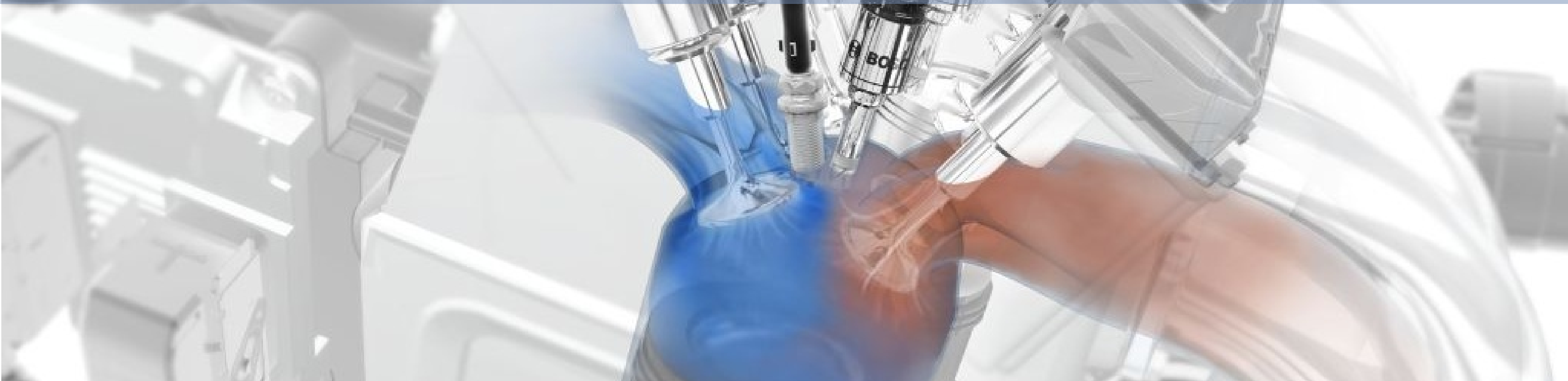
2013 DOE Vehicle Technologies Program Review

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

Arlington, Virginia
May 17th, 2013



Hakan Yilmaz(PI)
Oliver Miersch-Wiemers (Co-PI), Li Jiang (Co-PI)
Advanced Systems Engineering
Gasoline Systems, Robert Bosch LLC

Contract: DE-EE0003533
Project ID: ACE066

BOSCH

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

Budget

$24,556,737 – Total Project Budget
$11,953,786 – DOE Funding
$12,602,951 – Partner Funding

$17,429,220 – Combined P1 and P2 Budget
$8,444,733 DOE budget

$7,116,971 – Invoiced to DOE through 12/2012

$7,127,517 – Phase 3 Budget

Barriers and Targets

The project targets 25% fuel efficiency improvement to support energy independence and CO_2 reduction, while demonstrating SULEV emissions in a commercially viable system concept.

Barriers

- System complexity of advanced combustion
- Stringent emission requirements
- Fast adaptation of technology in the market

Timeline

Phase 1	Phase 2	Phase 3
Concept	Development	Application
Fundamental Research	Technology Development	Implementation and Vehicle Demo
9/30/2010-02/28/2012	03/01/2012-05/31/2013	06/01/2013 - 12/31/2014

Partners

US Department of Energy
Robert Bosch LLC
AVL
University of Michigan
Stanford University
Emitec

2013 DOE Annual Merit Review – ACCESS

Engine & Controls Development Phase II

- Target Multi Mode Combustion Engine is based on GM Ecotec 2.0 L DI Turbo platform
- All Base Engine HW design and improvements for target engine configuration lead by **AVL**
- All Engine Management System design and improvements for target system configuration lead by **Bosch**
- All Aftertreatment System design and improvements for emission concept lead by **Emitec**

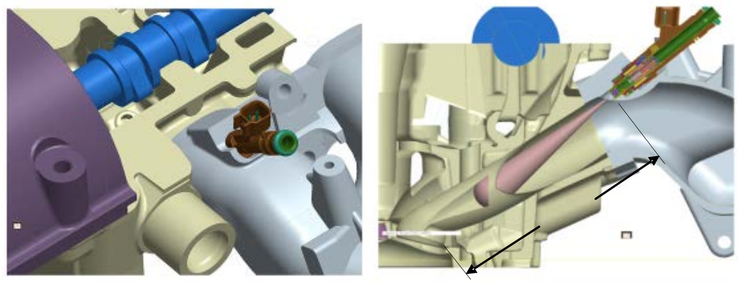
Start of Vehicle Implementation

Vehicle integration started.
First prototype engine installed and vehicle available for application, emission and fuel economy optimization.

Engine Hardware Prototype II

Cylinder Head Design for Central Mount Direct Injection and Variable Valve Actuation is completed
Prototype 2 engines are currently build.

Sub-System Implementation



Cam lift actuation, cooled EGR and dual injection system with high pressure DI + low pressure PFI.

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

Targets

- Demonstrate 25% fuel efficiency improvement over chosen vehicle baseline (GM HFV6 in Cadillac CTS)
- Meet SULEV emissions to demonstrate LEV3 emission capability
- Key systems and controls implemented and concept is commercially viable

System Complexity

Enabling Technology

- fuel direct injection
- downsizing with turbo charging
- variable valve timing and profile switch

- closed loop combustion control with in-cylinder pressure sensing
- adaptive fuel metering
- cooled high pressure EGR

- estimated total system cost within current market targets

commercially attractive

Technology to the Market

Products

- Engine Control Unit (ECU) with combustion controls.

  Fully implemented advanced combustion controls in a production level ECU meeting production A-sample requirements by mid of Phase 3. (no rapid prototyping tools required for OEM application)

- combustion pressure sensor

technology made available

Stringent Emissions

Demonstrating SULEV

- The advanced combustion concepts chosen show the potential to meet SULEV without expensive after treatment other than TWC.
- Exhaust after treatment system design (sizing and loading of the TWC) was performed based on experimental dyno data and simulation.
- Implementation and vehicle emission results will be demonstrated in Phase III.

meets 2025 emission goals

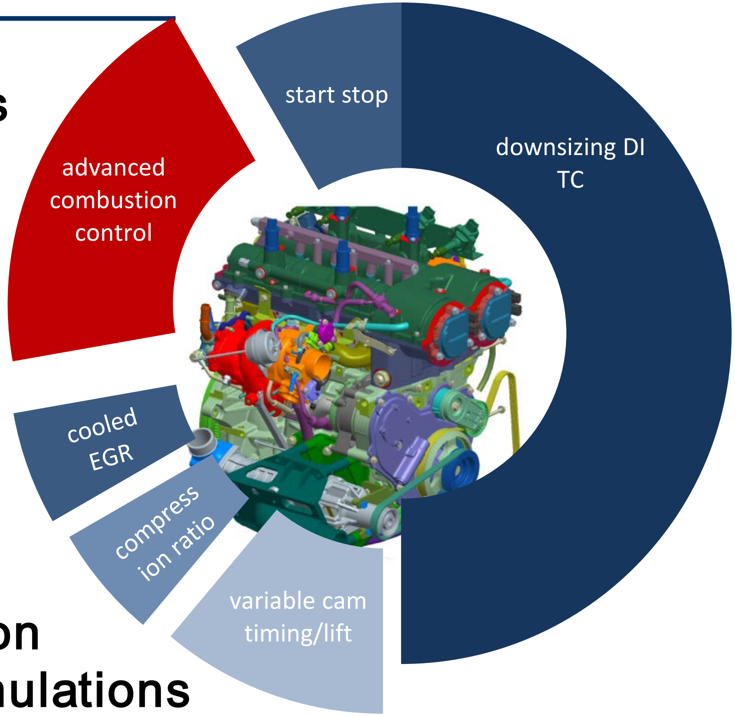
BOSCH

2013 DOE Annual Merit Review - ACCESS

Phase 1 (Research) → March 1st 2012 — Phase 2 (Development) — May 31st 2013 → Phase 3 (Integration)

Combustion development → Emission research → Controls development → Engine Build → Vehicle integration

Fuel Efficiency - Contributors



Relevant research and development areas to meet fuel economy and emission targets

- Advanced combustion control modeled and integrated for HCCI
- Control stability limit investigated (CFD)
- Actuator and sensor configuration set
- Characteristics of engine hardware determined and according engines build (compression ratio, cam profile, EGR loop)

Performance of the system demonstrated on transient engine dyno and validated by simulations

BOSCH

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

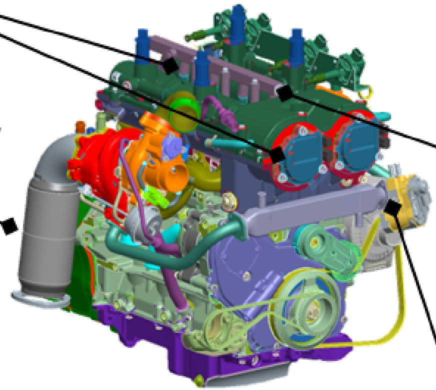
2013 DOE Annual Merit Review – ACCESS – Approach

