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

Arlington, Virginia
May 18th, 2012

“This presentation does not include any confidential material”
• Project Overview
• Relevance
• Approach
• Collaboration and Coordination
• Accomplishments and Future Work
• Summary
**2012 DOE Merit Review – ACCESS – Overview**

### 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

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

### Partners

- **US Department of Energy**
- Robert Bosch LLC
- AVL
- University of Michigan, Ann Arbor
- Stanford University
- Emitec
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Combustion Concept – Boosted Lean HCCI + Engine Downsizing

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

- 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, StartStop
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
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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
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COMBUSTION

SOFTWARE
ARCHITECTURE

CONTROLS
2012 DOE Merit Review – ACCESS – Accomplishments

- Concept Feasibility
- Fuel Econ. And Emissions
- Experimental Validation
- Biofuels investigation
- rCFD – LES and RANS

- Control-Oriented Modeling
- Engine Control Development
- Control Validation

- Optimal Combustion Mode Switch Strategies

- Multi-Mode Combustion ECU

- Base Engine Control Unit
- Controls Implementation
- Vehicle Interface

- Real-time Controls in ECU

Demo Vehicle
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

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

Industry support enables university researchers to focus on innovation
### Fundamental Combustion & Fuels

#### Approaches
- 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
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

<table>
<thead>
<tr>
<th>BSFC [g/kW-hr]</th>
<th>1500 RPM 2.0 bar BMEP</th>
<th>2000 RPM 3.0 bar BMEP</th>
<th>2500 RPM 2.0 bar BMEP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline 3.6L PFI Engine</strong></td>
<td>400</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td><strong>SI - Prototype 1 Engine</strong></td>
<td>300</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td><strong>HCCI - Prototype 1 Engine</strong></td>
<td>250</td>
<td>250</td>
<td>350</td>
</tr>
</tbody>
</table>

- * 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

- Control-Oriented Model Development
- Engine Control Development
- Control Validation
- Real-time Controls in ECU
- Optimal Combustion Mode Switch Strategies

- Concept Feasibility
- Fuel Econ. And Emissions
- Experimental Validation
- Biofuels investigation
- rCFD – LES and RANS

- Multi-Mode Combustion

- Base Engine Control Unit
- Controls Implementation
- Vehicle Interface

- Concept Feasibility
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HCCI Control Architecture

Model-based control to enable fast and robust HCCI transitions

- Coordinate exhaust valve and injection timing with mid-ranging control strategy
- Cylinder-to-cylinder balancing with cylinder-individual fuel control with reference cylinder approach
Control-Oriented Modeling of HCCI Combustion

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

Multi-Cylinder Engine

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

Main Actuator (inputs): EVC, SOI, mfuel

Target Performance Variable (output): CA50

Single-Cylinder Engine

Steady-State Engine Speed Sweep

Transient from 1600 to 1900 RPM

Steady-State EVC Sweep

Steady-State Fuel Quantity Sweep
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.
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

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
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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

Supercharging & Turbocharging
- Coordination of multiple boost devices

Tricore Microcontroller
- 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

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

Innovative ideas of researchers are quickly tested on the engine
Overview - Software Architecture

• 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

Approach

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

Team Competence / Project Management

- Base Engine Hardware
- Engine Mgmt. System Hardware
- Emission System
- Control Strategy
- Software Architecture
- Combustion Strategy
- Bio-Fuel Combustion

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