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

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2017 DOE Vehicle Technologies Review
June 9th, 2017

Project ID: ACS094
DE-EE0006839

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Innovation for the Real World

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: $14,719297 (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.

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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:

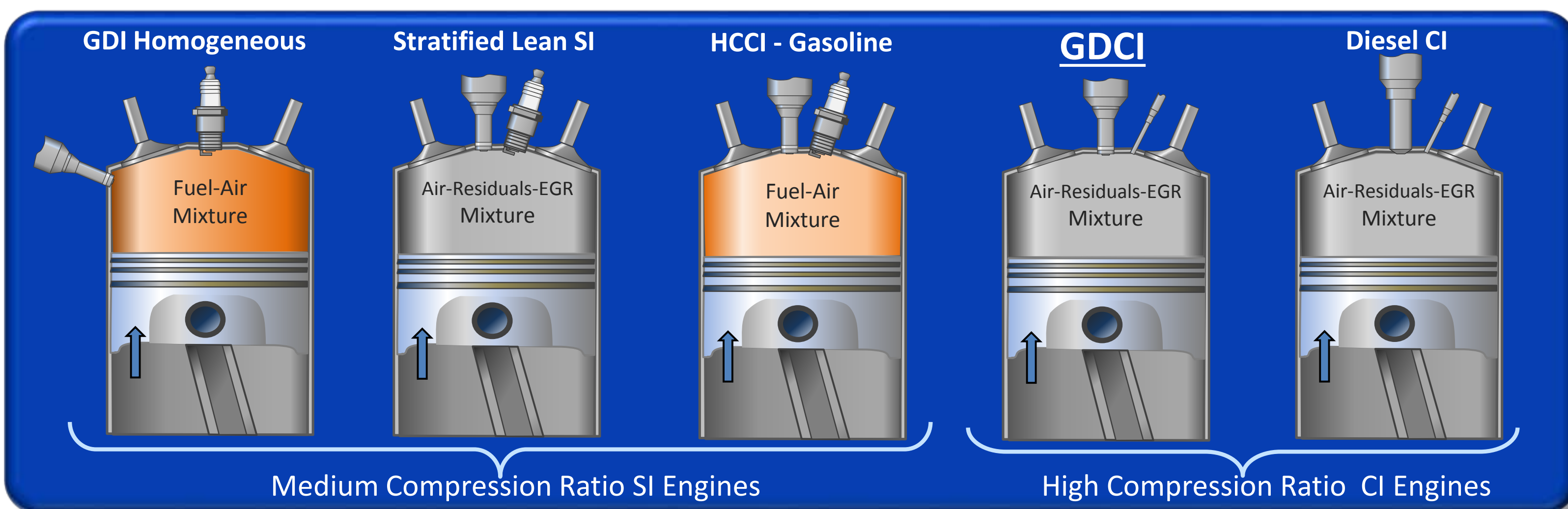
VT Program Barrier	Technical Risk Being Addressed
Combustion Regimes	Refinement of the GDCI combustion system to achieve near-ideal air/fuel mixture preparation for high efficiency and low emissions.
Emission Controls	Development of an aftertreatment system that is effective in dealing with the low temperature challenges of a highly efficient engine.
Engine Controls	Execute transient control with high EGR levels during real-world transient driving maneuvers and over a broad range of ambient conditions

