2014 DOE Vehicle Technologies Program Review

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

Arlington, Virginia
June 19th, 2014

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Advanced System Engineering
Gasoline Systems, Robert Bosch LLC

Award: DE-EE0003533
Project ID: ACE066

BOSCH

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

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Budget

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

$19,227,349 – Actual expenditure (12/2013)
$9,144,821 – DOE Funding
$10,132,528 – Partner Funding

$5,279,388 – Remaining (12/2013)
$2,808,965 – DOE Funding
$2,470,423 – Partner Funding

Barriers and Targets

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.

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, 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

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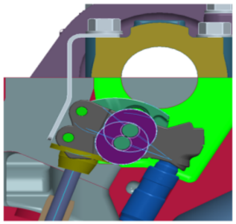
Engine & Controls Development Phase III

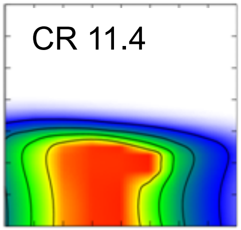
- Target Multi Mode Combustion Engine is based on the GM Ecotec 2.0 L DI Turbo platform
- Base Engine HW design, improvements for target engine configuration and engine build led by **AVL**
- Engine Management System design, engineering and implementation led by **Bosch**
- Aftertreatment System design and emission concept led by **Emitec**

Vehicle Implementation

Build completed for development vehicle. Prototype engine installed and vehicle available for application, emission and fuel economy optimization with advanced combustion modes.

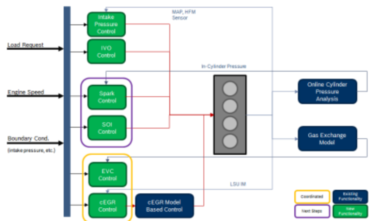
Engine Hardware Prototype IIb

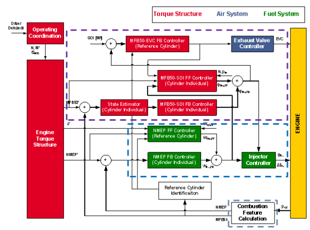




Prototype cylinder head design and cam profile switching mechanism upgraded and compression ratio adjusted for target combustion concepts.

Controls Implementation





Advanced combustion control strategy, capable of real-time ECU implementation, demonstrated on engine and evaluated in development vehicle.

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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

- downsizing with turbo charging and fuel direct injection
- variable valve timing and profile switching
- cooled high pressure EGR with sensor based closed loop control
- combustion control with in-cylinder pressure sensing
- injector individual adaptive fuel metering
- 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
  (no rapid prototyping tools required for OEM application).
- cooled EGR sub system
- combustion pressure sensor

technology made available

Stringent Emissions

Demonstrating SULEV

- The advanced combustion concepts chosen show the potential to meet SULEV with conventional TWC system.
- Exhaust after treatment system design (sizing and loading of the TWC) was performed based on experimental dyno data and simulation.
- Vehicle emission optimization is focus of the current project phase.

meets 2025 emission goals

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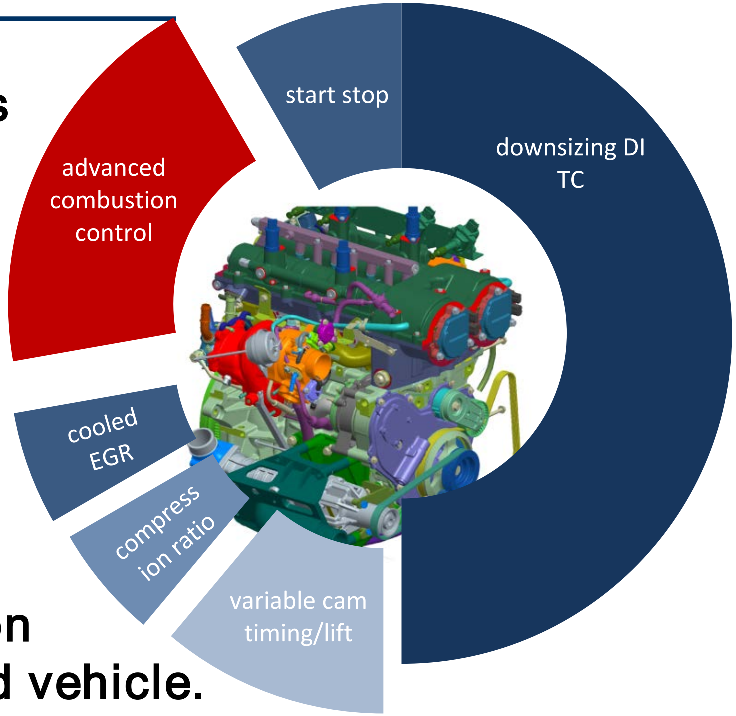
Phase 1 (Research) → Phase 2 (Development) → Jun 1, 2013 — Phase 3 (Integration) — Dec 31, 2014

Vehicle Integration → Control Application → Engine/Vehicle Calibration → Emission Development

Fuel Efficiency - Contributors



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

- Advanced combustion control modeled and integrated for HCCI and SACI
- Control stability limit investigated (CFD)
- Engine Management System configuration completed and concept implemented
- Hardware design finalized and prototype engines and vehicles built

Performance of the system and combustion concept demonstrated on engine dyno and vehicle.

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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

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

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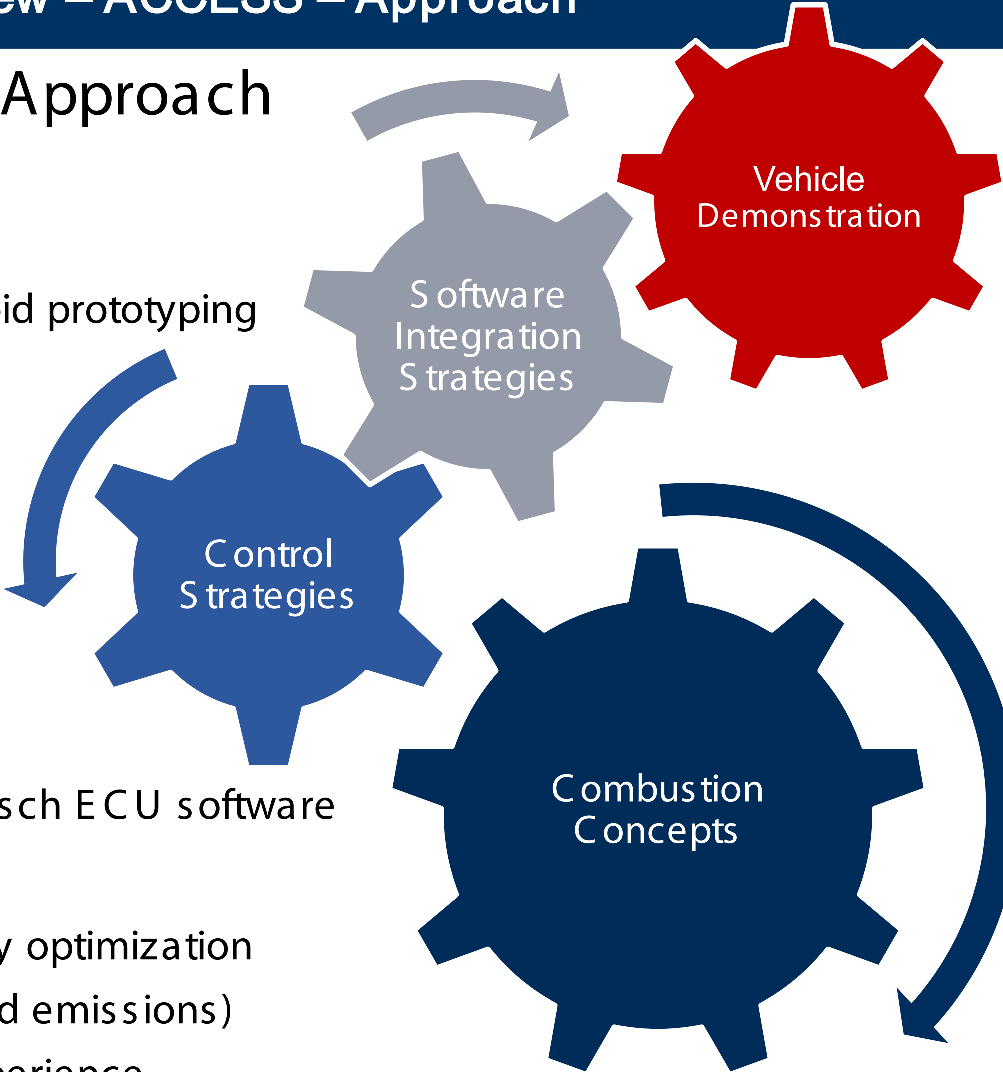
Multidisciplinary Team Approach



Control Strategies

- Engine Management System design
- Control strategy development w/ rapid prototyping

Combustion Concepts

- Engine system design
- Combustion concept evaluation w/ CFD simulations and experiments

Software Integration

- Engine Control Unit design
- Control algorithm integration into Bosch ECU software

Vehicle Demonstration

- Emission and aftertreatment strategy optimization
- Vehicle simulation (fuel economy and emissions)
- In-vehicle advanced combustion experience

Milestones

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

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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

Team Members

Robert Bosch Research and Technology Center (BOSCH)

Joel Oudart - Co-PI, Adv. Combustion
Dr. Alexandar Kojic - Project Management
Dr. Nikhil Ravi - Combustion Control
Dr. Eric Doran - CFD Simulations

Stanford University

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 (BOSCH)

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
Kyle Davidson - Vehicle Integration
Shyam Jade - Software Integration
Jacob Larimore - Combustion Modeling
Angela Dragan - Government Affairs

University of Michigan

Adv. Powertrain Control Laboratory

Prof. Anna Stefanopoulou - Co-PI, Adv. Controls
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
Vassilis Triantopoulos - Advanced Combustion
Prasad Shingne - Engine Simulations
Adam Vaughan - Combustion Modeling

AVL North America Powertrain Engineering (AVL)

Paul 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. Srikanth Reddy - Co-PI, After-treatment Sys.

