Ultra Efficient Light-Duty Powertrain with Gasoline Low-Temperature Combustion

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ACS094 Project Overview

**Timeline**
- Project start: 10/1/2014
- Project end: 3/31/2019
- Percent complete: 59%

**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

**Budget**
- Total project funding share:
  - DOE: $9,812,865 (40%)
  - Contractor: $14,719,297 (60%)
- Budget Period Funding:
  - BP1 10/2014-1/2016: $2,935,672
  - BP2 1/2016-8/2017: $3,442,329
  - BP3 9/2017-8/2018: $2,158,100
  - BP4 9/2018-3/2019: $1,276,763

**Partners**
- Delphi - Project Lead
- OEM partner – Alliance formed for project
- 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 approach 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:

- Characterize Gen2 GDCI vehicle and refine controls
- Design / package Gen3 vehicle
- Design and build Gen3 exhaust aftertreatment system
- Build Gen3 GDCI engine

<table>
<thead>
<tr>
<th>VT Program Barrier</th>
<th>Technical Risk Being Addressed</th>
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</thead>
<tbody>
<tr>
<td>Combustion Regimes</td>
<td>Refinement of the GDCI combustion system to achieve near-ideal air/fuel mixture preparation for high efficiency and low emissions.</td>
</tr>
<tr>
<td>Emission Controls</td>
<td>Development of an aftertreatment system that is effective in dealing with the low temperature challenges of a highly efficient engine.</td>
</tr>
<tr>
<td>Engine Controls</td>
<td>Execute transient control with high EGR levels during real-world transient driving maneuvers and over a broad range of ambient conditions</td>
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• **Objectives: (April 2016 – March 2017)**

  - Characterize Gen2 GDCI vehicle and refine controls
  - Design / package Gen3 vehicle
  - Design and build Gen3 exhaust aftertreatment system
  - Build 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 approach 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 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**

- **Milestones and go/no-go’s for FY 2016 and FY 2017**

<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 2.4.2.2</td>
<td>Gen3 Initial fuel system build</td>
<td>Milestone</td>
<td>Gen 3 fuel initial system built and available for testing including pumps, rails, high pressure lines, and rail pressure sensors</td>
<td>Q1 2016</td>
<td>Complete</td>
</tr>
<tr>
<td>Sub Task 2.2.1.2</td>
<td>Thermal System Simulation</td>
<td>Milestone</td>
<td>Simulation completed for Gen3 Thermal Management system and data available</td>
<td>Q2 2016</td>
<td>Complete</td>
</tr>
<tr>
<td>Sub Task 2.4.1</td>
<td>Design Gen3 MCE</td>
<td>Milestone</td>
<td>Gen3 GDCI engine and subsystems designed and ready for engine builds</td>
<td>Q3 2016</td>
<td>Complete</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>Q4 2016</td>
<td>Complete</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>Q1 2017</td>
<td>Complete</td>
</tr>
<tr>
<td>Subtask 2.6.4.2</td>
<td>Powertrain installation</td>
<td>Milestone</td>
<td>All major project related Gen 3 systems and subsystems are installed in the new vehicle. The vehicle has completed assembled and ready for final wiring and pumping</td>
<td>Q2 2017</td>
<td></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 Gen3 vehicle work.</td>
<td>Q3 2017</td>
<td></td>
</tr>
<tr>
<td>Sub Task 1.9.6.2</td>
<td>Vehicle level emissions testing at Umicore</td>
<td>Milestone</td>
<td>Umicore sampled and analyzed emissions from the Gen2 GDCI vehicle and provided results</td>
<td>Q4 2017</td>
<td></td>
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Any proposed future work is subject to change based on funding levels.
Technical Accomplishments and Progress: Overview

• Developed and refined engine controls and calibration
• Tested vehicle using Gen 1.8 and Gen 2 GDCI hardware
• Characterized Gen 2 GDCI multi-cylinder engine
• Designed Gen 3 GDCI engine hardware
• Built Gen 3 GDCI exhaust aftertreatment
• Built Gen 3 GDCI engine
• Performed initial fire and debug of Gen 3 GDCI engine
Technical Accomplishments and Progress: Vehicle Level Progress: Controls Refinement

- Combustion phasing control improved with refined algorithms
- Combustion stability improved through Partial Intake Stroke Fueling
- Inlet air temperature control within the target of +/- 1.5°C

Progress made in adapting control systems hardware, algorithms and software to Gen2 hardware configuration.
Technical Accomplishments and Progress: Vehicle Level Progress

• Fuel economy testing using room temperature start for EPA III

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

Results from Gen1 GDCI vehicle which does not meet emissions goals

DOE ATP-2 Target: 35% Combined FE Improvement

• Gen 2 Vehicle Build and Integration
  ▪ Replaced engine with Gen 2 version
  ▪ Updated Thermal Management System
    ▪ Full Gen 2 content,
    ▪ Pull-ahead Gen 3 Charge air Cooler 1

Gen2 GDCI vehicle has been built and is being used to develop controls with an emphasis on transient operation.
Technical Accomplishments and Progress: Emissions Characterization of Gen2 Engine with ORNL

- Team from ORNL visited Delphi to measure both engine out and tailpipe emissions for the Gen2 dynamometer engine.
- Engine was equipped with the Gen2 aftertreatment system, which included only oxidation catalysts.

