2012 DOE Vehicle Technologies Program Review

Advanced Combustion Concepts - Enabling Systems and Solutions (ACCESS) for High Efficiency Light Duty Vehicles

Arlington, Virginia
May 18th, 2012

Hakan Yilmaz
Global Technology Management
Gasoline Systems, Robert Bosch LLC

Contract: DE-EE0003533
Project ID: ACE066

"This presentation does not include any confidential material"

- **Project Overview**
- **Relevance**
- **Approach**
- **Collaboration and Coordination**
- **Accomplishments and Future Work**
- **Summary**

Budget

$24,556,737 – Total Project Budget
- $11,953,784 – DOE Funding
- $12,602,954 – Partner Funding

$9,987,412 – Phase I
- $4,764,644 DOE Budget
- ~ $4,586,000 invoiced to DOE

$7,441,808 – Phase II
$7,127,518 – Phase III

Barriers

Barriers
- Fuel efficiency as key market driver
- Stringent emission requirements
- System cost of advanced combustion

Targets
- >25% fuel efficiency improvement
- SULEV emissions capability
- Commercially viable system solution

Timeline

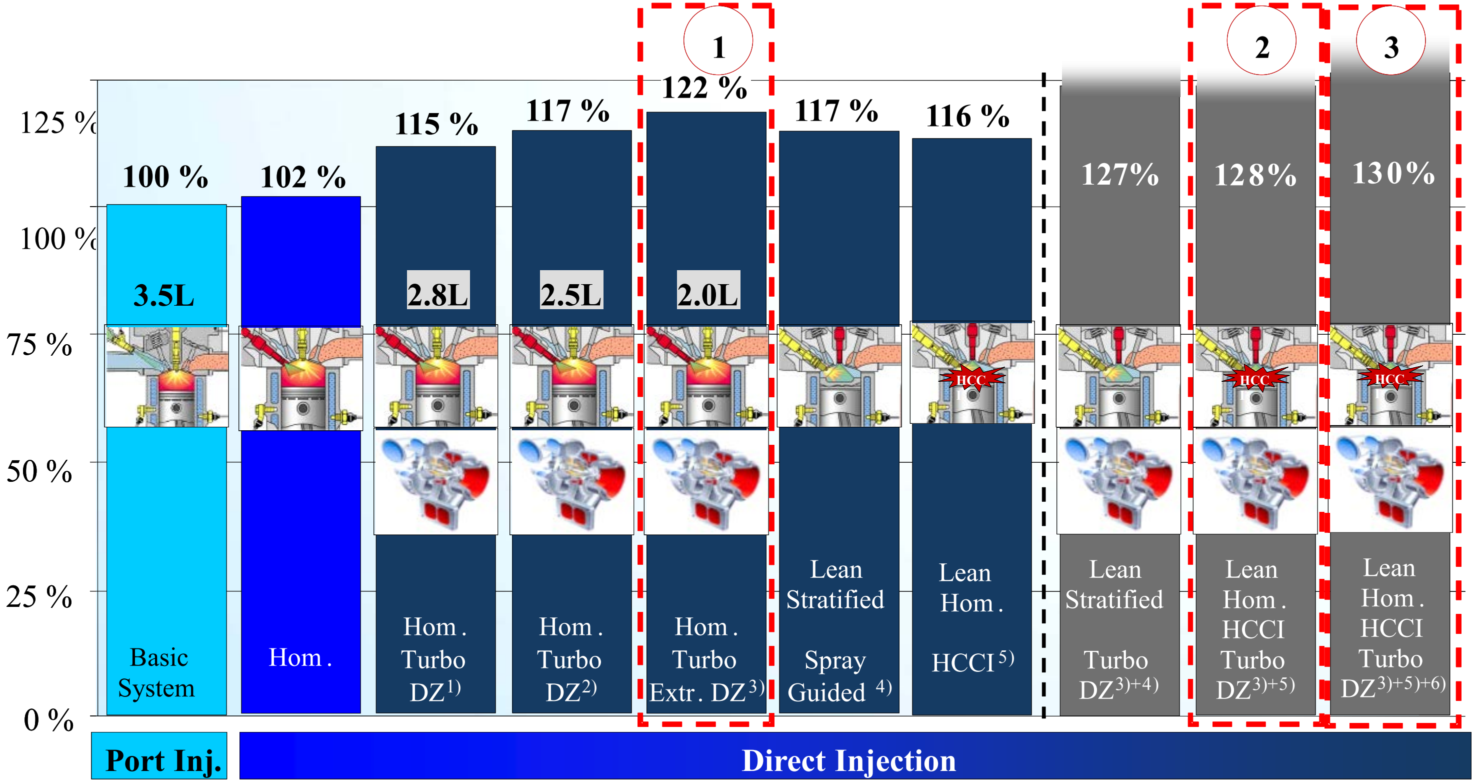
Phase 1 (1.5 yrs) Concept	Phase 2 Development	Phase 3 (1.5 yrs) Application
Fundamental Research	Technology Development	Implementation and Vehicle Demo
9/30/2010-02/28/2012	03/01/2012-02/28/2013	03/01/2013 – 09/29/2014

Partners

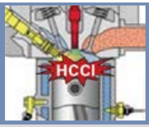
- US Department of Energy
- Robert Bosch LLC
- AVL
- University of Michigan, Ann Arbor
- Stanford University
- Emitec

- Project Overview
- **Relevance**
- Approach
- Collaboration and Coordination
- Accomplishments and Future Work
- Summary

Combustion Concept – Boosted Lean HCCI + Engine Downsizing



1) w/ 2xVVT in/out, 20% Downsizing
2) w/ 2xVVT in/out, 30% Downsizing
3) w/ VVT in/VVL out, 40% Downsizing
4) w/ 2xVVT
5) w/ 2xVVT, 2x 2-step VVL, ext. EGR, PDI
6) Dual Fuel System, Start-Stop



→Homogenous pre-mixture of air, fuel & residuals
→Controlled auto-ignition and flameless combustion

Overall Project Objectives

- Baseline Powertrain: 3.6L V6, PFI, 6 Speed
- Target Powertrain: 2.0L I4, DI, Turbo, 6 Speed –Multi Mode Combustion SI/HCCI
- >25% Fuel Economy Improvement Compared to Baseline
- SULEV Emissions Capability
- By mid 2014 commercially viable, production feasible, system solution

Phase 2 Targets for Phase 3 Go/No Go Decision

- Modeling, simulation, or test results of selected technologies indicate technical feasibility of achieving project goals.
- The cost benefit analysis shows that the project is on a specific path to deliver a commercially viable engine and vehicle system.

Annual Objectives – March 2012 to March 2013

- Finalize control strategy architecture for a multi-mode combustion engine
- Integration of proposed air path and HCCI combustion control strategies into ECU software
- Prototype level 2 updates and proof of combustion concept for vehicle readiness
- Implementation of rCFD LES Combustion model

- Project Overview
- Relevance
- **Approach**
- Collaboration and Coordination
- Accomplishments and Future Work
- Summary

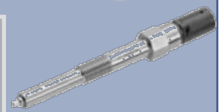
ACCESS Multi Mode Combustion System Configuration

Customized Engine Management (ECU)

- Novel combustion algorithms
- Model based control

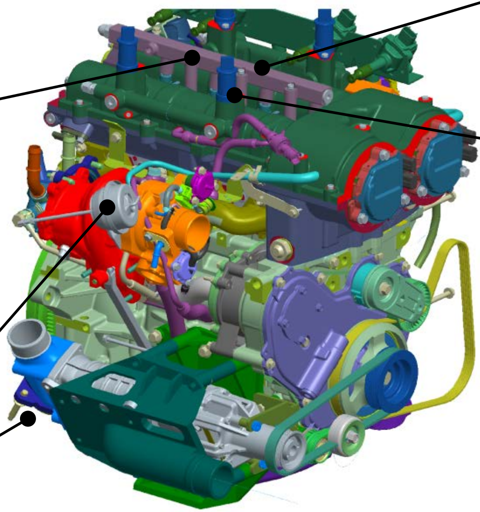
In-Cylinder Pressure Sensing

- Direct combustion feedback
- Closed loop control

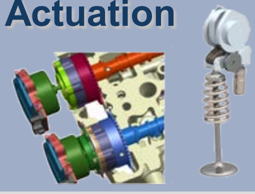


DI + PFI Injection

- Solenoid Multi-Hole DI
- Central mount
- Split injection small pulse
- Laser drilled holes
- Simultaneous DI+PFI inj.