- 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

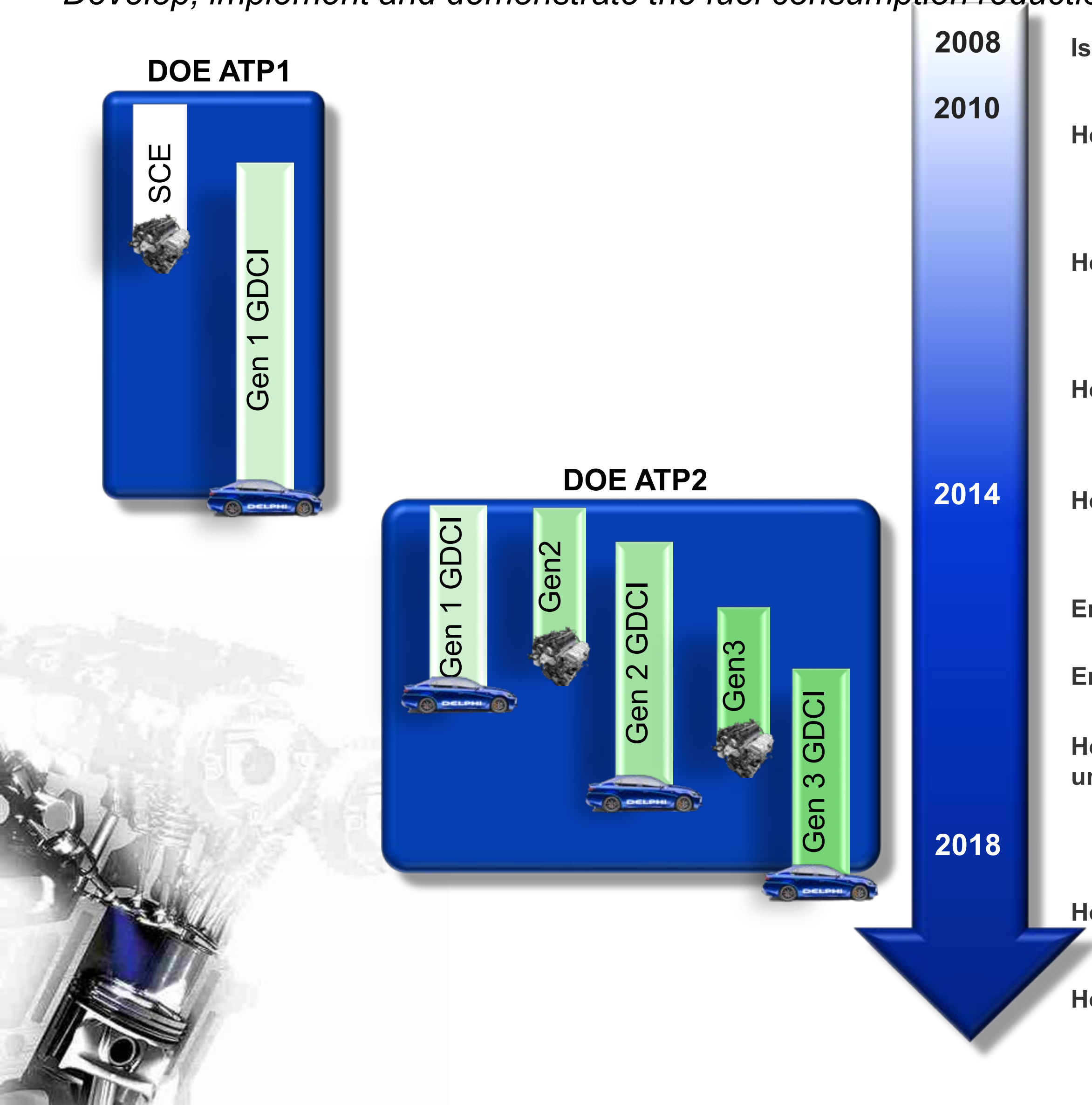
Approach / Strategy

- 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*

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 2.4.2.2	Gen3 Intitial fuel system build	Milestone	Gen 3 fuel initial system built and available for testing including pumps, rails, high pressure lines, and rail pressure sensors	Q1 2016	Complete
Sub Task 2.2.1.2	Thermal System Simulation	Milestone	Simulation completed for Gen3 Thermal Management system and data available	Q2 2016	Complete
Sub Task 2.4.1	Design Gen3 MCE	Milestone	Gen3 GDCI engine and subsystems designed and ready for engine builds	Q3 2016	Complete
Sub Task 2.6.2	Vehicle Design	Milestone	Vehicle packaging studies complete and ability to build Gen3 GDCI vehicle is assured.	Q4 2016	Complete
Sub Task 2.4.2	Build Gen3 MCE	Milestone	Gen3 engine assembly built and ready for debug	Q1 2017	Complete
Subtask 2.6.4.2	Powertrain installation	Milestone	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	Q2 2017	
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 Gen3 vehicle work.	Q3 2017	
Sub Task 1.9.6.2	Vehicle level emissions testing at Umicore	Milestone	Umicore sampled and analyzed emissions from the Gen2 GDCI vehicle and provided results	Q4 2017	

