Flex Fuel Optimized SI and HCCI Engine

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Project ID #: ACE021

Overview

Timeline

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

Phase 2: 80% complete by 03/25/11

Budget

Total Project Funding (all phases)

– DOE $1,401,299
– Recipient $ 584,240

DOE funding obligated/budgeted

– FY 10 $444,172/$444,172
– FY 11 $250,000/$517,638
– FY 12 $ /$439,489

Recipient (up to date):
Chrysler: $108.5K labor, one prototype engine and an extra head
MSU: $73K (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
(John Opra and Ron Reese)

Objectives

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

FY10/FY11 Objectives (Review Period):

a)Develop a control oriented (real-time) hybrid combustion model to study SI and HCCI mode transition characteristics and to be used for model-based combustion mode transition control.

b)Develop a cost effective and reliable dual combustion mode engine (multi-cylinder) using cost effective actuating system (two-step valves and electrical cam phasing system).

c)Develop a model-based SI and HCCI mode transition control system (hardware and control strategy) for smooth mode transition using iterative learning control.

d)Study the combustion mode transition for the target engine through combustion visualization.

Milestones

FY10/FY11 Milestones:

Month/Year	Milestone or Go/No-Go Decision
May-10 (✓)	Go/No-Go decision: Complete target engine selection with engine simulation and analysis; develop and validate control oriented (real-time) engine model; and complete design and fabrication of the target optical engine.
May-11 (80%)	Milestone: Complete engine system integration (two-step valve and electrical phasing)
May-11 (80%)	Go/No-Go decision: Complete optical engine combustion tests; and design/ fabricate engine control system capable of combustion sensing (feedback) and combustion mode transition control.

Approach

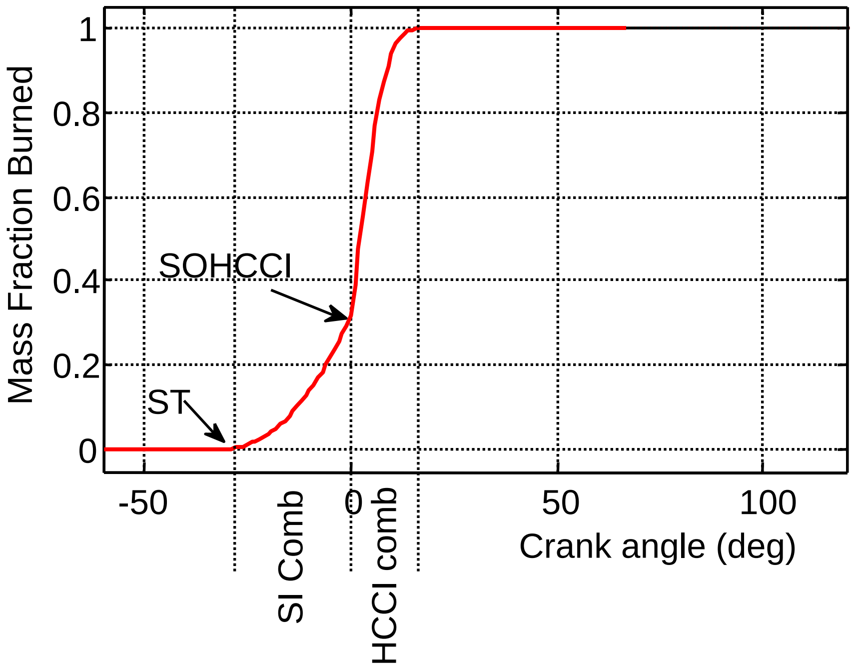
Using a combination of engine modeling, model-based combustion control, and engine experiments to develop a smooth SI and HCCI combustion mode transition control strategy for a flex fuel engine.

- Control Oriented (real-time) engine modeling: Develop a control oriented hybrid (spark assistant) combustion model for model-based combustion mode transition control. This forms the foundation of developing "effective engine control."
- Model-based dynamic engine control: Develop a model-based SI and HCCI mode transition dynamic control strategy for smooth mode transition using iterative learning control (stead-state optimized control parameters are NOT optimal during transitional operation). This requires accurate "combustion modeling."
- Using production feasible hardware: Engine actuating and sensing hardware to be production feasible with low cost to make it possible to have low "cost" HCCI capable SI engines.
- Optical and metal engine experiments: Using both optical and metal engine experimental results to calibrate engine model and to validate the developed control strategies for smooth mode transitions between SI and HCCI combustions for blends of gasoline and ethanol.
- Technology transfer: work with our industrial partner, Chrysler Group LLC, during the project period to ensure smooth technology transfer to industry.