Variable Valve Actuation



- 2x Var. phasing (CamPhasers)
- 2x Var. lift (TwinLift or cont. var.)
- Fast and accurate actuation

Boosting Device

- 2-stage TCSC system
- HCCI map extension

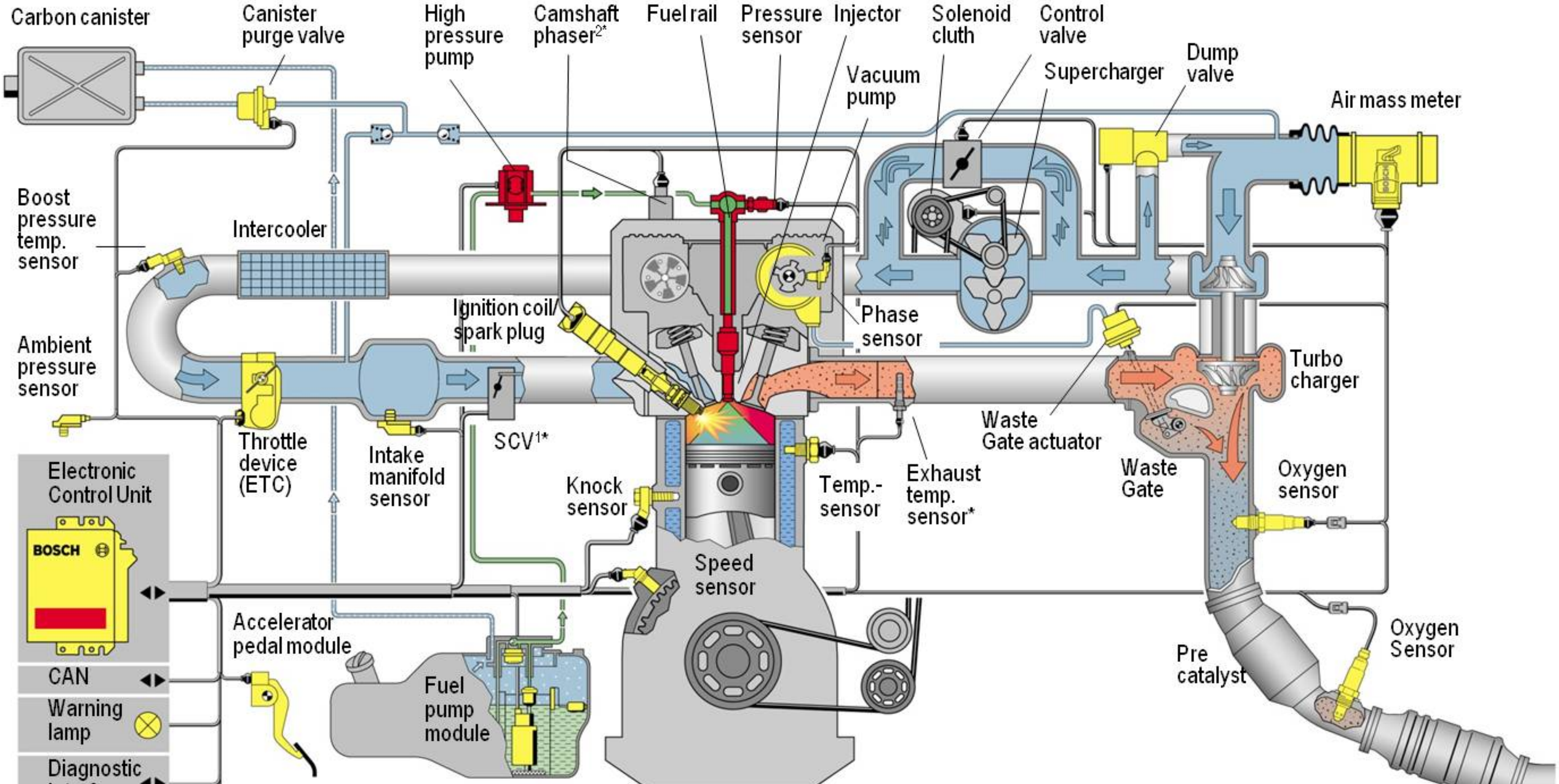
External EGR System

- EGR control
- EGR cooling
- Map extension

Advanced Aftertreatment

- Three-way catalyst
- Optimized for multi-mode combustion

Multi Mode Combustion System Configuration – Prototype 1 Architecture



ETC = Electronic Throttle Control
[1] Swirl or tumble control valve (on/off or continuous)
[2] Camshaft phaser: intake side (exhaust phasing optional)

* optional
Bosch components
Bosch components specifically for DI

- Project Overview
- Relevance
- Approach
- Collaboration and Coordination
- Accomplishments and Future Work
- Summary

ACCESS Project Organization

US Department of Energy
- Project / Contract Management
- Technical Merit / Milestone Reviews

Steering Committee
- Project Scope Definition
- Technical Merit / Milestone Reviews

Robert Bosch LLC - Sub
Research and Technology Center (RTC)
- *HCCI and Bio Fuels Thermodynamics*
- *Combustion Modeling and Simulations*
- *HCCI Engine Controls*

Robert Bosch LLC - Prime
Gasoline Systems (GS)
- *Project Lead*
- *Engine Management System Concept*
- *Engine Controls & Application*

AVL - Sub
Powertrain Engineering
- *Engine & Vehicle Simulations*
- *HCCI Combustion System Research*
- *HCCI Engine Design and Development*

Stanford University - Sub
- *HCCI and Bio Fuels Thermodynamics*
- *Combustion Modeling and Simulations*
- *Single Cylinder Engine Operation*

University of Michigan - Sub
Advanced Powertrain Controls Laboratory
- *Control Oriented Models*
- *HCCI / SIDI Engine Controls*
- *Engine Sub-System Controls*

Emitec - Sub
- After-Treatment System and Simulation
- 3-Way Catalyst Development
- Lean NOx After-Treatment Development

Chevron Energy Technology Company
External Support
- Fuel Property Consultation
- Fuel Samples for Combustion Testing

University of Michigan - Sub
Walter E. Lay Automotive Laboratory
- *Physics Based Combustion Modeling*
- *Combustion Development & Testing*
- *Single / Multi Cylinder Engine Research*

US OEM's
- Information Exchange
- Technology Alignment

ACCESS Project Organization

Robert Bosch LLC
Research and Technology Center (RTC)

David Cook – **Co- PI - CFD Simulations**
Joel Oudart – **Advanced Combustion/Biofuels**
Nalin Chatuverdi – Modeling and Controls
Aleksander Kojic – Controls
Nikhil Ravi – Controls
Eric Doran – CFD Simulations
Arjun Sharma – CFD Simulations

Robert Bosch LLC
Gasoline Systems (GS)

Hakan Yilmaz – **PI**
Li Jiang – **Co -PI** – Engine Controls
Oliver Miersch-Wlemers – **Co-PI** – System
Angela Dragan – Project Management
Jeff Sterniak – Combustion Concept
Julien Vanier – System Integration
Alan Mond – System Concept

AVL
Powertrain Engineering

Dusan Polovina – **Co -PI** – Combustion
Roger Faber – Project Management
Vasile Frasinel – Design
Kevin Roth – Calibration
Chris Erhardt – Engine Assembly & Dyno

Stanford University

Heinz Pitsch – **Co -PI** –CFD Simulations
Mittal Varun – CFD Simulations
Chris Edwards – Thermodynamics
Julie Blumreiter – Thermodynamics
Ben Kessel – Thermodynamics

University of Michigan, Ann Arbor
Advanced Powertrain Controls Laboratory

Anna Stefanopoulou – **Co – PI – Engine Controls**
Eric Hellström – Research Fellow – Engine Controls
Yi Chen – Air Path Modelling / Controls
Patrick Gorzelic – Combustion Mode Switching
Shyam Jade – Combustion Modelling / Controls
Jacob Larimore – Combustion Mode Switching

Emitec

Ulrich Pfahl – **Co -PI** – After -Treatment
Jan Kramer – **Co -PI** – After -Treatment
Markus Downey – System Application

Chevron Energy Technology Company (ETC)

– Technical Consultation
– Advisory and Information Exchange

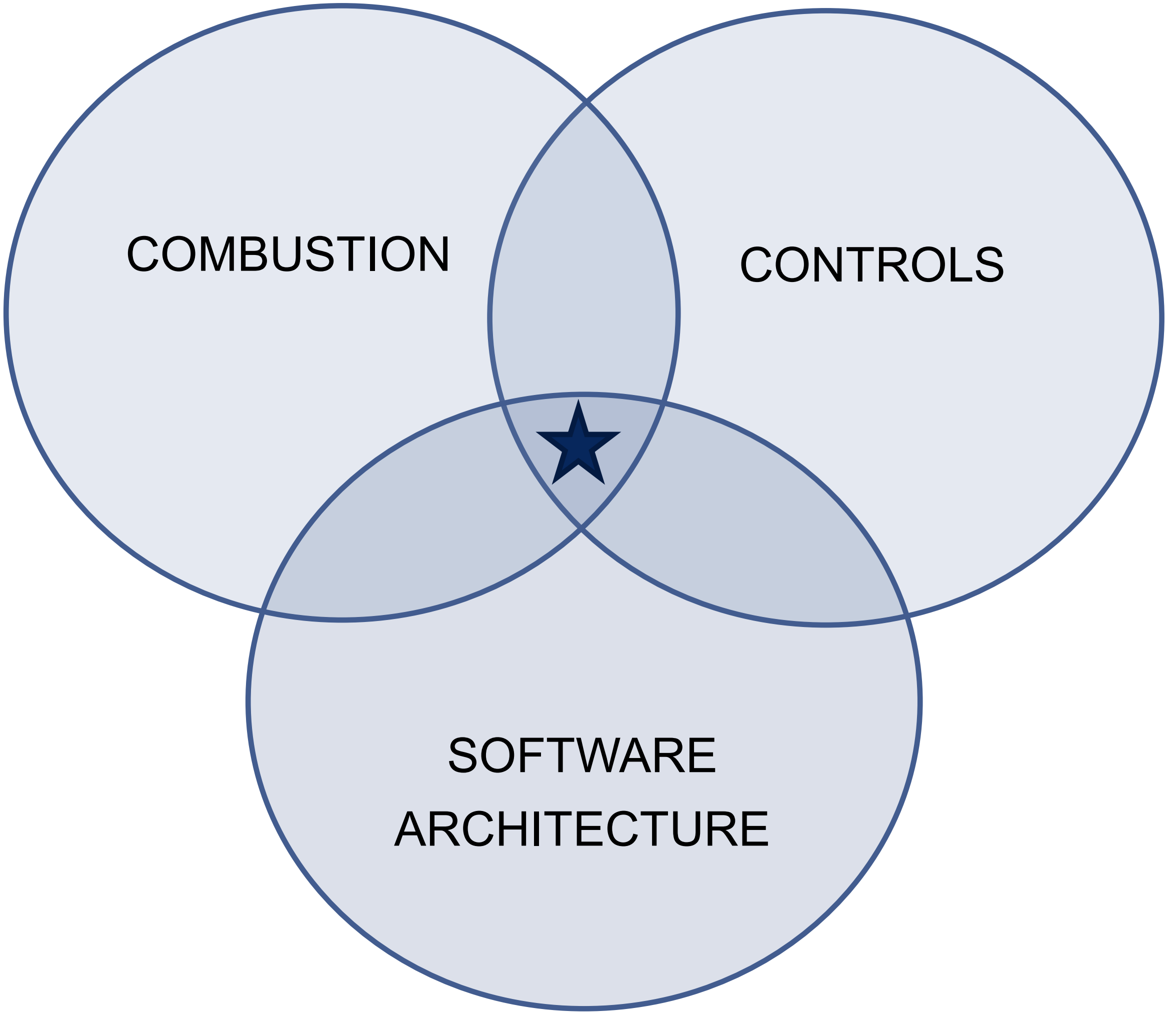
University of Michigan, Ann Arbor
Walter E. Lay Automotive Laboratory