US OEMs

→ Information Exchange
→ Technology Alignment

Multidisciplinary team with 30+ researchers and engineers

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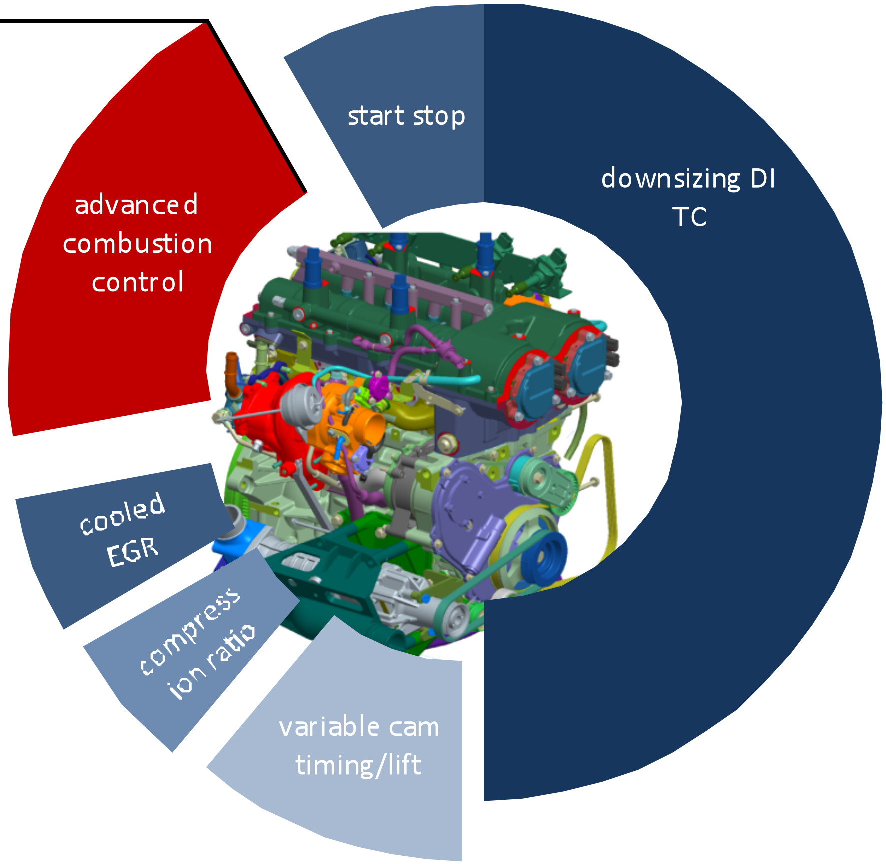
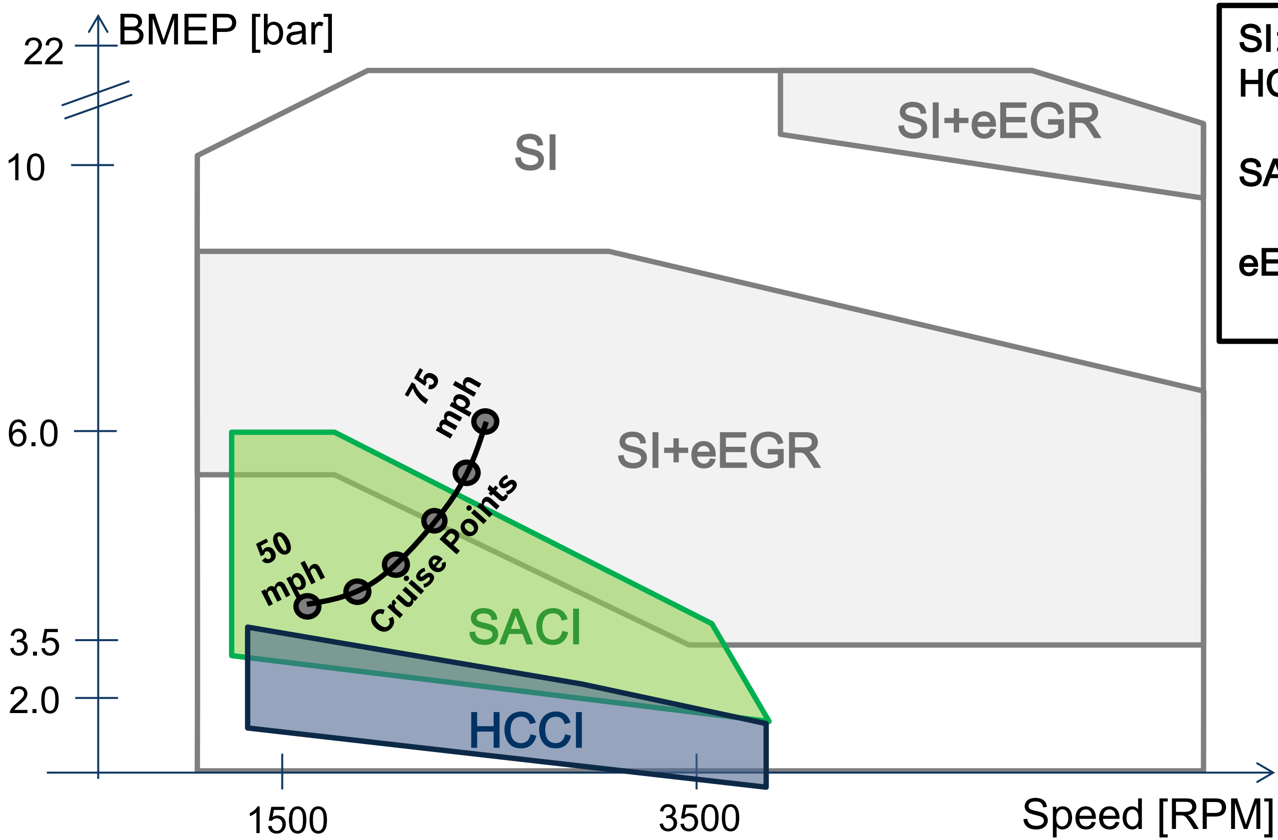
Overview

- Multi-Mode Combustion Strategy
  - Operation Regime
  - Fuel Efficiency
  - Emissions Performance

- Multi-Mode Combustion Controls
  - HCCI Controls
  - SACI Controls
  - Combustion Mode Switch



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 benefits in highly visited operating points, while high peak load capability ensures vehicle performance

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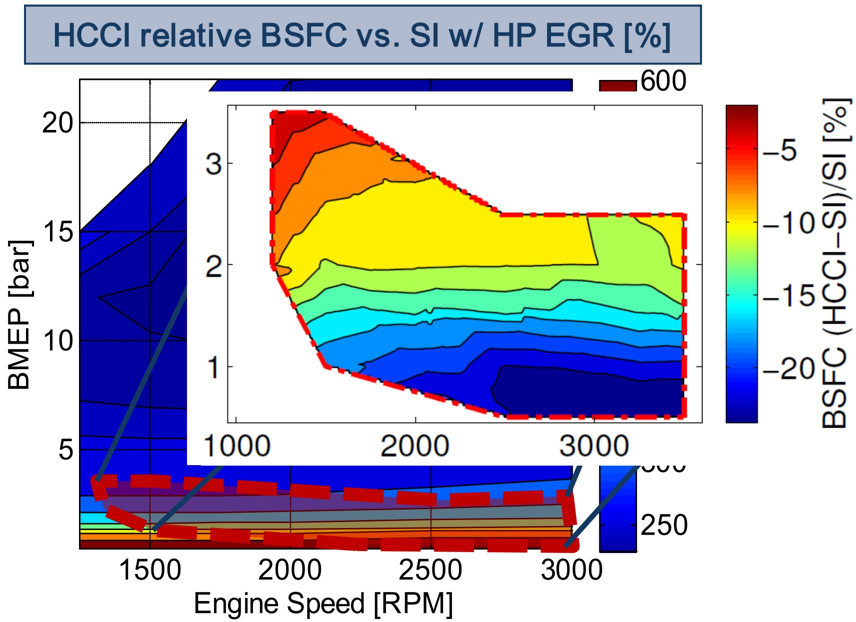
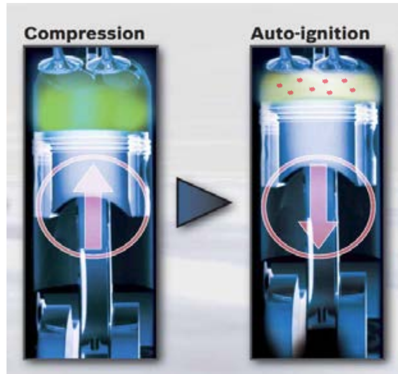
HCCI Concept Development

Homogeneous Charge Compression Ignition

- Hot trapped residuals, air, and fuel are compressed
- Auto-ignition happens from numerous sites near TDC
- Low temperature flameless reaction rapidly takes place





Benefits:

- High thermal efficiency
- Low NOx even when lean

Challenges:

- Limited operating range
- Combustion noise

HCCI can enable high thermal efficiency with low engine out emissions at low load

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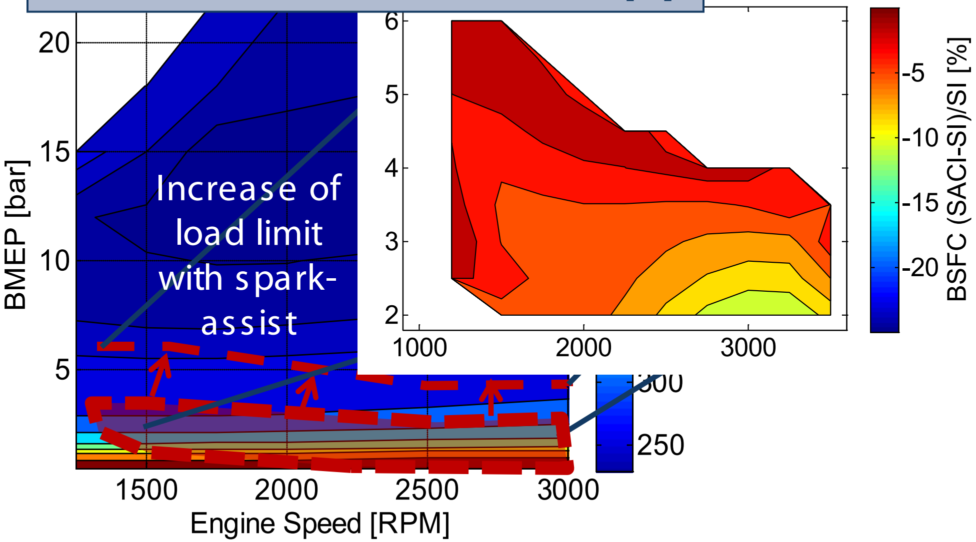
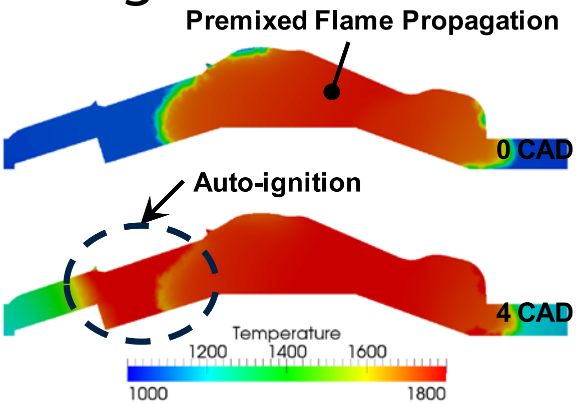
Extension of Advanced Combustion Range with SACI

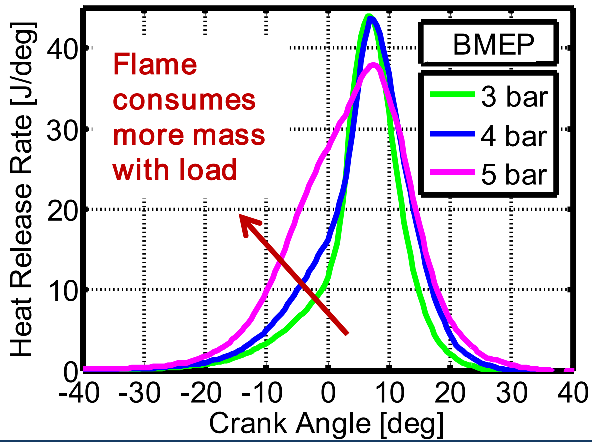
Spark Assisted Compression Ignition

Flame propagation compresses unburned mixture to auto-ignition

- Lower peak heat release rate
- Large stochiometric operating range







Spark assist extends advanced combustion range w/o boosting or lean aftertreatment