Technical Accomplishments:

a) Control oriented engine modeling/validation (Hybrid Combustion)

- **Completed development of the control oriented engine model**
  - Modeled hybrid combustion mode
  - Two zone SI combustion model
  - One zone HCCI combustion model
  - Model is validated against the off-line GT-Power model
  - Model is implemented into an HIL (hardware-in-the-loop) system for real-time simulations

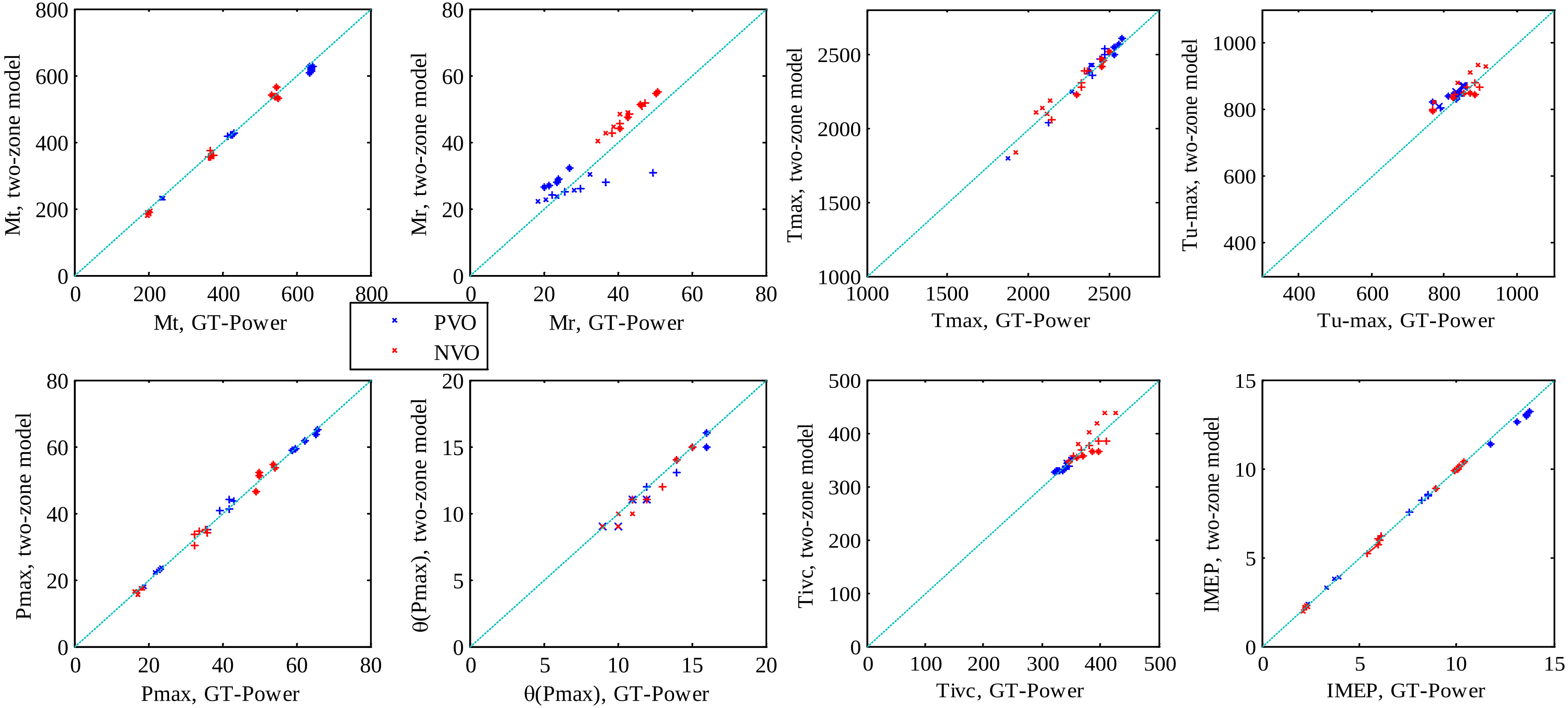


Control oriented engine model features

- Combustion info (pressure, temperature, etc.) is updated every crank degree.
- The start of HCCI combustion timing is checked every crank degree.
- Engine IMEP and net torque is calculated every combustion event
- The engine flow is modeled using conventional mean-value modeling technique to reduce the computational throughput.

