# Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion

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2016 DOE Vehicle Technologies Review
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Project ID: ACE094
DE-EE0006839

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# ACE094 Project Overview

## Timeline

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

## 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: $14,719297 (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

## Partners

- Delphi - Project Lead
- OEM partner - in negotiation
- University of Wisconsin - Madison
- Oak Ridge National Lab
- Umicore

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# 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.*

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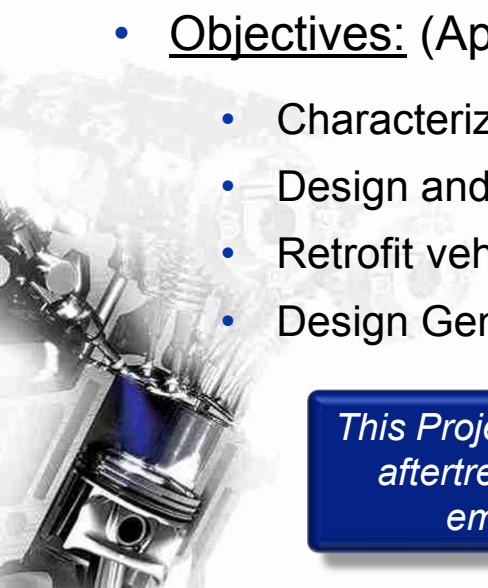
# Relevance and Project Objectives

- 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*

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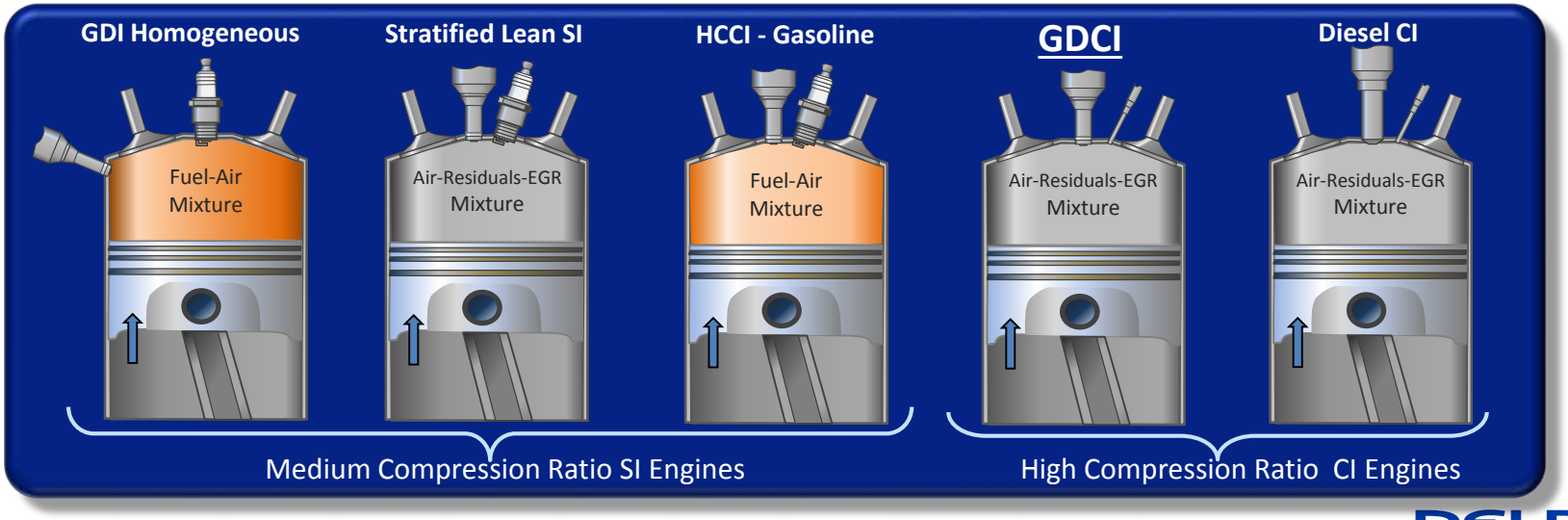
# Approach / Strategy