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

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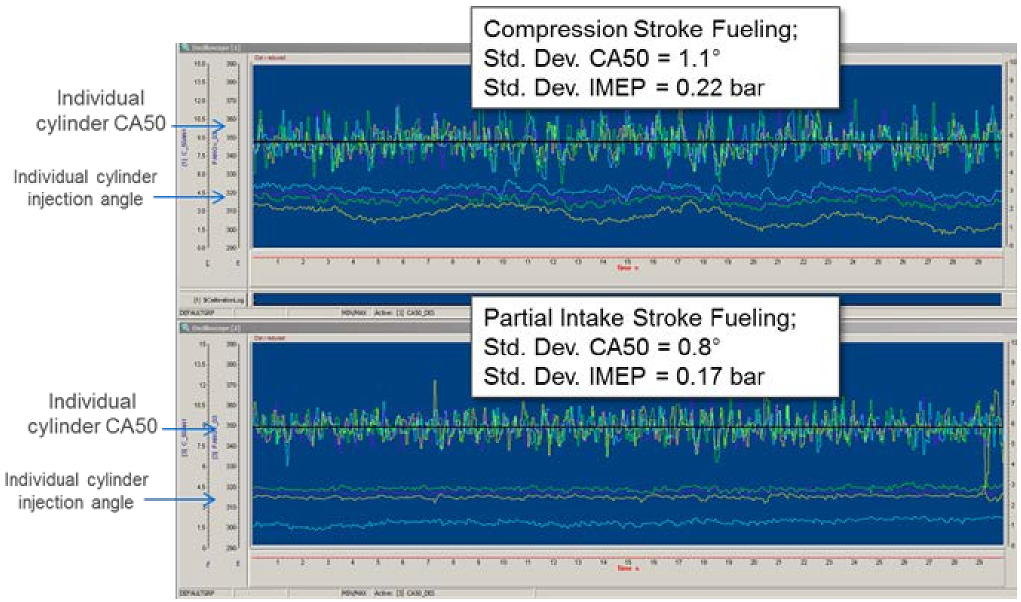
Technical Accomplishments and Progress: Overview

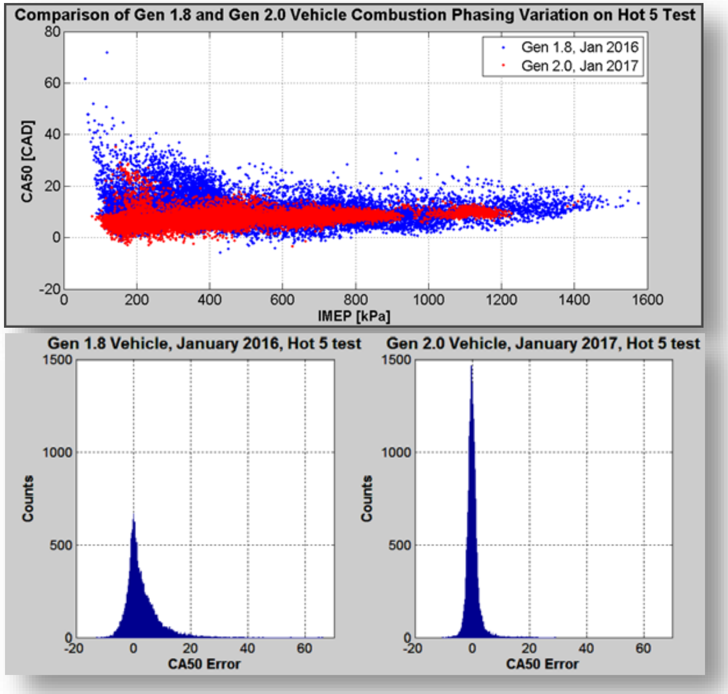
- Developed and refined engine controls and calibration
- Tested vehicle using Gen 1.8 and Gen 2 GDCI hardware
- Characterized Gen 2 GDCI multi-cylinder engine
- Designed Gen 3 GDCI engine hardware
- Built Gen 3 GDCI exhaust aftertreatment
- Built Gen 3 GDCI engine
- Performed initial fire and debug 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