Technical Accomplishments:

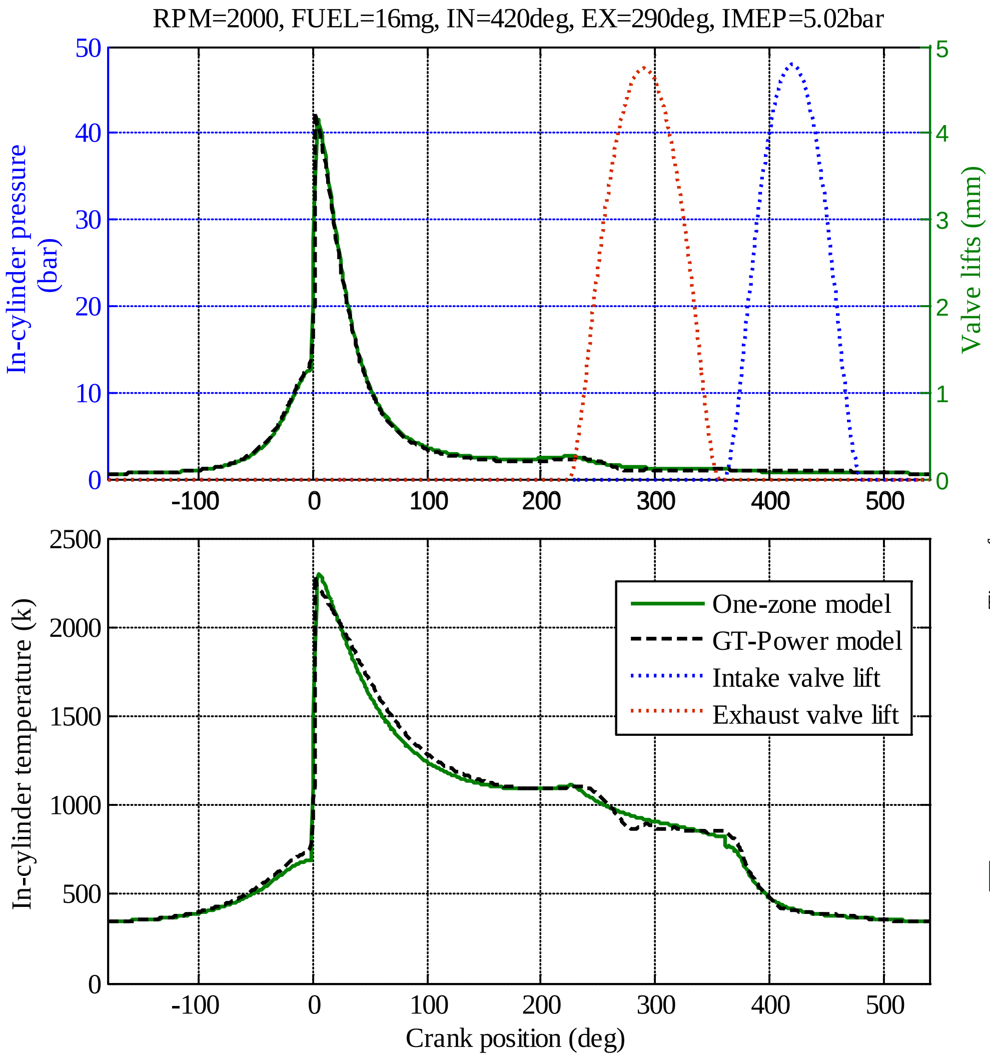
a) Control oriented engine modeling and validation (SI Combustion)

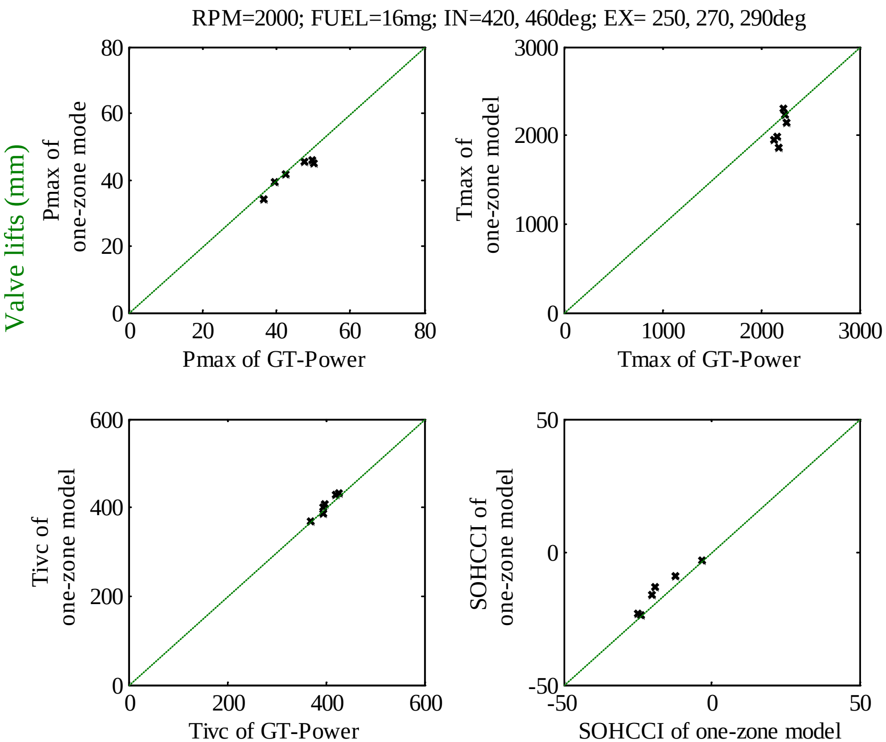


- The control oriented simulation results were compared with these from GT-Power simulations and it is concluded that the simulation accuracy is suitable for model-based control development and validation.