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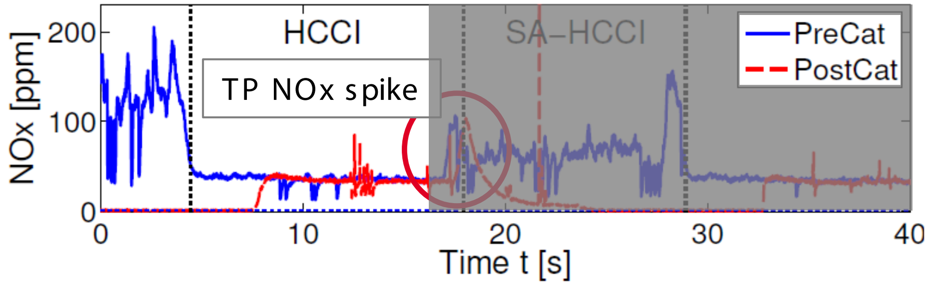
Multi-Mode Combustion Aftertreatment Challenge

Lean – Stoichiometric Mode Switch

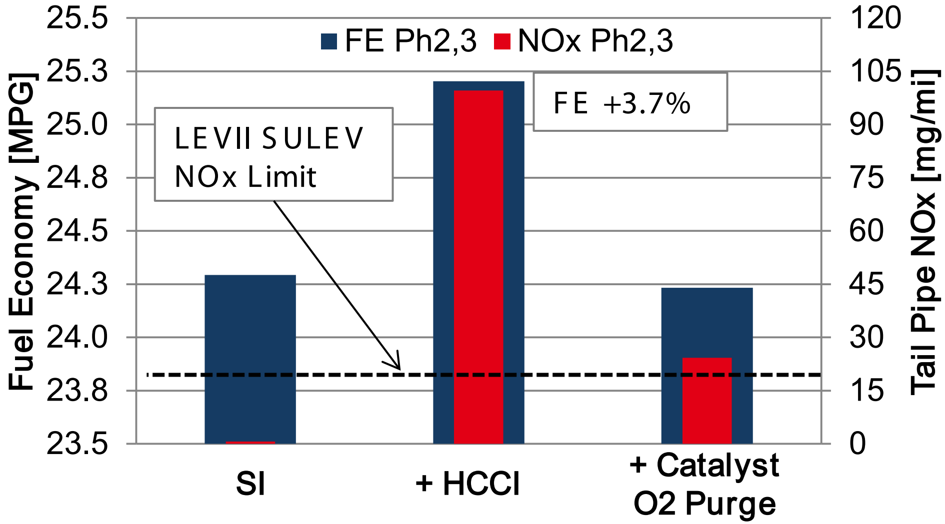
- Lean HCCI
  - Oxygen stored in TWC until full
  - No NOx conversion



- Stoichiometric modes
  - Catalyst efficiency is still low until stored oxygen is depleted

Drive cycle simulations

- Benefit of HCCI wiped out by catalyst depletion
- SULEV emission levels unreachable without additional aftertreatment



FE penalty of mode switch mandates full-time stoichiometric operation

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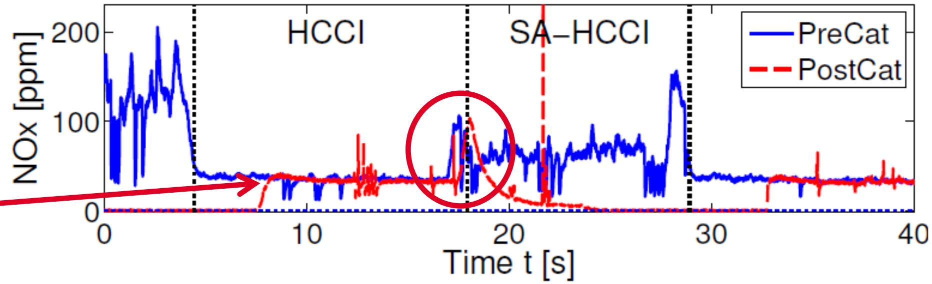

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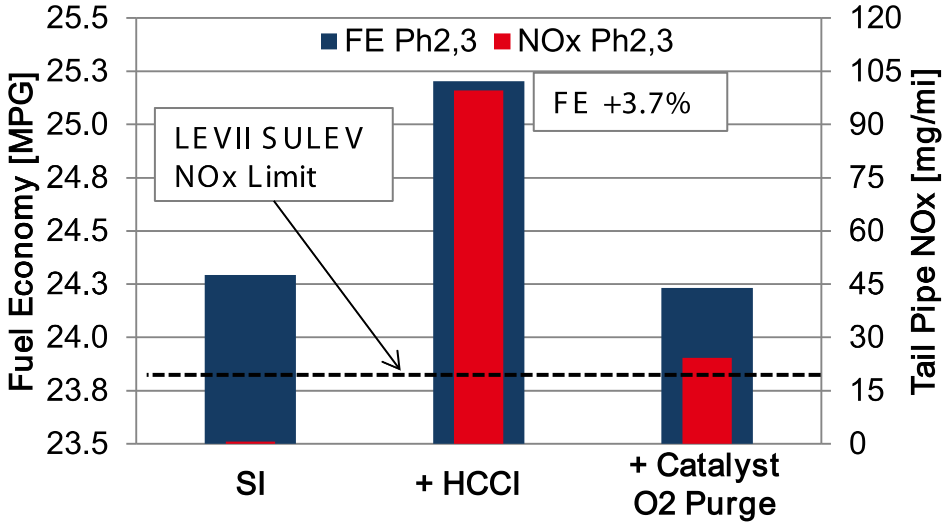

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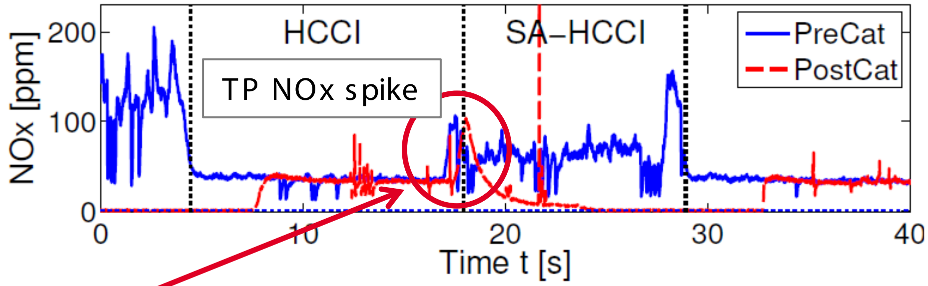

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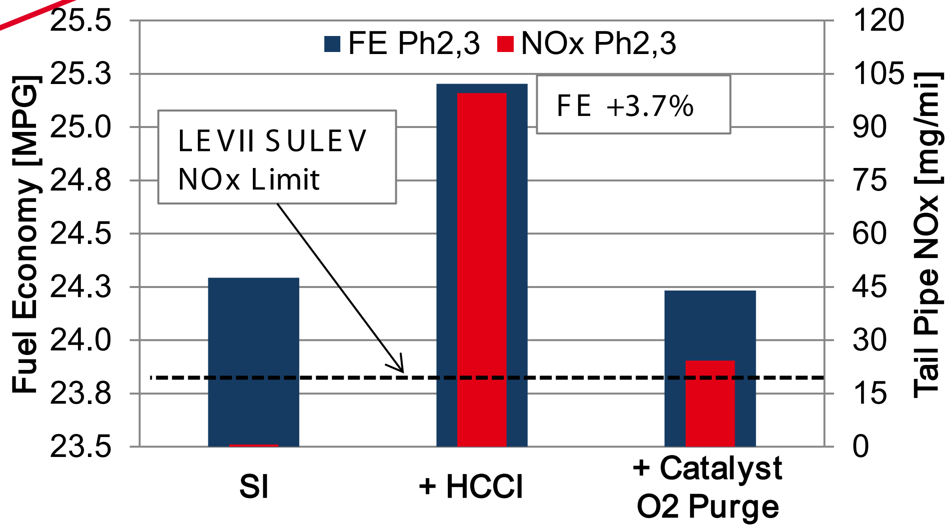

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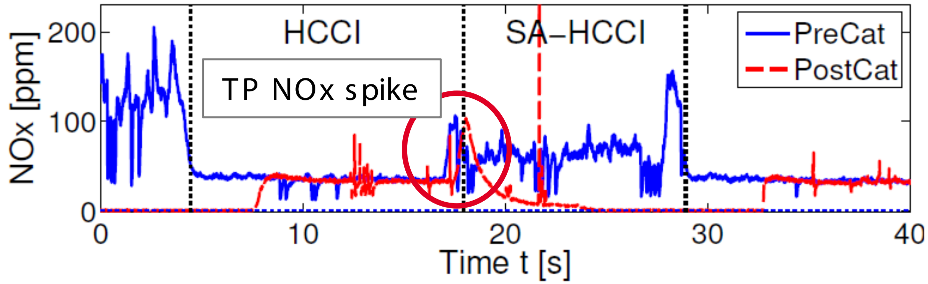

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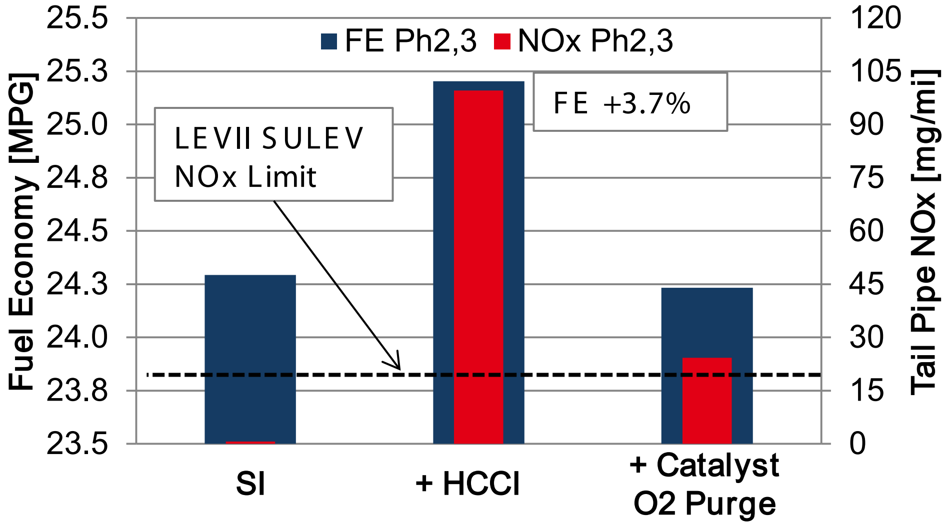

