Flex Fuel Optimized SI and HCCI Engine

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(05-15-2013)

Project ID #: ACE021

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Overview

- **Timeline (planed)**

  Phase 1: 10/01/09 ~ 05/31/10 ✓
  Phase 2: 06/01/10 ~ 05/31/11 ✓
  Phase 3: 06/01/11 ~ 03/31/12 ✓
  Phase 4: 04/01/12 ~ 09/30/12

  Project no-cost extended to 09/30/13

- **Budget**

  Total Project Funding (all phases)
  - DOE $1,401,299
  - Recipient $ 584,240

  DOE funding
  - FY 10 $444,172
  - FY 11 $517,638
  - FY 12 $439,489

  Recipient (up to date):
  Chrysler: $270.3K estimated (labor, prototype engine and parts)
  MSU: $235.6K (in-kind)

- **Barriers**
  - Lack of modeling capability for combustion and emission control: Development of a control oriented (real-time) hybrid combustion model for model-based mode transition control between SI and HCCI combustions.
  - Lack of effective engine control: Development of a model-based SI and HCCI mode transition control strategy for smooth combustion mode transition using iterative learning control.
  - Cost (high HCCI engine cost): Development of a cost effective and reliable dual combustion mode engine (multi-cylinder and flex fuel) using cost effective actuating system (two-step valves and electrical cam phasing system).

- **Partners**
  - Michigan State University
  - Chrysler Group LLC

Objectives

Demonstrate an SI and HCCI dual-mode combustion engine (multi-cylinder), that is commercially viable, for a blend of gasoline and E85.

FY12/FY13 Objectives (Review Period):

a) Completed SI and HCCI combustion tests of the target optical engine with two-step valve and electrical cam phasing and used the test data for control calibrations.

b) Completed the fabrication and integration of the target four-cylinder engine with the target two-step valve and electrical cam phasing.

c) Completed the integration of the prototype four cylinder engine with the engine prototype controller and validated in dynamometer tests.

d) Completed the SI combustion mapping in engine dynamometer and compare the results with the test data based upon the conventional valve-train.

e) Continue improving the control oriented engine model, especially during the charge mixing process.

Milestones

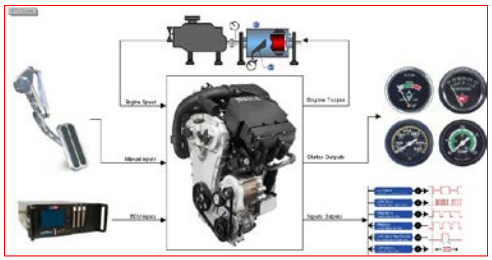
FY12/FY13 Milestones:

Month/Year	Milestone
May-12 (✓)	Completed optical engine tests with both SI and HCCI combustion modes using the target engine valve-train (two-step valve and electrical phasing).
October-12 (✓)	Completed target four cylinder engine integration with the prototype engine controller.
March-13 (✓)	Completed baseline engine mapping in SI combustion mode and compare the results with the engine data with conventional valve-train.

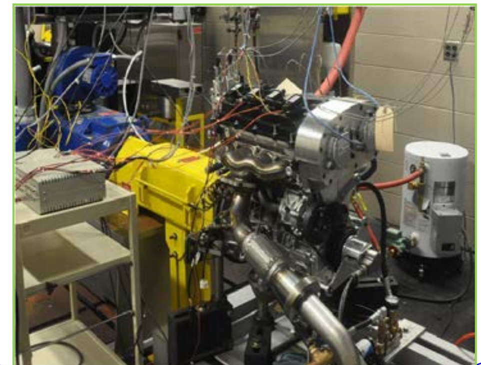
Approach

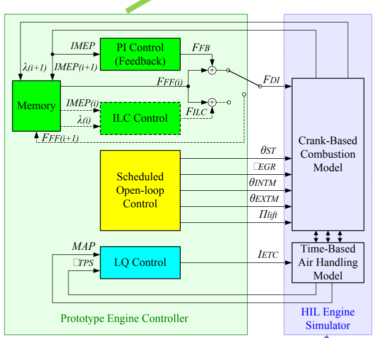
Using a combination of engine modeling, model-based combustion control, and engine experiments to develop a smooth SI and HCCI combustion mode transition control strategy for a flex fuel engine.