- 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

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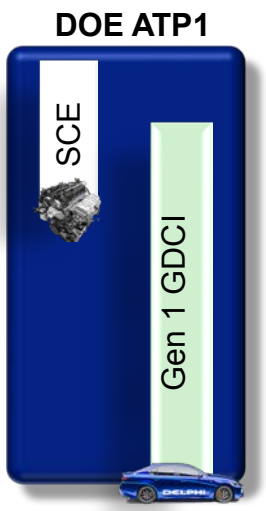
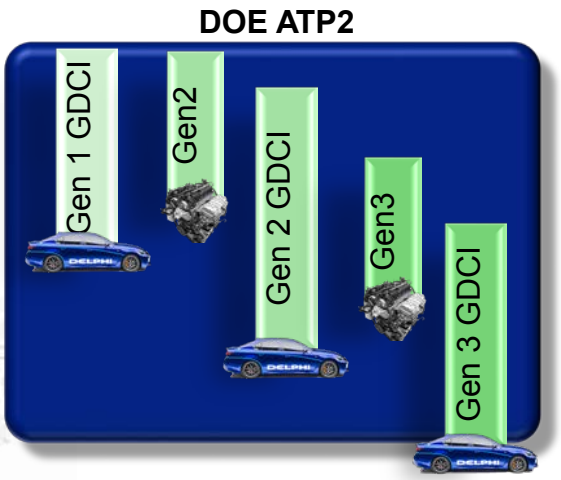
# Approach / Strategy

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




**2008** — Is the concept viable?

**2010** — How to design an engine around the concept?

How to control the engine?

How to make a vehicle drivable?

**2014** — How to meet FE and emissions targets?

Engine design upgrades?

Engine control upgrades?

How to have the vehicle function under all operating conditions?

**2018** — How to meet all regulatory requirements?

How to have a production-level of performance?

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# Approach / Strategy: Milestones

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

**Project Decision Points**

Recipient: Delphi
Project: Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion

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

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# 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

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# Technical Accomplishments and Progress:
# Vehicle Level Progress

- Fuel Economy Testing using room temperature start for EPAIII

| Test Cycle | Improvement over Baseline |
|---|---|
| EPAIII | 33 % |
| HWFET | 30 % |
| Combined | 32 % |

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

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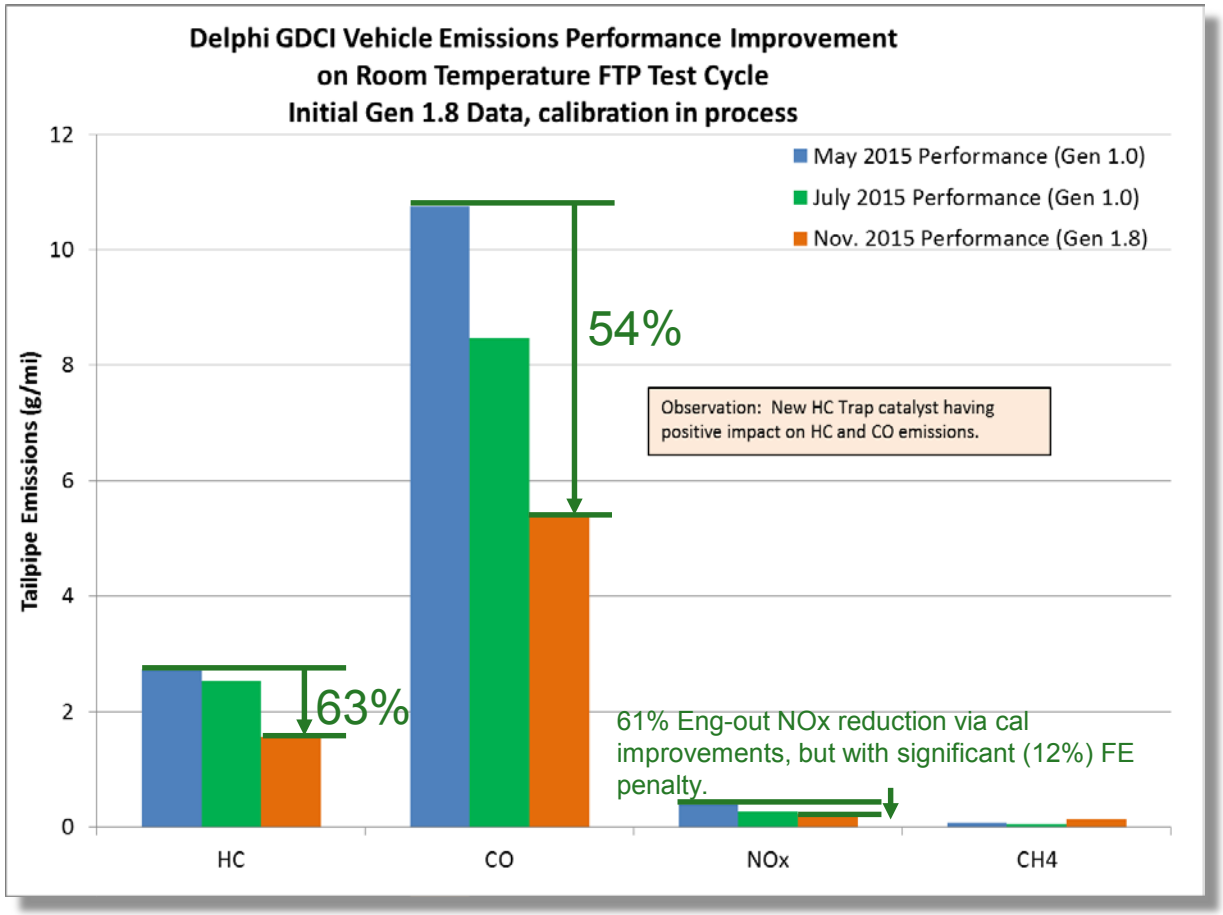
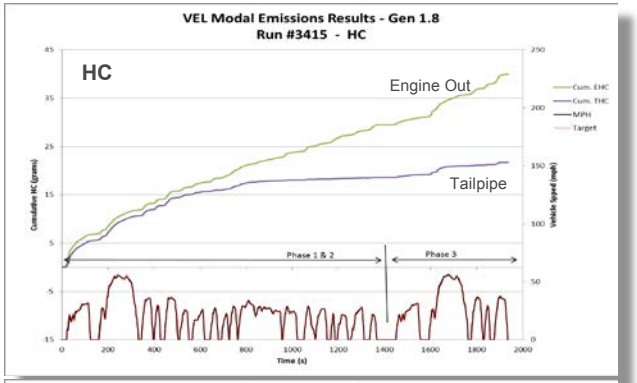
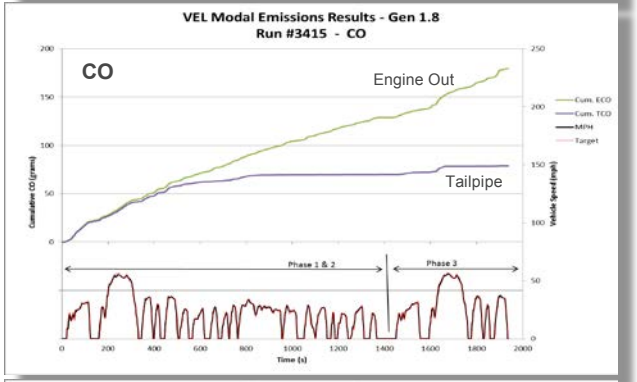
# Technical Accomplishments and Progress:
# Vehicle Level Progress: Emissions