Combustion stability improvement with Partial Intake Stroke Fueling



Combustion phasing control improvement with refined algorithms

Progress made in adapting control systems hardware, algorithms and software to Gen2 hardware configuration

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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
EPA III	33%
HWFET	30%
Combined	32%

Results from Gen1 GDCI vehicle which does not meet emissions goals

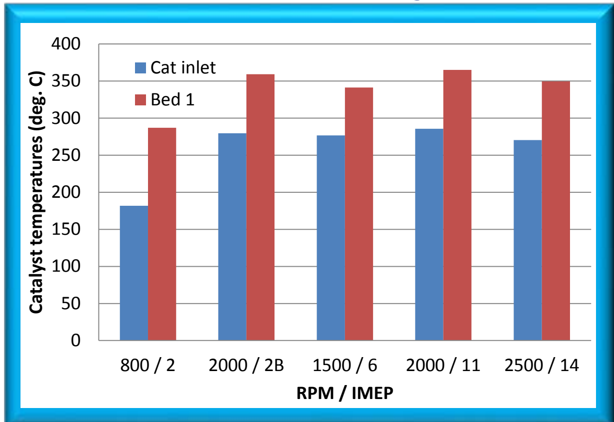
DOE ATP-2 Target: 35% Combined FE Improvement

- 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

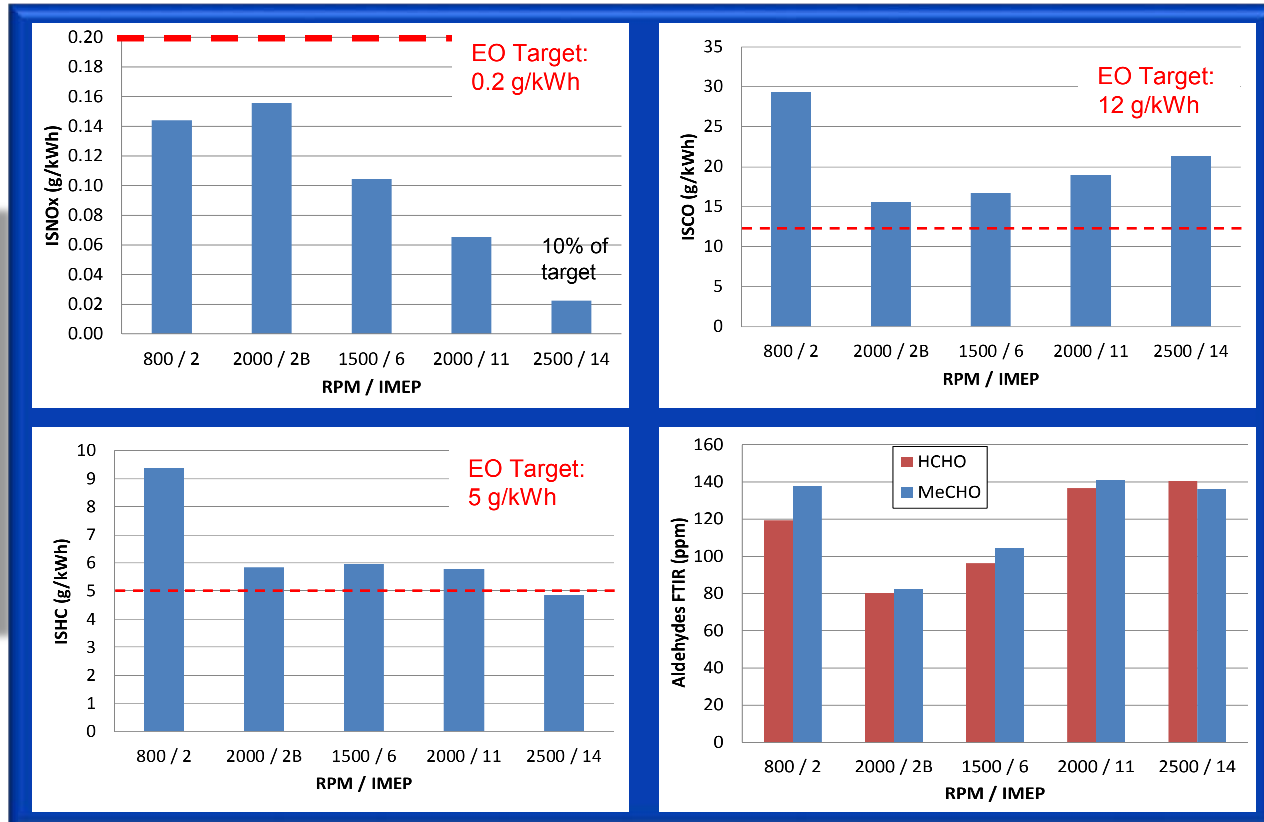
Gen2 GDCI vehicle has been built and is being used to develop controls with an emphasis on transient operation.