Enabling Systems and Components

Emission Aftertreatment
- SULEV optimized three way catalyst
- Fast light off lambda control

Variable Valve Actuation
- Electric Cam Phasing
- 2-Step Cam Profile Switching

Engine Management System w/ Cylinder Pressure Sensing
- Cylinder Pressure Sensing Feedback
- Torque-Driven Multi-Mode Combustion Coordination



Dual Injection System
- Solenoid Multi-Hole Injector w/ Flexible Spray Design
- Central Mounted DI with High Precision Control for small quantity
- PFI for PM emission improvement

External EGR System
- Advanced Combustion Enabler
- Intake Manifold Oxygen Sensing

Go/No-Go Decision

Phase 1	Phase 2	Phase 3
Fundamental Research	Technology Development	Application & Vehicle Demo
2010.10	2012.03	2013.06 – 2014.12

- Simulation and experimental data engine demonstrating the feasibility of selected technologies to achieve project goals → Prototype II Engine
- Cost / Benefit analysis indicating the proposed approach is commercially viable

Baseline Powertrain:

3.6L V6, PFI, 6 Speed MT with SI Combustion

Target Powertrain:

2.0L I4, DI, Turbo, 6 Speed MT with Multi-Mode Advanced Combustion and Start-Stop System

BOSCH

2013 DOE Annual Merit Review – ACCESS – Approach

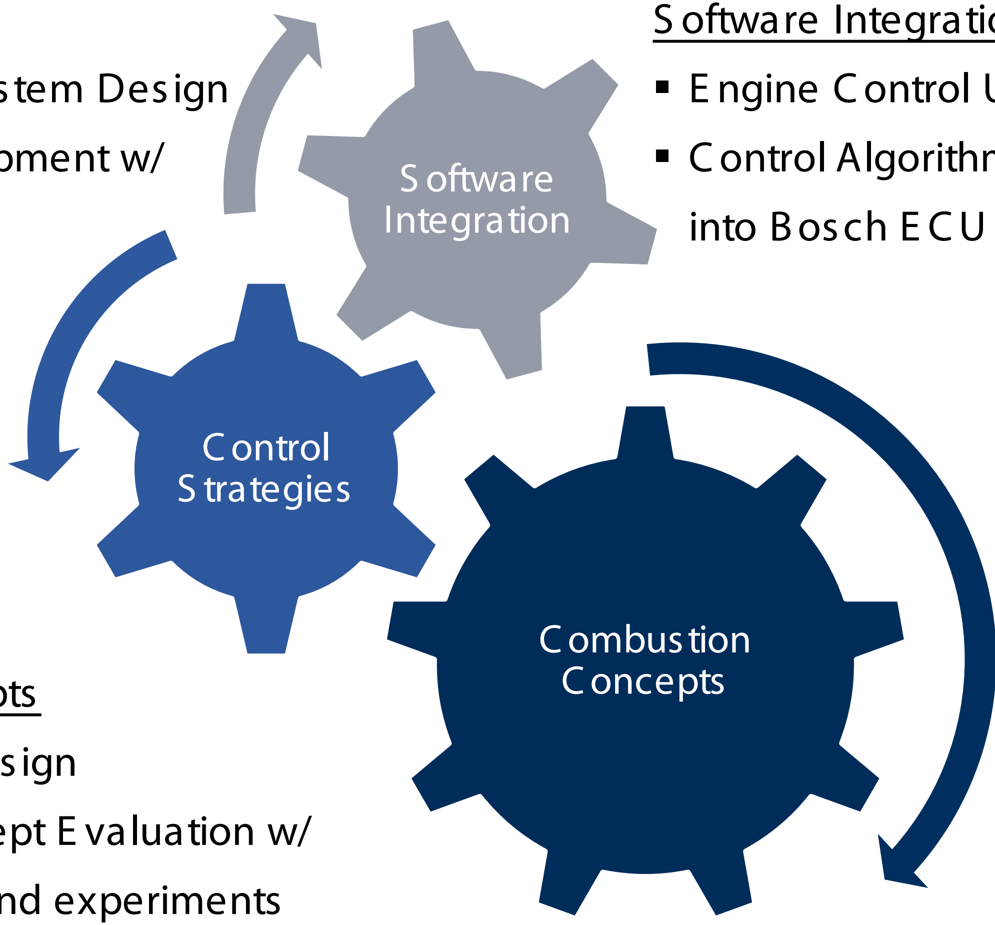
Multidisciplinary Team Approach

Control Strategies

- Engine Management System Design
- Control Strategy Development w/ rapid prototyping

Software Integration

- Engine Control Unit Design
- Control Algorithm Integration into Bosch ECU software



Combustion Concepts

- Engine System Design
- Combustion Concept Evaluation w/ CFD simulations and experiments

BOSCH

2013 DOE Annual Merit Review – ACCESS – Approach

Milestone

	Milestone	
Phase I	Complete simulations demonstrating the feasibility of proposed technologies	✓
	Evaluate fuel economy and emission performance of HCCI combustion with prototype I engine	✓
	Establish control architecture for HCCI combustion	✓
Phase II	Demonstrate fuel economy and emission performance with prototype II engine	✓
	Complete integration of controls for HCCI combustion into production-ready ECU	✓
	Complete vehicle integration enabling drive-cycle testing	✓
Phase III	Validate controls for advanced combustion on production-ready ECU	
	Evaluate fuel economy and emission performance with demonstration vehicle	

BOSCH

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

Organization Chart

US Department of Energy
Project / Contract Management

Steering Committee
Project Scope Definition

Robert Bosch Research and Technology Center
Combustion Modeling

Robert Bosch LLC Gasoline Systems
Project Lead
System Concepts

AVL North America Powertrain Engineering
Combustion Development
Engine Design

Stanford University
Combustion Modeling Research

University of Michigan
Engine Control & Combustion Research

Emitec
After-treatment System Development

2013 DOE Annual Merit Review – ACCESS – Collaboration & Coordination

Team Members

Robert Bosch Research and Technology Center

Dr. Dave Cook - **Co-PI, CFD Simulations**
Dr. Alexandar Kojic - Project Management
Joel Oudart - Advanced Combustion
Dr. Nalin Chatuvedi - Modeling & Controls
Dr. Nikhil Ravi - Combustion Control
Dr. Eric Doran - CFD Simulations

Stanford University

Prof. Heinz Pitsch - **Co-PI, CFD Simulations**
Prof. Chris Edwards - **Co-PI, Adv. Combustion**
Julie Blumreiter - Advanced Combustion

Chevron Energy Technology Co.

→ Technical Consultation
→ Advisory and Information Exchange

Robert Bosch LLC Gasoline Systems

Hakan Yilmaz - **PI**
Oliver Miersch-Wiemers - **Co-PI, Project Mmgt.**
Dr. Li Jiang - **Co-PI, Technical Lead**
Jeff Sterniak - Combustion Concepts
Julien Vanier - Software Integration
Jason Schwanke - Control System
Ben Wilcox - Vehicle Integration
Nicholas Quinnell - Software Integration
Angela Dragan - Government Affairs

University of Michigan

Adv. Powertrain Control Laboratory

Prof. Anna Stefanopoulou - **Co-PI, Adv. Controls**
Dr. Erik Hellstrom - Adv. Controls
Shyam Jade - HCCI Combustion Control
Jacob Larimore - Combustion Modeling
Patrick Gorzelic - Combustion Mode Switch
Yi Chen - After-treatment System
Sandro Nuesch - Vehicle Simulations

Walter E. Lay Automotive Laboratory

Dr. Stani Bohac - **Co-PI, Adv. Combustion**
Dr. Jason Martz - Combustion Simulations
Vasileios Triantopoulos - Advanced Combustion
Janardhan Kodavsal - CFD Simulations
Prasad Shingine - Engine Simulations
Adam Vaugh - Combustion Modeling
Vijai Manikandan - Comb. Mode Coordination

AVL North America Powertrain Engineering

Pual Whitaker - **Co-PI, Combustion System**
Dusan Polovina - **Co-PI, Combustion System**
Roger Faber - Project Management
David Mckenna - Combustion System
Matthew Dunlavey - Engine Design

Emitec

Dr. Ulrich Pfahl - **Co-PI, Project Management**
Dr. Srinath Reddy - **Co-PI, After-treatment Sys.**