Control-oriented engine models developed with GT-Power simulations

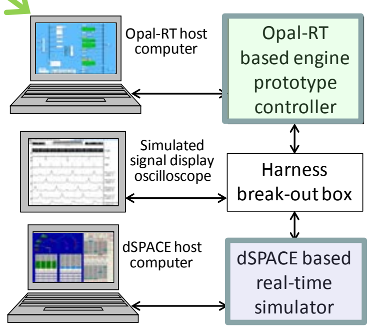


Multi-cylinder metal engine



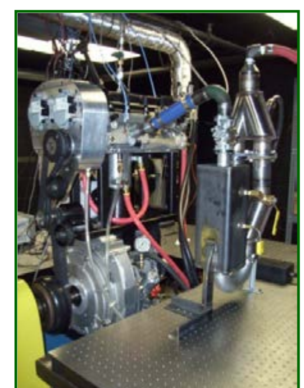


Model-based control strategy



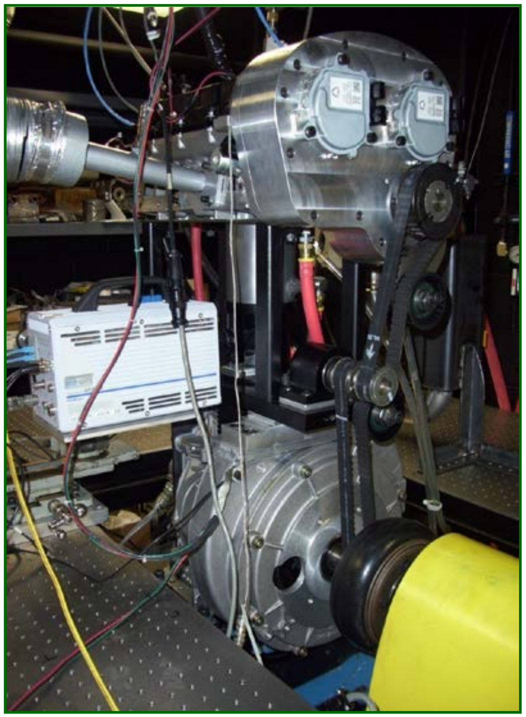
HIL simulation to validate the control strategy