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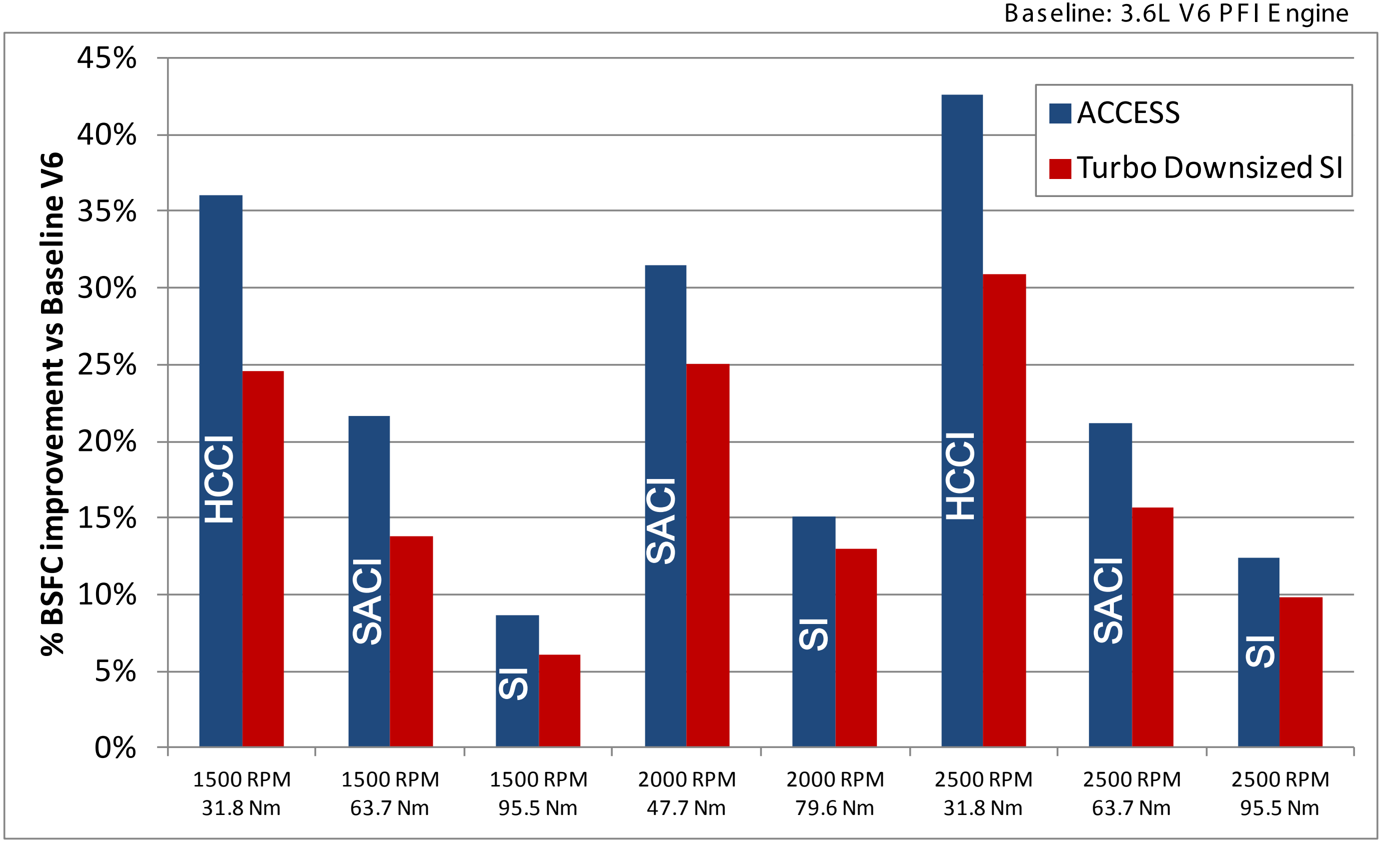
Fuel Efficiency Gains – Prototype II Engine



Engine Dyno at AVL

Prototype II Engine

Prototype II engine data demonstrate significant fuel efficiency improvements over baseline engine at frequently-visited drive-cycle operation points

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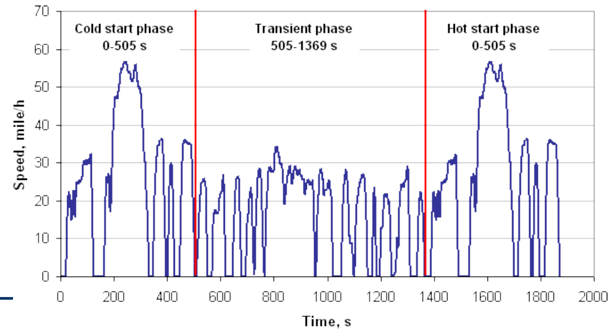
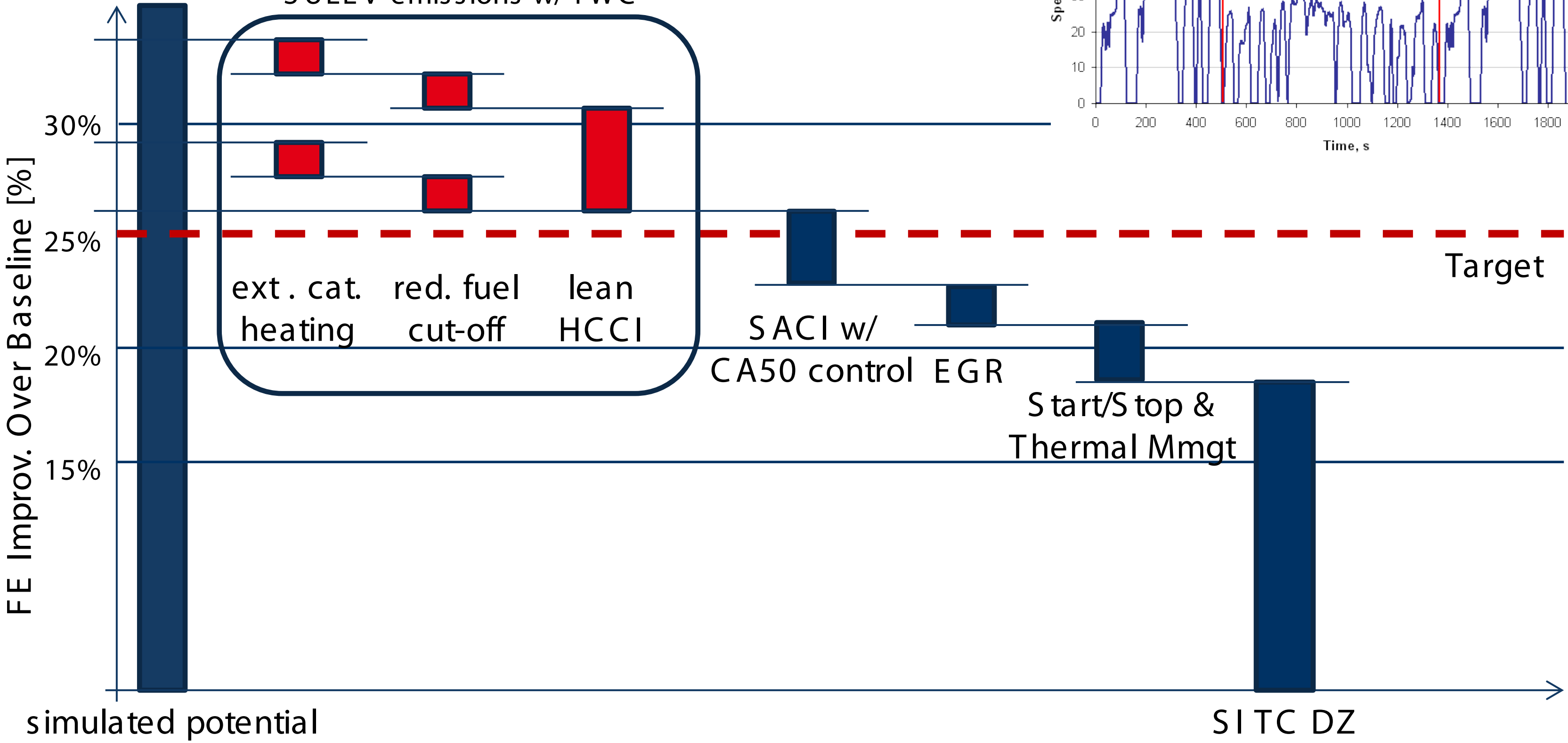
Vehicle Fuel Economy Walk





Challenges existing but project remains on track to meet 25% target

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Vehicle Fuel Economy and Emission Status

Emissions

Currently ~2x SULEV target

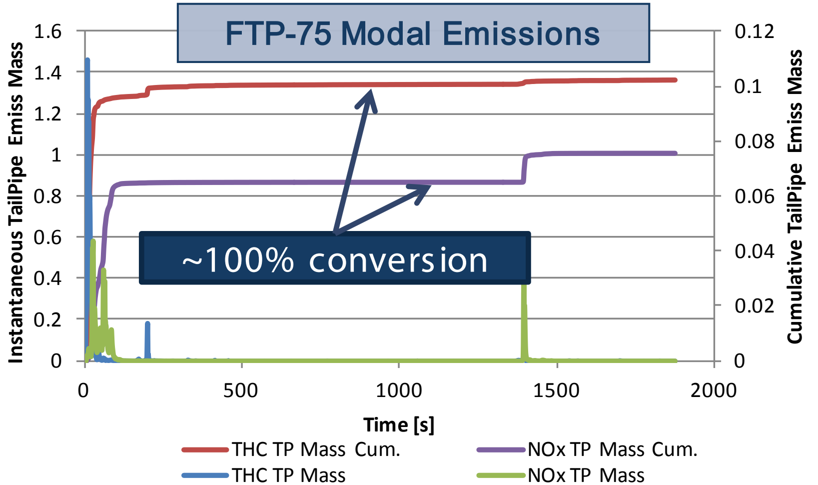
Near 100% conversion efficiency when warm

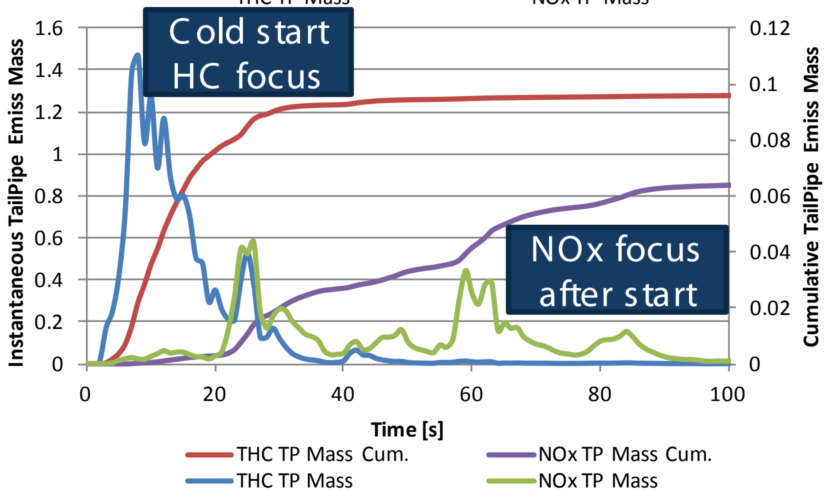
Mitigation for HC during catalyst light off

- Enhanced split injection calibration
- Wastegate actuation for faster light off
- Modified exhaust valve timing with ePhaser