US OEMs

→ Information Exchange
→ Technology Alignment

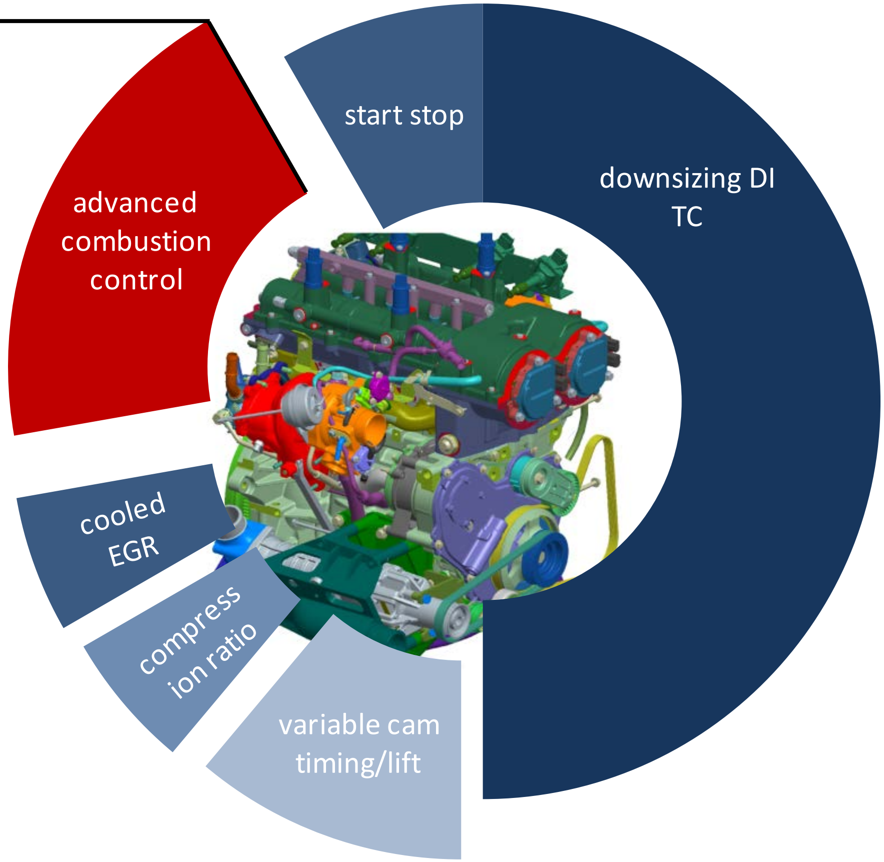
Multidisciplinary team with 40+ researchers and engineers

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

BOSCH

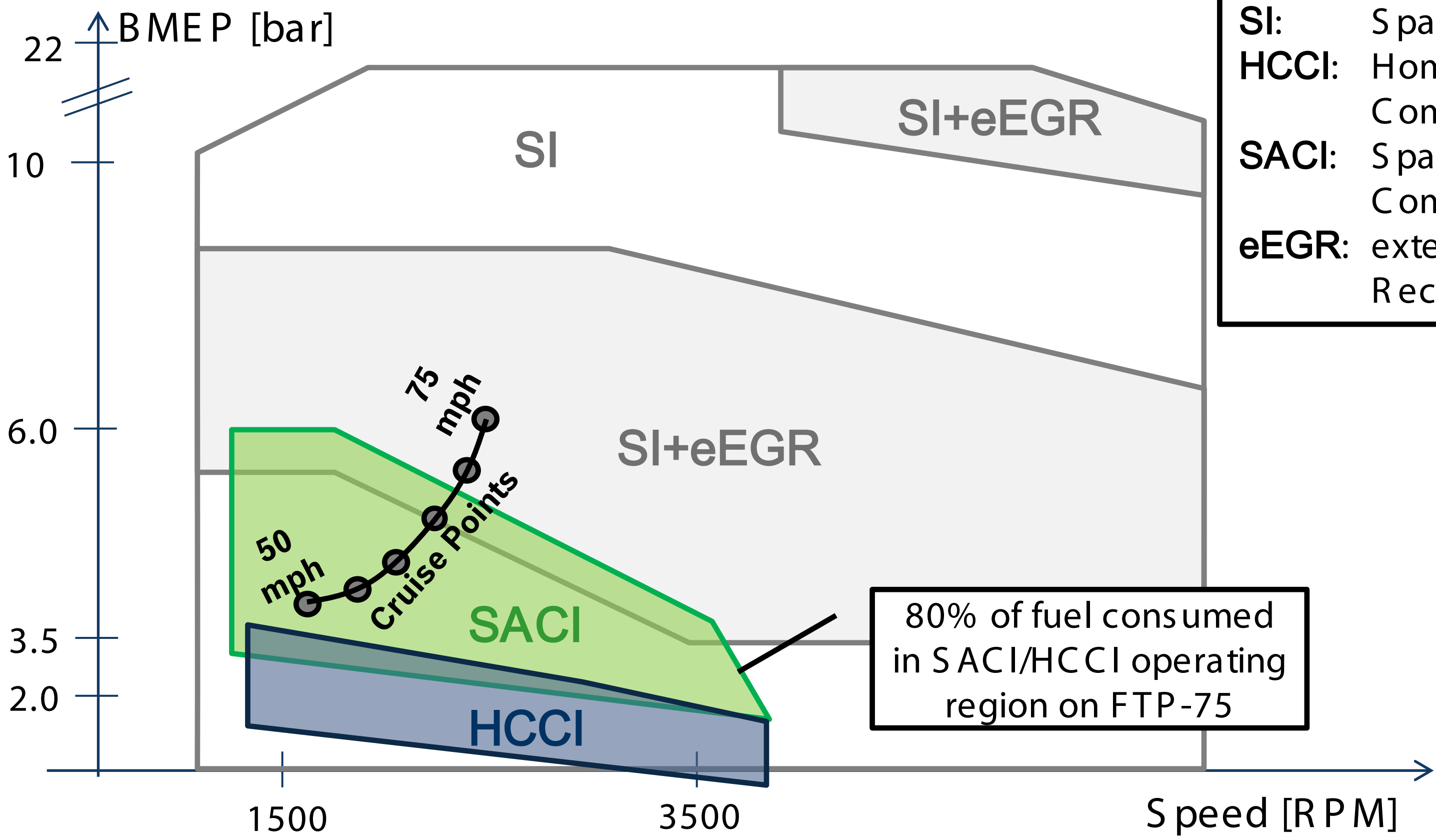
Overview

- Multi-Mode Combustion Strategy
  - Operation Regime
  - Fuel Efficiency
- HCCI Combustion
  - Control Sensitivity Analysis
  - Control Algorithm and Performance
- Combustion Mode Switch Strategy
  - Performance Evaluation



BOSCH

Multi-Mode Combustion Operation Regime

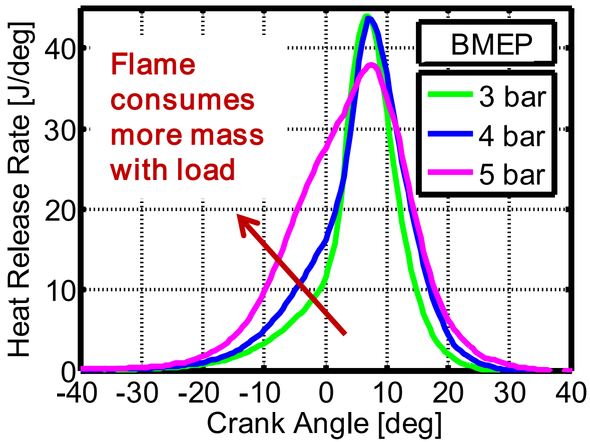


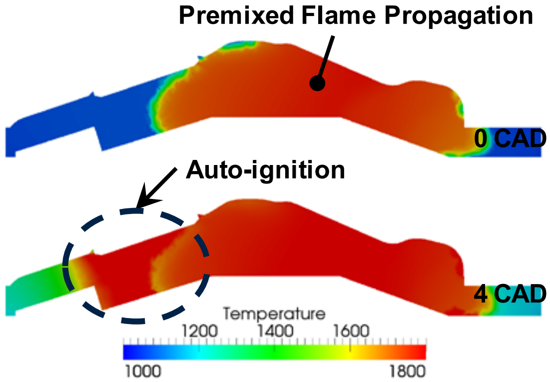
SI: Spark Ignition
HCCI: Homogeneous Charge Compression Ignition
SACI: Spark Assisted Compression Ignition
eEGR: external Exhaust Gas Recirculation

Advanced combustion enables fuel economy benefit in highly visited operating area, while high peak load capability ensures vehicle performance

Extension of Advanced Combustion Range with SACI

- SACI: flame propagation forces unburned mixture to auto-ignition conditions
  - allow reduction in trapped residual gas to achieve auto-ignition and reduces peak heat release rate
    → extension of high-load limits of adv. combustion
  - reduced trapped residual mass increases potential fresh air mass induction
    → eliminates need for boosting device to cover frequently visited drive-cycle operating regime
  - allow operation at stoichiometric
    → eliminates need for lean NOx trap (LNT) to convert increased NOx emission resulted from less dilution