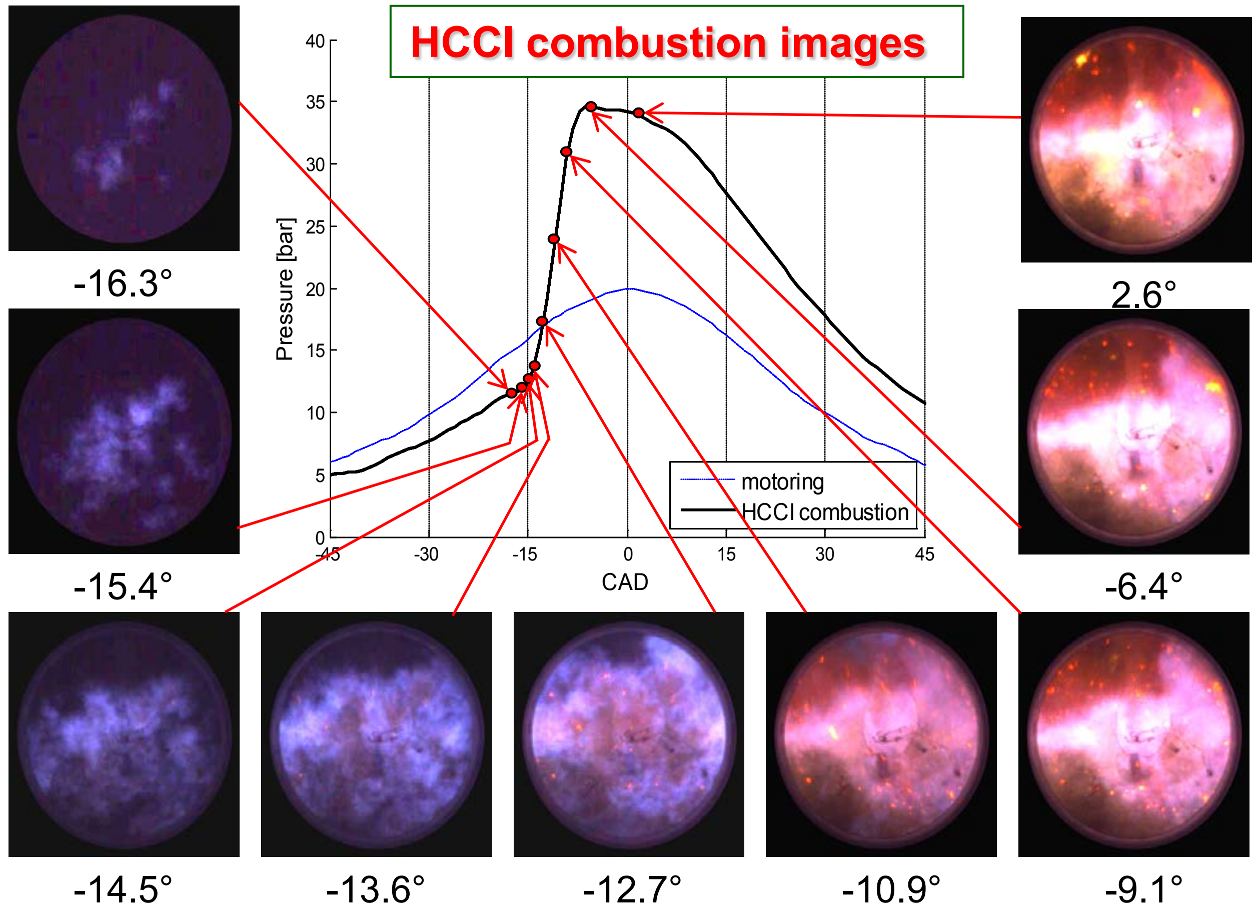
Single cylinder optical engine



Technical Accomplishments

a) Completed optical engine SI and HCCI combustion tests

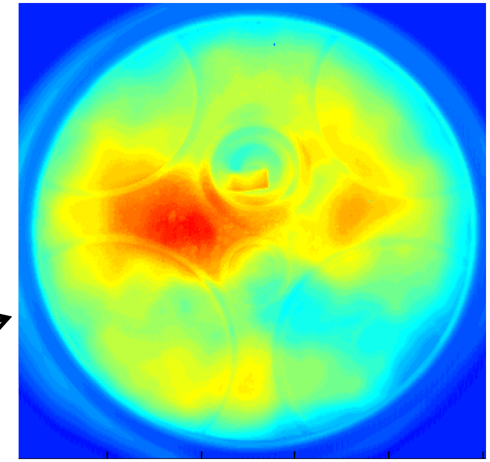




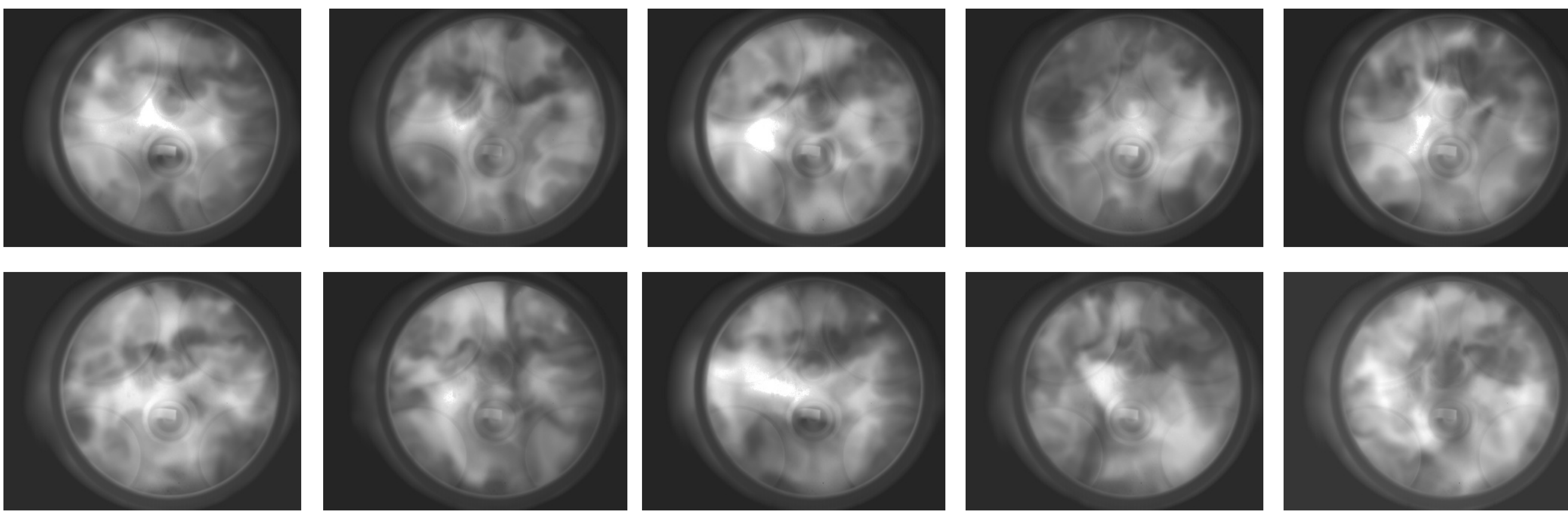
Technical Accomplishments

- IR imaging can be used to capture mixing of fresh intake air with hot recompressed gas IVO timing
- 10 images were taken at the same CAD on ten consecutive cycles. An average image of these ten image can be useful for showing larger mixing trends

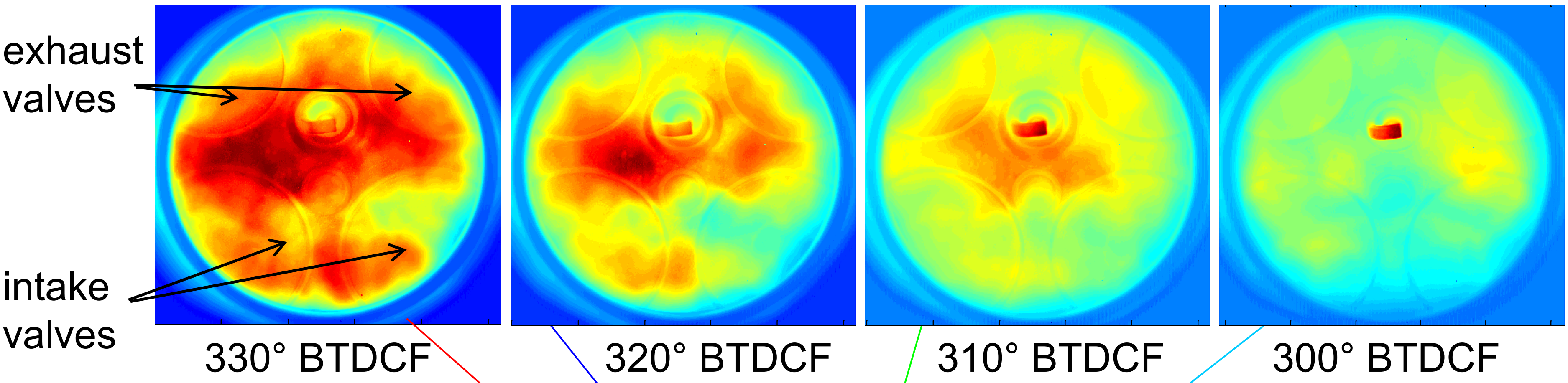
Resulting average image (color scaled)

