Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion

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Project ID: ACE094
DE-EE0006839
ACE094 Project Overview

**Timeline**
- Project start: 10/1/2014
- Project end: 9/01/2018
- Percent complete: 33%

**Budget**
- Total project funding share
  - DOE: $9,812,865 (40%)
  - Contractor: $14,719,297 (60%)
- Budget Period Funding
  - BP1 2014-2015: $2,935,672
  - BP2 2015-2016: $3,442,329
  - BP3 2016-2017: $2,158,100
  - BP4 2017-2018: $1,276,763

**VT Programmatic Barrier**
- Improve the efficiency of light-duty engines for passenger vehicles through advanced combustion and minimization of thermal and parasitic losses.
- Project primarily addresses VT Program Barriers:
  - A: Advanced engine combustion regimes
  - B: Emission controls
  - D: Effective engine controls

**Partners**
- Delphi - Project Lead
- OEM partner - in negotiation
- University of Wisconsin - Madison
- Oak Ridge National Lab
- Umicore
Relevance and Project Objectives

• Relevance:
  - The Advanced Combustion Engine R&D (ACE R&D) subprogram supports the mission of the Vehicle Technologies Program to develop more energy-efficient and environmentally friendly technologies for highway transportation vehicles.
  - This project directly addresses two of the three primary ACE R&D directions:
    • Improve the efficiency of light duty engines for passenger vehicles and heavy duty engines for commercial vehicles through advanced combustion research and minimization of thermal and parasitic losses;
    • Develop aftertreatment technologies integrated with combustion strategies for emissions compliance and minimization of efficiency penalty.

• Project Goal:
  - The project will develop, implement and demonstrate a low temperature combustion scheme called Gasoline Direct-injection Compression Ignition (GDCI). The project will demonstrate a 35% fuel economy improvement over the baseline vehicle while meeting Tier 3 emissions levels.

This Project supports the Vehicle Technologies Program's goal to improve the efficiency of light duty engines for passenger vehicles through advanced combustion and minimization of thermal and parasitic losses.
Relevance and Project Objectives

• **Project Objective:** Demonstrate the fuel consumption reduction capability of GDCI combustion at a vehicle level. The primary project focus is on a number of technical risks which must be overcome for a production-viable technology:
  
  • Development of an aftertreatment system that is effective in dealing with the low temperature challenges of a highly efficient engine.
  • Further refinement of the GDCI combustion system to achieve near-ideal air/fuel mixture preparation for high efficiency and low HC and CO emissions
  • Demonstration of transient control with high EGR levels during real-world transient driving maneuvers and over a broader range of ambient conditions

• **Objectives: (April 2015 – March 2016)**
  
  • Characterize Gen2 GDCI multicylinder engine on performance dynamometer
  • Design and build Gen2 exhaust aftertreatment system for Gen2 vehicle
  • Retrofit vehicle with Gen2 GDCI hardware and update engine controls
  • Design Gen3 GDCI engine

*This Project supports the Vehicle Technologies Program’s goal to develop aftertreatment technologies integrated with combustion strategies for emissions compliance and minimization of efficiency penalty*
Approach / Strategy

- The project will employ a unique low temperature combustion scheme called Gasoline Direct-injection Compression Ignition (GDCI) to achieve the targeted fuel economy improvements.
  - High compression ratio with multiple late injections (similar to diesel)
  - Gasoline which vaporizes and mixes easily at low injection pressure
  - Low-temperature combustion process for Partially-Premixed Compression Ignition

- The project will develop an aftertreatment system approach that works with the low-temperature challenges of a highly efficient engine:
  - Address: system content, system architecture, combustion strategies and catalysts materials
  - Collaboration with Oak Ridge National Lab and Umicore Autocat USA
Approach / Strategy

Develop, implement and demonstrate the fuel consumption reduction capability of GDCI at a vehicle level.

Is the concept viable?

How to design an engine around the concept?

How to control the engine?

How to make a vehicle drivable?

How to meet FE and emissions targets?

Engine design upgrades?

Engine control upgrades?

How to have the vehicle function under all operating conditions?

How to meet all regulatory requirements?

How to have a production-level of performance?
### Approach / Strategy:

**Milestones and go/no-go’s for FY 2015 and FY 2016**

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Task Title</th>
<th>Milestone Type</th>
<th>Milestone Description</th>
<th>Anticipated Quarter</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub Task 1.5.2</td>
<td>Build Gen2 engines</td>
<td>Milestone</td>
<td>Gen2 GDCI engine assemblies built and ready for debug</td>
<td>Q1 2015</td>
<td>Complete</td>
</tr>
<tr>
<td>Task 1.3</td>
<td>Engine and Vehicle Simulation</td>
<td>Milestone</td>
<td>GT Drive engine simulation completed for the Gen2 in the ATP1 vehicle</td>
<td>Q2 2015</td>
<td>Complete</td>
</tr>
<tr>
<td>Subtask 1.8.1</td>
<td>ORNL characterize Gen 2 GDCI LTC emissions</td>
<td>Go/No-Go</td>
<td>Gen2 engine built and characterized - Go/No-Go for Gen2 vehicle build activities</td>
<td>Q3 2015</td>
<td>Complete</td>
</tr>
<tr>
<td>Sub Task 1.8.2</td>
<td>Develop and build aftertreatment for Gen2 GDCI</td>
<td>Milestone</td>
<td>Exhaust aftertreatment system designed and built for use on the Gen2 GDCI development vehicle.</td>
<td>Q3 2015</td>
<td>Complete</td>
</tr>
<tr>
<td>Sub Task 1.7.3</td>
<td>Gen2 engine controls on Start Cart</td>
<td>Milestone</td>
<td>Start Cart upgraded to a Gen2 Engine and Control system to support the follow-on vehicle development phase.</td>
<td>Q4 2015</td>
<td>In Process</td>
</tr>
<tr>
<td>Sub Task 2.4.2.9</td>
<td>Aftertreatment built for Gen3 MCE dyno testing</td>
<td>Milestone</td>
<td>Aftertreatment materials developed at Umicore and exhaust system built at Delphi CTCM for the Gen3 multi-cylinder dynamometer test engines.</td>
<td>Q1 2016</td>
<td>In Process</td>
</tr>
<tr>
<td>Sub Task 2.4.2</td>
<td>Build Gen3 MCE</td>
<td>Milestone</td>
<td>Gen3 engine assembly built and ready for debug</td>
<td>Q2 2016</td>
<td>In Process</td>
</tr>
<tr>
<td>Sub Task 2.6.2</td>
<td>Vehicle Design</td>
<td>Milestone</td>
<td>Vehicle packaging studies complete and ability to build Gen3 GDCI vehicle is assured.</td>
<td>Q3 2016</td>
<td>In Process</td>
</tr>
<tr>
<td>Subtask 2.5.4</td>
<td>Gen3 engine built and characterized</td>
<td>Go/No-Go</td>
<td>Gen3 dyno engine efficiency and emissions evaluated to determine if project is ready for build of Gen3 vehicle.</td>
<td>Q4 2016</td>
<td>In Process</td>
</tr>
<tr>
<td>Task 2.3.3</td>
<td>Test and refine MCE system</td>
<td>Milestone</td>
<td>Benchmark SI engine mapped and refined for fuel efficiency and emissions. Data ready for use in comparison to the GDCI multi-cylinder test engines.</td>
<td>Q4 2016</td>
<td>In Process</td>
</tr>
</tbody>
</table>
Technical Accomplishments and Progress: Overview

• Develop and refine engine controls and calibration
• Evaluate Fuel Efficiency on test cycles
• Test vehicle using Gen 1.0 and Gen 1.8 GDCI hardware
• Develop and characterize Gen 2 GDCI multi-cylinder engine
• Design Gen 3 GDCI base engine
• Design Gen 3 GDCI exhaust aftertreatment
Technical Accomplishments and Progress: Vehicle Level Progress

• Fuel Economy Testing using room temperature start for EPAIII

<table>
<thead>
<tr>
<th>Test Cycle</th>
<th>Improvement over Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPAIII</td>
<td>33 %</td>
</tr>
<tr>
<td>HWFET</td>
<td>30 %</td>
</tr>
<tr>
<td>Combined</td>
<td>32 %</td>
</tr>
</tbody>
</table>

DOE ATP-2 Target: 35% Combined FE Improvement

• Gen 1.8 engine hardware update
  ▪ Completed a partial hardware upgrade of vehicle to Gen 2 level content
    • Gen 2 Exhaust Manifold
    • Modified VTG turbo rack control
    • Re-located / new EGR valve
    • Electric engine coolant pump (replaces mechanical pump)
    • Gen 2 high pressure fuel pump
    • Post-turbo Hydrocarbon Trap / Oxidation catalyst
Technical Accomplishments and Progress: Vehicle Level Progress: Emissions

Reduced emissions via calibration and Gen 1.8 aftertreatment

- Post-turbo Hydrocarbon Trap / Oxidation catalyst
- No NOx aftertreatment (Gen 1.8 aftertreatment system is a test mule system, not a system targeted at a specific emissions standard)

Delphi GDCI Vehicle Emissions Performance Improvement on Room Temperature FTP Test Cycle
Initial Gen 1.8 Data, calibration in process

Observation: New HC Trap catalyst having positive impact on HC and CO emissions.