Technical Accomplishments:

a) Control oriented engine modeling and validation (HCCI Combustion)



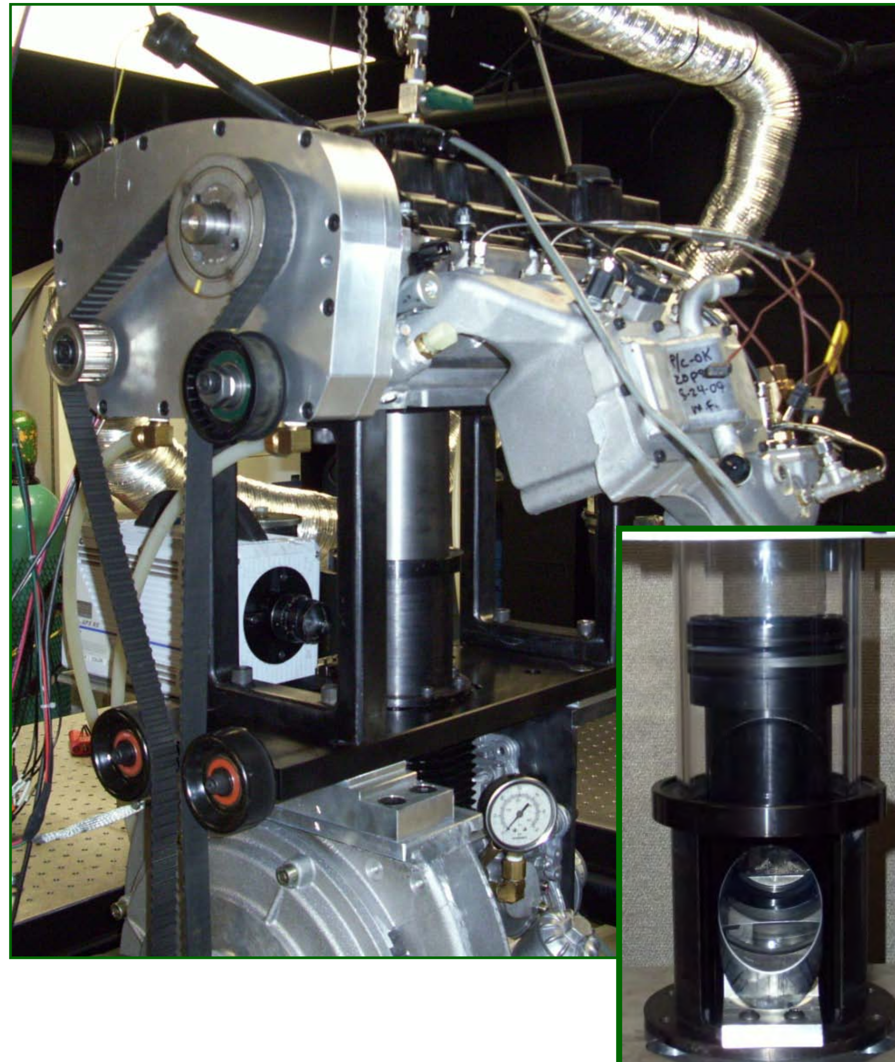


- Good correction was also obtained for the HCCI combustion between the control oriented and GT-Power models.

Technical Accomplishments:

b) Engine system development (Optical target engine and spray tests)

- Completed optical target engine design and fabrication.
- Completed injector spray bench tests and the results show:
  - The target direct injector is robust to the blend of ethanol and gasoline.
  - The droplet SMD (Sauter Mean Diameter) variation is 6.5% between gasoline and E85.
  - The droplet volume distribution DV90 variation is 8.5% between gasoline and E85.
- Engine components provided by Chrysler Group LLC.
- HCCI capable optical engine is under fabrication.