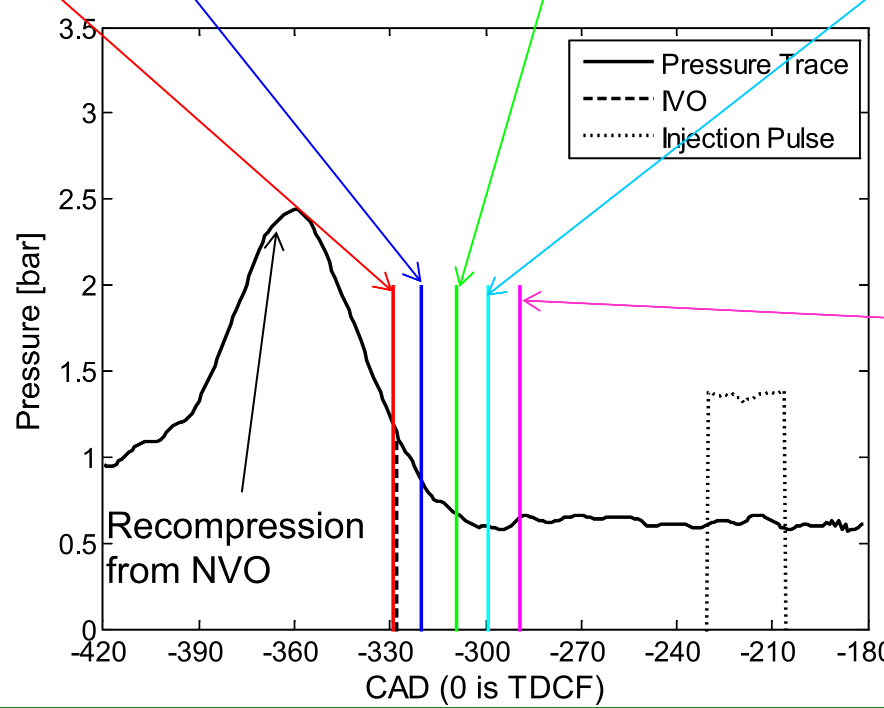


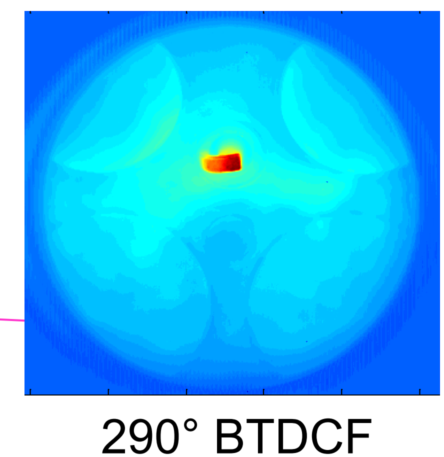
10 raw images taken at the same CAD on consecutive cycles