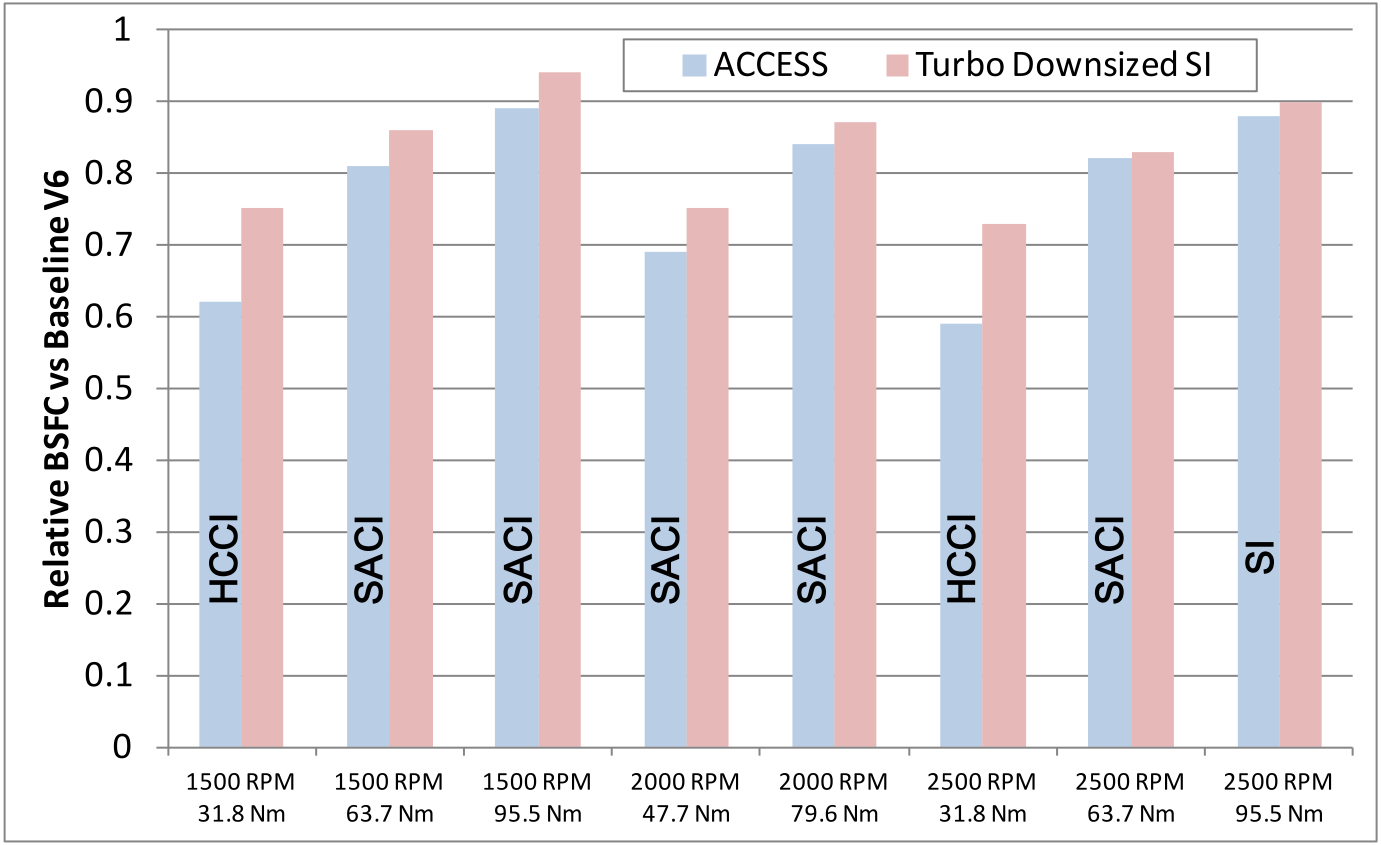


Combustion Chamber Cross-Section

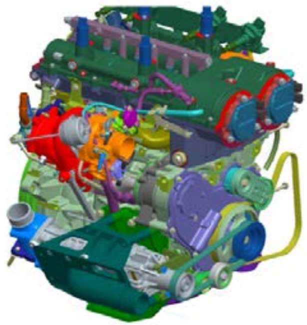
SACI extends low-temperature combustion range w/o 2-stage boosting and LNT[1]

1. LNT: Lean NOx Trap

Fuel Efficiency of HCCI & SACI – Prototype I Engine



Engine Dyno at AVL



Prototype I Engine

Prototype I Engine Data of HCCI & SACI Combustion demonstrate desired fuel efficiency improvement at frequently-visited drive-cycle operation points

BOSCH

Fuel Economy – Vehicle Simulations w/ Prototype I Engine Data

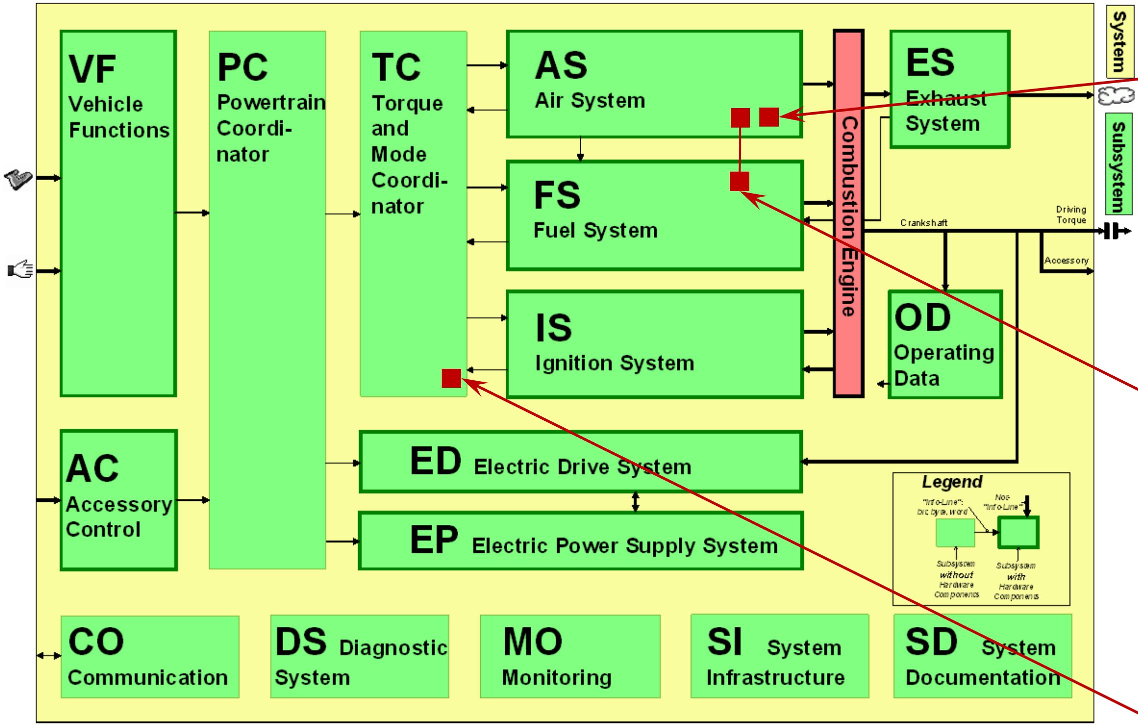
Engine / Combustion Modes	FE-FTP75 [mpg]	ΔFE-FTP75 [%]	FE-HWFET [mpg]	ΔFE-HWFET [%]
Sim: Baseline 3.6L V6 Engine / SI	20.7	-	34.0	-
Sim: ACCESS Prototype I Engine / SI	26.2	+26.6%	39.7	+16.8%
Sim: ACCESS Prototype I Engine / SI & NA HCCI (lean)	27.4	+32.4%	40.9	+20.3%
Sim: ACCESS Prototype I Engine / SI & NVO SACI (stoichiometric)	26.9	+30.0%	42.0	+23.5%
Sim: ACCESS Prototype I Engine / SI & NA HCCI (lean) & NVO SACI (stoichiometric)	27.7	+33.8%	42.4	+24.7%
Sim: ACCESS Prototype I Engine / SI & NVO SACI (stoichiometric) + Start-Stop	27.3	+31.8%	42.0	+23.5%

* Note that vehicle simulation based fuel economy prediction are derived from optimized combustion under steady-state operations

Vehicle simulations w/ prototype I engine data confirm program fuel economy target

