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
- 20% Complete

Budget

- Total project funding
  - DOE $3M
  - Contractor $0.6M
- Received in FY09 - $0.36M
- Funding for FY10 - $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

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 (incl. 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 1st year Milestones

Task	Goals and 1st 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: >55% thermal efficiency in HD over operating 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: Achievement of lifted flame combustion at high load with moderate orifice diameters and injection pressures utilizing blends of isooctane and n-heptane.
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 to improve fundamental understanding of combustion
D - **System-level engine optimization**	Efficient engine system transient control algorithms and strategies appropriate for engine speed/load mode transitions Milestone: Identify load range possible with a combination of low- and high-pressure EGR systems

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

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

Approach: Apply multi-objective optimization genetic algorithm (MOGA) with KIVA-Chemkin and KIVA-G models.

Accomplishments: Heavy-duty engine optimized with diesel, gasoline and ethanol fuels at a full-load (21 bar), low EGR (30% - conventional diesel) condition. Finding: fuel-type less important at high load.

- Unibus-type or two-stage combustion, late 2nd injection to control PPRR
- Long 2nd injection duration → diffusion burn → high soot (> 10xEPA)
  - higher PPRR with high octane fuel, less 1st injected amount w/ diesel

Plans for Next Year: Optimization with dual fuel (diesel/gasoline/E85). Explore Low Temperature Combustion (higher EGR rates) at high-load

SOI1 ~-60°; Inj. Press 1 & 2 ~1400 bar; Spray angle ~ 75°; # Holes ~9
CO ~ 20 g/kWh; UHC ~ 4.5 g/kWh

Fuel	NOx	Soot	GISFC	PPRR	SOI2	Inj1 %	Swirl
Diesel	0.63	0.27	220	3.6	4.1	10	1.22
Gasoline	0.74	0.24	203	9.7	4.9	34	0.96
E10	0.62	0.15	209	9.8	6.3	35	0.89

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

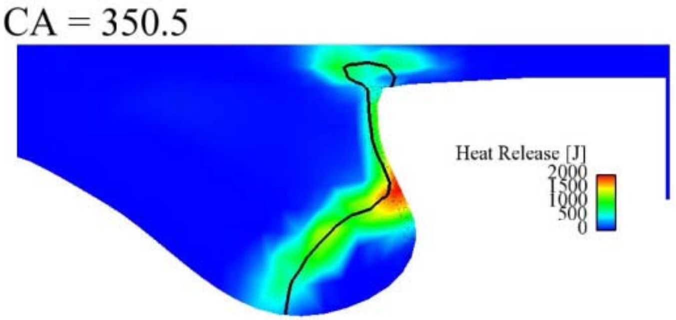
Improved understanding of primary mixing and combustion processes controlling high power density and mode switching

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

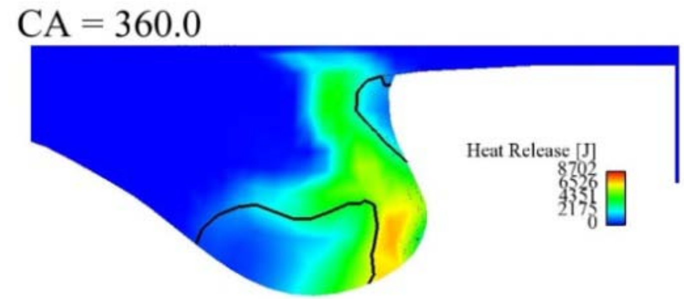
Accomplishments: Upgraded multi-mode combustion model with scale similarity LES model and dynamic coefficient. Matched engine results for both resolved and sub-grid scalar dissipation rate data of Task C.3

Continued testing of LES combustion model on additional engines and operating modes (figures shown - GM 1.9L engine, 66% EGR)

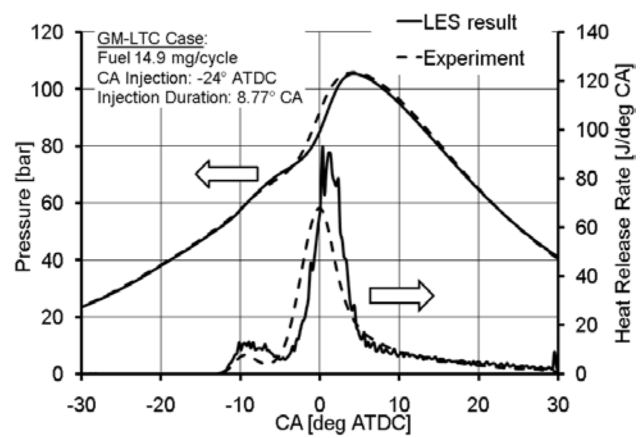
Plans for Next Year: Evaluation of appropriate criteria for applying LES to engine simulations