Technical Accomplishments





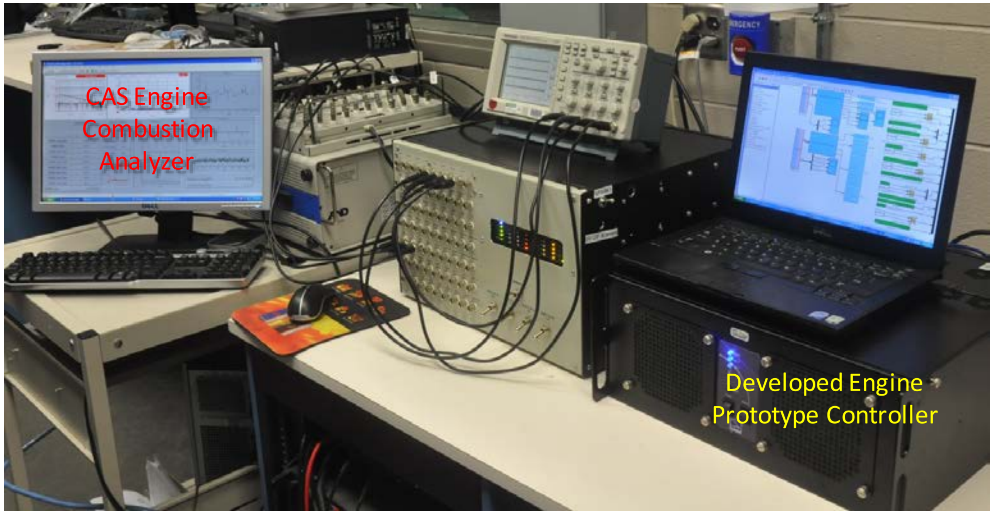


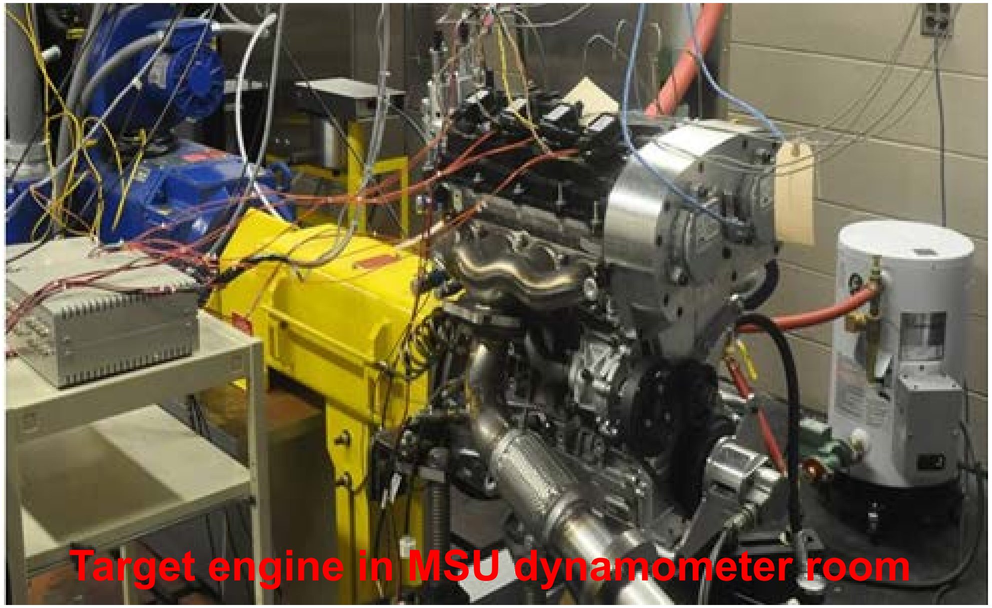
- Five groups of 10 images were taken at 5 different CAD locations, each 10 CAD apart starting at the end of recompressions near IVO
- The result is these five average IR images that show how mixing is occurring as the intake valve opens
- Mixing after pilot injection during recompression depends on inject. timing

Technical Accomplishments

b) Completed four-cylinder engine integration

- Chrysler four cylinder baseline DI engine modified with high compression ratio (11.5:1), two-step valve and electrical cam phasing.
- Prototype engine controller, capable of pressure based combustion feedback, is integrated with the target engine.
- Engine control functionality has been validated through engine tests and real-time combustion analysis is available through A&D combustion analysis system.





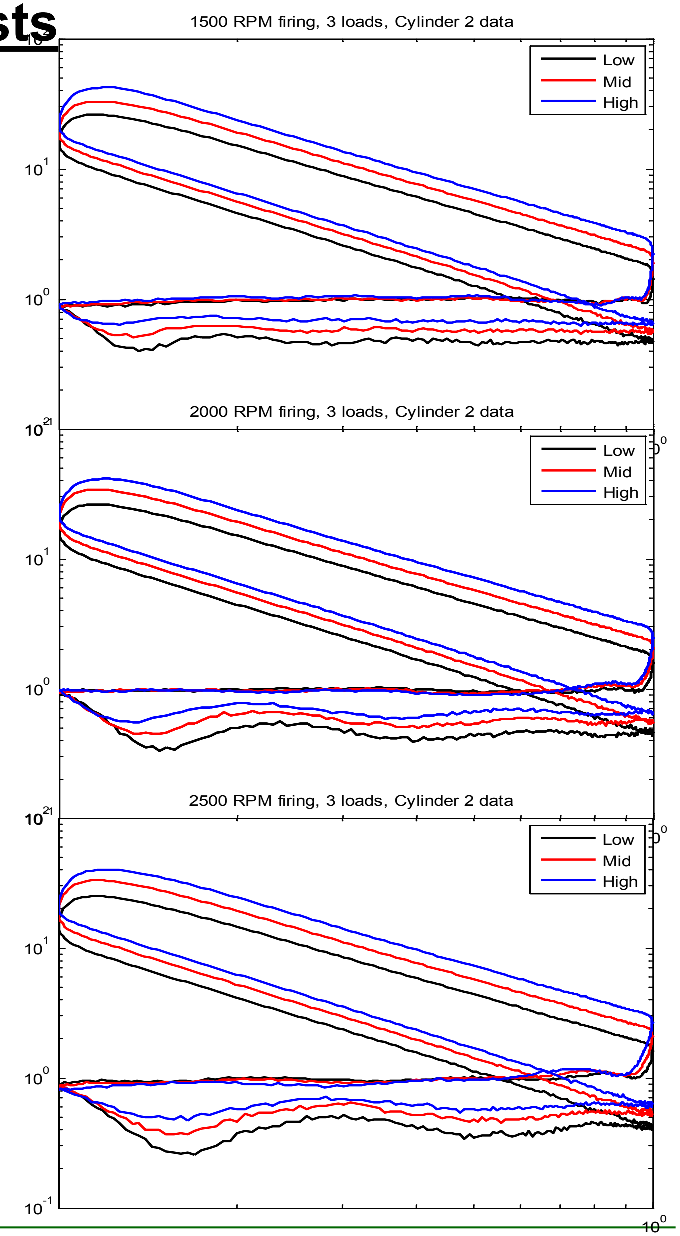
Technical Accomplishments

c) Completed target engine SI combustion tests

Baseline engine tests were conducted in SI combustion mode with high valve lift and existing valve timing from Chrysler.

- All tests with normalized air-to-fuel ratio at λ=1
- Injection timing of 300° BTDC based on existing Chrysler data with 10 MPa DI injection pressure

These test points will serve as a benchmark for running in SI and HCCI modes at similar loads and speeds. PV diagrams will be used for studying how HCCI operation affects pumping losses and breathing.