Stani Bohac – **Co -PI** – Combustion
Jason Martz – Combustion Simulation
Vasileios Triantopoulos – Experimental Research
Janardhan Kodavasal – Chemical Kinetics Modelling
Prasad Shingne – 1D Engine Simulation
Adam Vaughan – Experimental Research
Vijai Manikandan – Multi-Mode Operation Optimization

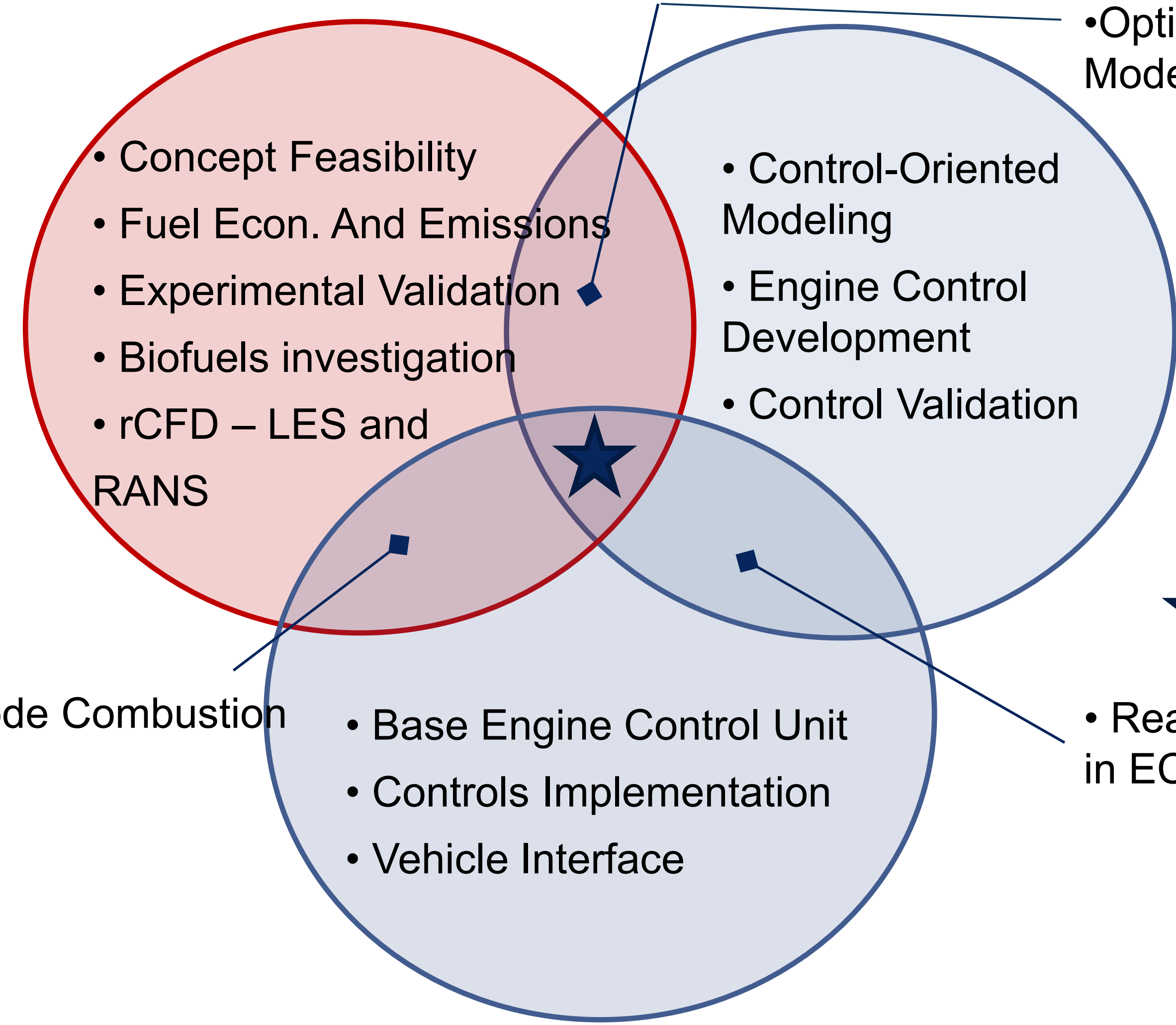
US OEMs

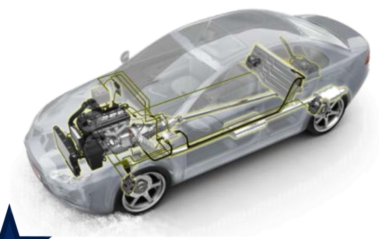
– Information Exchange
– Technology Alignment

- Project Overview
- Relevance
- Approach
- Collaboration and Coordination
- **Accomplishments and Future Work**
- Summary


COMBUSTION
CONTROLS
SOFTWARE ARCHITECTURE

•Optimal Combustion Mode Switch Strategies





★ Demo Vehicle

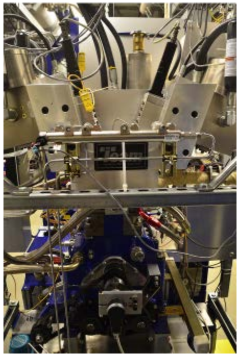
• Multi-Mode Combustion ECU

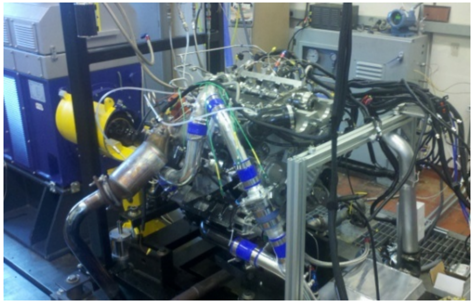
• Real-time Controls in ECU

BOSCH

Engine Test Cells at University Partners

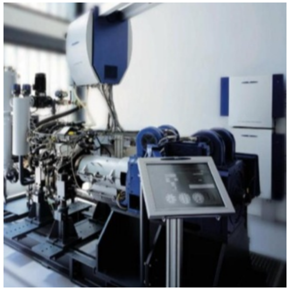
- Single-cylinder research engine lab with Fully Flexible Valve Actuation (FFVA) at Stanford operational
- Two multi-cylinder engine dynamometers (one steady-state, one fully transient) operational at University of Michigan Automotive Research Laboratory
- Prototype 1 engine operational at University of Michigan since 03/2012
- Resident Bosch engineers at Stanford University and University of Michigan

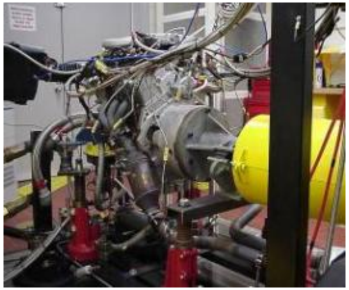

Stanford University


Transient Dyno Cell
University of Michigan

Engine Test Cells at Industry Partners

- HCCI combustion development and parameterization with Prototype 1 engine at AVL test cell since 10/2011
- SI calibration with Prototype 2 engine at Bosch test cell scheduled 07/2012
- All experimental set-ups have same Engine HW and Engine Management System

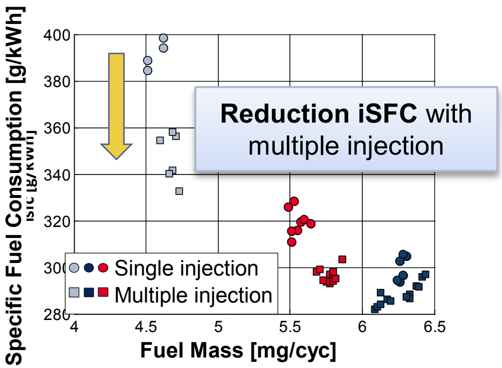

AVL test cell


Bosch test cell

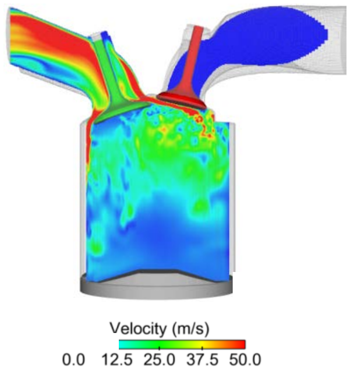
Industry support enables university researchers to focus on innovation