Cool flame heat release



Main combustion heat release

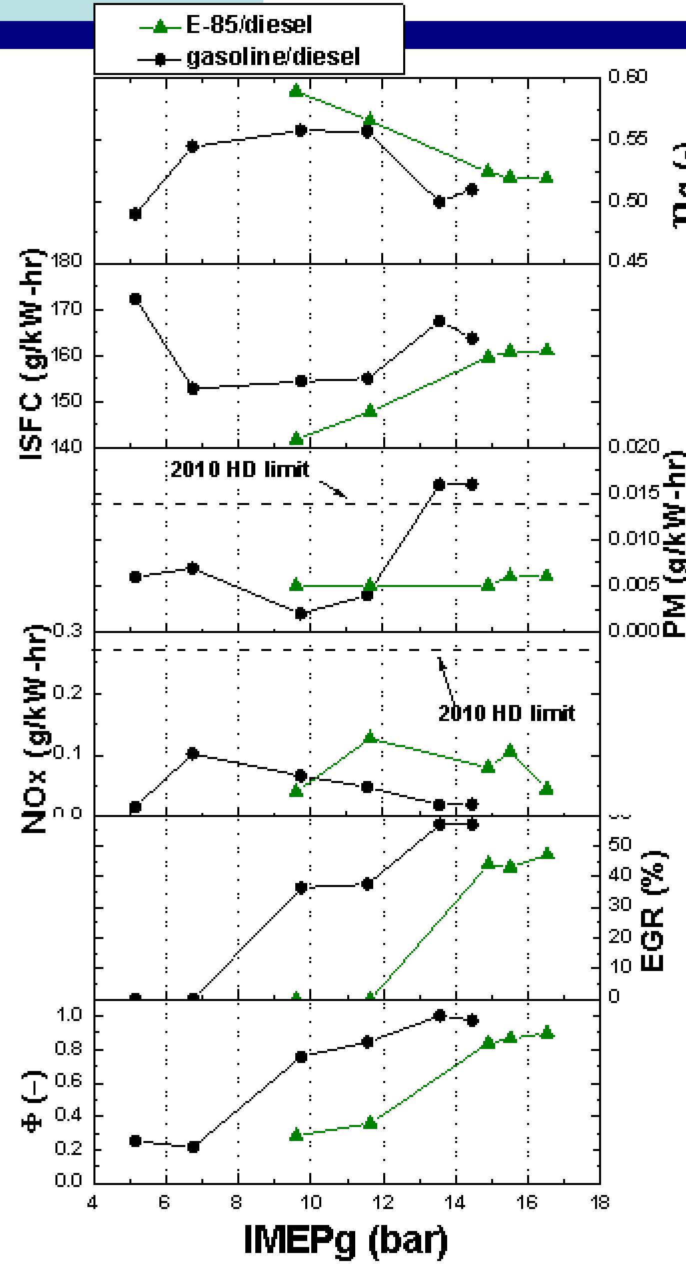


Control of dual fuel reactivity gradient provides high-efficiency, low-emissions operation, with combustion phasing control at both high and low engine loads without excessive rates of pressure rise.

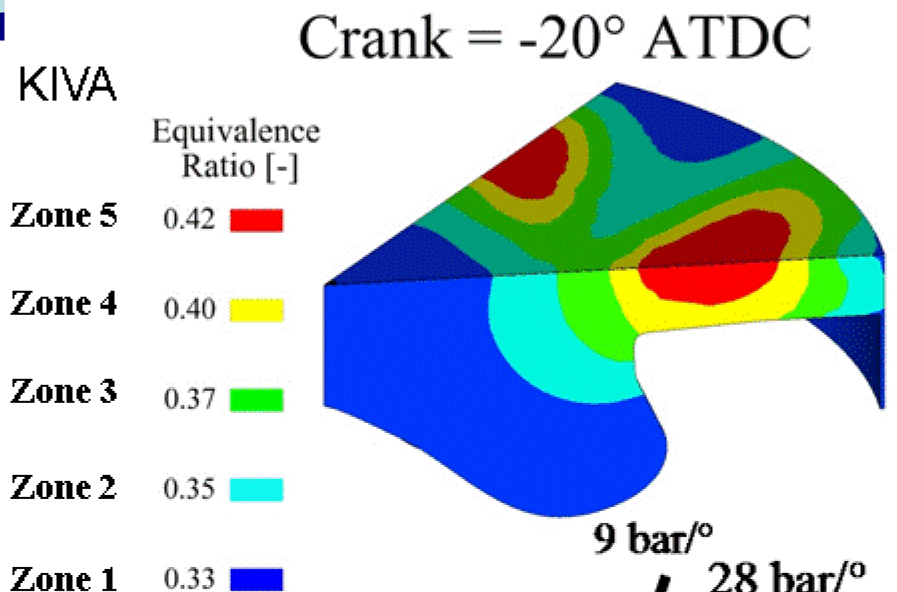
Approach: Use Caterpillar 3401 HD diesel engine with dual-fuel port injection of gasoline and optimized early-cycle, direct multiple injections of diesel fuel

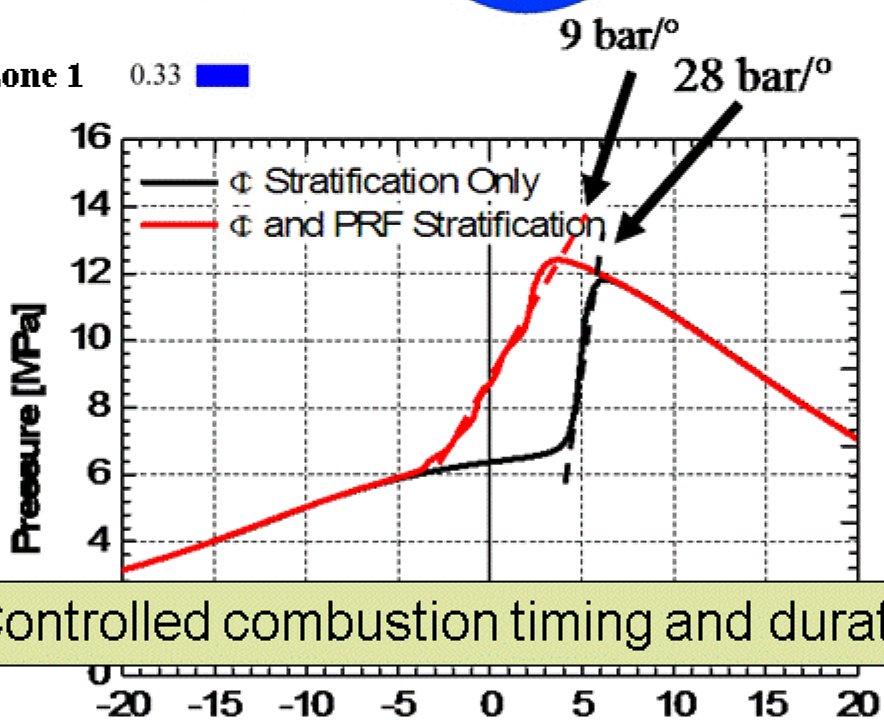
Accomplishments: US EPA 2010 heavy-duty emissions regulations easily met in-cylinder without after-treatment, while achieving ~53-59% thermal efficiency with PRR < 10 bar/deg..