BOSCH

Bosch ECU Control Architecture



Air Path Control for EGR and Advanced Valve-train

- Modeling
- Control Development
- ECU Integration

Model-Based Control for Advanced Combustion

- Modeling
- Control Development
- ECU Integration

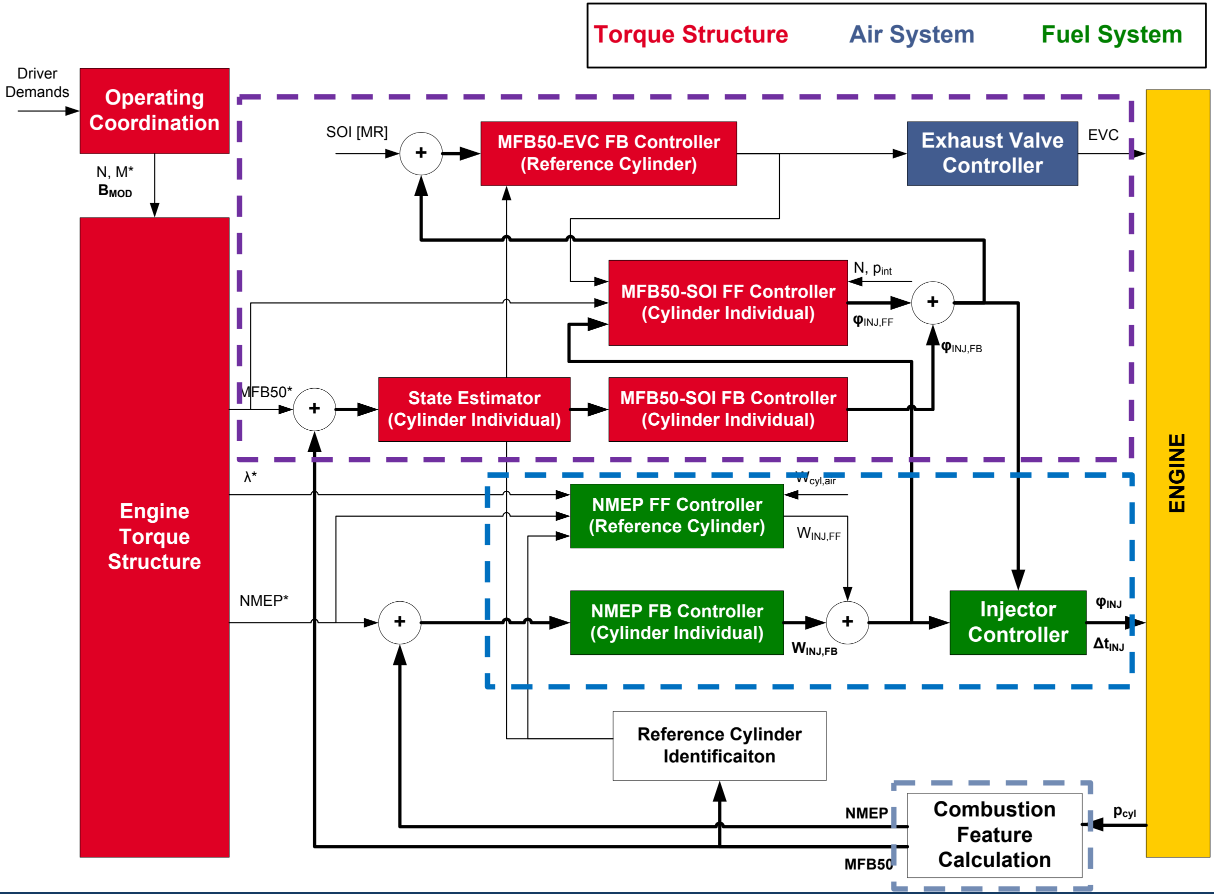
Multi-Combustion Mode Coordination

- Modeling
- Control Development
- ECU Integration

Torque demand driven engine control architecture enables multi-mode combustion control

BOSCH

HCCI Combustion: Control Strategy



Combustion Phasing Control

- Mid-Ranging Control of SOI and EVC
- Model-Based FF Control of SOI to enable fast transitions
- FB Control of SOI to enable MFB50 balancing

Torque Control

- FB Control of fuel quantity to enable NMEP balancing

Cylinder Pressure Sensing

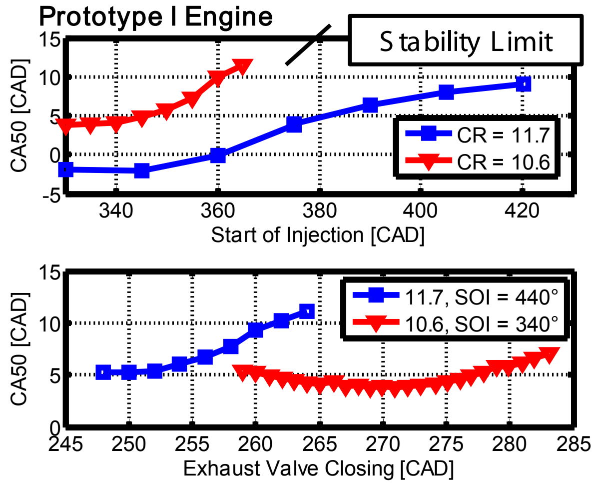
- ECU integrated real-time calculation of MFB50, NMEP

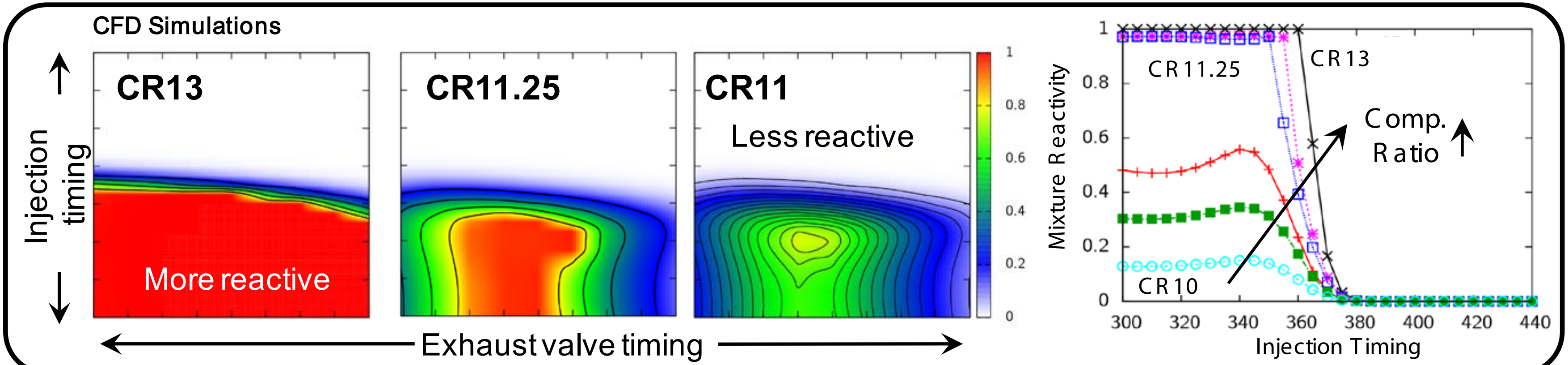
Model-based control to enable fast and robust HCCI transitions

BOSCH

HCCI Control Sensitivity Analysis: Compression Ratio Impacts

- High CR is required to achieve robust auto-ignition
- Insufficient CR restricts control actuator range
  - requires early SOI to promote NVO reactions to reach auto-ignition
  - can lead to non-monotonic response to EVC





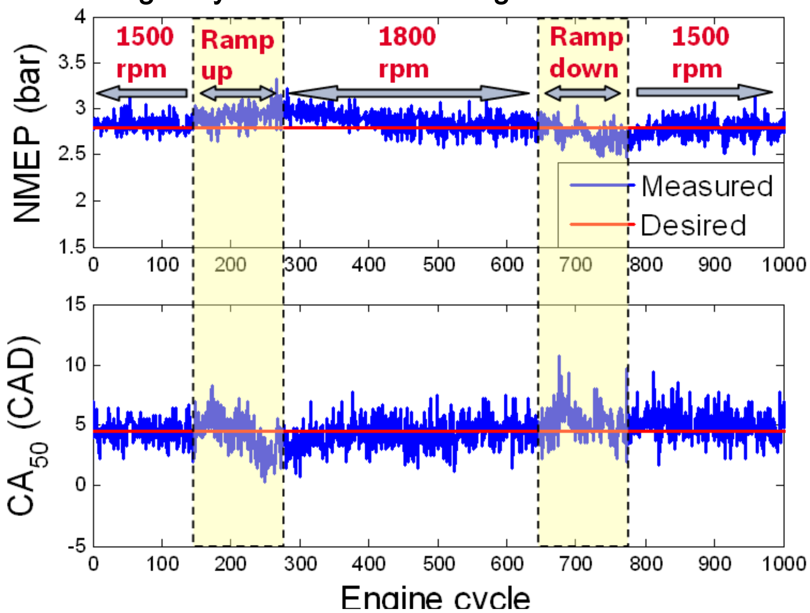
CFD simulation and prototype I engine data concluded CR11.7 for prototype II engine

BOSCH

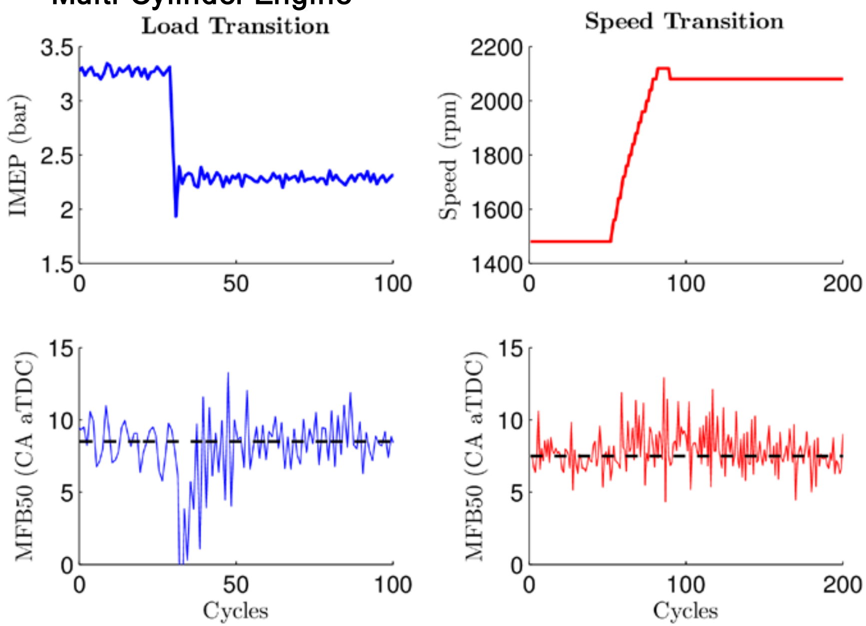
HCCI Combustion Control: Performance

- Validated HCCI control strategies on single and multi-cylinder engines using engine-in-the-loop rapid prototype techniques under engine speed and load transients