Mitigation for NOx after catalyst light off

- Catalyst oxygen storage target optimization



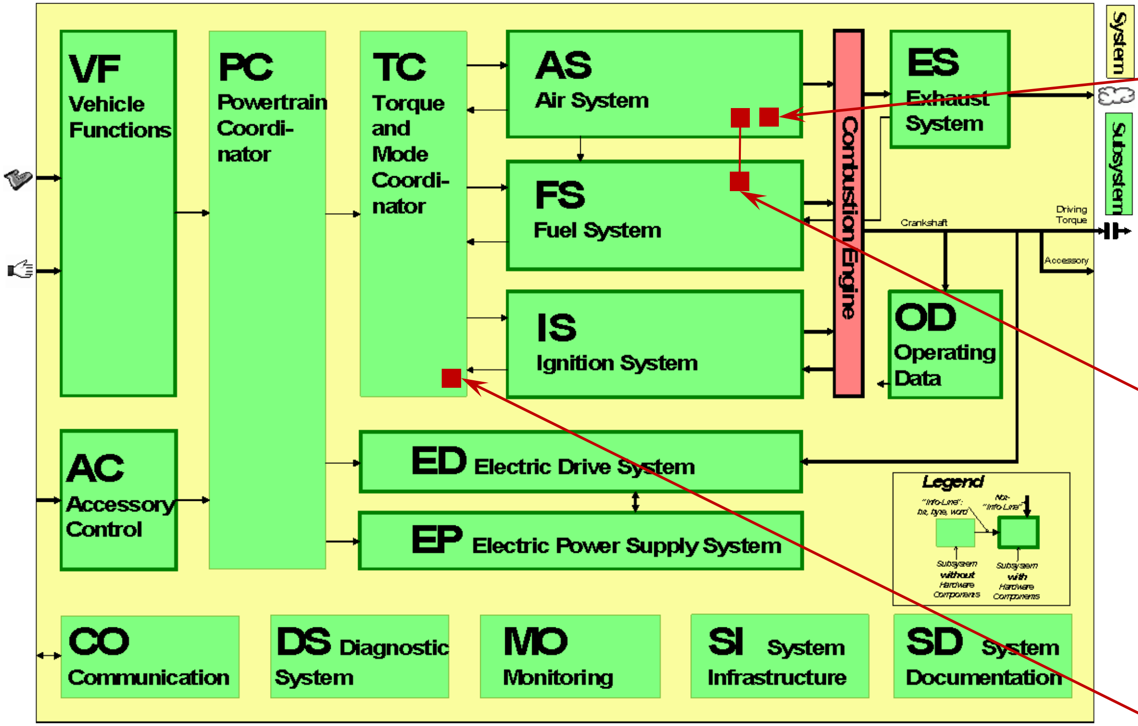


Fuel Economy

Stock CTS	P2b SI w/o EGR	Rel. Improv.
18.04 mpg	21.28 mpg	18.0%

Modularized Bosch ECU Control Architecture

Key Development Areas for Advanced Combustion



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

Advanced Combustion Controls
- 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

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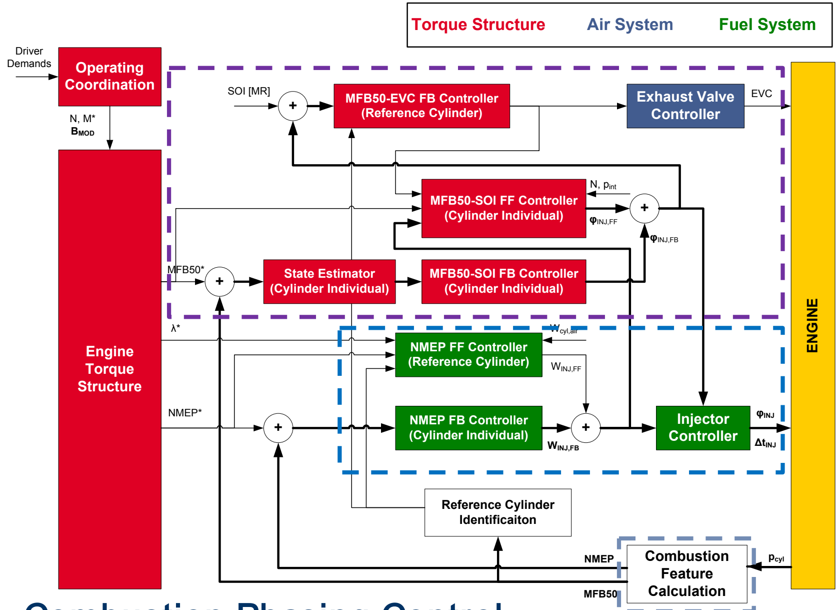
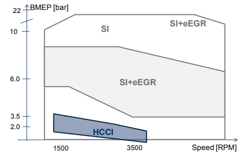
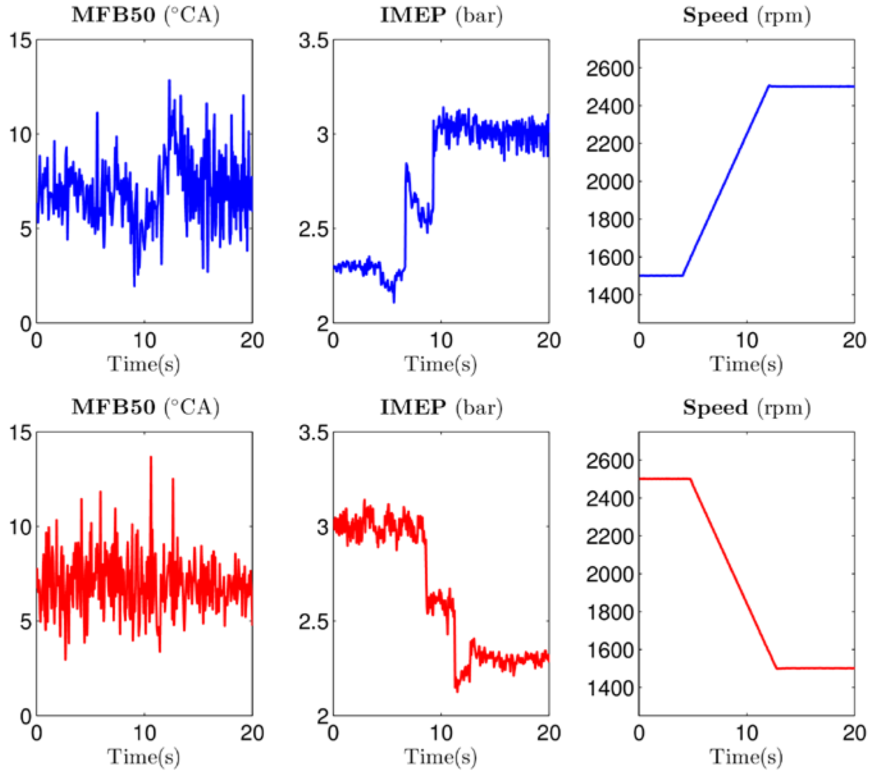
HCCI Combustion Control







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

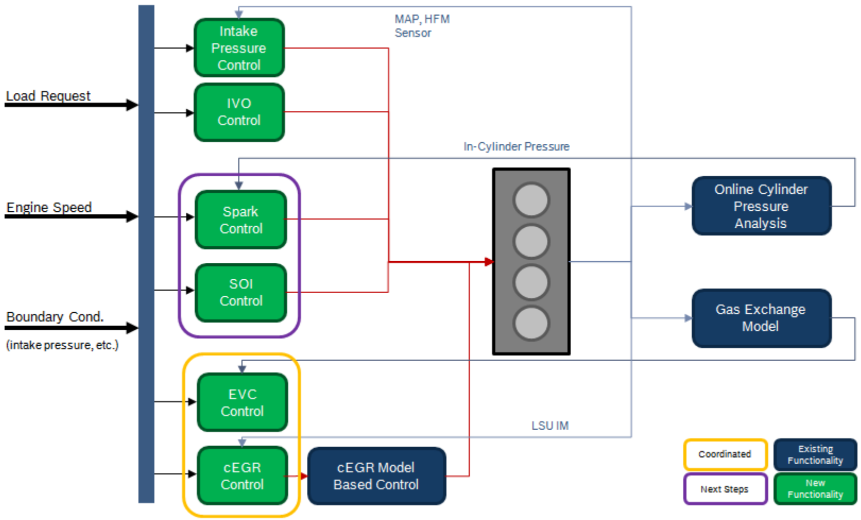
- FB Control of fuel quantity to enable NMEP balancing

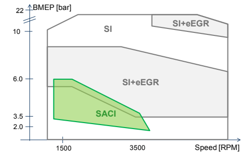
Cylinder Pressure Sensing

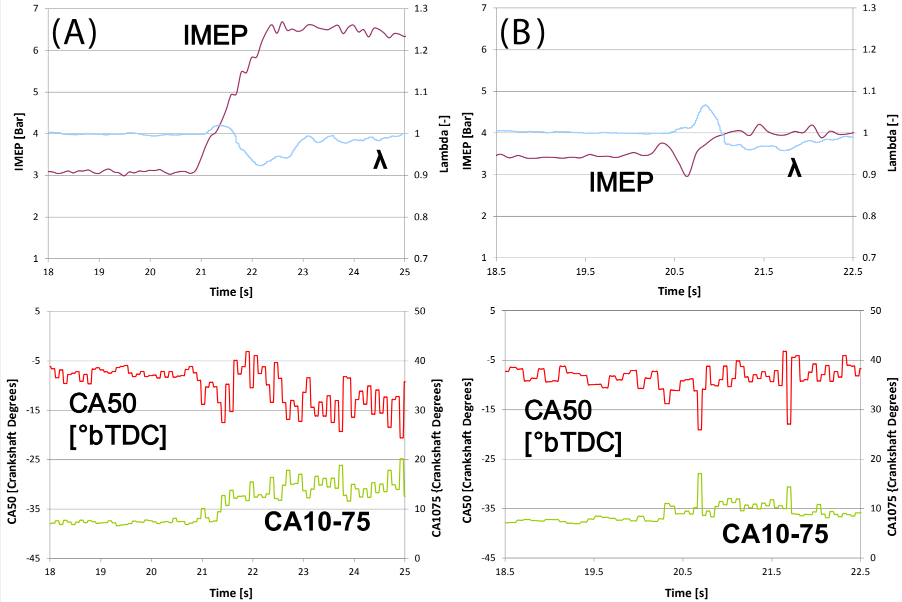
- ECU integrated real-time calculation of MFB50, NMEP

HCCI control validated on prototype multi-cylinder engine over typical drive cycle transients

SACI Combustion Control







Controller Input-Output:

	MFB50	MFB10-90	λ
Spark	++	+	
cEGR	+	++	+
EVC	+	+	++

multi-cylinder engine:

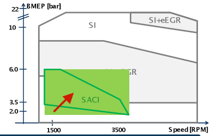
(A) load transition: 2.5bar to 5.5bar BMEP ramp @ 1500RPM

(B) speed transition: 3bar BMEP @ 1500 to 2500RPM ramp

SACI combustion control evaluated on prototype multi-cylinder engine

IVO: Intake Valve Open | **EVC:** Exhaust Valve Closing | **SOI:** Start of Injection | **cEGR:** cooled Exhaust Gas Recirculation | **HFM:** Mass Flow Rate | **MAP:** Manifold Absolute Pressure | **LSU-IM:** Intake Manifold Oxygen Sensor