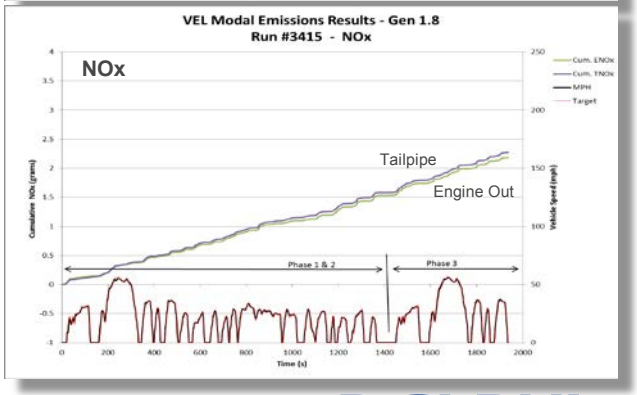
Reduced emissions via calibration and Gen 1.8 aftertreatment

- 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)

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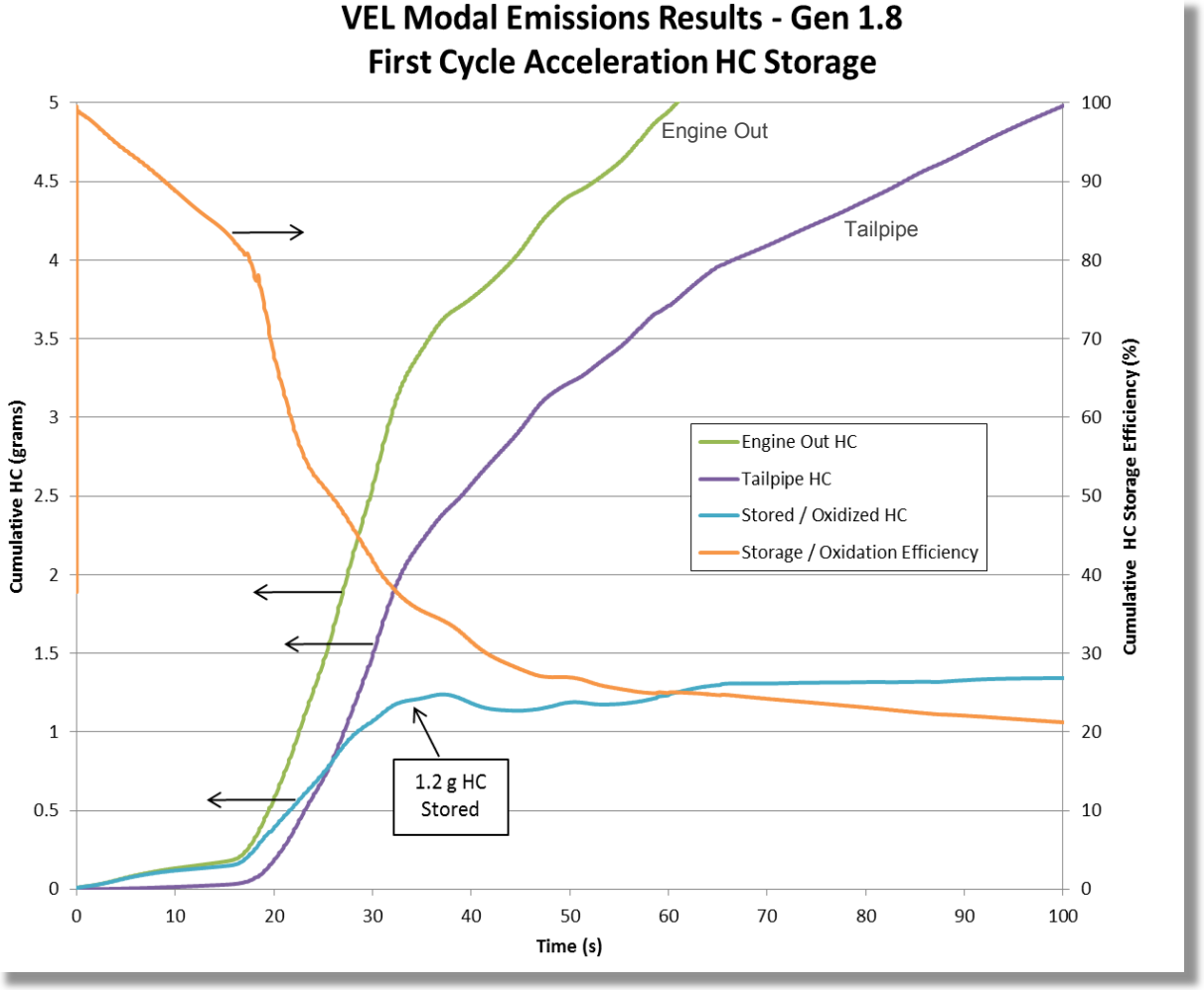
# Technical Accomplishments and Progress:
# Vehicle