Fundamental Combustion & Fuels

Strategies for low load at 1500rpm



LES of HCCI Gas Exchange



Approach

- Single cylinder research engine (SCRE) with Fully Flexible Variable Valve actuators (Stanford University)
- Investigation of injection strategies for robust HCCI under low load condition
- rCFD RANS to investigate extreme high and low load HCCI
- Development of rCFD LES method for engine simulation in SI and HCCI modes

Results

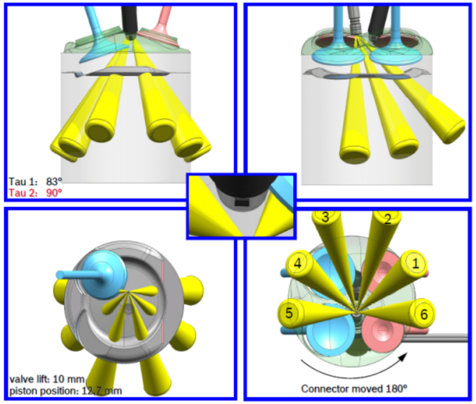
- Engine test bench operational with DI + PFI Injection, Fully Flexible VVA, Boost (<3000rpm)
- Key fuel injection strategy for low load HCCI identified
- rCFD RANS: HCCI Combustion model applied for baseline case
- rCFD LES: Gas exchange validated

Future Work

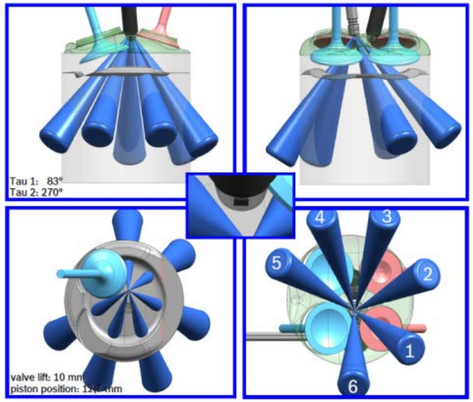
- Define optimized valve lift profiles for Prototype 2 engine
- Investigation of SI/HCCI mode switch
- HCCI investigation with biofuels
- Investigate low load HCCI operation with rCFD RANS
- Develop boosted HCCI operation strategies

2012 DOE Merit Review – ACCESS – Accomplishments

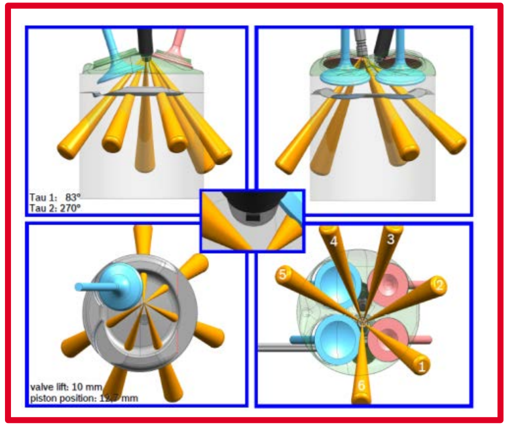
Spray Development for Direct Injection



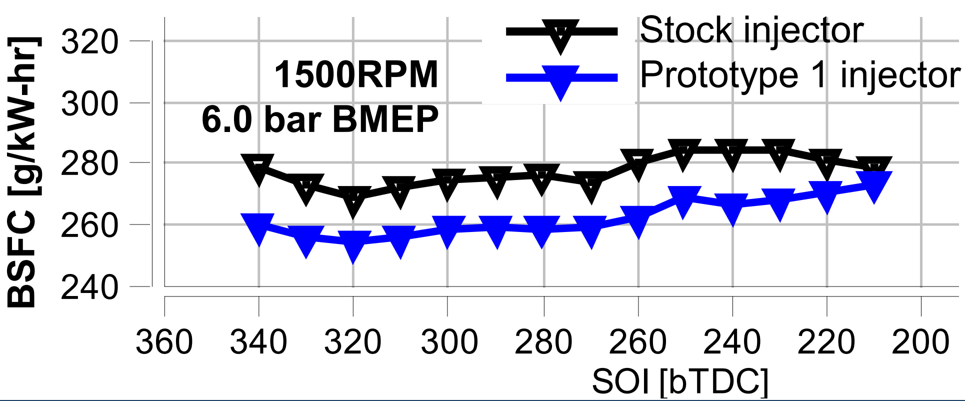
Stock Injector

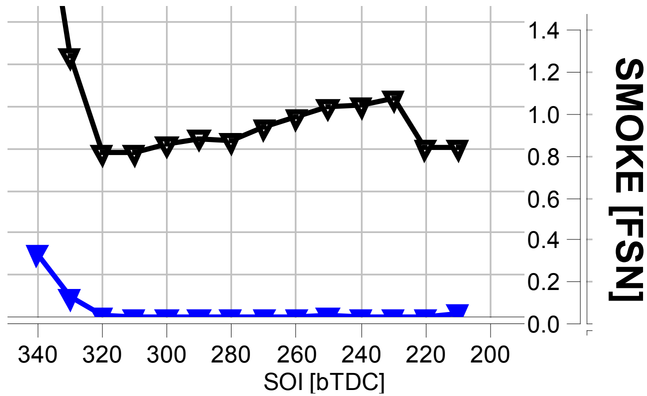


Prototype I Injector



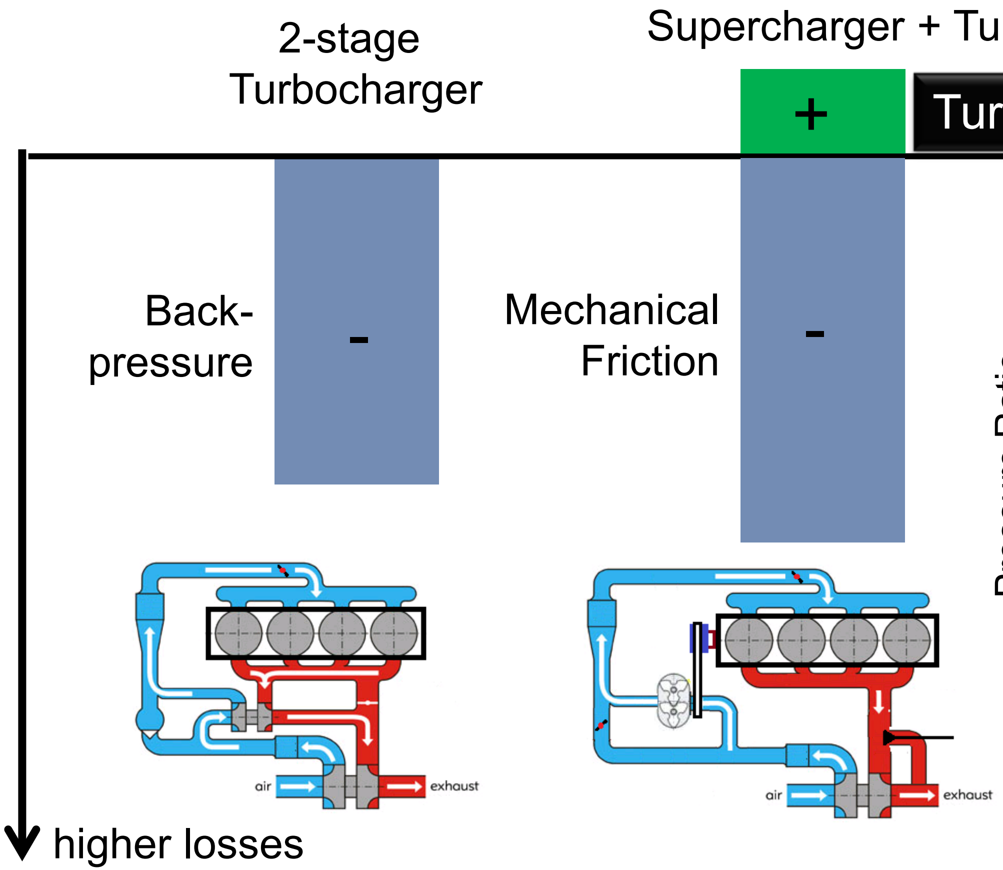
Prototype II Injector

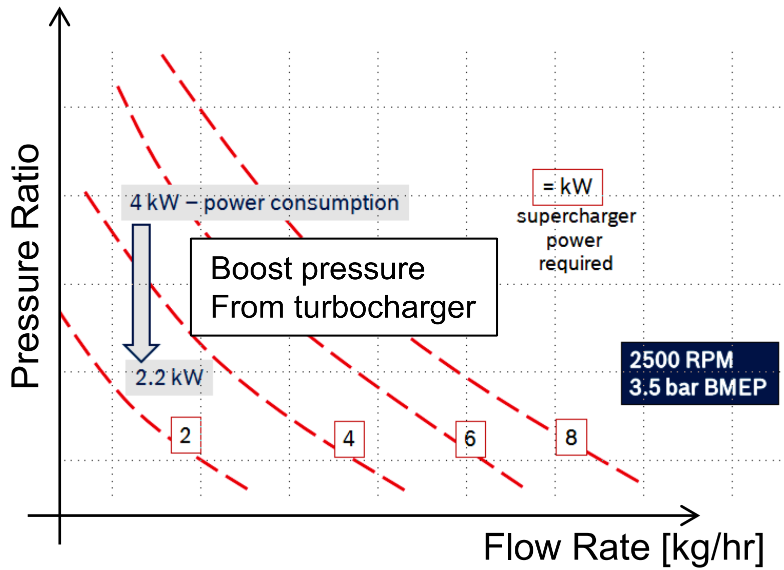




Better mixture preparation in SI mode shows 1-3% BSFC gains on Prototype 1 engine