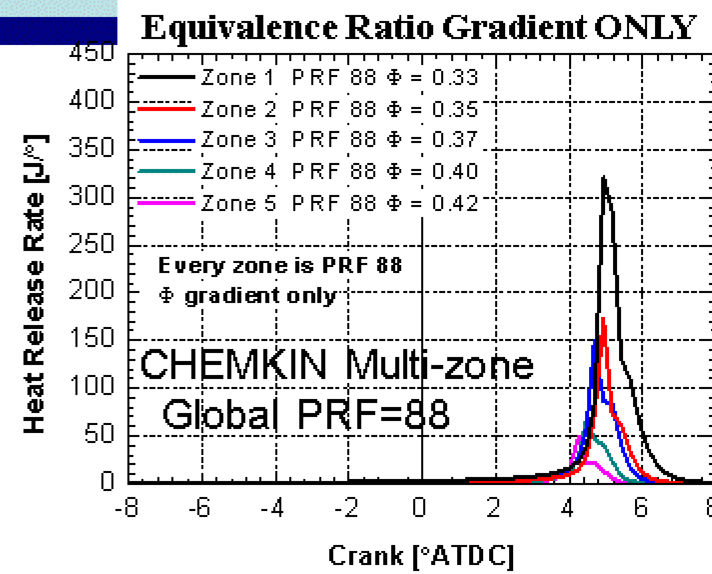
Plans for Next Year: Further optimization of dual fuel operation over wide speed and load ranges (current optimization focused on 10 bar)

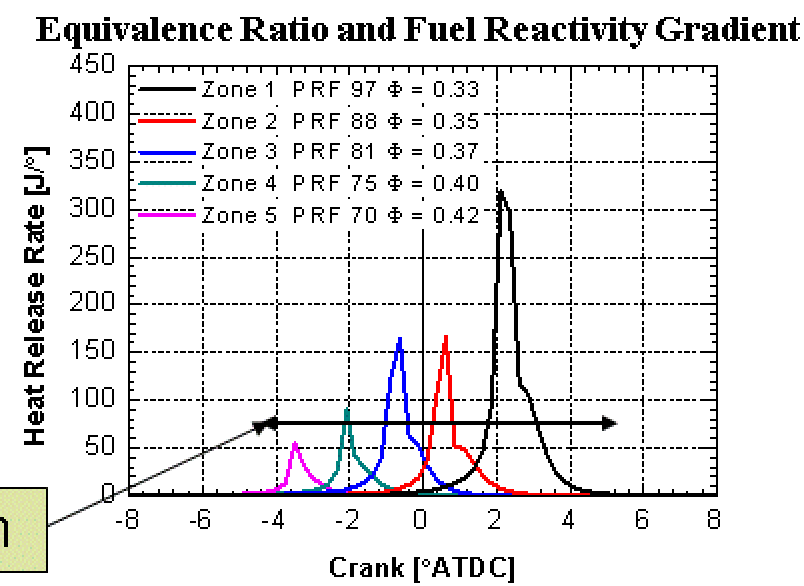


Reactivity vs. Equivalence Ratio Stratification









Controlled combustion timing and duration

Single inject IMEP=5.5 bar, 2300 rev/min

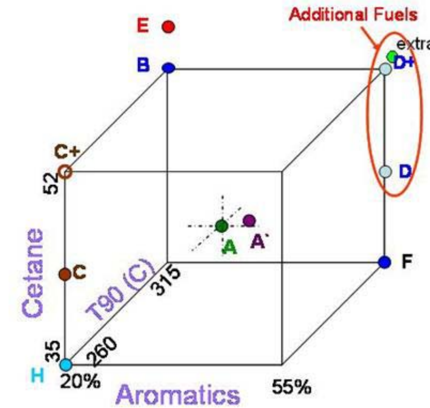
Task A.4: Experimental investigation of chamber design, fuel injection, intake boosting and fuel properties in a LD engine - Foster/Ghandhi

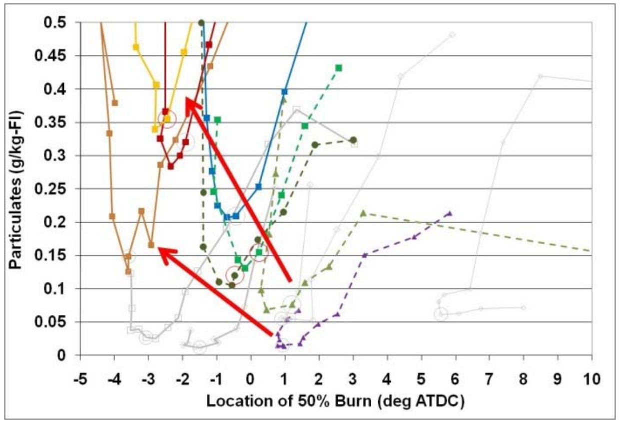
Investigate potential of achieving LTC-D operation with different nozzle geometries and with a range of fuels