Level Progress: Emissions

- Demonstrated HC storage of 1.2g during initial 34s of EPAIII test

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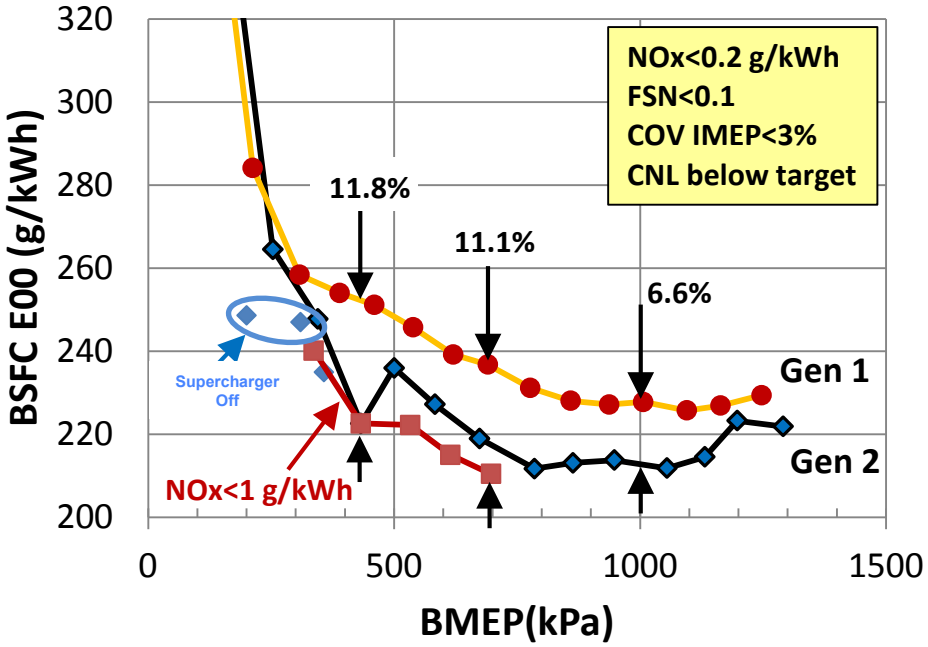
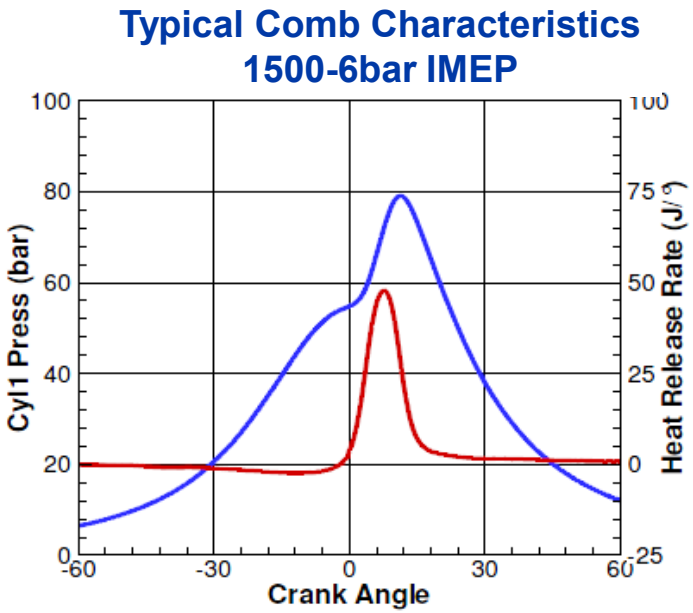
# Technical Accomplishments and Progress:
# Dynamometer Testing – Gen 2 GDCI