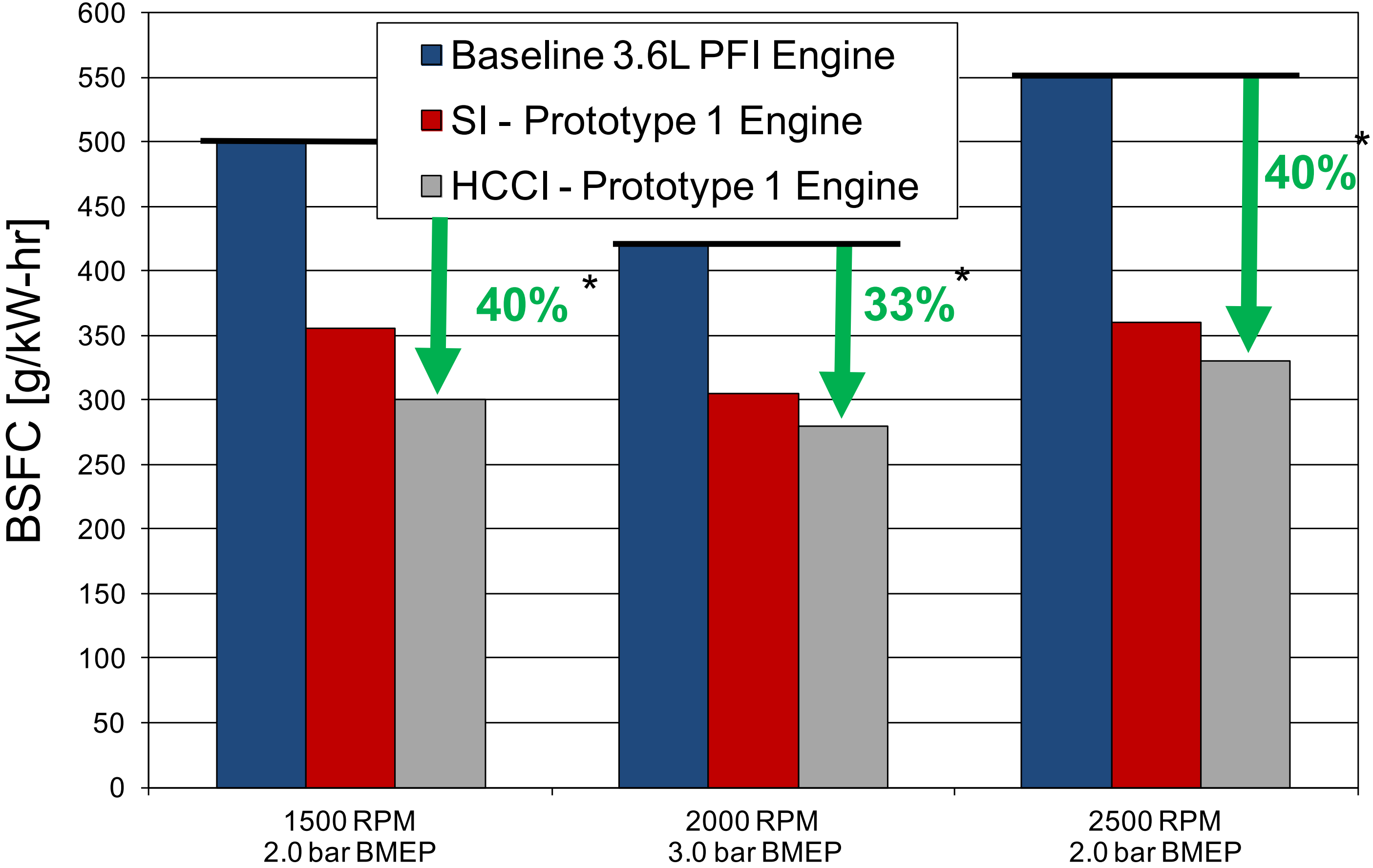
Boosting Strategy for Lean HCCI





Supercharged HCCI shows high potential when assisted by low-pressure turbocharger

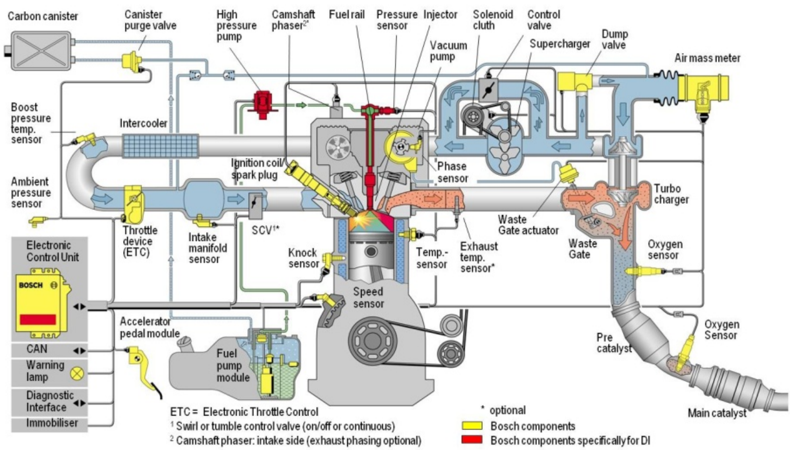
Experimental Fuel Economy Results from Prototype 1 Engine



* Optimized to 50ppm NOx; Further optimization of boosting system in progress to reduce to 10ppm NOx

Steady-state results show > 33% FE improvement with downsized HCCI over baseline

Overview – Combustion System



Approach

- Steady state and transient boosted HCCI operation used to achieve BSFC targets with optimized NOx emissions.
- High fidelity combustion model for fundamental multi-mode combustion.
- Simulation of FTP75 cycle on UofM transient dyno to develop boosted HCCI concepts.
- Demonstration vehicle to validate final results.

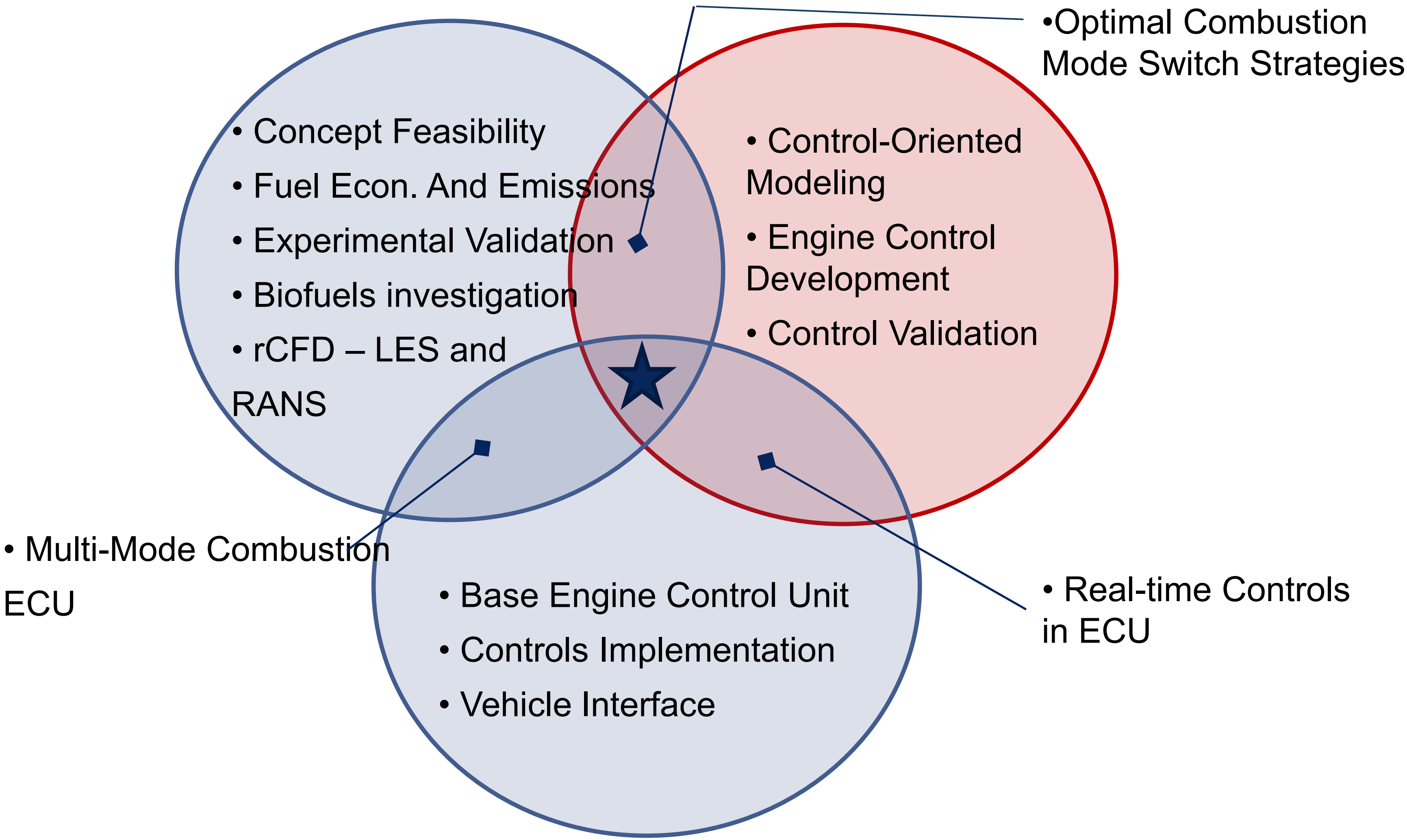
Major Accomplishments

- Prototype 1 engine built successfully and operational at AVL since 10/2011
- Transient dynamometer was commissioned at University of Michigan and operational
- Boosted HCCI comparison (SC vs TC) completed at University of Michigan
- CFD models validated for baseline operation