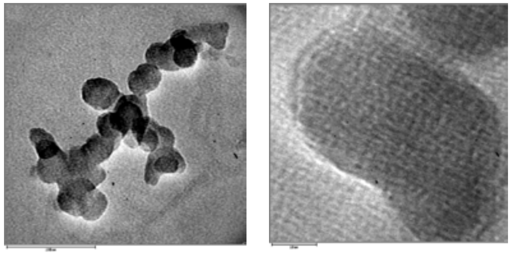
Approach: Use advanced injection systems with different nozzle configurations, on research GM 1.9L diesel engine with fuels from BP fuel matrix and selected bio-fuels (SME and PME)

Accomplishments: Completed BP Fuel matrix, which included high cetane, high volatility and high aromatic fuels. Low volatility, high cetane and high aromatic content causes increased particulate. Ran SME and PME bio-fuel blends, evaluated HC speciation, particulate morphology.

Plans for Next Year: Continue to evaluate the effect of fuel characteristics on LTC. Explore injection and geometry variation, assess soot.







LTC SME B100 amorphous nanostructures

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

Optimized in-cylinder mixtures can increase fuel efficiency

Approach: Visualize combustion using optical engine with the same geometry as metal engine of Subtask A.4, (1.9L GM engine)

Accomplishments: Optical and metal in-cylinder pressures compared. Drop-down liner system redesigned for reduced compliance and improved sealing. Developed flexible premixed fueling system for dual-fuel studies.

Plans for Next Year: Commence optical engine testing with dual fuels

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

Soot formation is reduced with well-mixed lifted flames

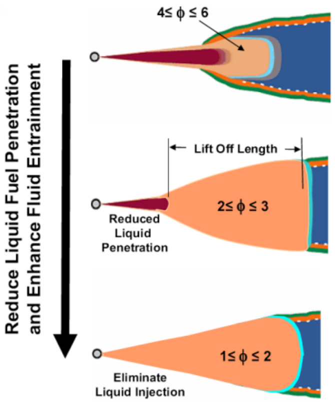
Approach: Explore lifted flame combustion in optical engine.

Accomplishments: Evaluated lift-off and liquid lengths.

Designed new piston cap to accommodate larger lift-offs

- Large bowl diameter > 80% of bore for optical access

Redesigned Bowditch piston extension for new cap design



Plans for Next Year: Investigate limits of ELOC and soot formation for different in-cylinder conditions using a suite of laser/optical diagnostics.

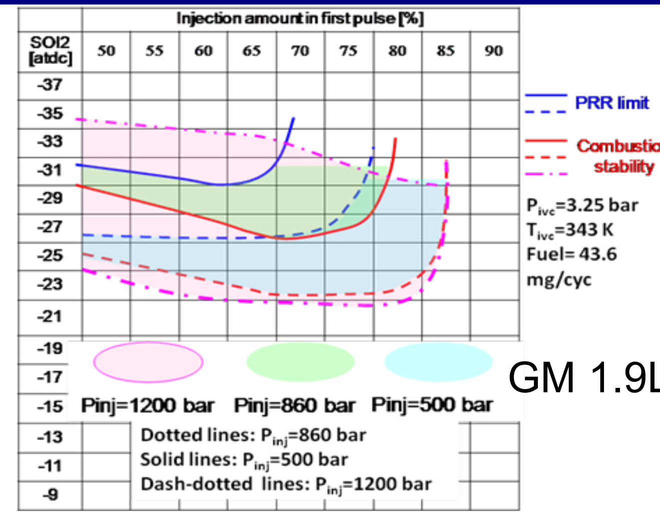
Task C.1: Develop multi-mode combustion models and reduced chemistry mechanisms – *Reitz*

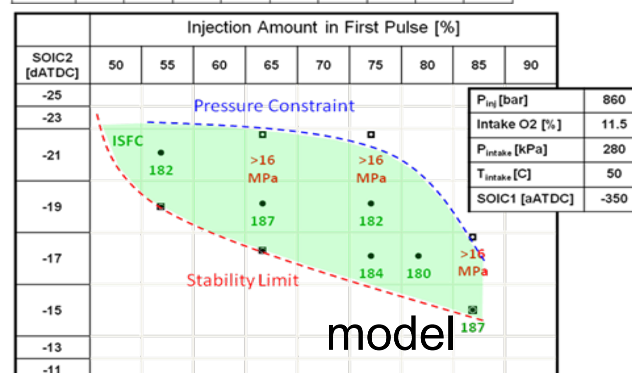
CFD predictions of combustion are essential tool for exploration of new combustion regimes

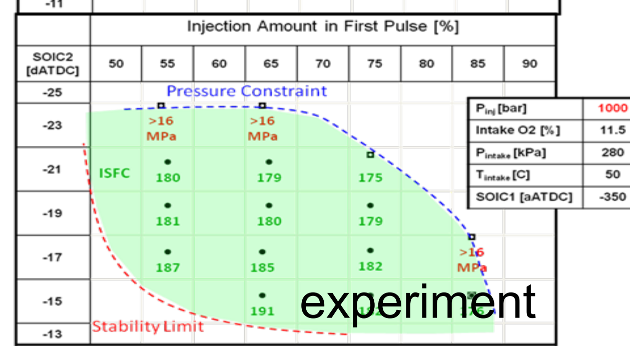
Approach: Multi-component fuel vaporization and reduced chemistry models developed and applied to study combustion regimes, including dual-fuel and gasoline CI combustion under a range of multiple injection, injection pressure, EGR, and conditions.