Engine out emissions similar to SI engine

Exhaust temperatures much lower than SI engine
Technical Accomplishments and Progress: Hardware Design: Gen 3 GDCI Fuel Injection System

“Wetless” Fuel System Concept for Low Smoke

**Engine**
- Long stroke increases clearance for late injection
- Zero swirl and squish to minimize heat losses

**Fuel System**
- Central mount GDi
- 350+ bar injection pressure

**Fuel Injector**
- Wide spray angle matched to piston bowl
- High injection rate
- Fast atomization spray
- Extensive simulation and testing in 2016

Injector and spray characteristics are one of the most important design factors for successful GDCI combustion control.
Technical Accomplishments and Progress: Hardware Design: Gen 3 GDCI Fuel Injection System

Fuel Injection Strategy

**Part Load**
- Best operation using early injection
- Avoid over mixed operation (HCCI region)

**High Load**
- Use GDCI late injection
- Shorter mixing time requires higher injection pressure
- New wetless system greatly reduces smoke
- Strong pressure dependency for late injection

**Fuel Injection Strategy** is a key control factor for successful GDCI combustion control.
Technical Accomplishments and Progress: Hardware Design: Gen 3 Exhaust Aftertreatment

Engine out emissions for GDCI are comparable to engine out emissions for gasoline spark ignition engines however exhaust temperatures are significantly lower than exhaust temperatures of gasoline spark ignition engines and present the major challenge to meeting future emission regulations.

An exhaust aftertreatment system has been developed to conserve the limited available exhaust heat and is undergoing initial testing now.
Technical Accomplishments and Progress: Hardware Design and Build: Gen 3 Engines

- New aftertreatment system
- EGR system with reduced volume for faster response
- Low mass, fast, electric intake air heaters
- New high pressure injectors
- Updated thermal management system
- Long stroke base engine
- Cylinder head with compact, integral exhaust manifold with pre-turbo catalyst
- Gen3 GDCI engine first fire Feb 2017
Technical Accomplishments and Progress: Dynamometer Testing – Gen 3 GDCI

- Gen 3 Multi cylinder engine first fire February 2017 on performance dynamometer
- BSFC significantly improved relative to Gen 1 and Gen 2 engines in early data
  - Target for Gen 3 engines: 200 g/kWh

\[
\text{BSFC E00 (g/kWh)} \quad \text{vs.} \quad \text{BMEP (kPa)}
\]

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

The Gen3 multicylinder GDCI engine has been built and is undergoing Engine dynamometer break-in – Early results are very encouraging.
Responses to Previous Year Reviewers’ Comments

Included in the excellent feedback from the 2016 AMR were some questions about GDCI torque capabilities: “The approach should consider torque/power targets and time to torque.”

Response:

- Preliminary torque and power tested on the Gen1 engine. BMEP target of 20 bar was achieved at 2000 and 2500 rpm. Full load development was a lower priority for Gen 1 but the Gen3 engines are designed for late injection and low full-load smoke.

- Excess air available in lean combustion, can increase torque rapidly (next combustion event). Max rate limited by available oxygen. Controllable rate without excessive noise limited by EGR transport delay.
Another area of feedback from the 2015 AMR was on collaboration and communication with others working on low temperature combustion / PCCI. “ANL is doing significant work on GCI combustion fundamentals, and the reviewer wondered why Delphi is not making use of this.”

Response:
- The project team has connected with other researchers doing similar work. In the past year Argonne National Lab, Sandia National Lab, Lund University and Oakridge National Lab have all visited and overviewed the GDCI progress and equipment. Discussions have recently begun with Co-Optima with the hopes to work with that team and perhaps run tests on the GDCI hardware.

Further 2015 AMR Feedback: “A major milestone will be benchmarking with alternative approaches.”

Response:
- GDCI will be benchmarked against a modified 1.8L Turbocharged GDi engine. A VW Gen 3 EA888 has been updated with Delphi/Tula Dynamic Skip Fire (outside of DOE funding) and is in the process of being fully mapped. This engine represents a future state of the art spark ignition engine that will be in the market at the time that GDCI would be introduced to production.
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 Alliance Partners
OEM ‘Alliance’ formed to provide project guidance and ‘path to production’ feedback. (Consult)

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

- Refine and demonstrate aftertreatment system that is effective in dealing with the low temperature challenges of a highly efficient engine.

- Further refine the GDCI combustion system, using Gen3 hardware, to achieve near-ideal air/fuel mixture preparation for high efficiency and low HC and CO emissions.

- Demonstrate transient control with high EGR levels during real-world transient driving maneuvers and over a broader range of ambient conditions.

Any proposed future work is subject to change based on funding levels.
Proposed Future Work

Next Steps

• Map Gen 3 GDCI engine on performance dynamometer

• Characterize Gen 3 GDCI engine emissions on performance dynamometer

• Complete controls preparations for Gen 3 engine content and vehicle controls architecture using Gen 2 vehicle.

• Build vehicle using Gen3 GDCI hardware and controls
  ▪ Build Gen3 engine
  ▪ Install Gen3 thermal management system
  ▪ Install controllers and harnesses

Any proposed future work is subject to change based on funding levels.
Summary

• Excellent progress has been made over the past year

• Project tasks and milestones are on track.

• OEM ‘Alliance’ formed

• Primary areas of technical accomplishments since the start of the project include:
  ▪ Characterization of Gen 2 GDCI engine out emissions
  ▪ Development and refinement of engine controls and calibration using Gen 2 vehicle
  ▪ Build and fire of Gen 3 GDCI engine

• Future Work for Calendar Year 2017 / 2018:
  ▪ Map and characterize Gen 3 GDCI engine
  ▪ Complete controls preparations for Gen 3 engine content and vehicle controls architecture.
  ▪ Build Gen 3 Vehicle.

Any proposed future work is subject to change based on funding levels.
Thank you to the Department of Energy for supporting this project.
Technical Accomplishments and Progress:
Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

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

![Graph of engine out emissions comparison]

*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.