SI/SACI Combustion Mode Switch Strategy

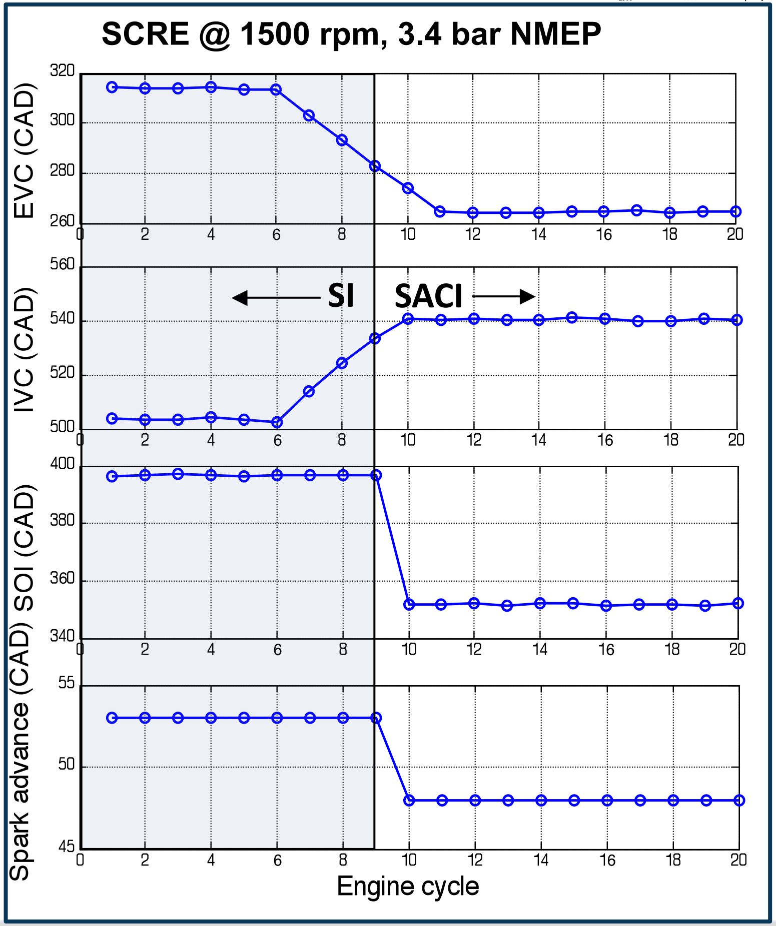


Performance Targets: torque neutral, stable combustion phasing, stoichiometric operation

Key Actuators: intake & exhaust valve timing, throttle position, spark timing, fuel injection timing & mass

SI→SACI Strategy:

- SI with low lift IV and EV
- De-throttle SI with coordinated NVO & EGR
- Regulate phasing with SOI, spark
- **Switch into SACI**



Combustion mode switch strategy identified on single-cylinder research engine

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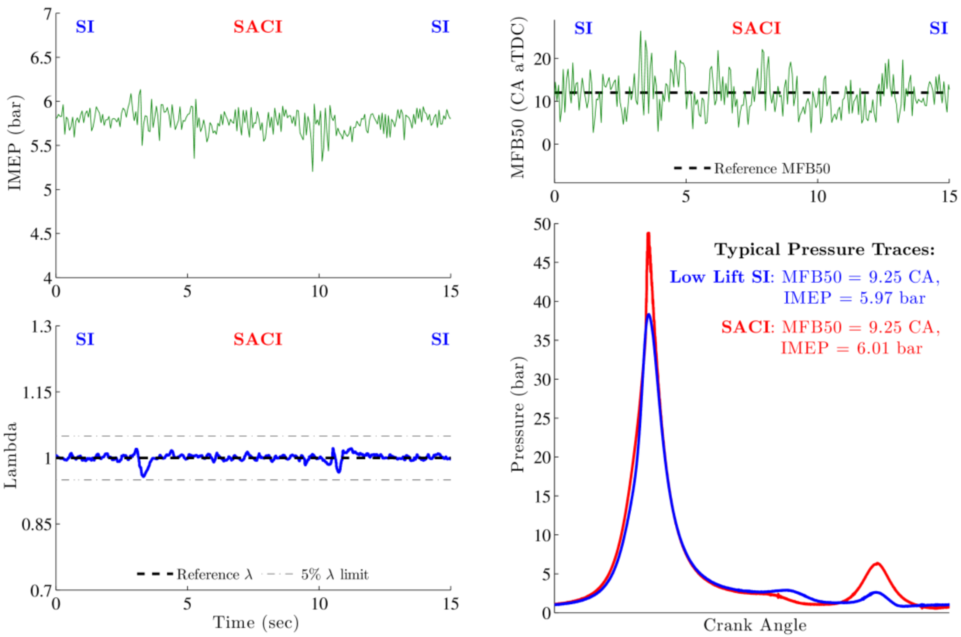
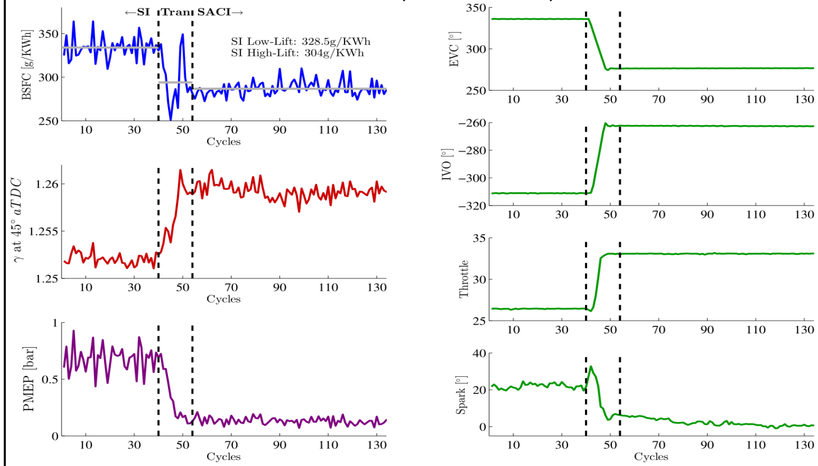
SI/SACI Combustion Mode Switch

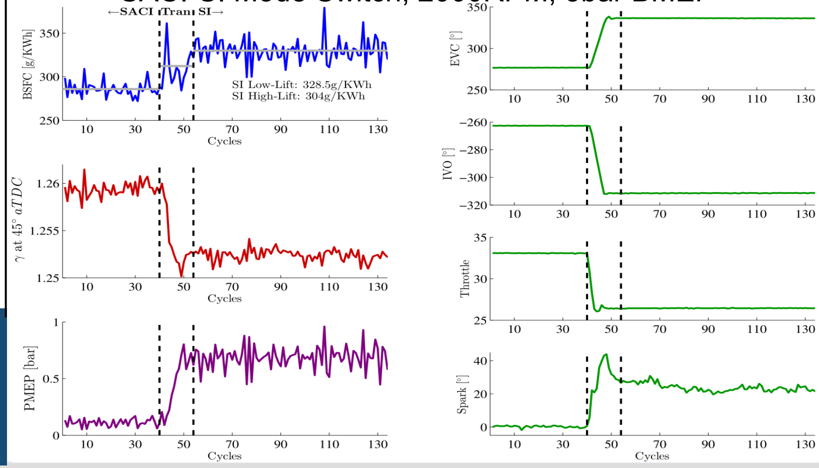
SI-SACI-SI Mode Switch, 2000RPM, 5bar BMEP



SI-SACI Mode Switch, 2000RPM, 3bar BMEP



SACI-SI Mode Switch, 2000RPM, 3bar BMEP



SI/SACI combustion mode switch strategy evaluated on prototype multi-cylinder engine

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

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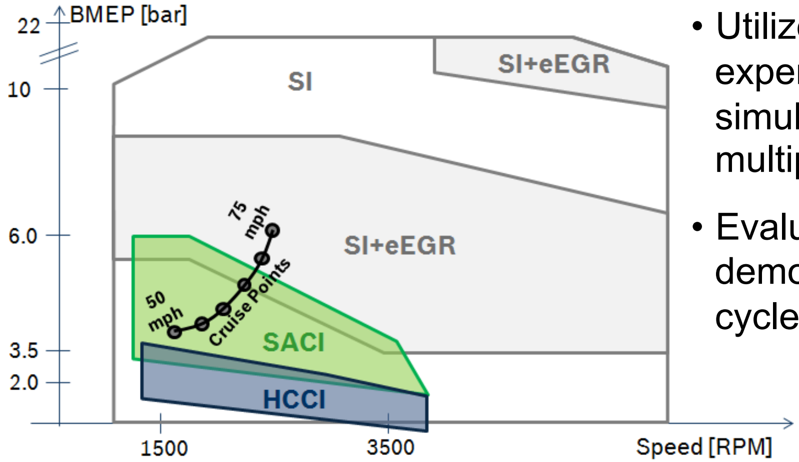
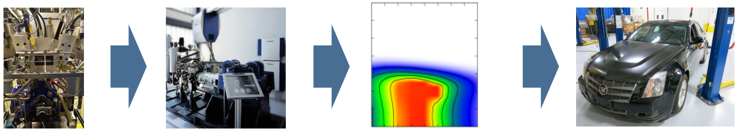
2014 DOE Annual Merit Review – ACCESS – Summary and Future Work

Combustion System Summary – Approach



- Utilize advanced combustion concepts derived from extensive experiments on single and multi-cylinder engines, as well as simulation, to demonstrate the fuel economy potential of multiple mode advanced combustion operation in a vehicle.
- Evaluate tradeoff between efficiency and emissions and demonstrate SULEV potential of the concept under drive cycle conditions.



Combustion System Summary – Major Accomplishments

- Advanced combustion concepts finalized for vehicle implementation.
- Engine operation conditions and transient performance requirements defined by using vehicle-level simulations as well as vehicle tests.
- Evaluated emissions and after-treatment performance impact of transient HCCI operation and mode switch on the transient dyno.
- Vehicle demonstration focusing on stoichiometric advanced combustion operation modes to support the SULEV emission requirement.

