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Project Overview

Relevance

Approach

Collaboration and Coordination

Technical Accomplishments

Summary and Future Work
### 2013 DOE Annual Merit Review – ACCESS

#### Budget

<table>
<thead>
<tr>
<th>Total Project Budget</th>
<th>DOE Funding</th>
<th>Partner Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$24,556,737</td>
<td>$11,953,786</td>
<td>$12,602,951</td>
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</table>

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

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

- **Phase 3 Budget**
  - $7,127,517

#### Barriers and Targets

The project targets 25% fuel efficiency improvement to support energy independence and CO2 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

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
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<tbody>
<tr>
<td>Concept</td>
<td>Development</td>
<td>Application and Vehicle Demo</td>
</tr>
<tr>
<td>Fundamental Research</td>
<td>Technology Development</td>
<td>06/01/2013 - 12/31/2014</td>
</tr>
</tbody>
</table>

- **Phase 1**
  - Concept Fundamentals
  - 9/30/2010 - 02/28/2012

- **Phase 2**
  - Development
  - 03/01/2012 - 05/31/2013

- **Phase 3**
  - Application
  - 06/01/2013 - 12/31/2014

#### Partners

- US Department of Energy
- Robert Bosch LLC
- AVL
- University of Michigan
- Stanford University
- Emitec
## Engine & Controls Development Phase II

1. Target Multi Mode Combustion Engine is based on GM Ecotec 2.0 L DI Turbo platform
2. All Base Engine HW design and improvements for target engine configuration lead by **AVL**
3. All Engine Management System design and improvements for target system configuration lead by **Bosch**
4. 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.
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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

## 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

### 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.

## 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

- Technology to the Market
  - technology made available

- Stringent Emissions
  - meets 2025 emission goals
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
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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

**Go/No-Go Decision**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Fundamental Research</td>
<td>Technology Development</td>
<td>Application &amp; Vehicle Demo</td>
</tr>
<tr>
<td>2010.10</td>
<td>2012.03</td>
<td>2013.06 - 2014.12</td>
</tr>
</tbody>
</table>

**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

- 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
2013 DOE Annual Merit Review – ACCESS – Approach

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

Control Strategies

Combustion Concepts

Software Integration
2013 DOE Annual Merit Review – ACCESS – Approach

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
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# Team Members

## Chevron Energy Technology Co.
- Technical Consultation
- Advisory and Information Exchange

## Stanford University
- Prof. Heinz Pitsch - Co-PI, CFD Simulations
- Julie Blumreiter - Advanced Combustion

## University of Michigan
- 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

## Robert Bosch LLC - Gasoline Systems
- Hakim Yilmaz - PI
- Oliver Miersch-Wiener - Co-PI, Project Management
- Dr. Li Jiang - Co-PI, Technical Lead
- Jeff Serniak - Combustion Concepts
- Julien Vanier - Software Integration
- Jason Schwanke - Control System
- Ben Wilcox - Vehicle Integration
- Nicholas Quinlan - Software Integration
- Angela Dragan - Government Affairs

## AVL North America - Powertrain Engineering
- 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. Ulrich Pfahl - Co-PI, Project Management
- Dr. Srinath Reddy - Co-PI, After-treatment Sys.

## US OEMs
- Information Exchange
- Technology Alignment

## Walter E. Lay Automotive Laboratory
- Dr. Stani Bohac - Co-PI, Adv. Combustion
- Dr. Jason Martz - Combustion Simulations
- Vasileios Triantopoulos - Advanced Combustion
- Janardhan Kodavasal - CFD Simulations
- Prasad Shingine - Engine Simulations
- Adam Vaugh - Combustion Modeling
- Vijay Manikandan - Comb. Mode Coordination

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2013 DOE Annual Merit Review – ACCESS – Collaboration & Coordination

Multidisciplinary team with 40+ researchers and engineers
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Overview

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

- HCCI Combustion
  - Control Sensitivity Analysis
  - Control Algorithm and Performance

- Combustion Mode Switch Strategy
  - Performance Evaluation
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

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

1. LNT: Lean NOx Trap
Prototype I Engine Data of HCCI & SACI Combustion demonstrate desired fuel efficiency improvement at frequently-visited drive-cycle operation points.
### Fuel Economy – Vehicle Simulations w/ Prototype I Engine Data