Accomplishments: Reduced PRF-Ethanol mechanism developed (55 species, 184 reactions); Operation ranges of gasoline double injection compression ignition (GDICI) predicted. Good agreement with GM 1.9L experiments for full load (16 bar IMEP) using a two-component gasoline model (PRF87).

Plans for Next Year: Further validation of GDCI regimes; Application of models to dual fuels.







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

Provide better control/understanding of the mixing of NH_3 & NOx in SCR systems, to allow engine to be optimized for low fuel consumption.

Approach: CFD modeling with LES/RANS turbulence models in combination with breakup models and urea transport/chemistry

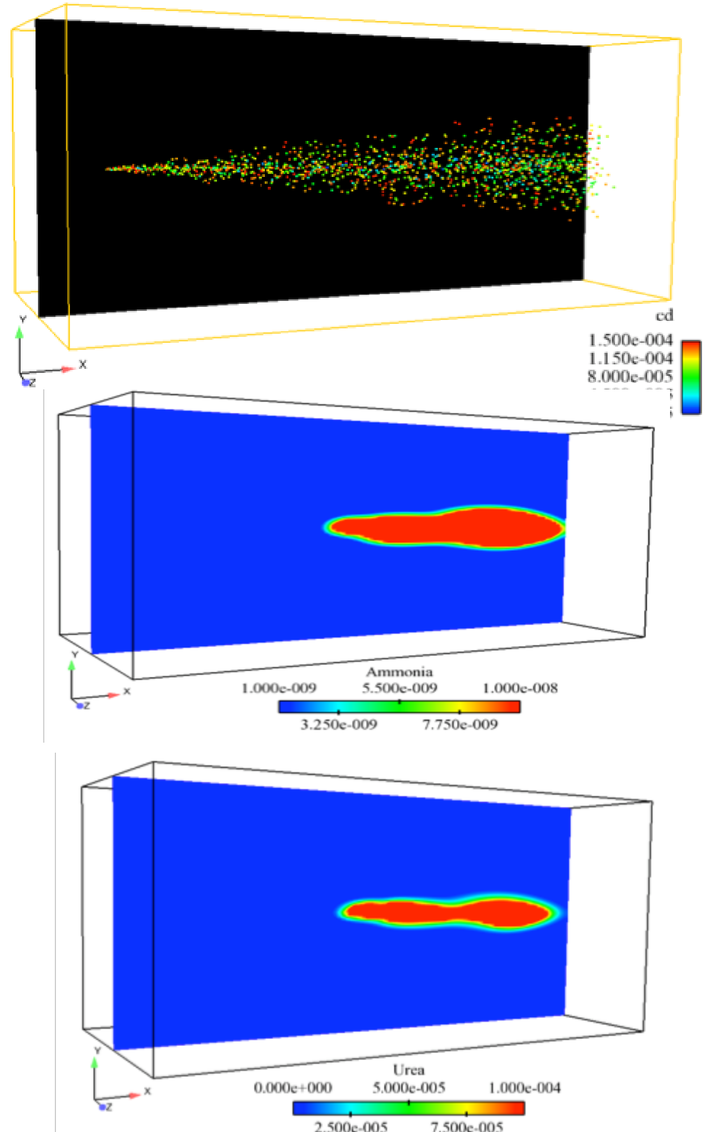
Accomplishments: Completed validation of water spray (Urea-Water-Solution) in a cross-flow configuration.

Modified droplet vaporization model for Urea.

Added chemistry submodel for thermal decomposition of urea gas into NH_3 and HNCO

Plans for Next Year: Perform calculations of UWS spray into a cross and co- hot gas flows

Further validation of spray models



HNCO Isocyanic acid

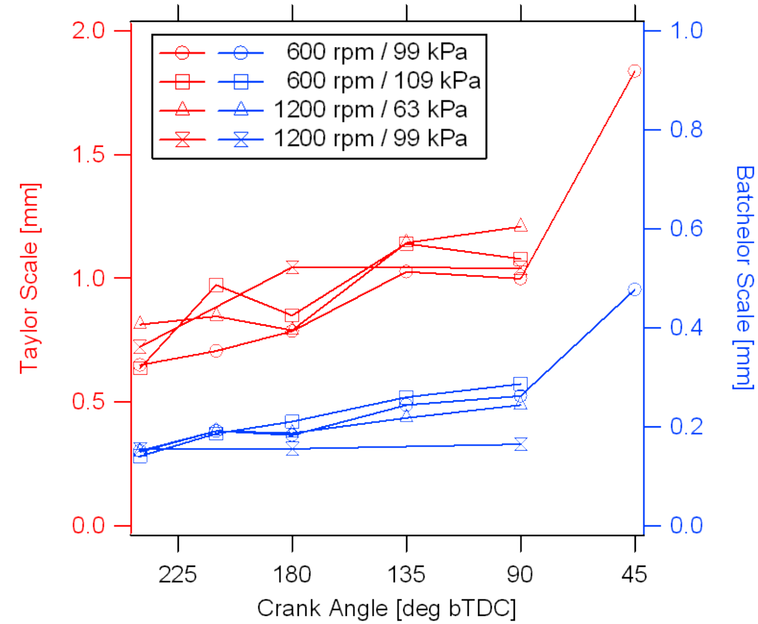
Task C.3: Measurements and control of turbulence mixing in engine flows – *Ghandhi*