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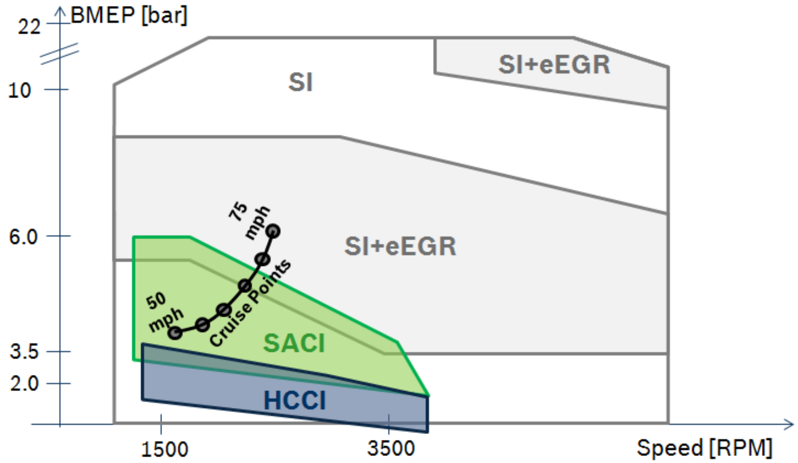
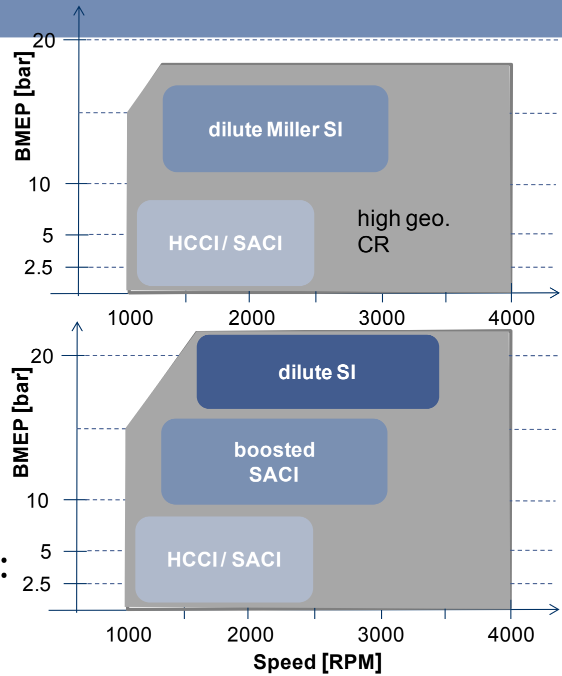
Combustion System Future Work





Extending advanced combustion to future systems:

→ Stoichiometric high CR HCCI Single Cylinder Investigations
- Synergy with dilute Miller cycle SI concept
  - SI in engine peak efficiency region, HCCI in what would otherwise comprise throttled region
- Exploring boosted region with diesel-like CR
- Using high pressure capable, optical access to study and mitigate ringing through charge preparation

→ Boosted SACI Multi-cylinder Investigations
- Determine efficiency potential, valving strategy (PVO & NVO), and engine requirements for boosted SACI concept

→ Transient HCCI modeling for combustion control
- Intra-cycle combustion modeling and control with charge preparation strategy
- HCCI actuator trajectory optimization through enhanced phenomenonological boosted HCCI model

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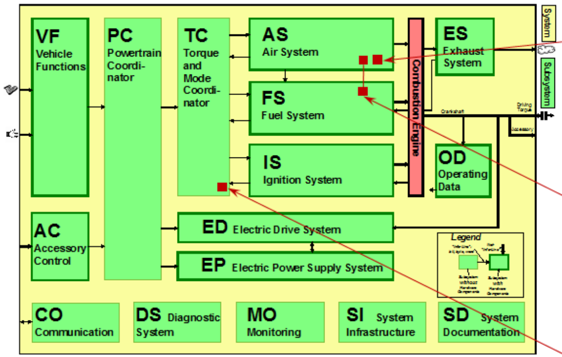
Controls System Summary – Approach

Key Development Areas for Advanced Combustion



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

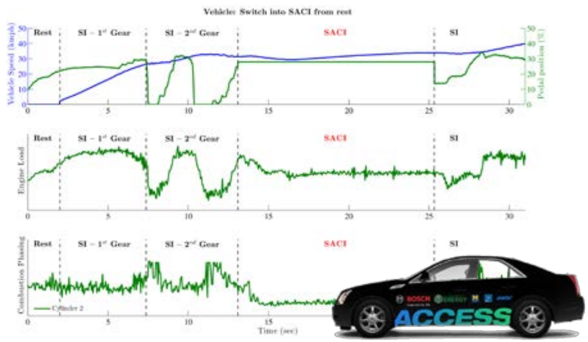
Advanced Combustion Controls
- Modeling
- Control Development
- ECU Integration

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

- Utilize simulation and experimental data to define controls strategy for SACI operation and combustion mode switch.
- Validate the operable range and dynamic requirements for advanced combustion modes accounting for combustion and controllability limits.
- Implement real time controls in production-ready engine control unit, using rapid prototyping function development techniques.

Controls System Summary – Major Accomplishments

- SACI combustion control and mode switch strategies evaluated on multi-cylinder engine transient dyno
- Model based HCCI combustion control and mode switch strategy are evaluated on multi-cylinder transient dyno
- Proposed control strategies are validated for real-time operations and compatible with in-production ECU
- Vehicle is operational with advanced combustion



1st trial of SACI combustion in vehicle

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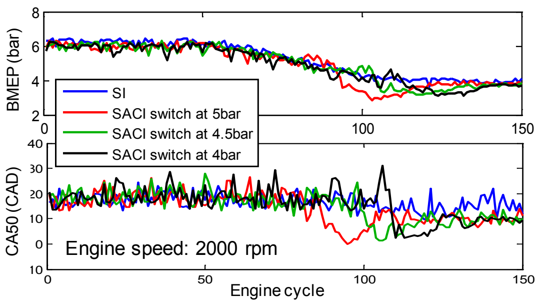
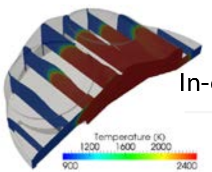
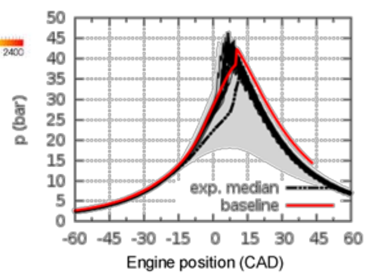
Controls System Future Work

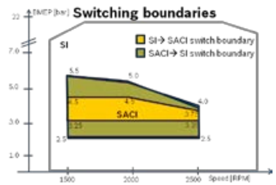




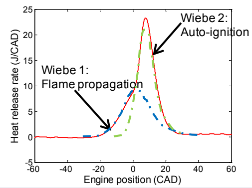
In-cylinder flame propagation



- Complete integration of multi-mode combustion strategies into production-ready engine control unit
- Complete vehicle calibration to improve driving experiences with advanced combustion mode
- Improve the multi-mode coordination strategy by exploring the combustion mode switching boundaries between SI and SACI
- Given the different combustion mode switching behaviors observed, it is likely the switching boundaries of in/out of SACI mode will be different



- Complete CFD modeling of premixed combustion characterized for SACI, providing insights for model simplification
- Evaluate robustness of advanced combustion control under varying environmental conditions on single-cylinder engine
- Improve control-oriented modeling of SACI combustion with findings from CFD modeling



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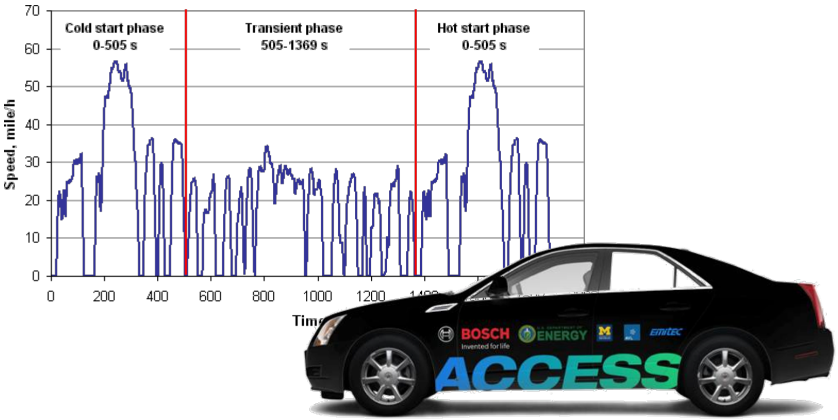
Overview – Aftertreatment System



Approach

- Low cost three way catalyst aftertreatment solution for multi-mode combustion concept
- Full-time stoichiometric operation in spark ignited and advanced combustion modes to minimize mode switch penalties
- Evaluate potential transient lean NOx handling aftertreatment options to extend benefits of low temperature (low NOx) combustion process to lean operation in multi-mode concept

Major Accomplishments

- Determined aftertreatment system performance during transient mode switch conditions to evaluate tradeoff between fuel economy and emissions for lean HCCI concept
- Performed initial vehicle cold start and emissions calibration to evaluate baseline performance
- Designed SCR package, developed coating process, and built initial passive SCR substrate

Summary

- Initial FTP-75 drive cycle emissions results promising with key areas for cold start emissions reductions identified
- Excellent three way catalyst performance after light-off confirmed
- Lean HCCI with TWC alone not suitable for low emissions high efficiency concept → some lean aftertreatment would be required

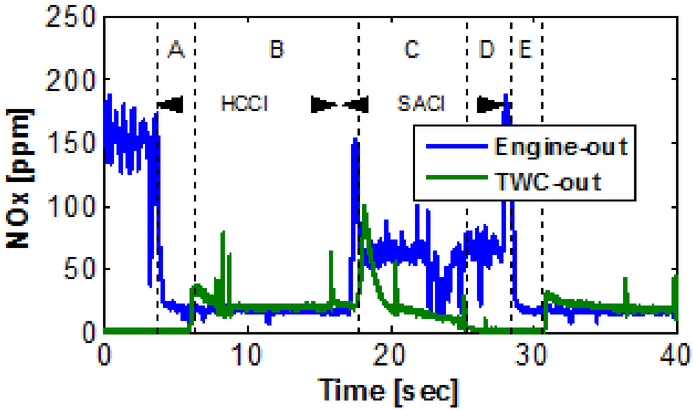
Aftertreatment System Future Work

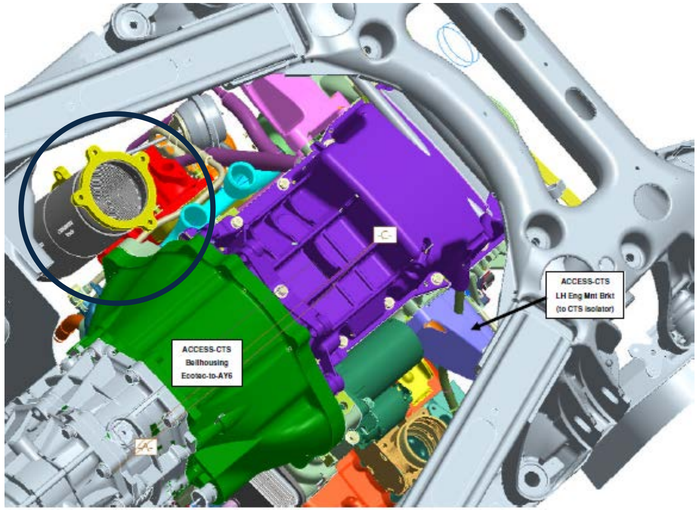
Improving the tradeoff of efficiency and emissions

→ <u>Aftertreatment for lean state operation</u>
- Passive SCR performance transient operation
    - Lean HCCI → stoich transition
    - Low emission, fuel cut-off enabler

→ <u>Cold start emission optimization</u>
- Explore the system benefits during run-up and catalyst heating phases utilizing capabilities of multi-mode combustion platform
    - Cam profile switching, extended range cam phaser, PFDI fuel system

→ <u>Handling mode switch and SACI transients</u>
- Define cost optimization potential of TWC system accounting for air-fuel ratio deviations in transient operation of multi-mode combustion concept