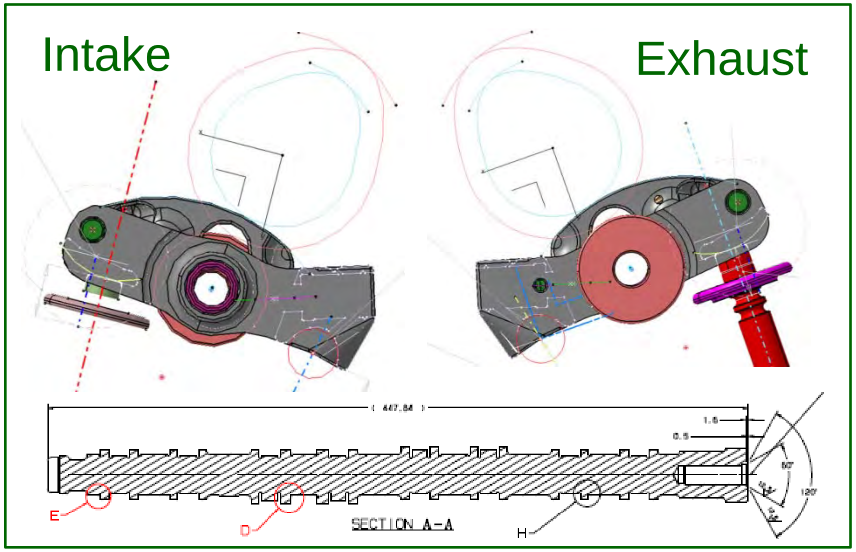


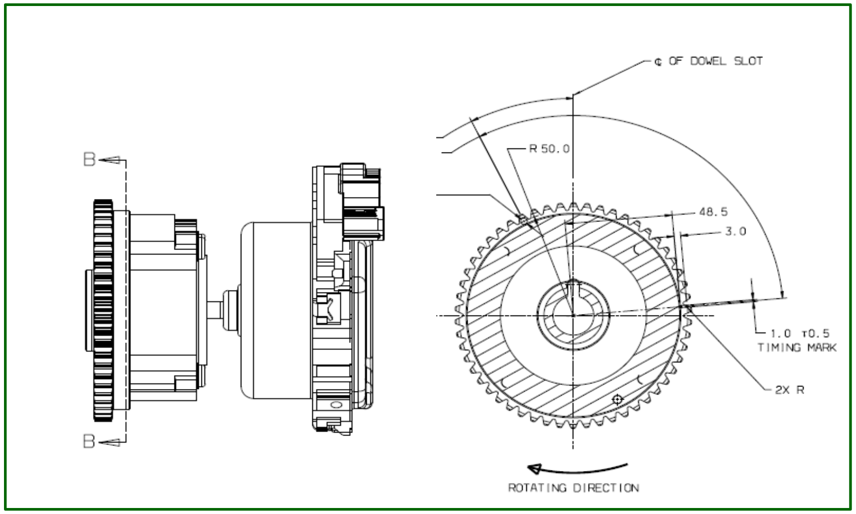
Technical Accomplishments:

b) Engine system development (Valve system selection and design)

- **Completed redesign of implementing cam driven intake and exhaust valve system with two-step lift**
  - Chrysler and MSU worked closely with Delphi and redesigned engine valvetrain to fit Delphi two-step valve system into the target engine head.
  - Optimal valve lifts and intake/exhaust valve center timings of both high and low lifts were obtained through intensive GT-Power simulations.

- **Completed the integration of the electrical cam phasing system**
  - Chrysler and MSU worked with the electrical cam phasing actuator supplier and resigned cam system to fit the new cam phasing system.
  - Intensive GT-Power simulations conducted to determine required cam phase range.





Technical Accomplishments:

b) Engine system development (Engine control system)

- **Engine prototype controller core**
  - Worked with Opal-RT and completed a dual-processor prototype controller design (left).
  - The controller is capable of processing crank based pressure or ionization signals for model-based combustion control
  - Control strategy is programmed in Matlab/Simulink and auto-coded into the target processors.

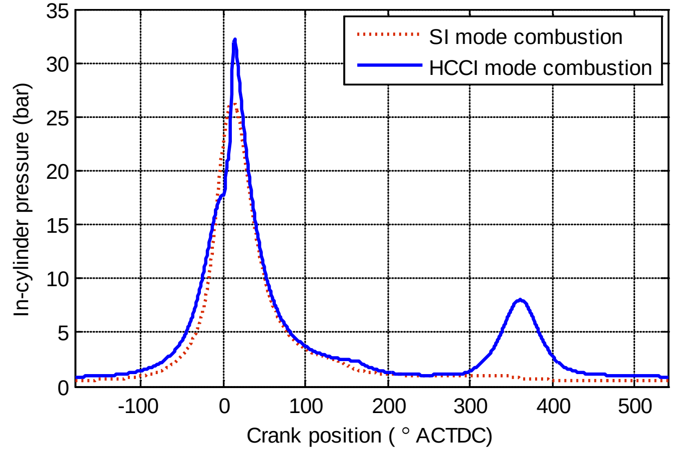
- **Engine controller I/O box**
  - Engine actuator drivers (injector, two-step lift, cam phase, etc.) and sensor signal conditioning electronics (pressure, ionization, etc.) are developed to accommodate the feedback and control requirements of the HCCI capable SI engine (both optical and metal).