61% Eng-out NOx reduction via cal improvements, but with significant (12%) FE penalty.
Technical Accomplishments and Progress: Vehicle Level Progress: Emissions

- Demonstrated HC storage of 1.2g during initial 34s of EPAIII test
Technical Accomplishments and Progress: Dynamometer Testing – Gen 2 GDCI

- Gen 2 Multi cylinder engine characterized on performance dynamometer
- BSFC significantly improved relative to Gen 1 engine
  - 211 to 214 g/kWh over wide load range
  - Target for Gen 3 engines: 200 g/kWh

**Typical Comb Characteristics**

- NOx<0.2 g/kWh
- FSN<0.1
- COV IMEP<3%
- CNL below target

*The Gen2 multicylinder GDCI engine has been characterized on the engine dynamometer and approved for Gen2 vehicle use.*
Technical Accomplishments and Progress: Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- Engine out emissions: Comparison of SI versus GDCI (Gen1 vehicle)

Engine out emissions for Gasoline Direct-injection Compression Ignition are comparable to engine out emissions for gasoline spark ignition engines
Technical Accomplishments and Progress: Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- Exhaust system temperature SI vs GDCI - compare

Gasoline Direct-injection Compression Ignition exhaust temperatures are significantly lower than exhaust temperatures of gasoline spark ignition engines and present the major challenge to meeting future emission regulations.
## Technical Accomplishments and Progress:

### Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

<table>
<thead>
<tr>
<th>Approach</th>
<th>Planned Method</th>
<th>Simulation</th>
<th>Design</th>
<th>Integration</th>
<th>Engine Level Test</th>
</tr>
</thead>
</table>
| Conserve Exhaust Heat             | * Integral, air-gap insulated exhaust manifold  
 * Insulated turbo-charger & pre-catalyst exhaust                                              | ✔️         | ✔️     | ✔️          |                   |
| Increase Exhaust Temperatures     | Fast, high-power intake air heater  
 (supports exhaust heating)                                                                  | ✔️         | ✔️     | ✔️          |                   |
| - Cold Starts                     |                                                                                                   |            |        |             |                   |
| Increase Exhaust Temperatures     | Expanded exhaust rebreathing                                                                     | ✔️         | ✔️     | ✔️          | ✔️                |
| - Light-to-Medium Loads           |                                                                                                   |            |        |             |                   |
| Close-Coupled Catalyst           | Pre-Turbo, Gasoline Oxidation Catalyst (GOC)                                                     | ✔️         | ✔️     | ✔️          | ✔️                |
| Trap HC on Cold Start             | Post-turbo HC trap and GOC  
 (release HC above light-off temperature)                                                          | ✔️         | ✔️     | ✔️          | ✔️                |
| Lean NOx Reduction                | Close-coupled SCR system                                                                          | ✔️         |        |             |                   |
| Low Temperature Catalysis         | Use lower temperature catalysts;  
 Umicore development and application                                                              | ✔️         |        |             |                   |
Technical Accomplishments and Progress: Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- Developmental stages of exhaust aftertreatment architecture:

- Gen 3 MCE exhaust aftertreatment architecture:
Technical Accomplishments and Progress:
Hardware Design and Build: Gen 3 Engines

- **Gen 2 GDCI Engine**
  - Cylinder head with compact, integral exhaust manifold with pre-turbo catalyst
  - New log style fuel rail, Fuel pump mounted to Cam Cover
  - New high pressure injectors
  - Low mass electric intake air heaters
  - Updated thermal management system
  - New aftertreatment system
  - New high mass electric intake air heaters
  - Gen 2 GDCI Engine
Collaboration and Coordination with Other Institutions

**Oak Ridge National Laboratory** - National Lab
- Analyze exhaust emissions samples after sample collection at the Delphi facility. (Collect, Analyze, Consult)

**Automotive OEM Partner**
- In negotiation

**University of Wisconsin Madison** - University
- Characterization testing of gasoline fuel injectors. (Test)

**Umicore Autocat USA** – Tier 1 Supplier
- Prepare and test low temperature exhaust aftertreatment samples. (Analyze, Design, Formulate, Build, Consult)
Remaining Challenges and Barriers

• Development of an aftertreatment system that is effective in dealing with the low temperature challenges of a highly efficient engine.

• Further refinement of the GDCI combustion system to achieve near-ideal air/fuel mixture preparation for high efficiency and low HC and CO emissions

• Demonstration of transient control with high EGR levels during real-world transient driving maneuvers and over a broader range of ambient conditions
Proposed Future Work

Next Steps

• Further develop and refine controls and calibration of Gen2 GDCI vehicle for improved fuel economy and emissions with an emphasis on transient operation.

• Construct Gen3 GDCI engine with next generation hardware including fuel injectors and aftertreatment architecture.

• Develop low temperature exhaust aftertreatment system based on GDCI emissions data and temperature profiles:
  ▪ Delphi and ORNL working closely with Umicore

• Build vehicle using Gen3 GDCI hardware and controls
Summary

• Excellent progress has been made over the past year

• Project tasks have not changed from original plan but momentum has been slowed due to OEM partner negotiations

• Primary areas of technical accomplishments since the start of the project include:
  - Characterization of Gen 2 GDCI multi-cylinder engine
  - Development and refinement of engine controls and calibration using vehicle with Gen 1 and Gen 1.8 level hardware
  - Design and initial build of Gen 3 GDCI hardware

• Future Work for Calendar Year 2016 / 2017:
  - Build and characterize Gen 3 GDCI engines
  - Develop low temperature exhaust aftertreatment system based on Gen 3 architecture
  - Refine controls and calibration of GDCI for improved fuel economy and emissions with an emphasis on vehicle transient operation.
Thank you to the Department of Energy for supporting this project.