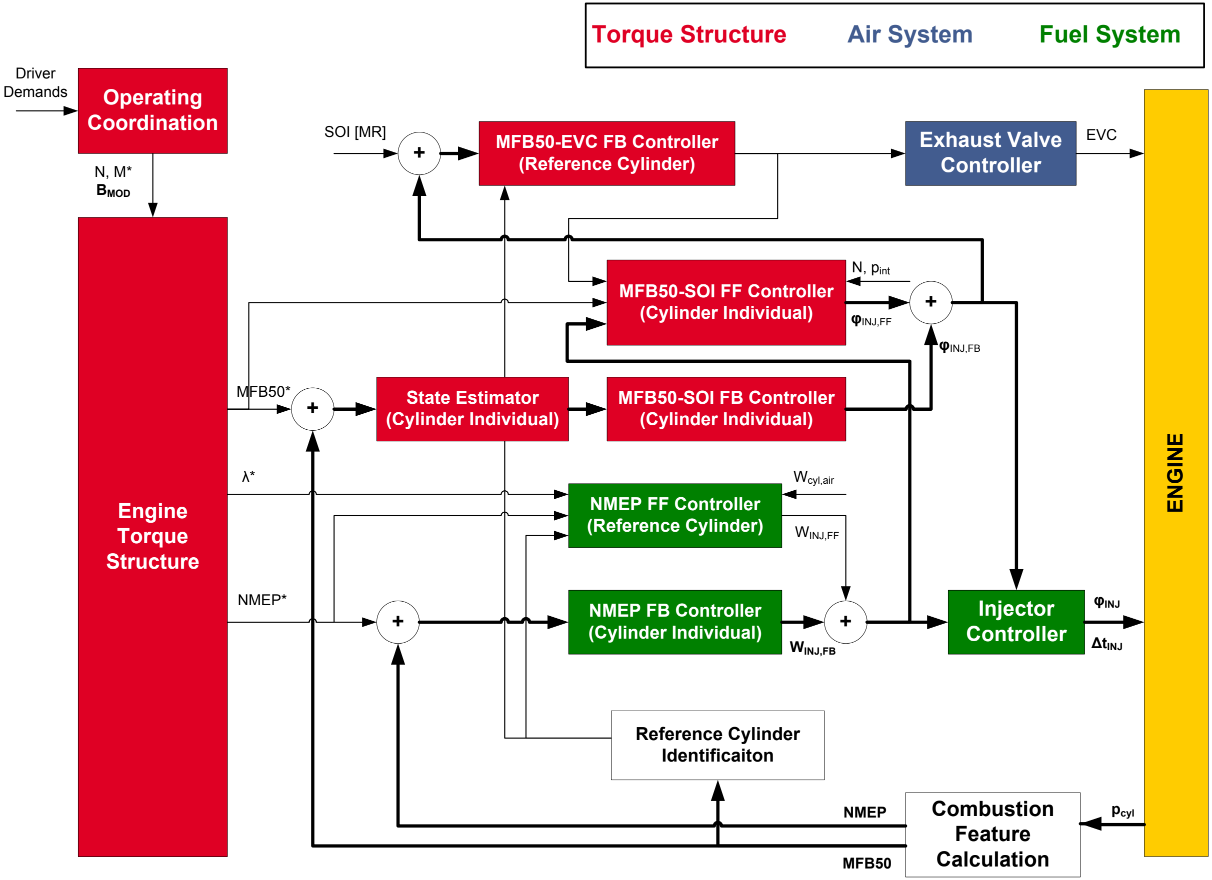
Future Work

- Experiment optimized TC-SC boosting system
- Combustion development and validation of Prototype 1 engine on transient dynamometer
- Parameterization of multi mode combustion
- Prototype level 2 updates and proof of combustion concept for vehicle readiness

2012 DOE Merit Review – ACCESS – Accomplishments



HCCI Control Architecture

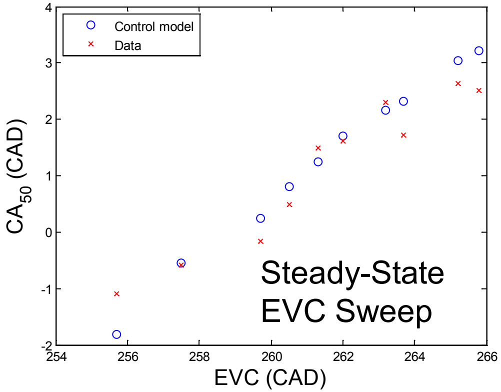


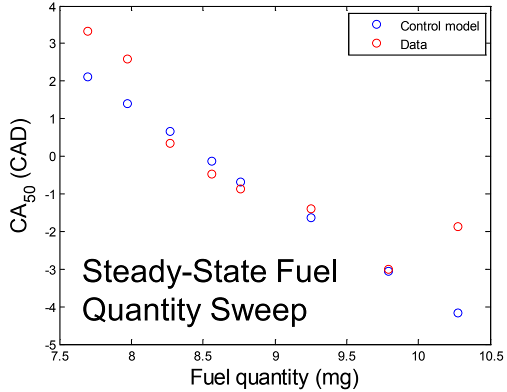
- Coordinate exhaust valve and injection timing with mid-ranging control strategy
- Cylinder-to-cylinder balancing with cylinder-individual fuel control with reference cylinder approach

Model-based control to enable fast and robust HCCI transitions

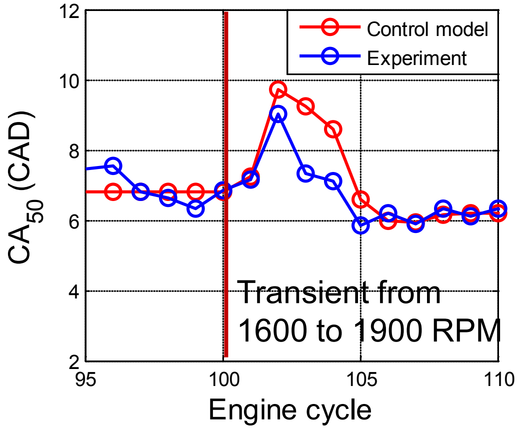
Control-Oriented Modeling of HCCI Combustion

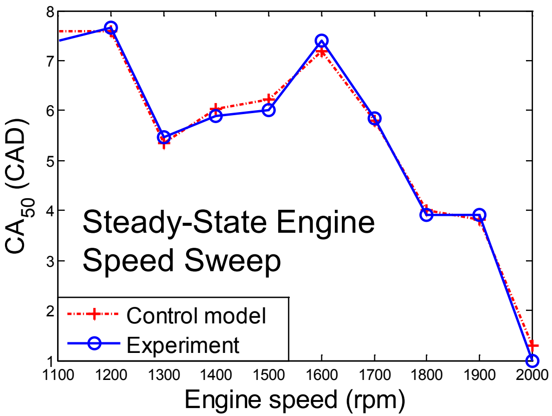
Multi-Cylinder Engine



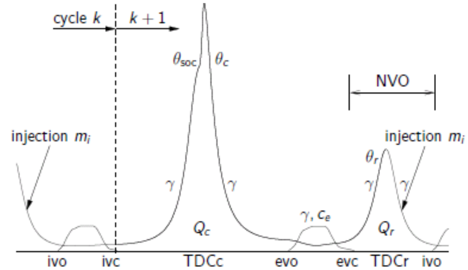


Single-Cylinder Engine





Model Structure



Main Combustion States (state): T, [O2], [fuel]

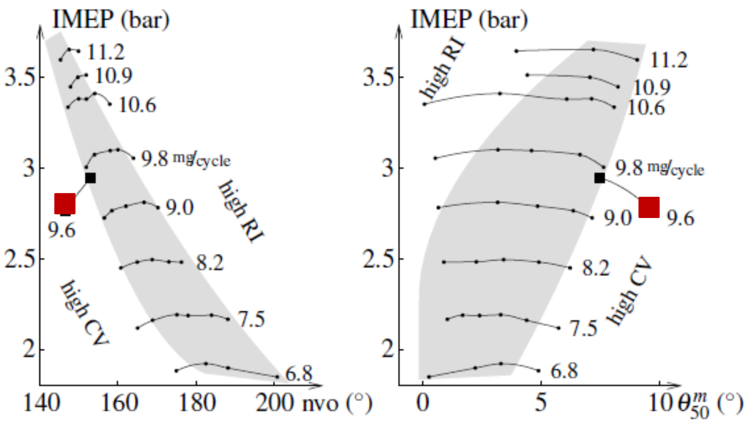
Main Actuator (inputs): EVC, SOI, m_{fuel}