Single-Cylinder Research Engine

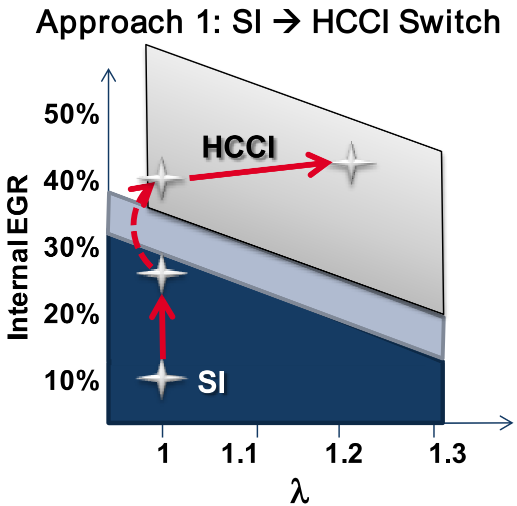


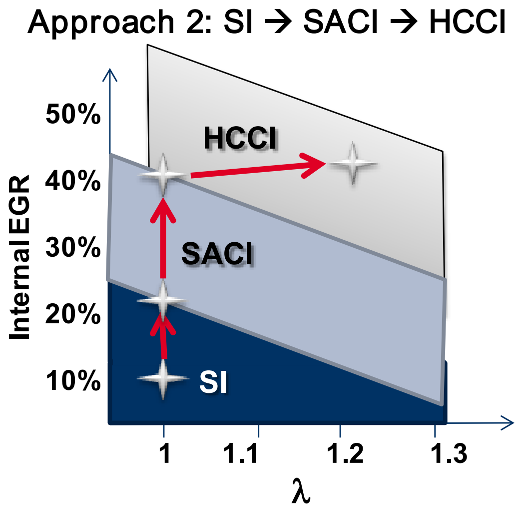
Multi-Cylinder Engine



Proposed HCCI control strategies validated on multiple engine platforms

SI-HCCI Combustion Mode Switch: Strategy

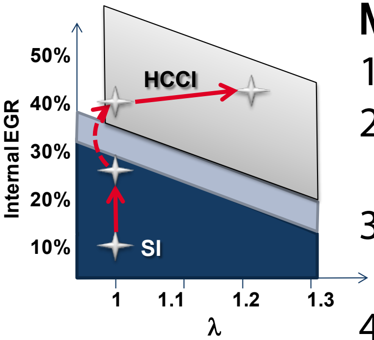




Key Performance Indicator	Mode switch strategy		
	SI→HCCI EV High to Low lift	SI→HCCI EV/IV low lift	SI→SACI → HCCI EV/IV low lift
Efficiency	-	++	++
SI combustion stability	-	+	+
Switch robustness	o	+	++
Controller Feasibility	+	+	o

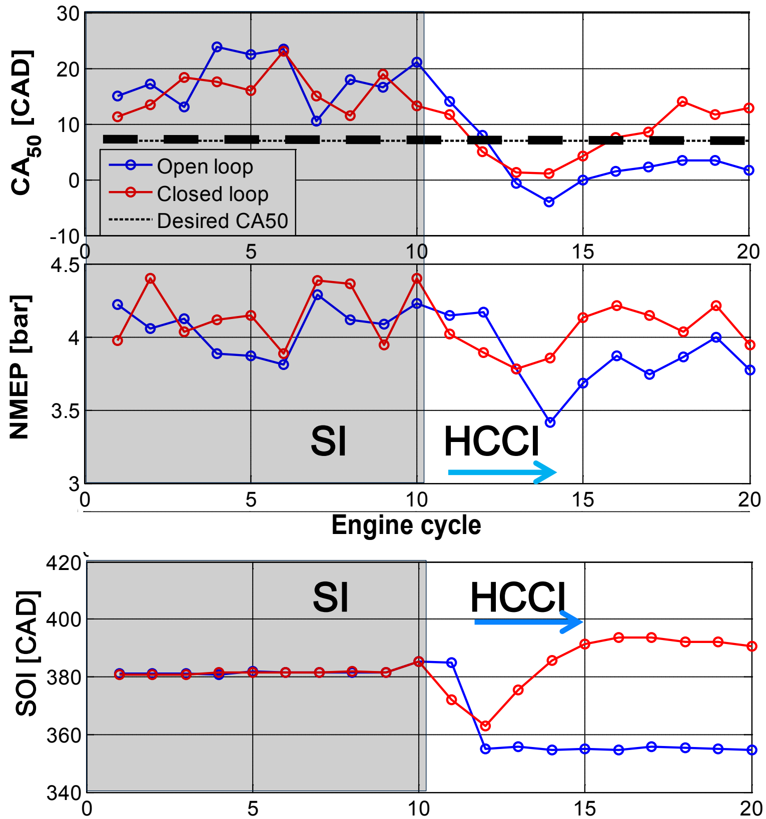
BOSCH

SI-HCCI Combustion Mode Switch: Performance



Mode Switch Strategy

1. SI with low lift IV and EV
2. Dethrottle SI increasing iEGR while increasing NVO
3. Regulate comb. phasing with SOI
4. Switch into lean HCCI



➔ Proposed mode switch strategy demonstrated robust performance at multiple operation pts.

➔ Closed-loop SOI controller for combustion phasing during mode switch resulted in improved transient response at SCRE

Proposed combustion mode switch strategy demonstrated desired performance

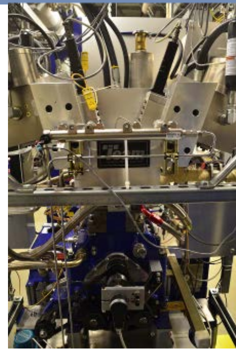
BOSCH

2013 DOE Annual Merit Review – ACCESS – Technical Accomplishment

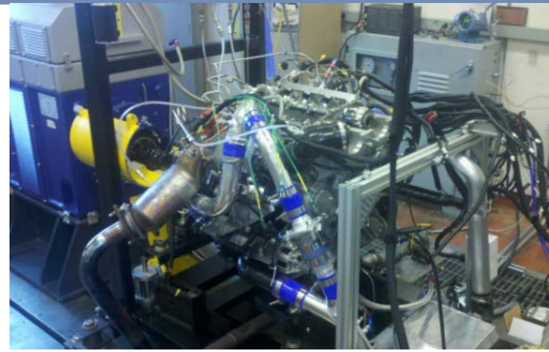
Combustion research and engine development

- Single-cylinder research engine with Fully Flexible Valve Actuation (FFVA) at Stanford.
- Four prototype engines running on dynamometers at University of Michigan, AVL and Bosch.
- **Engine hardware and combustion concept finalized.**

AVL test cell



Single-Cylinder Engine
Stanford University



Transient Dyno Cell
University of Michigan

Vehicle Integration

- Vehicle integration at Bosch started in Dec 2012.
- Emission and chassis roller bench available at Bosch, capable of measuring target emission level including particulate number and mass.
- **Test vehicle operational with initial SI calibration and available for vehicle chassis emission and fuel economy investigations.**

Prototype engine installed in emission and fuel economy test vehicle

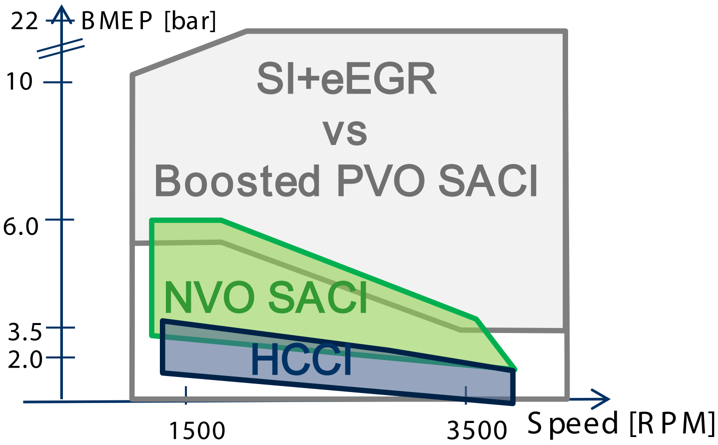
Combustion concept, prototype engine hardware and vehicle integration milestones met to demonstrate the projects goals in Phase III