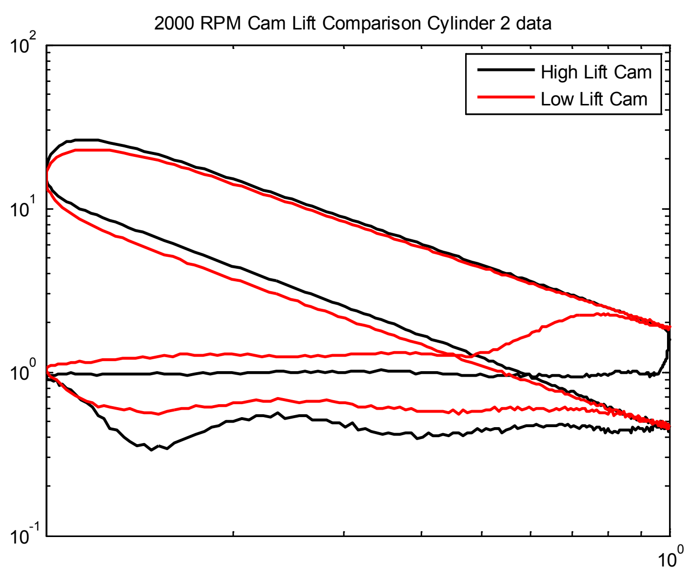


Speed	MAP [kPa]	IMEP [bar]	PMEP [bar]	Spark [CAD BTDC]	Injection Pulse [ms]	CA50 [CAD ATDC]	B1090 [CAD]	COV of IMEP
1500	47.7	4.54	0.50	24	1.90	8	23	2.2
	57.7	5.84	0.42	22	2.20	8	22	1.5
	66.1	7.51	0.37	19	2.60	8	18	1.4
2000	46.0	4.62	0.53	27	1.85	7	23	1.2
	56.4	5.98	0.44	23	2.20	9	21	1.7
	65.4	7.52	0.35	20	2.55	7	19	1.2
2500	42.0	4.51	0.59	25	1.85	8	24	1.3
	52.8	6.05	0.50	22	2.30	8	22	1.3
	62.9	7.77	0.44	19	2.70	9	22	1.3

Technical Accomplishments

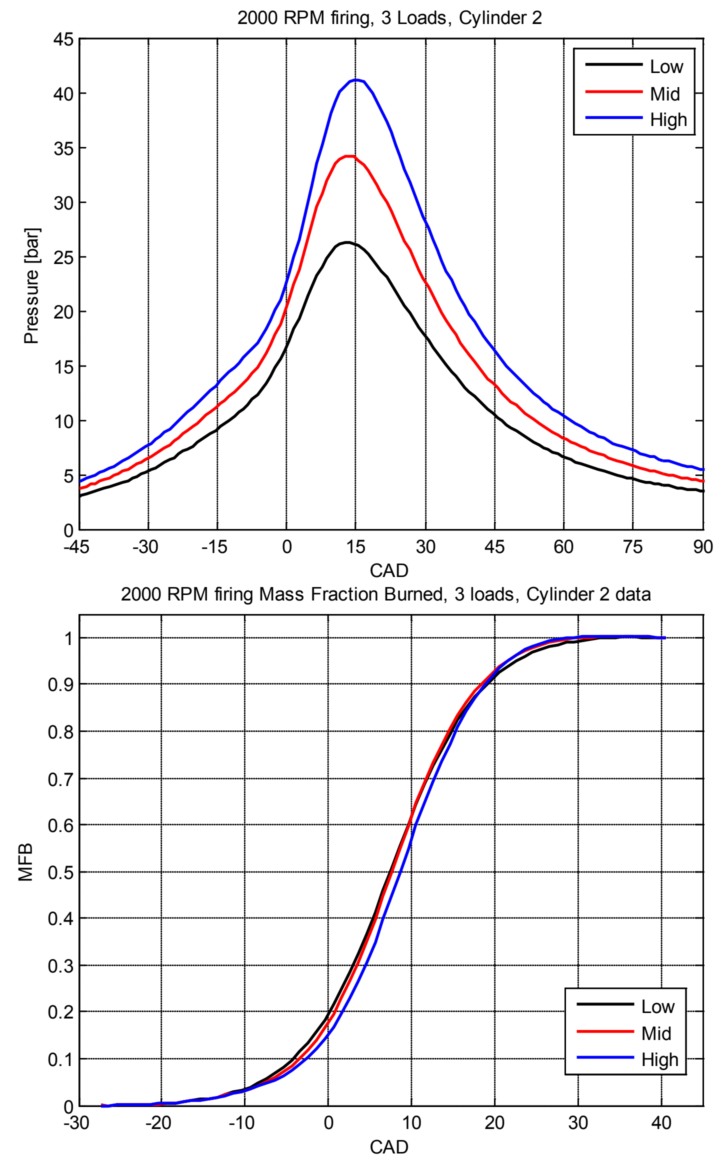
Valve lift comparison at 2000 RPM

SI combustion tests with different valve lifts were conducted at 2000RPM with around 4.5 bar IMEP for both high and low intake/exhaust lifts. It was observed that slow combustion occurs at low lift, and the PV diagram shows increased pump loss (see the table below). Valve timing will be further optimized in further to maximize benefit at low-lift.