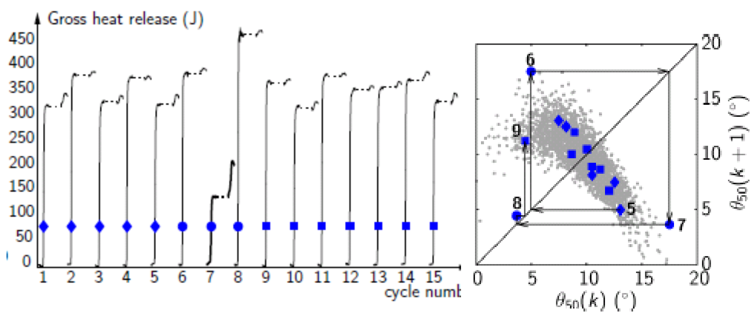
Target Performance Variable (output): CA50

Reduced-order model enables model-based control of HCCI combustion

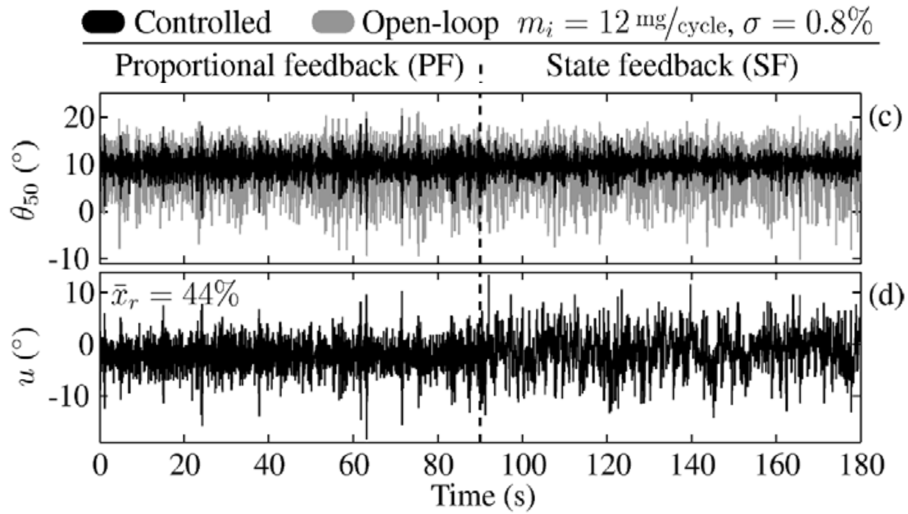
Modeling and Control for HCCI with High Cycle-to-Cycle Variation

Single-Cylinder Engine (UM) Observation





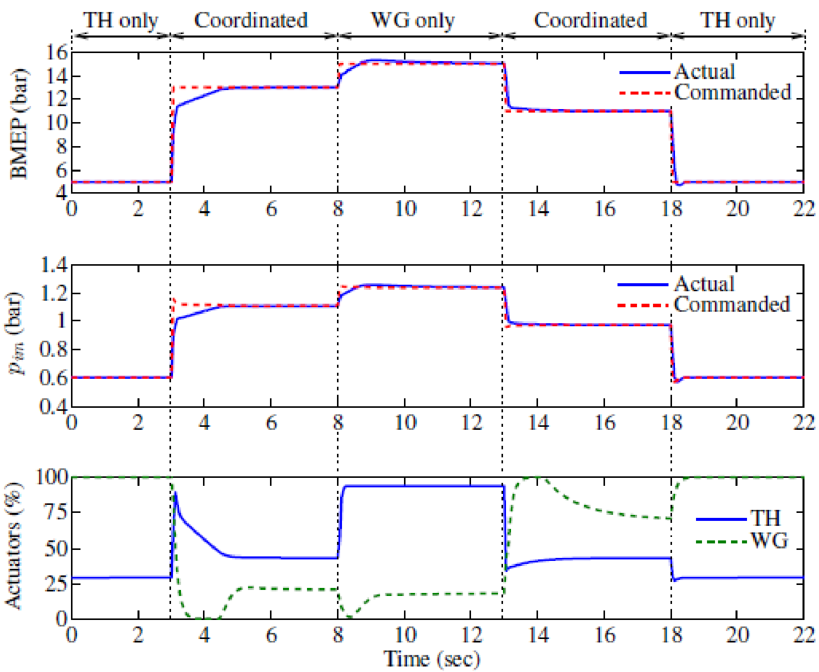
- High cycle-to-cycle variations were observed on both single and multi-cylinder engine at HCCI boundary operation conditions
- Simulation-based performance evaluation of controllers with injection timing as the key actuator



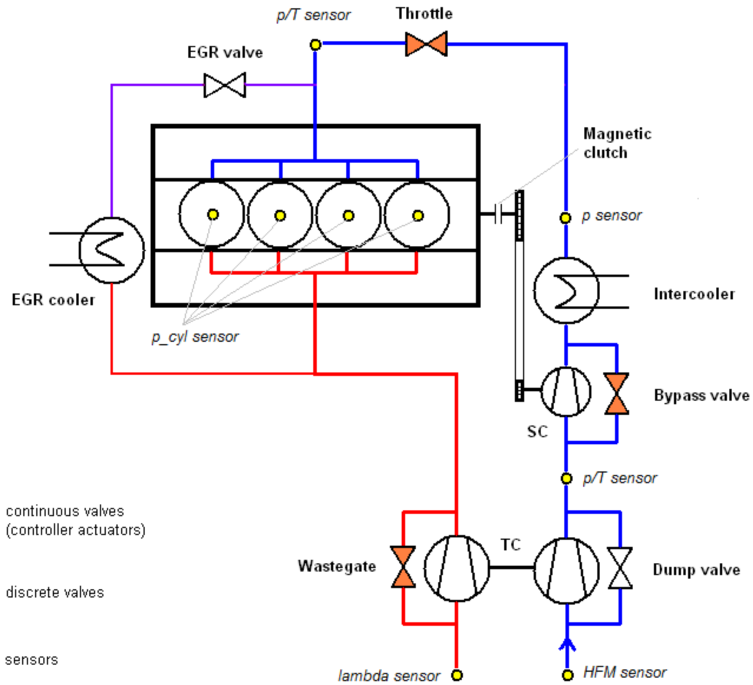
Robust control to enable stable HCCI combustion at boundary conditions

Boost Control with 2-stage TC-SC Air Path System

→ Simulation of model-based control of throttle and turbocharger wastegate

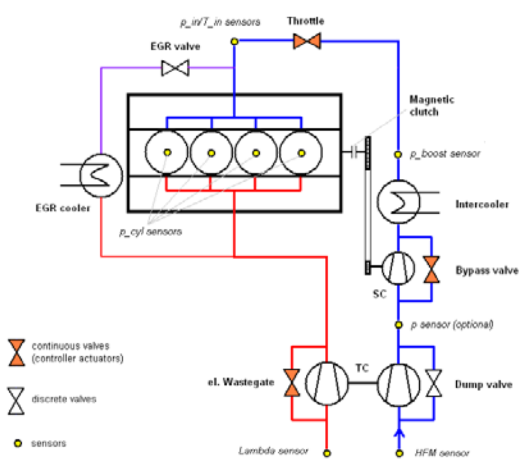


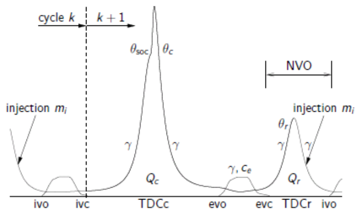
Engine Management System for target engine platform



Model-based boost control improves air charge transient response

Overview – Control System





States X: T, [O2], [fuel]
Inputs U: IVO, EVC, SOI, fuel, Sp
SC-Byp, WG, Thr, Egr,
CP-Int, CP-Exh, SC-C
Outputs Y: CA50, NMEP

Model $X_{k+1} = f(X_k, U_k); Y_k = g(X_k, U_k)$
Control $U_k = h(X_k, Y_{k,ss})$

Approach

- Simulation / Experiment based system dynamics and control sensitivity analysis
- Model-based combustion / air path control with cylinder pressure sensing feedback
- Engine-in-the-loop control algorithm validation via rapid prototyping techniques