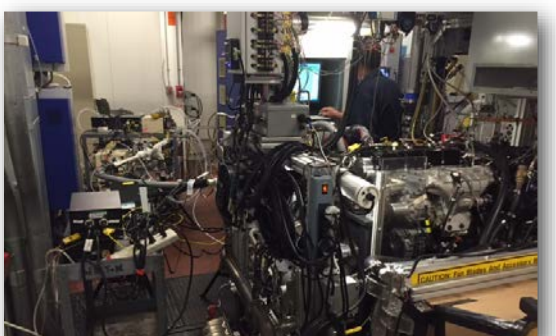
Technical Accomplishments and Progress: Emissions Characterization of Gen2 Engine with ORNL

Exhaust temperatures much lower than SI engine



Engine out emissions similar to SI engine





- 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.

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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

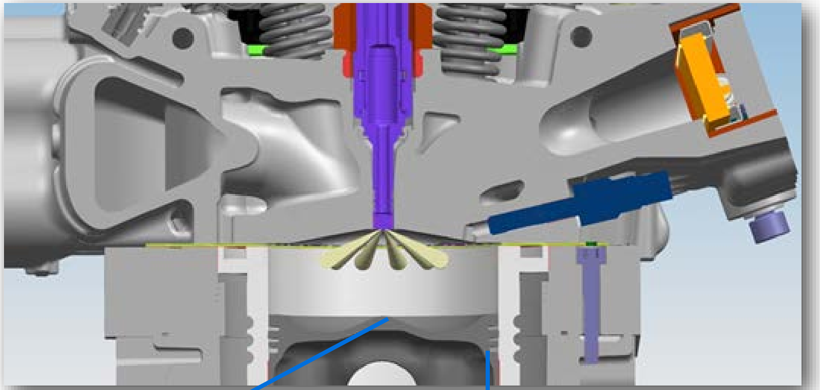
Fuel Injector

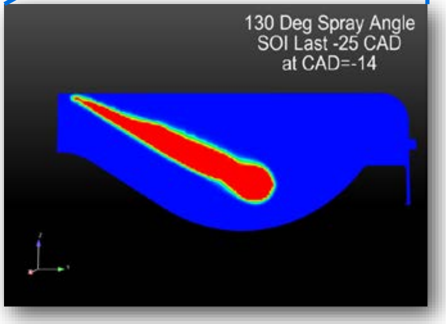
Wide spray angle matched to piston bowl

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)