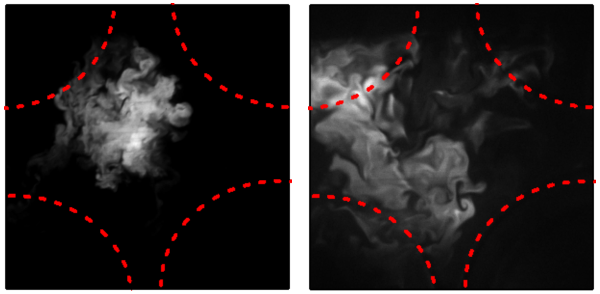
High-efficiency, low-emission combustion strategies require precise control of mixing

Approach: Develop needed understanding of mixing processes through high resolution in-cylinder 3-pentanone fluorescence measurements (30 μm resolution). Injected gas-jet method used to extend scalar measurements later into compression stroke.

Accomplishments: Used split intake port tracer doping to determine Taylor length scales and their evolution during the cycle. In-cylinder gas injection methodology developed for mixing measurements in the late compression stroke

Plans for Next Year: Complete characterization of turbulence spectrum during mixing over a range of timings and operating conditions





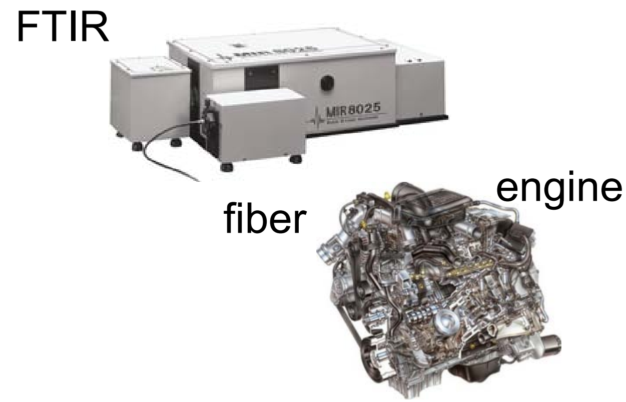
Task C.4: Crank-angle-resolved species and temperature measurements for improved understanding of chemistry and mixing – *Sanders*

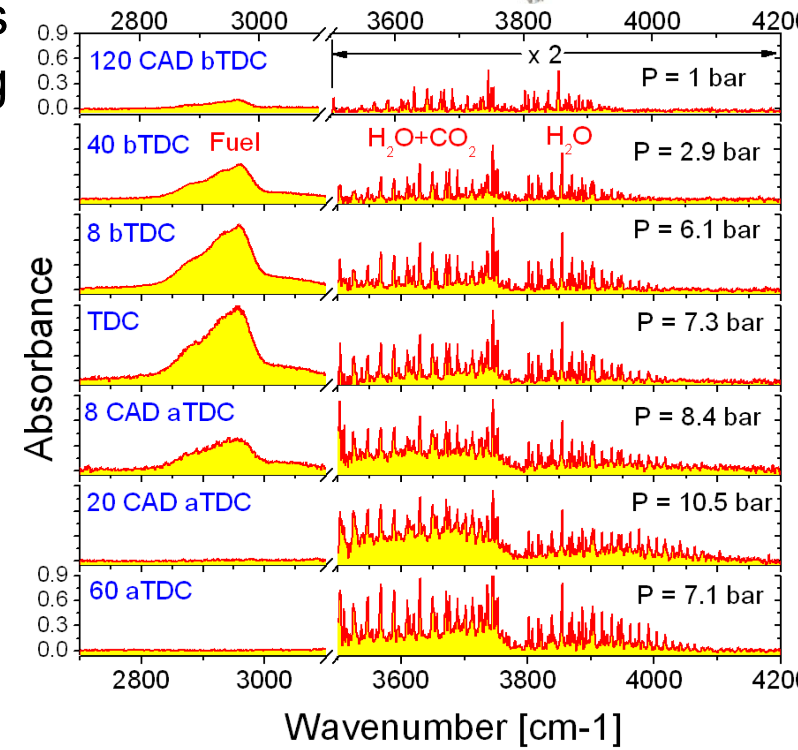
Comparison of measured and simulated in-cylinder species composition histories will help optimize low-temperature combustion processes.

Approach: Using advanced laser sensors and novel applications of traditional optical instruments, catalog in-cylinder gas properties under varied engine operating conditions.

Accomplishments: In-cylinder absorption spectra of fuel, H_2O and CO_2 have been recorded with crank angle resolution over the 2.4 - 3.7 μm range. Quantitative species concentrations and gas temperature have been inferred from the data.