Speed	Cam	MAP [kPa]	IMEP [bar]	PMEP [bar]	Spark [CAD BTDC]	Injection Pulse [ms]	CA50 [CAD ATDC]	B1090 [CAD]	COV of IMEP
1500	high lift	46.0	4.62	0.53	27	1.85	7.5	23.2	1.2
1500	low lift	46.8	4.49	1.06	38	1.90	8.3	26.7	1.7

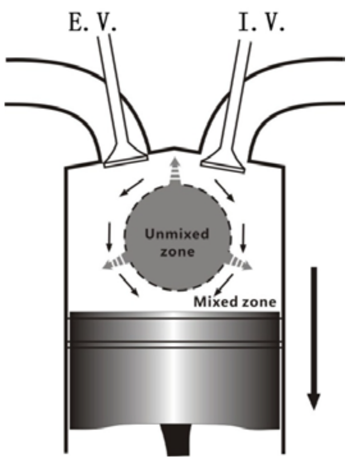
Pressure and MFB



Technical Accomplishments

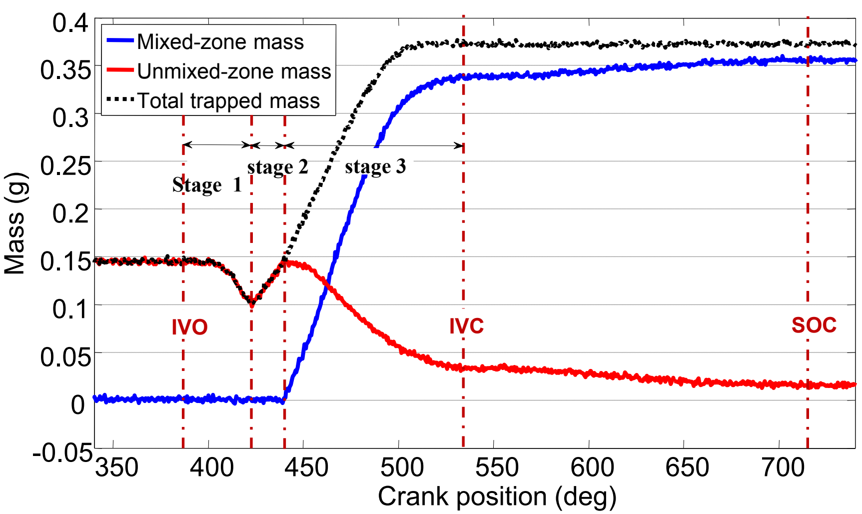
d) Improvement on charge mixing modeling

- HCCI combustion assumes Homogeneous Charge before compression ignition, while in practice it is Heterogeneous, especially with high EGR.
- One-zone control-oriented HCCI combustion model, developed earlier, assumes that the thermodynamic characteristics is uniformly distributed in the cylinder, leading large prediction error of the start of combustion (SOC).
- To accurately predict the SOC, it is proposed to use a two-zone HCCI combustion model for predicting SOC, which involves two-zone charge mixing and HCCI modeling.

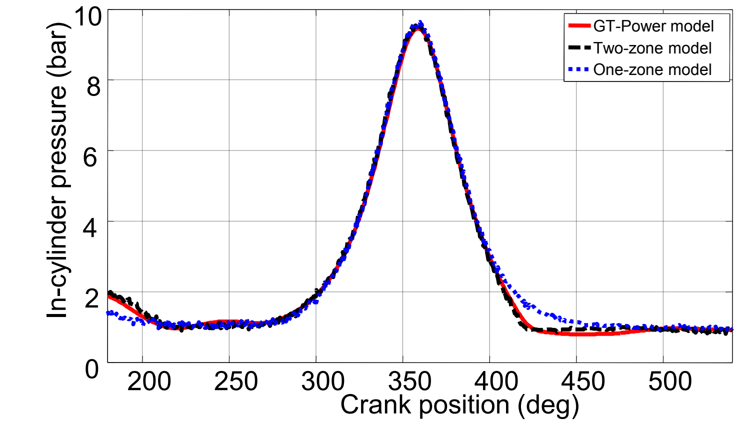


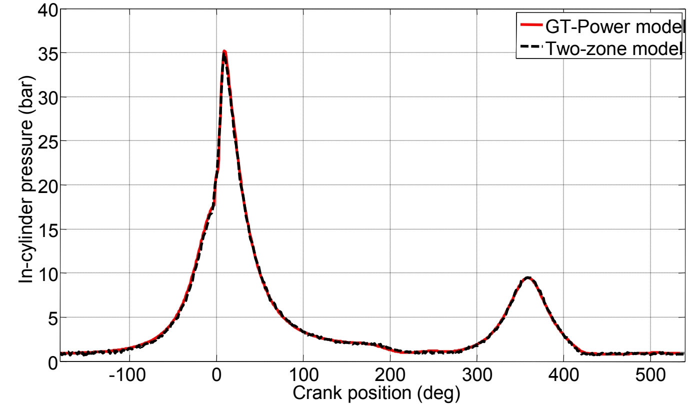
Mass transfer between fresh charge and residual is assumed to be mainly due to diffusion:

- Molecular diffusion
- Laminar diffusion
- **Turbulent diffusion**

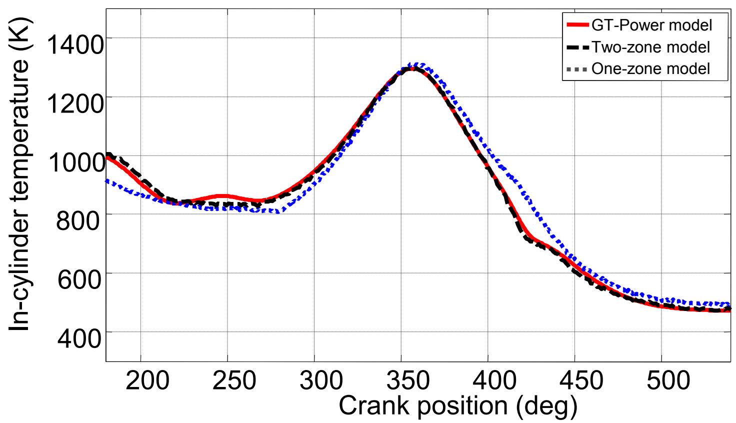


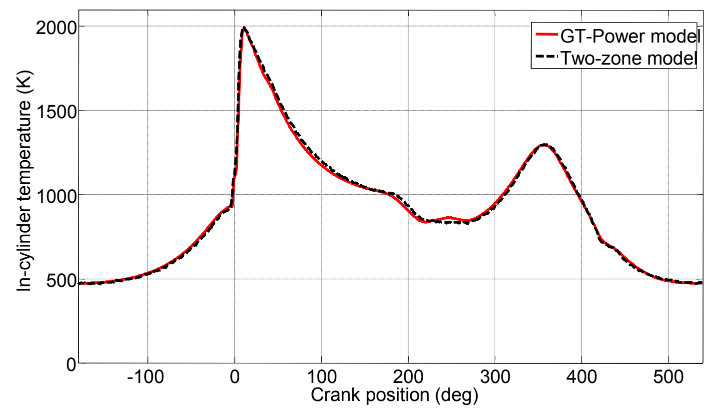
Technical Accomplishments





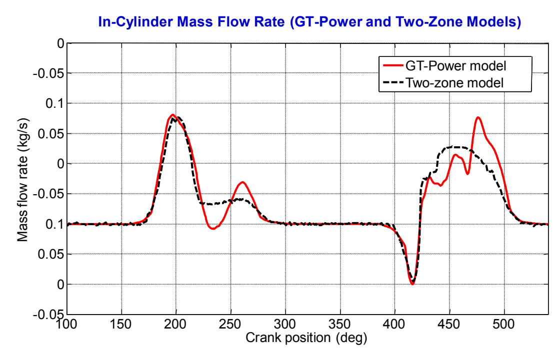
Pressure





Temperature

Model	FUEL (MG)	SOC	IMEP
GT-Power	13.2	2	4.2
Two-zone model	13.2	2	4.22
One-zone model (w/ flow dynamics)	13.2	4	4.23
One-zone model (w/o flow dynamics)	13.2	8	4.36



Technical Accomplishments (summary)

- Completed the integration of target four cylinder metal engine in the MSU dyno, along with the Opal-RT based engine prototype controller and A&D real-time combustion analysis system (CAS).
- Setup tests were conducted using the target pistons (with 11.5 compression ratio) and verified the functionality of the prototype engine control systems, including DI fueling, two-step valvetrain, electrical cam phasing, ignition system with ionization detection, etc.
- Baseline SI combustion mapping was conducted and the test results were comparable with the original engine data equipped with conventional vlavetrain.
- A new control-oriented charge mixing model was developed to model mixed and unmixed zones for improved estimation accuracy the start of combustion (SOC), which also enables the two-zone HCCI combustion model.
- The updated model was implemented into the MSU HIL simulation system and the simulation results show significant improvement on SOC prediction over one zone model and good agreement of in-cylinder pressure and temperature with these obtained from GT-Power model.

Collaborations

Industrial Partner (Chrysler Group LLC)

- Support over the past FY
  - Provided design engineering services to help MSU to complete the four-cylinder engine integration. Chrysler engineers visited MSU regularly and resolved many issues during the integration process.
  - Chrysler engineers work closely with MSU to provide special ignition coils that made ionization detection possible.
  - Chrysler engineers participated in optical and metal engine tests at MSU to help validate test results.
  - Engineering design review and support.

- Future support
  - Engineering support on final target engine tests.

Collaborations (cont'd)

Technology Transfer

- In the past year, MSU team worked closely with Chrysler through technical discussions and seminars to get the following technologies transferred. This includes:
  - The control strategy for combustion mode transition using the hybrid combustion mode with iterative learning and LQ tracking control.
  - The HIL (hardware-in-the-loop) simulation technology using the developed control oriented engine model for developing and validating control strategies of HCCI capable SI engines
- The MSU team is also working with Ricardo to integrate the developed hybrid combustion model into the Ricardo WAVE-RT modeling tool.

Future Work (Rest of Year)

The future work is to complete the project by the end of September, 2013, including

- Complete mapping the metal engine for SI and HCCI combustion (gasoline and E85)
- Validate the mode transition control on the metal engine
- Final report

Summary

Relevance: Ethanol blend flex fuel engine technologies for HCCI capable SI engines are being developed to provide smooth mode transition between SI and HCCI combustions

Approach: Using a combination of engine modeling, model-based combustion control and engine experiments to develop a smooth SI and HCCI combustion mode transition strategy

Key Enablers: Two-step lift electrical VVT, control oriented engine modeling, hybrid combustion, model-based combustion mode transition, iterative learning

Collaboration: Michigan State University (project lead), Chrysler Group LLC (industrial partner), Ricardo (modeling).

Technical Accomplishments:

- Completed the integration of target four cylinder metal engine in the MSU dyno, along with the Opal-RT based engine prototype controller and A&D real-time combustion analysis system (CAS).
- Setup tests were conducted using the target pistons (with 11.5 compression ratio) and verified the functionality.
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