- 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




*The Gen2 multicylinder GDCI engine has been characterized on the engine dynamometer and approved for Gen2 vehicle use.*

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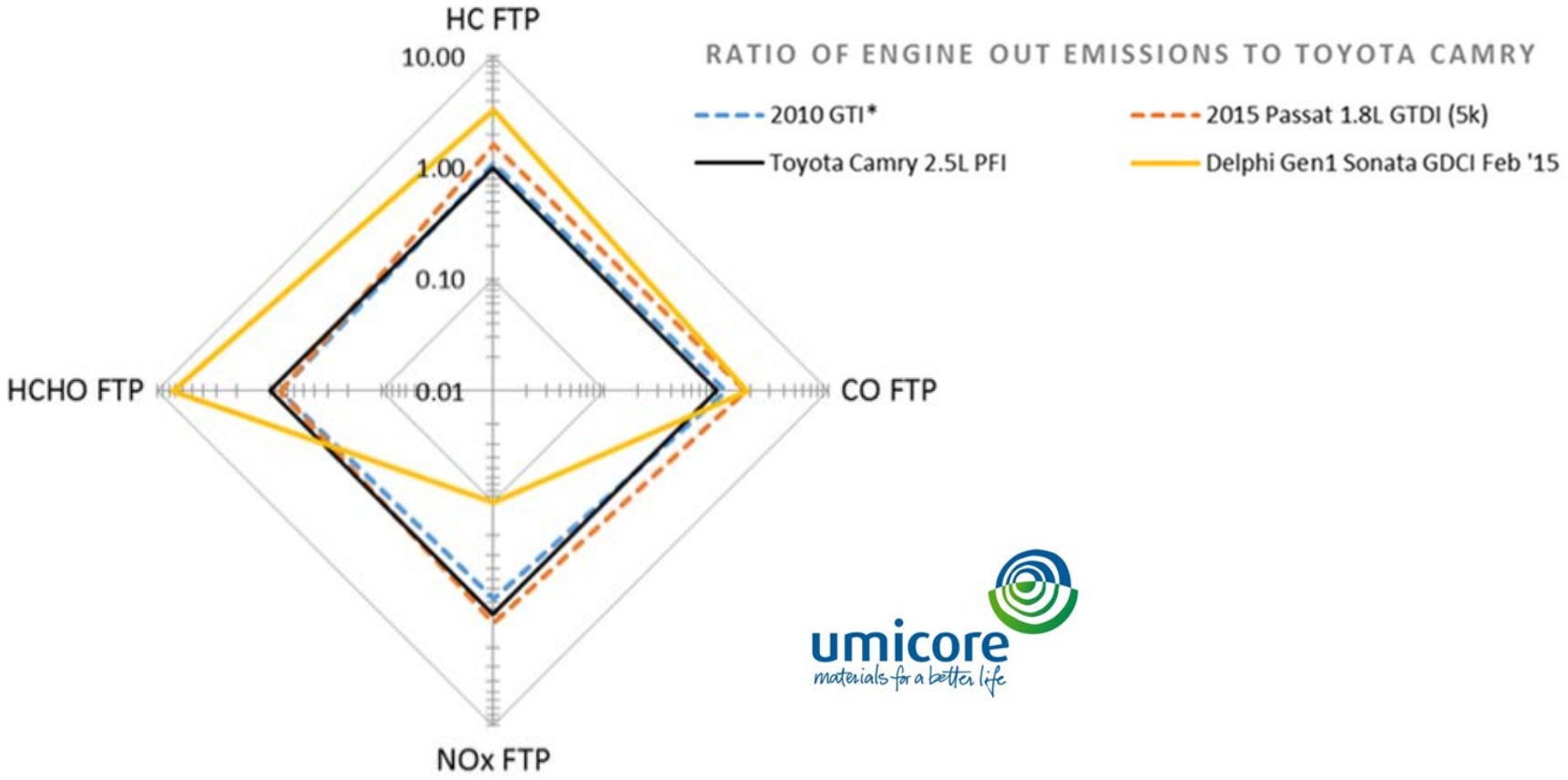
# Technical Accomplishments and Progress:
## Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