BOSCH

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

2013 DOE Annual Merit Review – ACCESS – Technical Accomplishment

Overview – Combustion System



Approach

- Define engine operating conditions and transient performance requirements using engine and vehicle-level simulations
- Develop advanced combustion concepts using simulations and experiments at single & multi-cylinder engines simultanesouly
- Evaluate system concept under drive-cycles conditions in vehicle and on UofM transient dyno

Major Accomplishments

- Finalized ACCESS prototype engine hardware
- Evaluated emissions and after-treatment performance during transient HCCI/SACI operation
- Identified hardware required for extension of HCCI/SACI load limit using 1D and 3D simulations

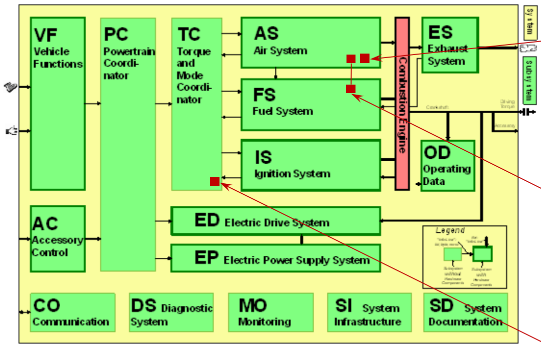
Future Work

- Parameterize target combustion modes for prototype II engine
- Experimentally validate fuel economy, emissions, and vehicle performance on drive cycles
- Experimental evaluate efficiency potential of high load dilute combustion concepts, including boosted PVO SACI and boosted SI with LP EGR

BOSCH

2013 DOE Annual Merit Review – ACCESS – Technical Accomplishment

Overview – Control System



Air Path Control for EGR and Advanced Valve-train
- Modeling
- Control Development
- ECU Integration

Model-Based Control for Advanced Combustion
- Modeling
- Control Development
- ECU Integration

Multi-Combustion Mode Coordination
- Modeling
- Control Development
- ECU Integration

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 architecture for a multi-mode combustion engine established
- HCCI combustion control strategy established and validated on multi-cylinder engine
- HCCI / SI combustion mode switch strategies established and performance evaluated on single-cylinder engine

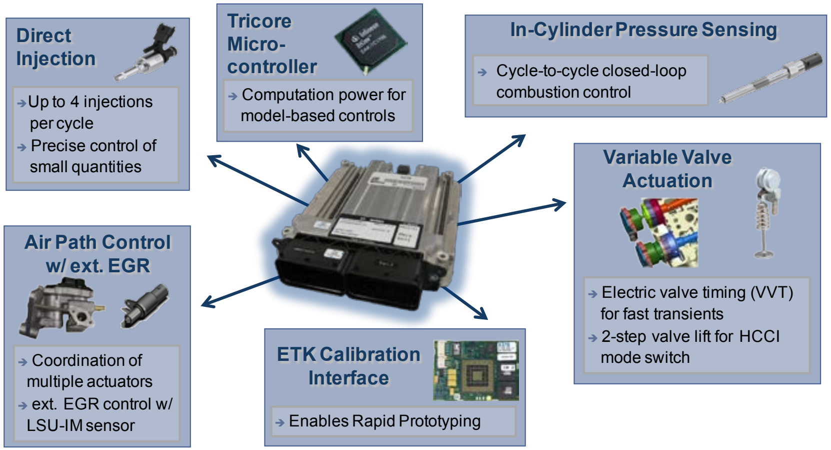
Future Work

- Establish and evaluate SACI combustion control strategy on multi-cylinder engine
- Evaluate and evaluate combustion mode switch strategies on multi-cylinder engine
- Evaluate proposed control strategies under drive-cycle conditions using engine-in-the-loop rapid prototyping approach

BOSCH

2013 DOE Annual Merit Review – ACCESS – Technical Accomplishment

Overview - Software Architecture



Approach

- Bosch Motronic engine control platform is used for Engine and Vehicle level development
- Engine Control Unit with integrated algorithms for multi mode combustion for production feasible proof of concept
- Validate new controllers using Rapid prototyping
- Integrate new controllers in ECU using production code generation

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
- Successful operation of prototype 1 engine with Bosch ECU
- Successful start of prototype engine

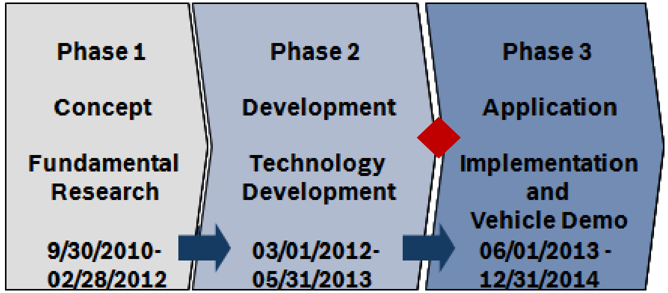
Future Work

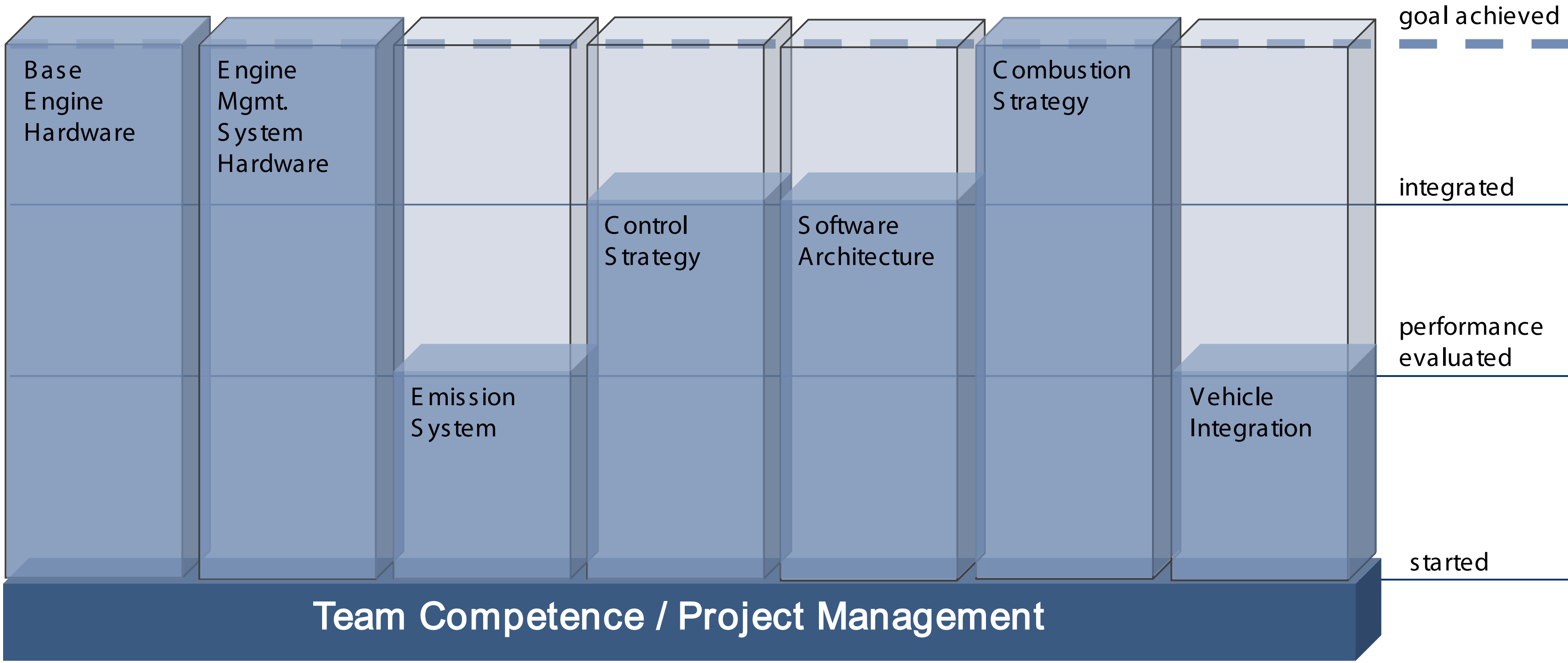
- Integration of HCCI actuator controls and combustion mode strategy into ECU software
- Evaluation of multi-mode combustion switch with engine-in-the-loop rapid prototyping
- Verification of engine management system for Prototype 2 engine architecture