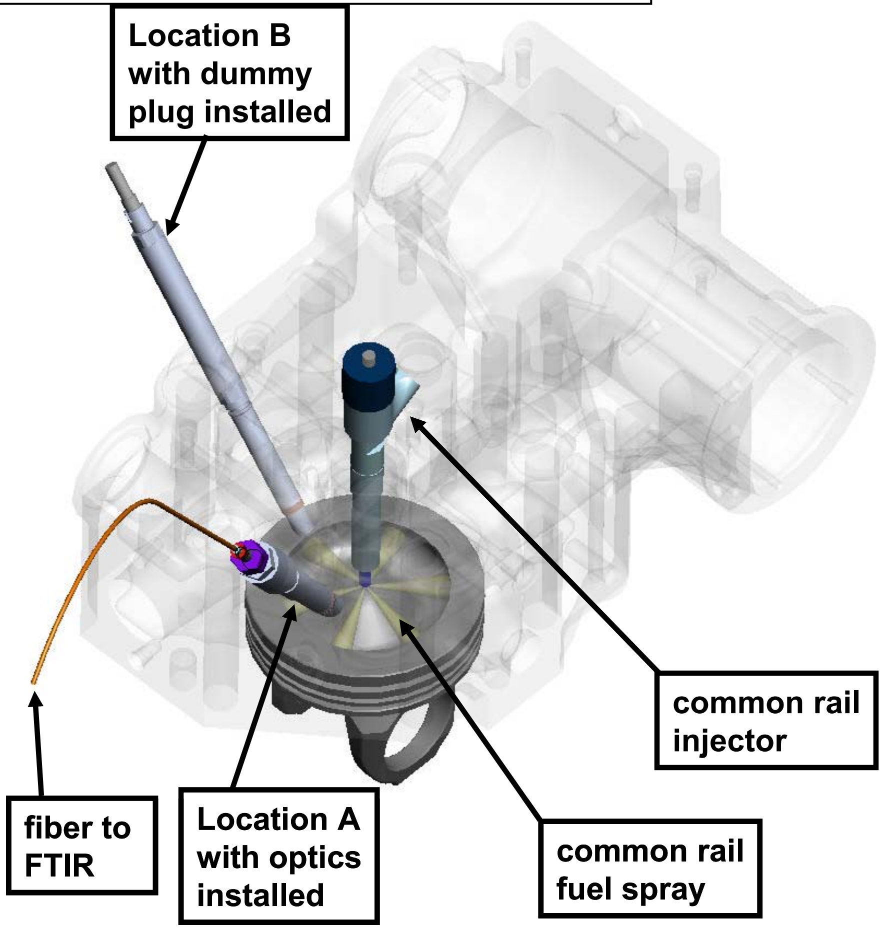
Plans for Next Year: Shorten test time from 30 min to 10 s, develop fiber access to 5 μm.

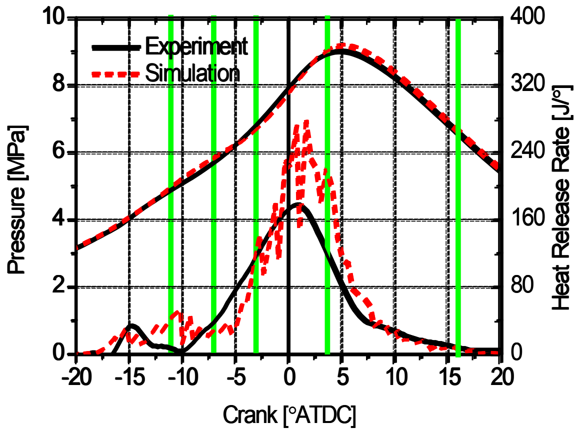


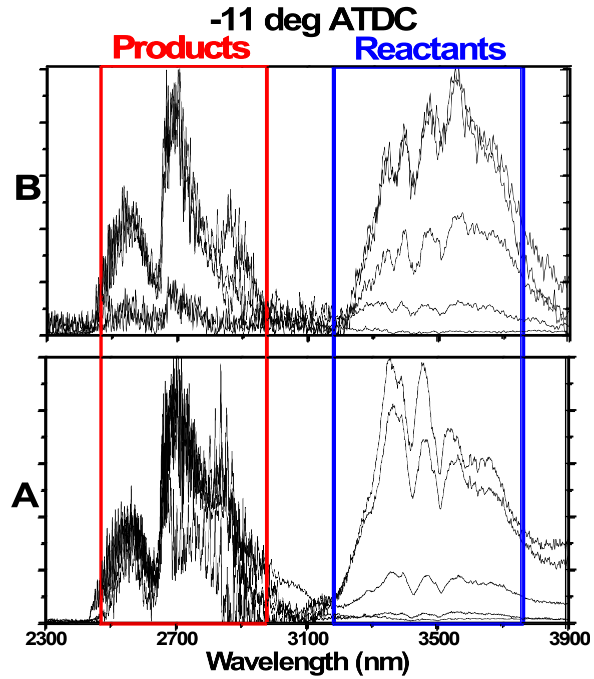


Optical Investigation of Fuel Reactivity PCCI

Splitter et al. SAE 2010-01-0345





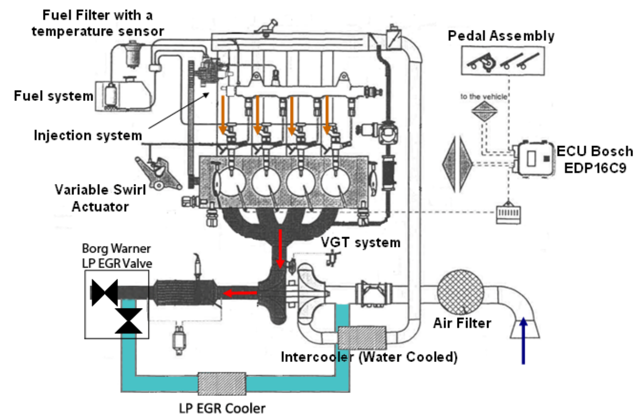


Fuel decomposition and combustion products form at a slower rate at location B, extending combustion duration

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: Incorporated a low pressure ERG loop to expand the load range; identified the fundamental engine phenomena which constrain transient behavior, then used this understanding to identify a more optimal way to achieve transient operation of combustion mode change with speed and load changes.