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

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*Engine out emissions for Gasoline Direct-injection Compression Ignition are comparable to engine out emissions for gasoline spark ignition engines*

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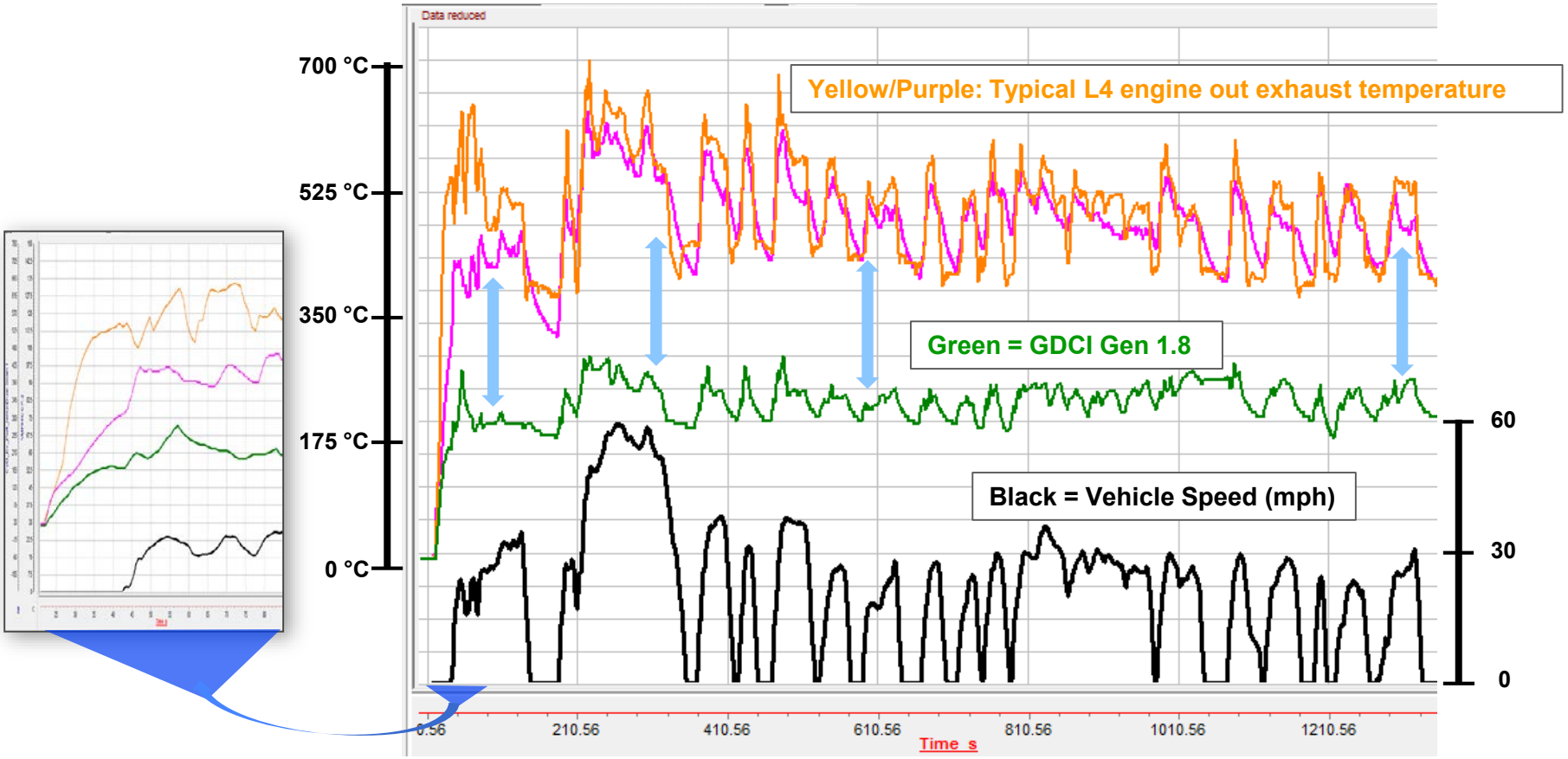
# Technical Accomplishments and Progress:
## Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- 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.*