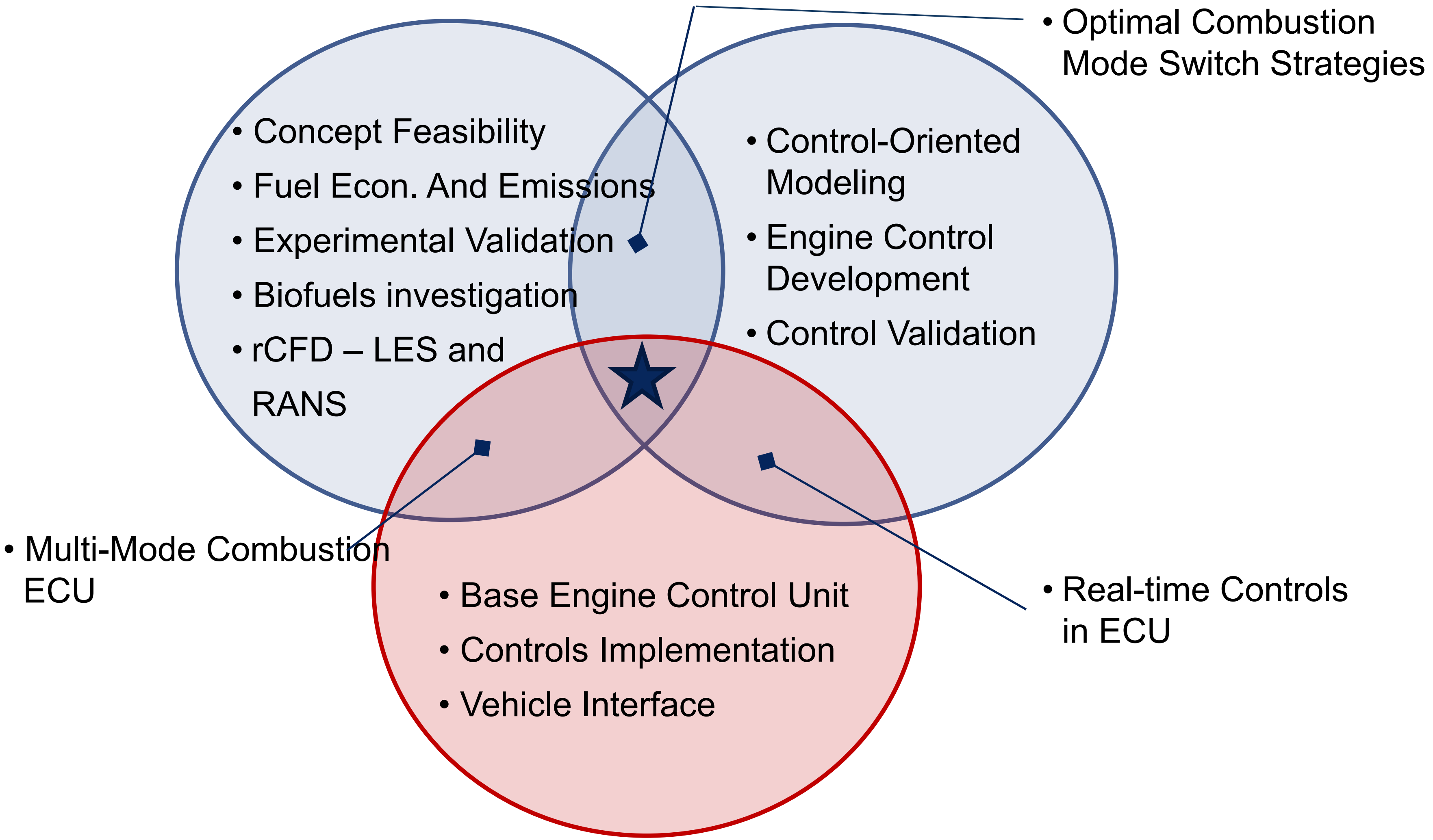
Accomplishments

- Control-Oriented HCCI combustion model validated for low/part load and light boost at varying speeds
- Control-oriented air path model and controls established for target engine configuration
- Actuator sensitivity analysis under HCCI combustion for Prototype 1 engine in progress

Future Work

- Establish controls for HCCI /SI combustion mode switch
- Finalize control strategy architecture for a multi-mode combustion engine
- Validate transient HCCI operation with Engine-in-the-loop vehicle simulation

2012 DOE Merit Review – ACCESS – Accomplishments



Motronic MED 17 Engine Control Unit (ECU) for Advanced Projects

- CPU: Infineon TriCore1797 microcontroller, 32 Bit, 180 MHz
- 6 HP injectors (HDEV5)
- 2 High pressure pump drivers (HDP5)
- 3 H-Bridges for electronic valves (DV-E)
- 18 low-side power stages
- 2 broad band O2 sensors (LSU4.9)
- 2 two-step O2 sensors (LSF4.2)
- 4 Variable camshaft controls (VVT)
- 6 Igniter drivers
- 4 CAN drivers
- 1 Hall-effect crankshaft sensor
- 4 Hall-effect camshaft sensors
- 6 Cylinder Pressure Sensors

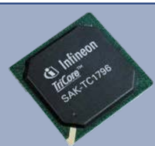
Bosch ECU enables advanced combustion controls

Bosch ECU Advanced Capabilities

Direct Injection

- Up to 4 injections per cycle
- Precise control of small quantities

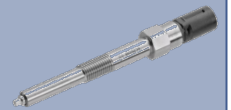
Tricore Micro-controller



- Computation power for model-based controls

In-Cylinder Pressure Sensing

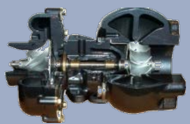
- Cycle-to-cycle closed-loop combustion control



Variable Valve Actuation

- Electric valve timing (VVT) for fast transients
- 2-step valve lift for HCCI mode switch

Supercharging & Turbocharging



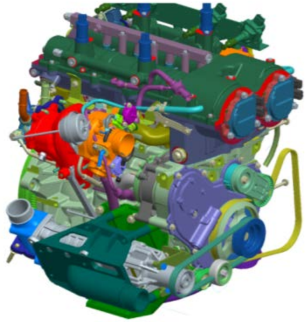
- Coordination of multiple boost devices

ETK Calibration Interface

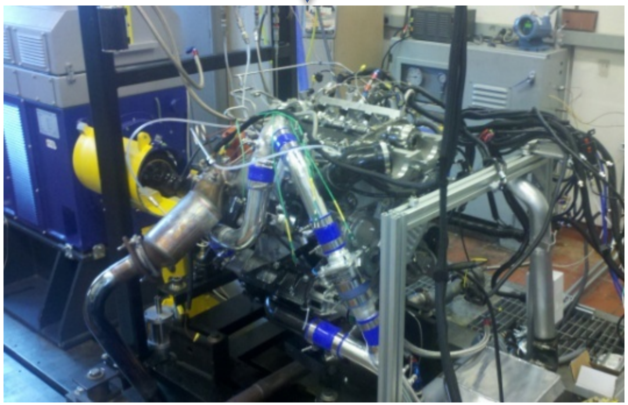
- Enables Rapid Prototyping

All engine component drivers and advanced controls running on single Bosch ECU

Controls Rapid Prototyping (RP) Setup at the University of Michigan Test Cell



Prototype Engine

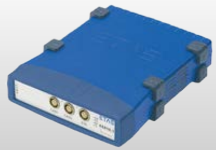


Transient Dynamometer

ECU

Calibration Software
INCA

RP Hardware
ES910



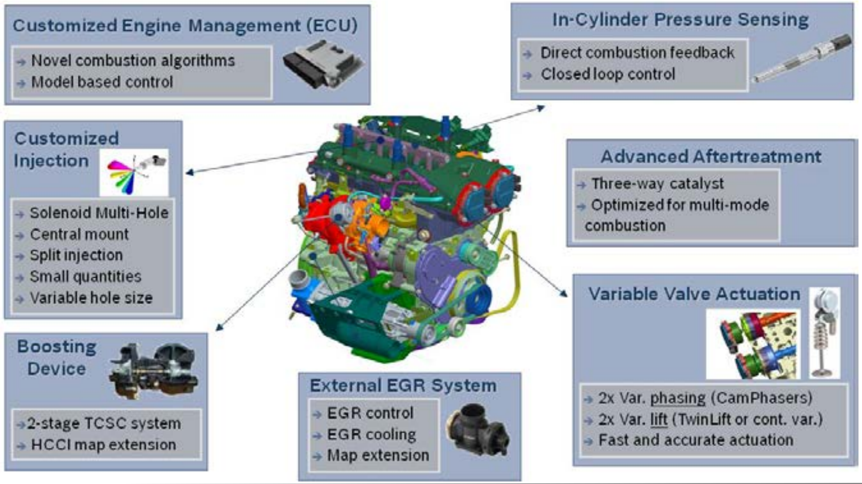
RP Software
INTECRIO

Models
- Simulink
- ASCET

Innovative ideas of researchers are quickly tested on the engine

2012 DOE Merit Review – ACCESS – Accomplishments

Overview - Software Architecture



Approach

- Bosch Motronic engine control platform to be used for Engine and Vehicle level development with all sub-system and system level functions
- Engine Control Unit with integrated algorithms for multi mode combustion for production feasible proof of concept
- Common ECU platform for all partners' research

Accomplishments

- Prototype Engine Control Unit (ECU) used by the project is built with additional drivers
- Integrated ECU software for Prototype 1 engine, including base HCCI control algorithms
- Rapid-Prototyping hardware operational on University of Michigan transient test cell
- Successful operation of prototype 1 engine with Bosch ECU

Future Work

- Integration of proposed air path and HCCI combustion control strategies into ECU software
- Evaluation of multi-mode combustion switch with engine-in-the-loop rapid prototyping
- Verification of engine management system for Prototype 2 engine architecture

- Project Overview
- Relevance
- Approach
- Collaboration and Coordination
- Accomplishments and Future Work
- **Summary**

Target

- >25% improved FE
- SULEV Capable
- Commercially Viable

Phase 1 (1.5 yrs) Concept	Phase 2 (1 yr) Development	Phase 3 (1.5 yrs) Application
Fundamental Research	Technology Development	Implementation and Vehicle Demo