Plans for Next Year: Study transient operation over wider load range with low pressure EGR

	Baseline	Early PCI (previous)	Early PCI (current)
Air\Fuel Ratio	35.6	21.6	22.7
Main Inj Timing [deg]	-0.5	-27.0	-12.0
Pilot Inj Timing [deg]	-14.5	n/a	-25.6
CA50 [deg]	10.2	-3.5	5.3
Pressure Rise [bar/deg]	1.43	5.59	2.21
Peak Pressure [bar]	49.6	67.5	52.1
COV IMEP [%]	3.87	1.67	2.85
BSFC [g/bkW-hr]	293	289	284
NOx [g/kg fuel]	4.92	0.37	0.39
UHC [g/kg fuel]	7.1	14.3	12.1
CO [g/kg fuel]	10.7	33.1	42.5
Soot [g/kg fuel]	0.28	0.01	0.22

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

Use modeling to guide engine experiments and study engine-after-treatment optimization to allow engine to be optimized for low fuel consumption.

Approach: Use coupled GT-Power with purpose-written emissions submodels. Combine models for engine, emissions, and after-treatment devices at a system level capable of simulating multiple cycles and operating transients

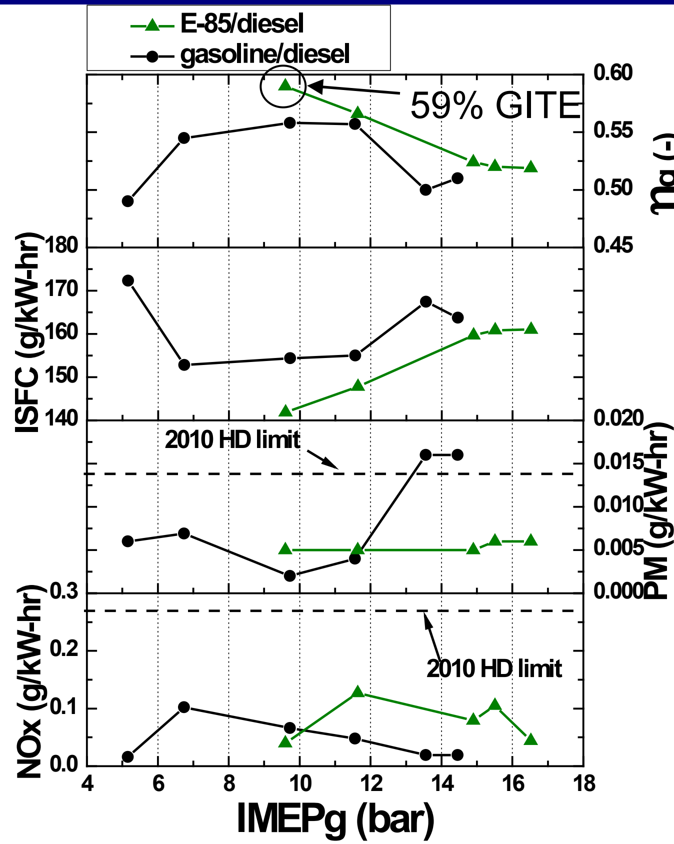
Accomplishments: Implemented and validated combined high and low pressure EGR systems for multi-cylinder engine model
Validated system level model for engine-out CO over a range of conditions
Evaluated potential of fuel savings by accounting for thermal inertia during DPF regeneration

Plans for Next Year: Use system model to study combustion control for near stoichiometric operation and high EGR. Investigate transient LTC-D and emissions

Optimization of Advanced Diesel Engine Combustion Strategies – Summary & Conclusions

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

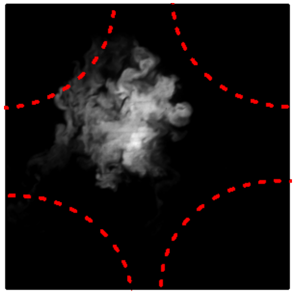


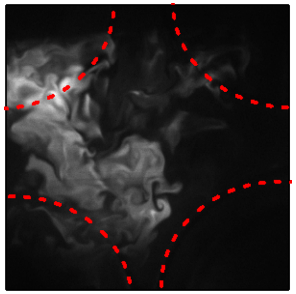
Accomplishments:

Advanced combustion regimes with optimized control of fuel/air/diluent mixture preparation and control of fuel reactivity distribution offer transformational improvements in engine efficiency (>50% Thermal Efficiency over engine operating range)

Plans for Next Year: Explore methods to further increase fuel efficiency while maintaining low emissions

- Further demonstrate LTC on HD and LD engines
- Optimize injection strategies, matched with piston
- Demonstrate and test transient control strategies





Tech. Transfer & Collaborations/Interactions

DOE LTC Consortium project DE-EE0000202

General Motors CRL

Woodward Engine Systems

Diesel Emissions Reduction Consortium (DERC) 22 members

Argonne National lab
Bosch
Borg Warner
Caterpillar Inc.;
Chevron;
Corning Incorporated;
Cummins, Inc. Emissions solutions;
Ford Motor Company;
GE Global Research;
GM R&D Planning and Powertrain;
John Deere Company;
Navistar;
Nippon Soken Inc.;
Oak Ridge National Laboratory;
PACCAR;
Renault;
TARDEC;
Thomas Magnete USA;
Toyota Technical Center USA;
Volvo Powertrain;
Woodward Governor;
Yanmar