2013 DOE Annual Merit Review – ACCESS – Summary

Program Targets

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





BOSCH

2013 DOE Annual Merit Review – ACCESS

2012 Q3 Quarterly Review
Bosch Plymouth, MI
October 18, 2013

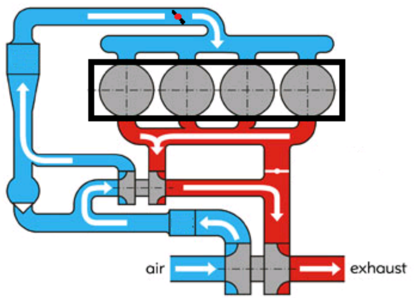
BOSCH

Technical Back-Up Slides

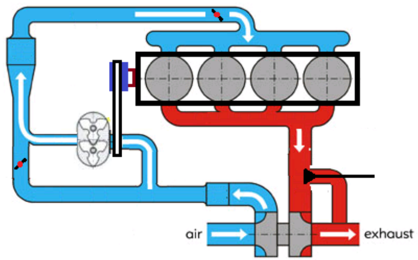
Boosting Device for HCCI: Supercharger vs. Turbocharger

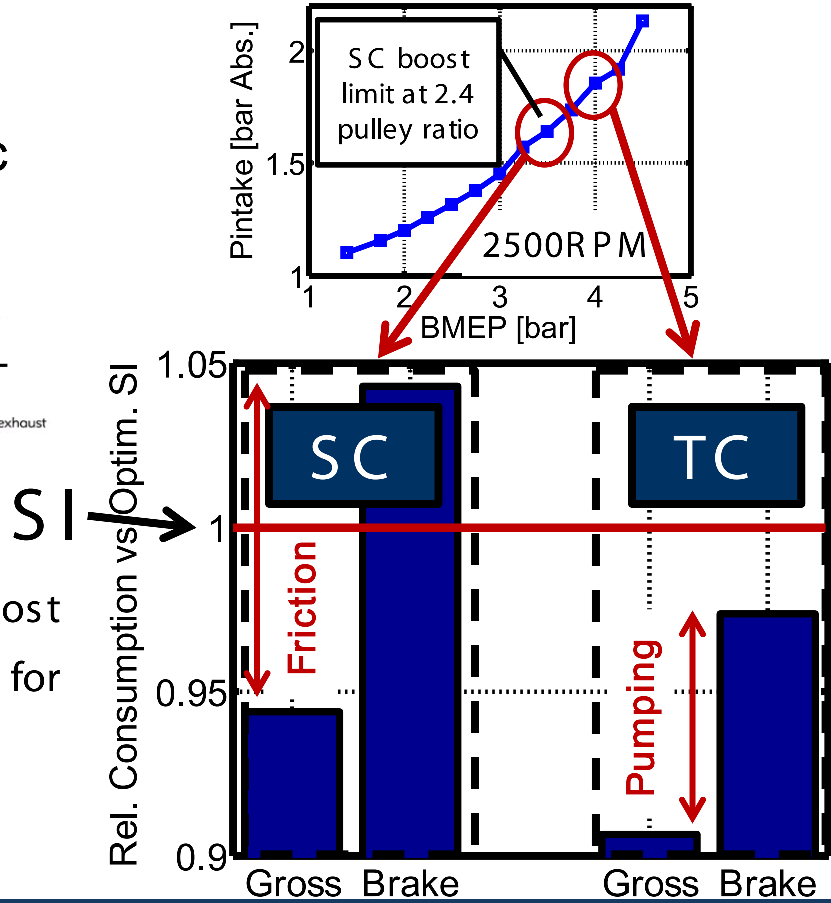
HCCI Dual Stage Boosting Concepts

Dual-Stage Sequential TC



Dual-Stage TC + SC





Cost of Boosting

- High dilution for HCCI requires significant boost
- Pumping losses for TC and crank input work for SC prevent realization of improved gross working cycle efficiency

Next generation of boosting devices are required for boosted advanced combustion

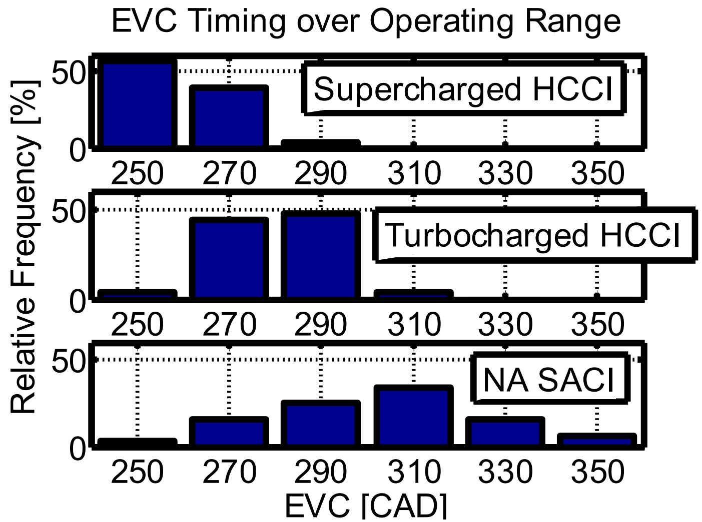
Cam Profile Design for SACI & HCCI

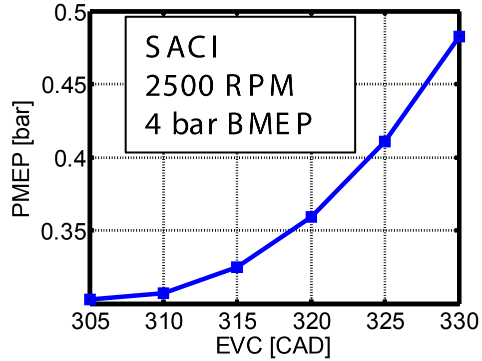
Trapped Residual Requirement – SACI vs. HCCI

- Wide range of trapped internal residuals requires large cam phaser authority
- Lower trapped internal residuals with increasing load results in later EVCs

Cam Profile Requirement– SACI vs. HCCI

- Later exhaust valve closing results in later exhaust valve opening → potentially after BDC
- Delayed EVO can result in significant pumping loss
- Extended camshaft profile duration can avoid this





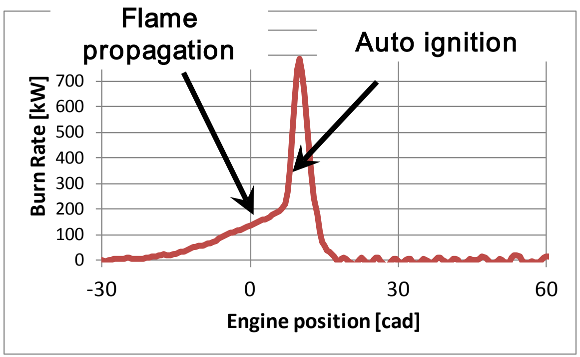
Extended cam duration and timing range required for optimized NA HCCI/SACI

BOSCH

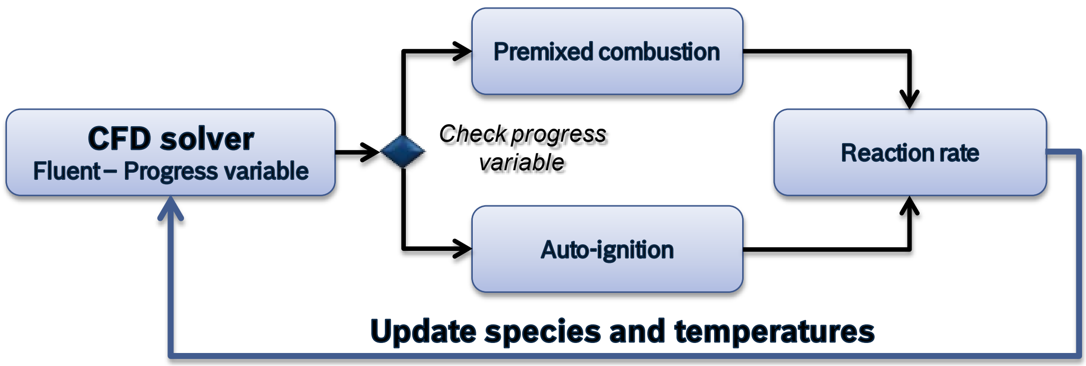
CFD Simulations: SACI Combustion

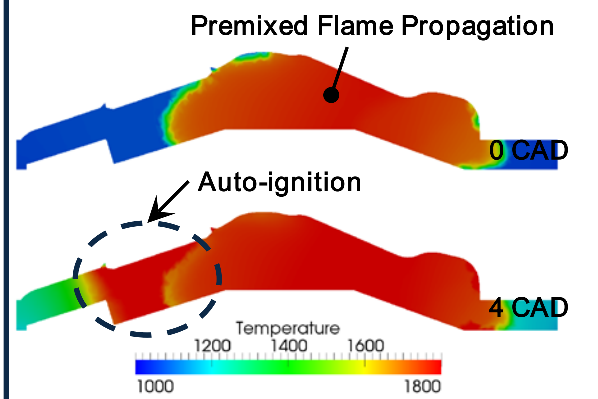
- Developed novel theoretical modelling approach for SACI combustion that includes premixed and auto-ignition combustion regimes

SACI on SCRE[1] w/ pure internal EGR



New framework for 3D RANS w/ premixed combustion and auto-ignition





Combustion Chamber Cross-Section

Established CFD simulation framework for SACI to acquire physical understanding

1. SCRE: Single Cylinder Research Engine