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# Technical Accomplishments and Progress:
## Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

| Improved Catalyst Performance for Gen 3 GDCI | | | | | |
|---|---|---|---|---|---|
| **Approach** | **Planned Method** | **Status** | | | |
| | | **Simulation** | **Design** | **Integration** | **Engine Level Test** |
| Conserve Exhaust Heat | * Integral, air-gap insulated exhaust manifold<br>* Insulated turbo-charger & pre-catalyst exhaust | ✓ | ✓ | ✓ | |
| Increase Exhaust Temperatures - Cold Starts | Fast, high-power intake air heater (supports exhaust heating) | ✓ | ✓ | ✓ | |
| Increase Exhaust Temperatures - Light-to-Medium Loads | Expanded exhaust rebreathing | ✓ | ✓ | ✓ | ✓ |
| 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 | ✓ | | | |

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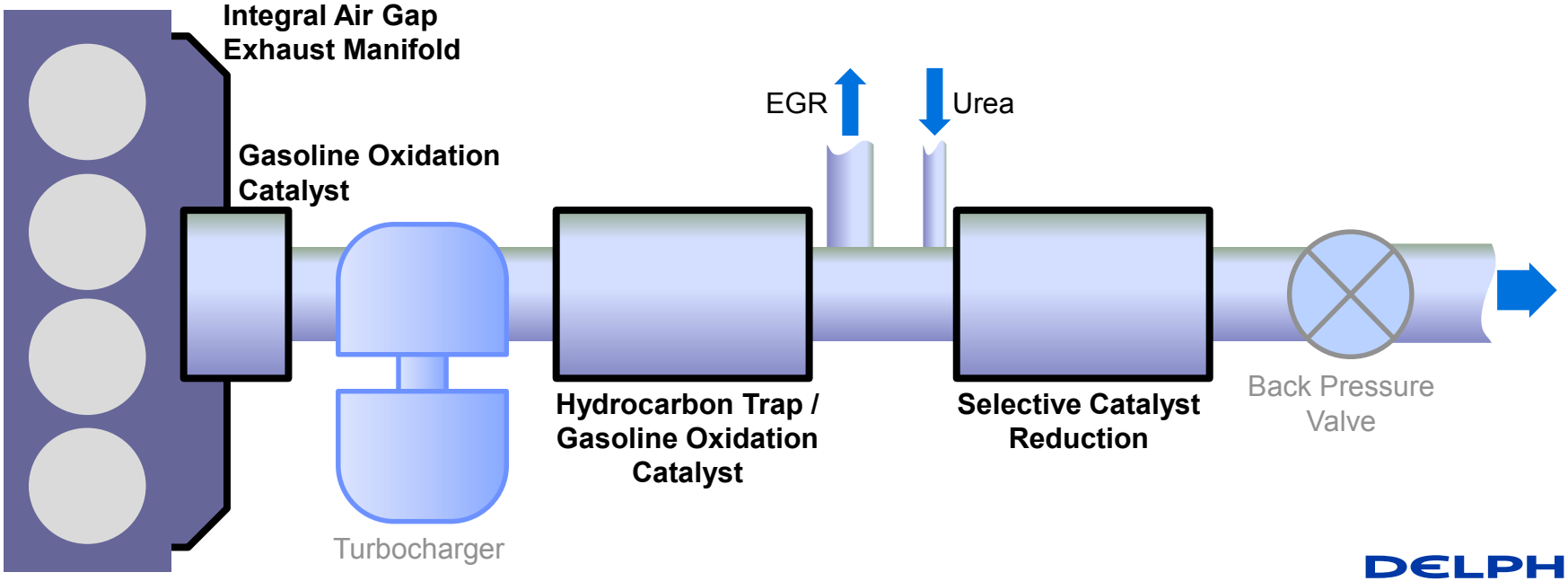
# Technical Accomplishments and Progress:
## Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- Developmental stages of exhaust aftertreatment architecture:


- Gen 3 MCE exhaust aftertreatment architecture:

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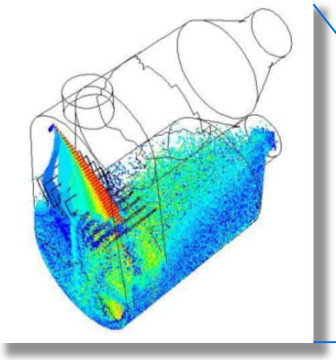
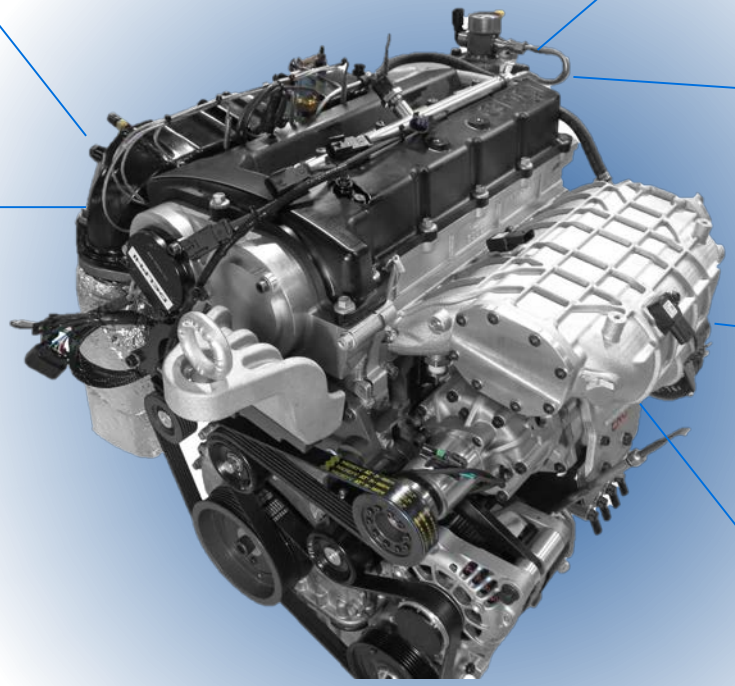
# Technical Accomplishments and Progress:
# Hardware Design and Build: Gen 3 Engines

**New aftertreatment system**



**New log style fuel rail,**
**Fuel pump mounted to Cam Cover**

**New high pressure injectors**

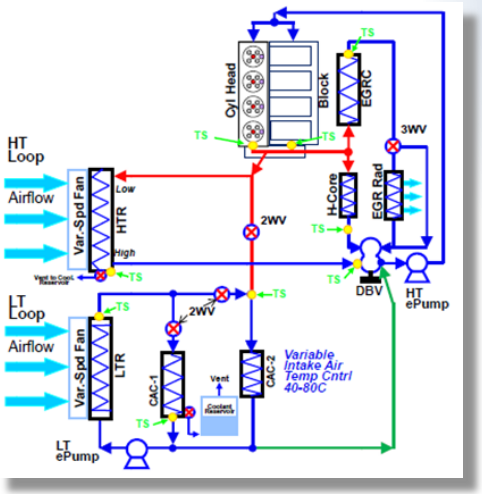


***Gen 2 GDCI Engine***

**Low mass electric intake air heaters**


**Cylinder head with compact, integral exhaust manifold with pre-turbo catalyst**

**Updated thermal management system**

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# 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)

OAK RIDGE National Laboratory

*Oak Ridge, TN*

**Automotive OEM Partner**

In negotiation

**University of Wisconsin Madison** - University

Characterization testing of gasoline fuel injectors. (Test)

ENGINE RESEARCH CENTER UNIVERSITY OF WISCONSIN - MADISON est 1946

*Madison, WI*

**Umicore Autocat USA** – Tier 1 Supplier

Prepare and test low temperature exhaust aftertreatment samples. (Analyze, Design, Formulate, Build, Consult)

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*Auburn Hills, MI*

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# 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

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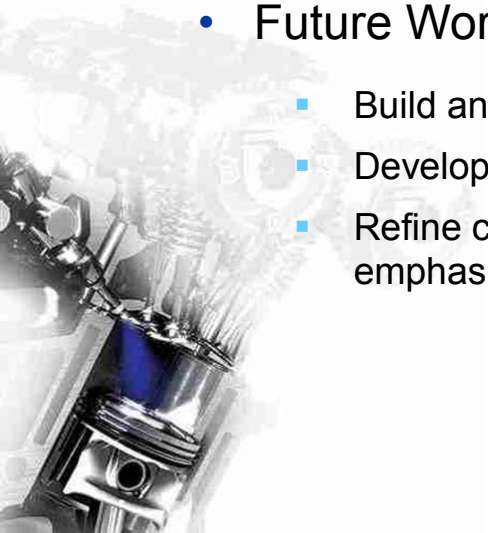
## Proposed Future Work
# Next Steps

- 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.



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Thank you to the Department of Energy for supporting this project.