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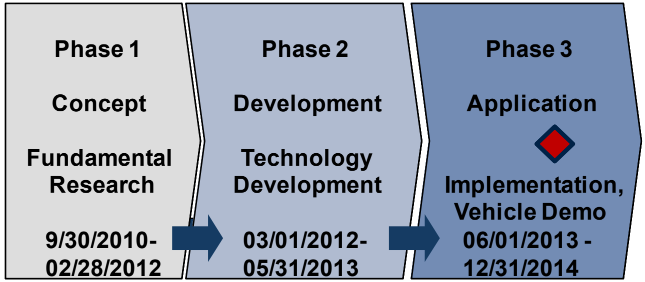
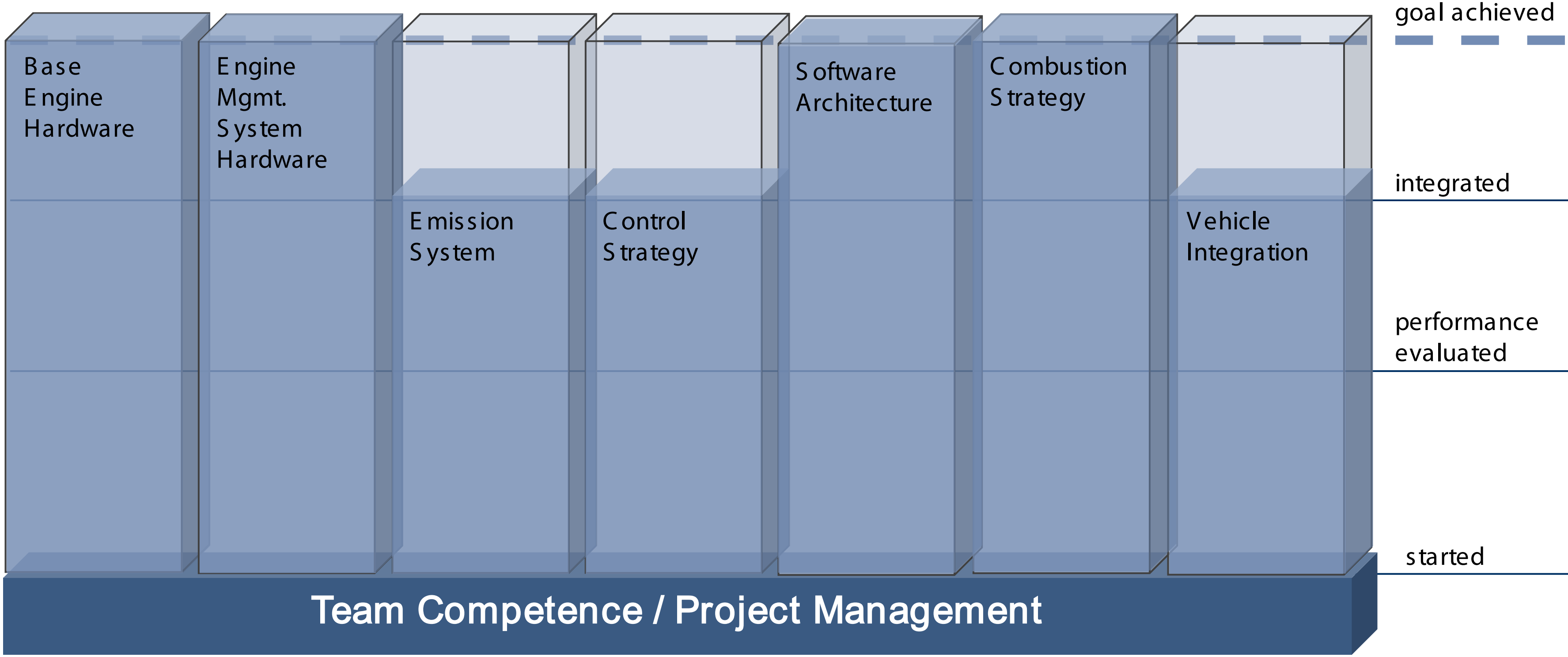
Program Targets

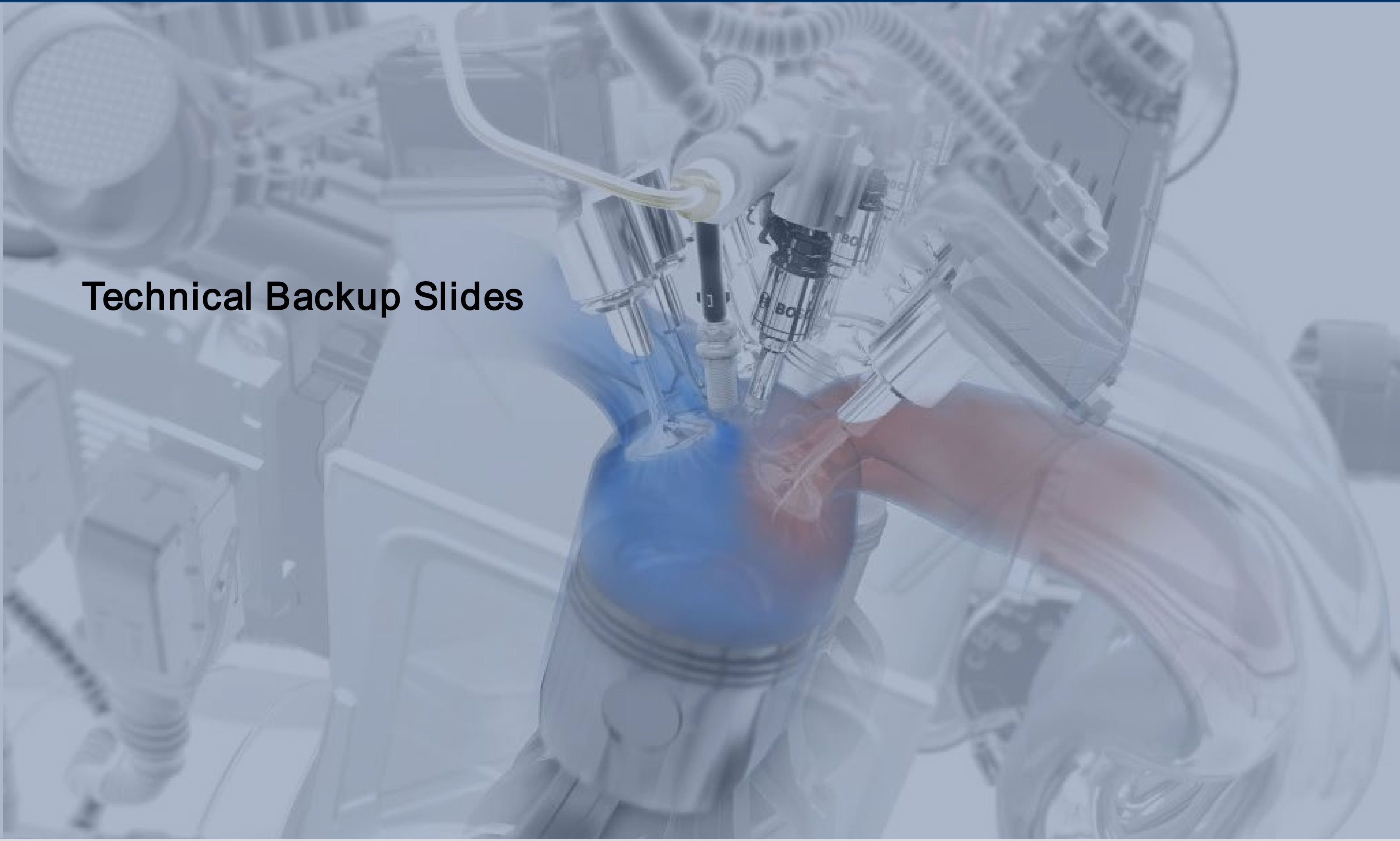
- >25% improved FE
- SULEV Capable
- Commercially Viable



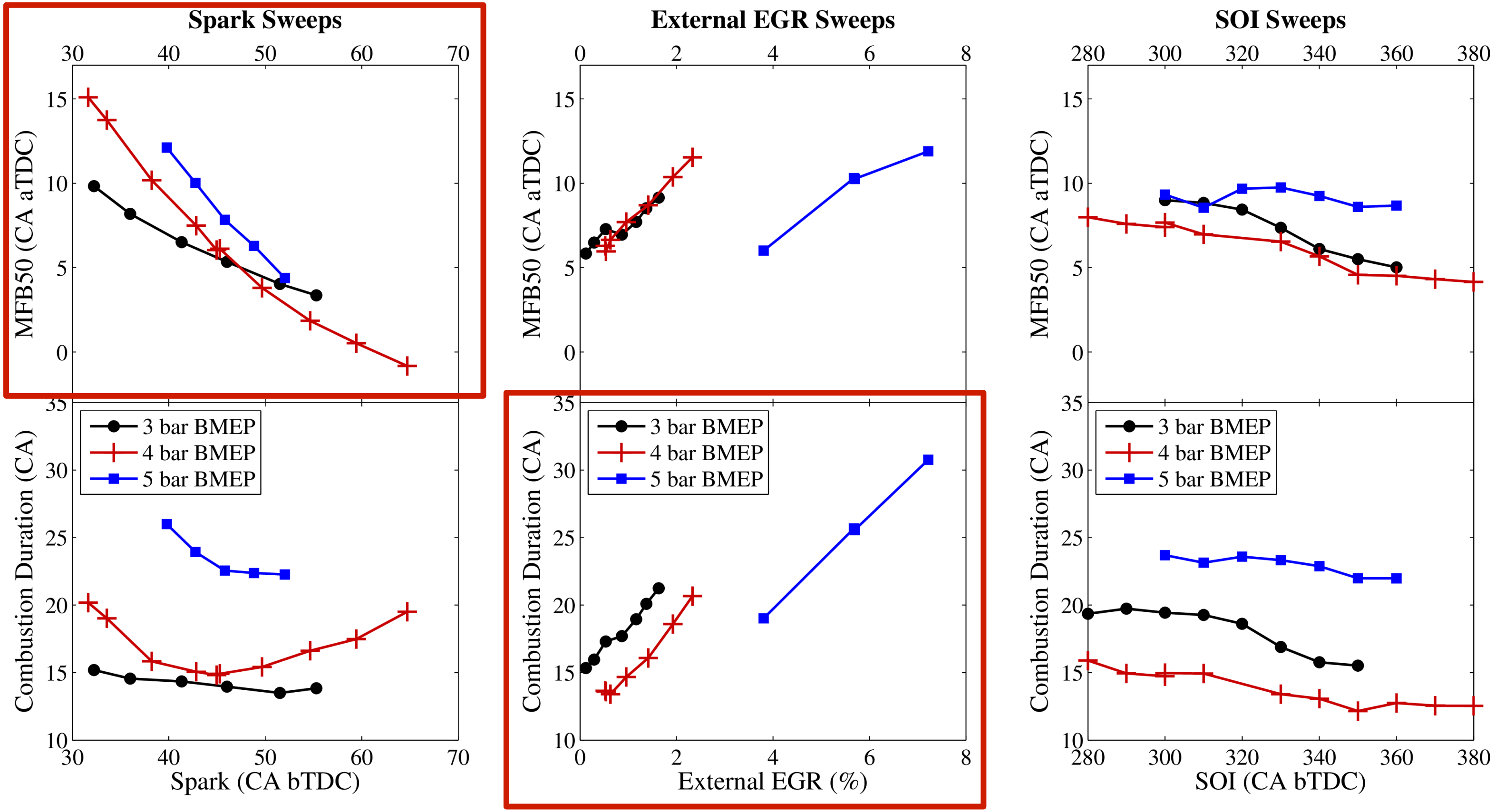


Impressions from first SACI Ride April 8th 2014

Technical Backup Slides



SACI Combustion Control: Key Actuators



Spark and EGR are identified as key actuators for combustion phasing and duration regulation, requiring coordinated control due to cross-sensitivity

All sweeps recorded at 1500 RPM on ACCESS multi-cylinder prototype engine