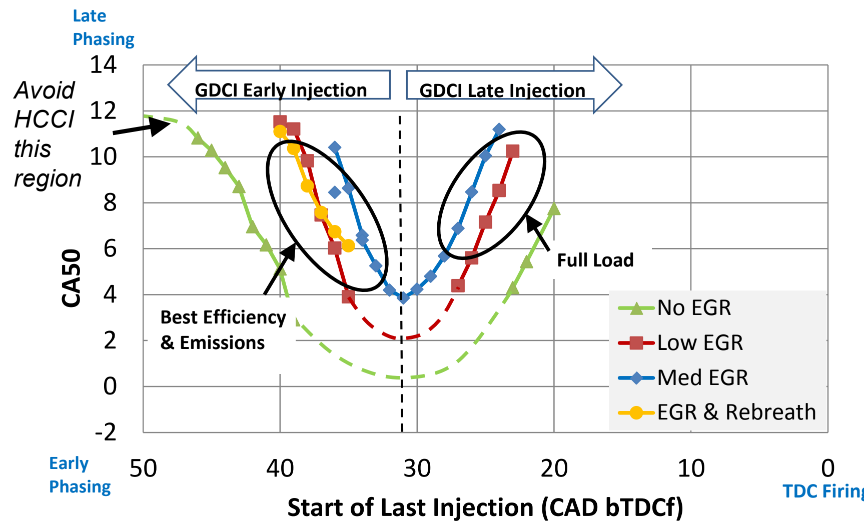
High Load

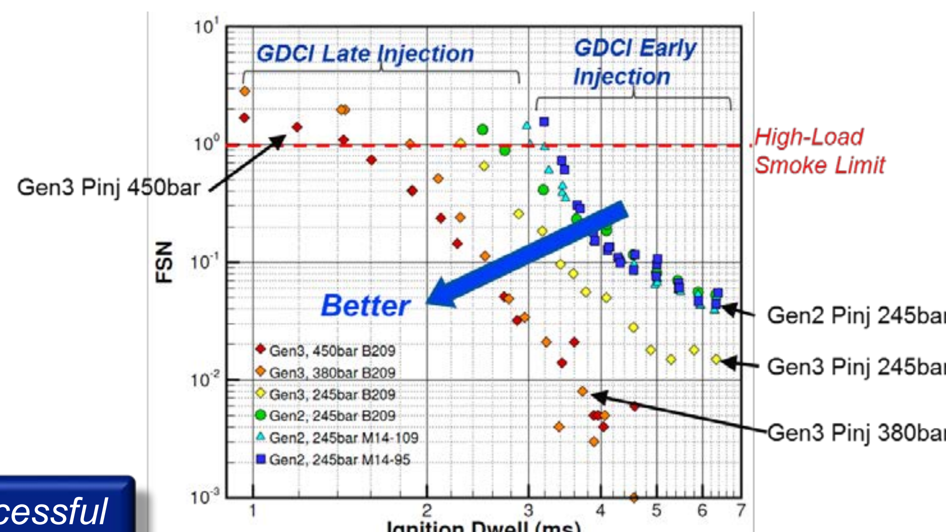
Use GDCI late injection

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.

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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.

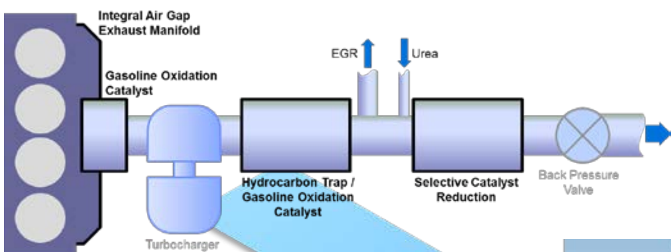
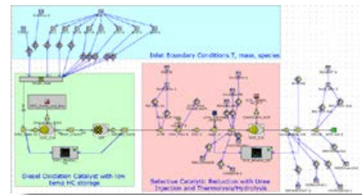
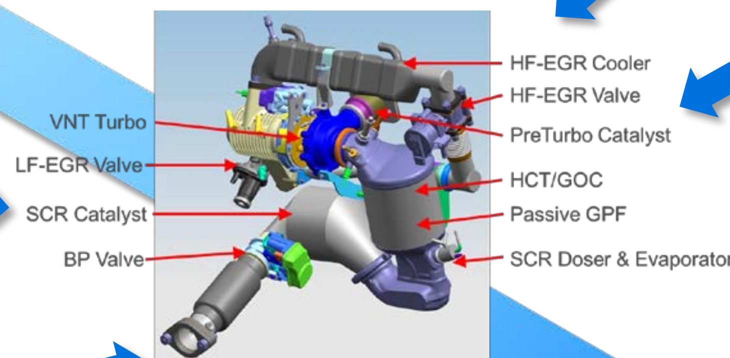