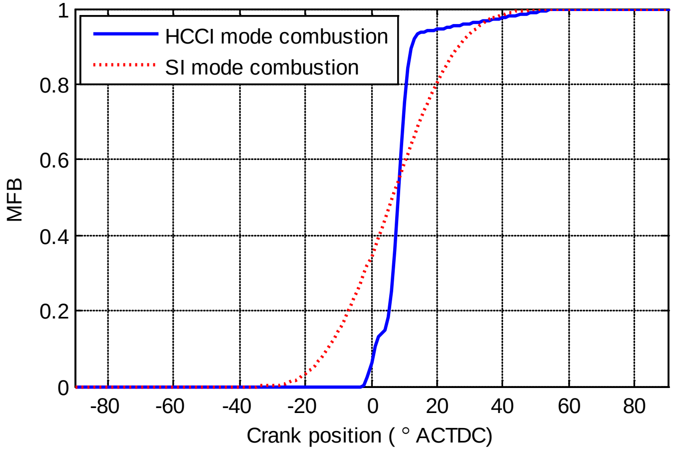
Technical Accomplishments:

c) Mode transition control strategy (control parameters of SI and HCCI)

Findings from mode transition simulations:

- ❑ Steady state engine control parameters are NOT optimal during mode transition due to engine cycle-to-cycle thermo dynamics
- ❑ Five out of seven engine control parameters during the mode transition cannot be controlled at individual cylinder level
- ❑ Proposed mode transition control strategy combines open loop optimal control and closed loop iterative learning control.
- ❑ EGR, VVT, and throttle actuators are not fast enough for one-cycle mode transition.





Actuator parameters at 2000 rpm with 4.5bar IMEP

	ST (ºACTDC)	EGR valve (%)	Throttle (%)	Fuel pulse (ms/cycle)	VVT_IN (ºAGTDC)	VVT_EX (ºBGTDC)	Valve lift
SI	-36	**3**	**16.6**	2.06	**70**	**100**	**high**
HCCI	N/A	**26**	**100**	1.6	**95**	**132**	**low**

Technical Accomplishments:

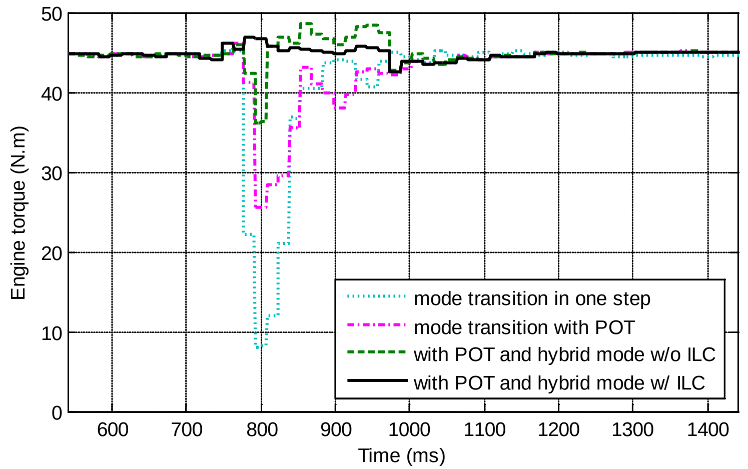
c) Mode transition control strategy (Mode transition simulation results)

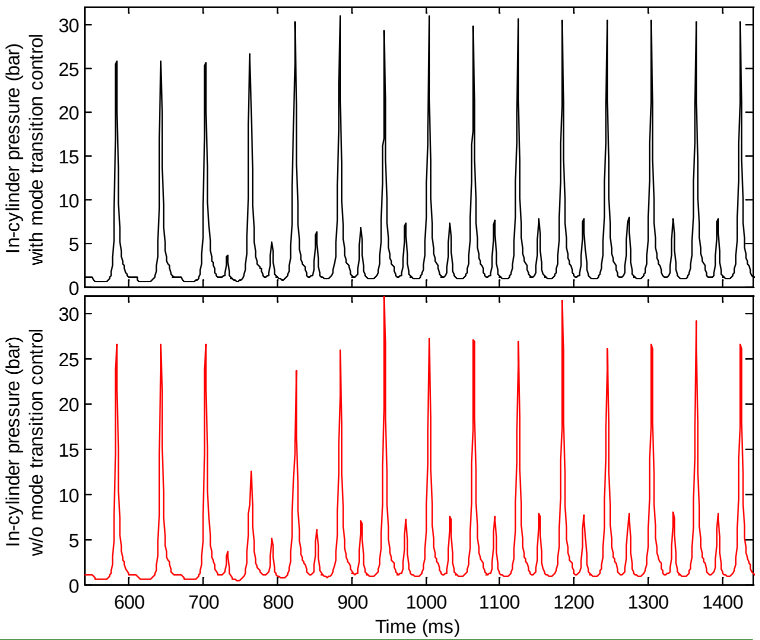
Four control strategies studied:

- Baseline one-step mode transition
- Proposed multi-step (cycle) mode transition
  1) Mode transition with the help of pre-opening (PO) throttle
  2) Mode transition with pre-opening throttle using the hybrid combustion mode
  3) Mode transition with iterative learning of pre-opening throttle and hybrid combustion mode

⇨ Option 3) provides satisfactory performance

	IMEP error (%)	Max dp/dθ (bar/ºcrank)	Torque error (%)
Baseline One step	51.6	3.4	81.8
1) PO Throttle	26.9	2.82	42.5
2) PO Throttle + Hybrid	12	2.65	18.6
3) (POT + Hybrid) with ILC	3.3	2.55	4.5





Technical Accomplishments:

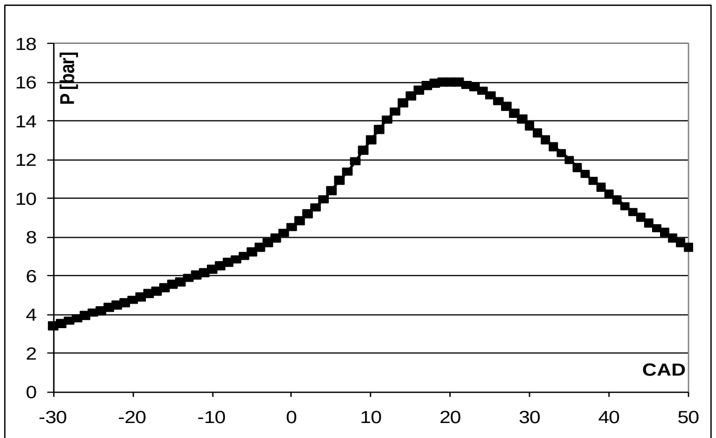
c) Mode transition control strategy (Summary)

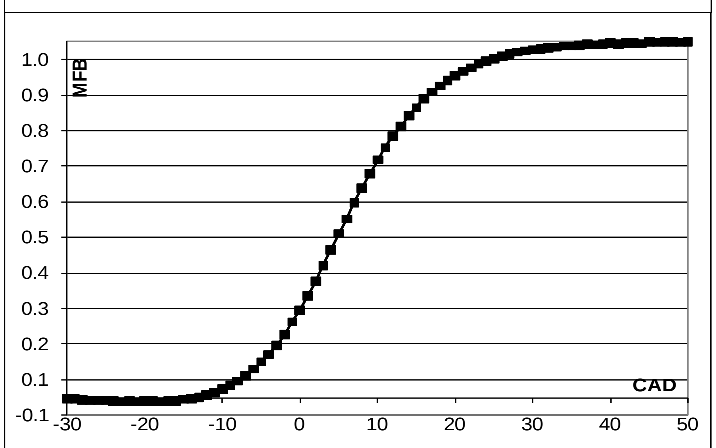
- The engine throttle, EGR, intake and exhaust valve phasing actuators can not be adjusted fast enough for one-cycle engine combustion mode transition.
  - ⇨ Optimal open loop control for slow actuators (EGR, throttle, VVTs, two step lift) with iterative learning for throttle pre-opening
  - ⇨ Hybrid combustion mode used to have a graduate combustion mode transition within two to three engine cycles.
- With the multiple cylinder engine configuration, individual cylinder cooled EGR rate, intake air (throttle), intake and exhaust valve timings can not be controlled independently.
  - ⇨ individual cylinder fueling and spark timing are used for individual cylinder control during hybrid combustion
  - ⇨ Iterative learning is used to optimize the transient individual cylinder control. This also makes the control robust to engine aging.
- Among the proposed mode transition control strategies, the multi-step (cycle) mode transition using hybrid combustion with iterative learning control provides the best performance.

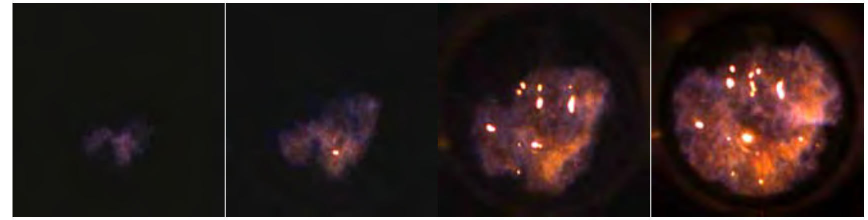
Technical Accomplishments:

d) Optical engine experiment (Optical engine SI combustion tests)

