reports.
- Fuel & Lubricant Technologies FY 2013 Annual Progress Report

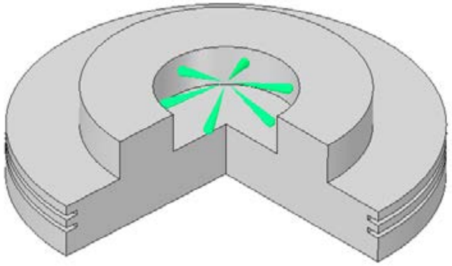
Future Work

- Continue development of LD and HD combustion systems.
- Test and analytically refine concept piston in LD engine.
  - Gasoline/diesel dual fuel RCCI.
  - Optimize piston shape/spray interactions.
- Complete particulate characterization study.
- Finish analytical model validation to gasoline / gasoline+EHN test data.
- Test concept piston with gasoline / gasoline+EHN.
- Continue HD combustion system development.
  - Analytical combustion system optimization.
  - Experimental load extension investigation.
  - Update HD engine with dual-fuel direct-injection head and investigate benefits.



WERC 2-zone piston installed and being tested





2 – zone piston optimization

Summary

<u>Relevance</u>

- Project is relevant to DOE goal of low emissions, high thermal efficiency engines.

<u>Approach</u>

- Advanced CFD spray and combustion models validated with engine experimental data from ORNL (LD), Caterpillar (HD) and UW-Madison (HD)
  → Models applied for improved dual-fuel RCCI combustion system design.

<u>Accomplishments</u>

- Work addressed a limiting factor of RCCI combustion, which is high peak pressure rise rate - PPRR limits RCCI load capability.
- Potential break-through 2-zone piston design developed analytically* addresses PPRR issue while maintaining low emissions and high thermal efficiency.
- Modeling shows that new piston design offers thermal efficiency and emissions advantages for both LD and HD engines
- Preliminary experimental results with new piston promising

<u>Collaborations</u>

- Successful collaboration between engine consulting company (WERC), engine industry partner (Caterpillar), government laboratory (ORNL) and university (UW-Madison).

<u>Future Work</u>

- Continue development and testing of new LD and HD combustion systems.

* patent pending