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<tr>
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<tbody>
<tr>
<td>Sim: Baseline 3.6L V6 Engine / SI</td>
<td>20.7</td>
<td>-</td>
<td>34.0</td>
<td>-</td>
</tr>
<tr>
<td>Sim: ACCESS Prototype I Engine / SI</td>
<td>26.2</td>
<td>+26.6%</td>
<td>39.7</td>
<td>+16.8%</td>
</tr>
<tr>
<td>Sim: ACCESS Prototype I Engine / SI &amp; NA HCCI (lean)</td>
<td>27.4</td>
<td>+32.4%</td>
<td>40.9</td>
<td>+20.3%</td>
</tr>
<tr>
<td>Sim: ACCESS Prototype I Engine / SI &amp; NVO SACI (stoichiometric)</td>
<td>26.9</td>
<td>+30.0%</td>
<td>42.0</td>
<td>+23.5%</td>
</tr>
<tr>
<td>Sim: ACCESS Prototype I Engine / SI &amp; NA HCCI (lean) &amp; NVO SACI (stoichiometric)</td>
<td>27.7</td>
<td>+33.8%</td>
<td>42.4</td>
<td>+24.7%</td>
</tr>
<tr>
<td>Sim: ACCESS Prototype I Engine / SI &amp; NVO SACI (stoichiometric) + Start-Stop</td>
<td>27.3</td>
<td>+31.8%</td>
<td>42.0</td>
<td>+23.5%</td>
</tr>
</tbody>
</table>

*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**
Torque demand driven engine control architecture enables multi-mode combustion control
HCCI Combustion: Control Strategy

**Torque Structure**
- **Operating Coordination**
  - Driver Demands
  - N, M* B(m)

**Air System**
- Engine Torque Structure
  - SOI [MR]
  - MFB50-EVC FB Controller (Reference Cylinder)
  - Exhaust Valve Controller

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

Proposed HCCI control strategies validated on multiple engine platforms.
SI-HCCI Combustion Mode Switch: Strategy

Approach 1: SI → HCCI Switch

Key Performance Indicator | Mode switch strategy
--- | ---
Efficiency | - | ++ | ++
SI combustion stability | - | + | +
Switch robustness | 0 | + | ++
Controller Feasibility | + | + | 0
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 SCR E

Proposed combustion mode switch strategy demonstrated desired performance
Combustion research and engine development

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

Vehicle Integration

2. Emission and chassis roller bench available at Bosch, capable of measuring target emission level including particulate number and mass.
3. Test vehicle operational with initial SI calibration and available for vehicle chassis emission and fuel economy investigations.

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

- 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 simultaneously
- 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

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Overview – Control System

• 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

Approach

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
### Overview - Software Architecture

<table>
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<tbody>
<tr>
<td><strong>Direct Injection</strong></td>
</tr>
<tr>
<td>- Up to 4 injecrions per cycle</td>
</tr>
<tr>
<td>- Precise control of small quantities</td>
</tr>
<tr>
<td><strong>Tricore Microcontroller</strong></td>
</tr>
<tr>
<td>- Computation power for model-based controls</td>
</tr>
<tr>
<td><strong>In-Cylinder Pressure Sensing</strong></td>
</tr>
<tr>
<td>- Cycle-to-cycle closed-loop combustion control</td>
</tr>
<tr>
<td><strong>Variable Valve Actuation</strong></td>
</tr>
<tr>
<td>- Electric valve timing (VVT) for fast transients</td>
</tr>
<tr>
<td>- 2-step valve lift for HCCI mode switch</td>
</tr>
<tr>
<td><strong>Air Path Control w/ ext. EGR</strong></td>
</tr>
<tr>
<td>- Coordination of multiple actuators</td>
</tr>
<tr>
<td>- ext. EGR control w/ LSU-IM sensor</td>
</tr>
<tr>
<td><strong>ETK Calibration Interface</strong></td>
</tr>
<tr>
<td>- Enables Rapid Prototyping</td>
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### 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
Program Targets
- >25% improved FE
- SULEV Capable
- Commercially Viable
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
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
Developed novel theoretical modelling approach for SACI combustion that includes premixed and auto-ignition combustion regimes.

Established CFD simulation framework for SACI to acquire physical understanding

1. SCRE: Single Cylinder Research Engine