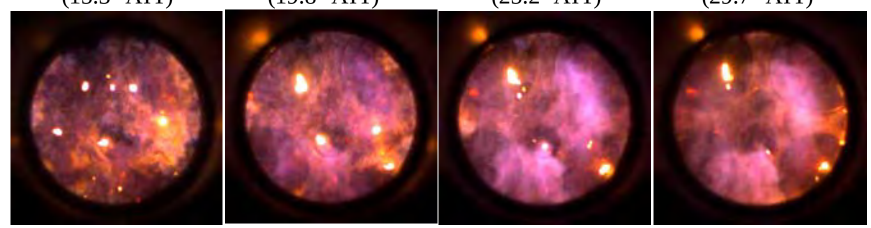
- Conducted optical engine SI combustion tests and the HCCI combustion is underway.







-19.7° ATDC (15.3° AIT) | -15.2° ATDC (19.8° AIT) | -9.8° ATDC (25.2° AIT) | -5.3° ATDC (29.7° AIT)



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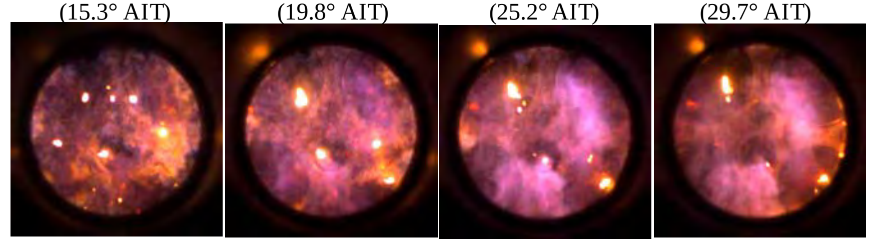
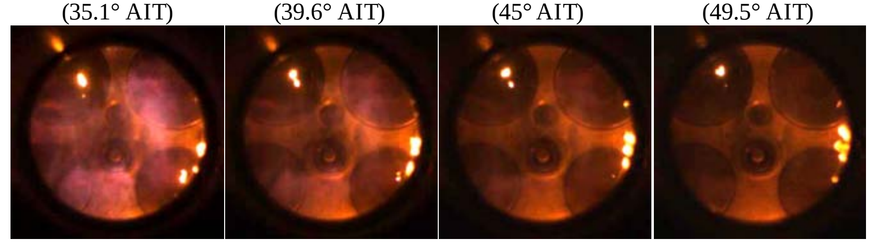


0.1° ATDC (35.1° AIT) | 4.6° ATDC (39.6° AIT) | 10° ATDC (45° AIT) | 14.5° ATDC (49.5° AIT)



19.9° ATDC (54.9° AIT) | 25.3° ATDC (60.3° AIT) | 29.8° ATDC (64.8° AIT) | 35.2° ATDC (70.2° AIT)

Collaborations

Industrial Partner (Chrysler Group LLC)

- Support over the past FY
  - Provide target engine hardware (one prototype engine and one engine head assembly).
  - Provide the GT-Power engine model for validating the developed control oriented engine model and optimizing valve lift and timings.
  - Design engineering services to integrate the two step lift valve and electrical cam phasing systems onto the target engine head.
  - Engineering review and support.
- Future support
  - Engineering support for modification of the target HCCI engine.
  - Review of developed control oriented model and mode transition control strategies.
  - Provide engineering requirements for the HCCI capable SI engine.

Collaborations (cont'd)

Technology Transfer

- A production viable control system for an HCCI capable SI engine
  - The control strategy for smooth combustion mode transition between SI and HCCI combustions using the hybrid combustion mode with iterative learning 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

- Feasibility study results of the ignition system with ionization combustion feedback vs. in-cylinder pressure sensing for
  - Start of combustion and combustion duration
  - Ethanol concentration

Future Work (Next Fiscal Year)

- Complete the integration of the two-step valve and electrical cam phasing system onto the target engine heads (one for single cylinder optical engine and one for the four cylinder metal engine)
- Complete the integration of prototype engine combustion control system (both hardware and control strategy) and validate it in the HIL simulations
- Complete the experimental validation of the proposed mode transition control strategy in single cylinder environment

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).

Technical Accomplishments:

- Developed a control oriented (real-time) hybrid combustion engine model and validated it using the results from GT-Power simulations. The developed model was implemented into the MSU HIL simulation system.
- Completed design of the HCCI capable SI engine head with two-step valve and electrical cam phasing systems. Fabrication is underway.
- Optical engine fabrication is completed.
- Injection droplet size spray tests completed and showed small droplet size deviation between gasoline and E85.
- Completed engine prototype control design and fabrication is underway
- HIL based combustion mode transition control was studied and it is concluded that the smooth mode transition can be achieved using multi-step (cycle) combustion mode transition with the help of hybrid combustion and iterative learning.