Diagram shown at 2016 AMR



Model	Wall Temp. (C)	Exhaust Temp. (C)	[illegible]	Urea Flow g/h	Uniformity %	Back Pressure Kpa	Mass Flow mg/s EGR NH3	EGR HNCO	SCR Inlet NH3	SCR Inlet HNCO	SCR Outlet NH3	SCR Outlet HNCO
4	300	450	23/27	0.24	65	0.52	0	0	2.00	60.8	8.04	56.2
7	300	450	41/56	0.75	90	2.21	0.7	23.7	3.34	246	8.02	243
7	300	450	41/59	0.24	92	2.11	0.8	8.47	1.43	79.5	3.24	76.2
7	300	450	21/25	0.24	92	0.72	0.36	6.93	2.18	74.0	5.03	71.2
8	300	450	23/27	0.24	97	0.81	0.01	7.09	3.58	69.9	5.17	65.2

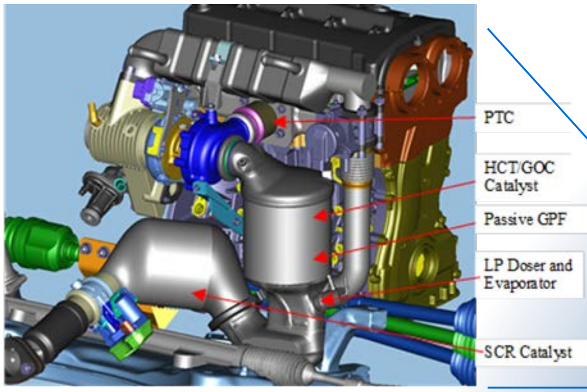


Completed Gen3 System in Dyno Lab

An exhaust aftertreatment system has been developed to conserve the limited available exhaust heat and is undergoing initial testing now

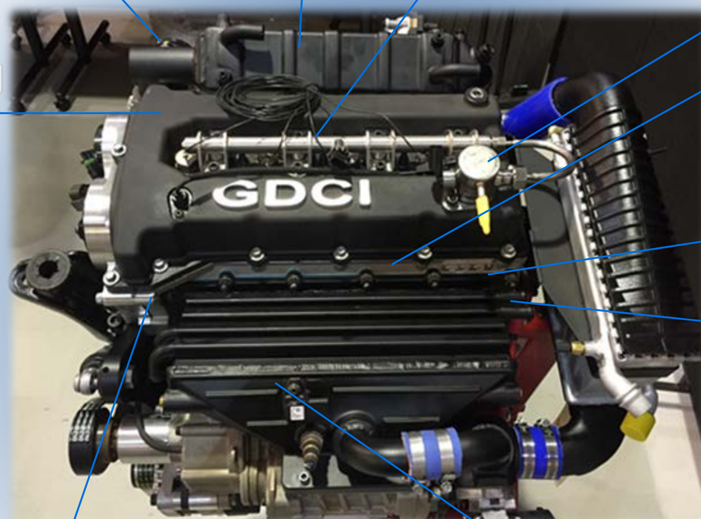
Technical Accomplishments and Progress: Hardware Design and Build: Gen 3 Engines

New aftertreatment system



EGR system with reduced volume for faster response

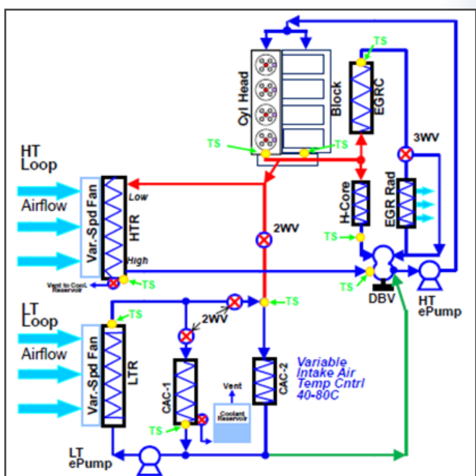
New high pressure injectors



Gen3 GDCI engine first fire Feb 2017

Low mass , fast, electric intake air heaters

Updated thermal management system



Long stroke base engine

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

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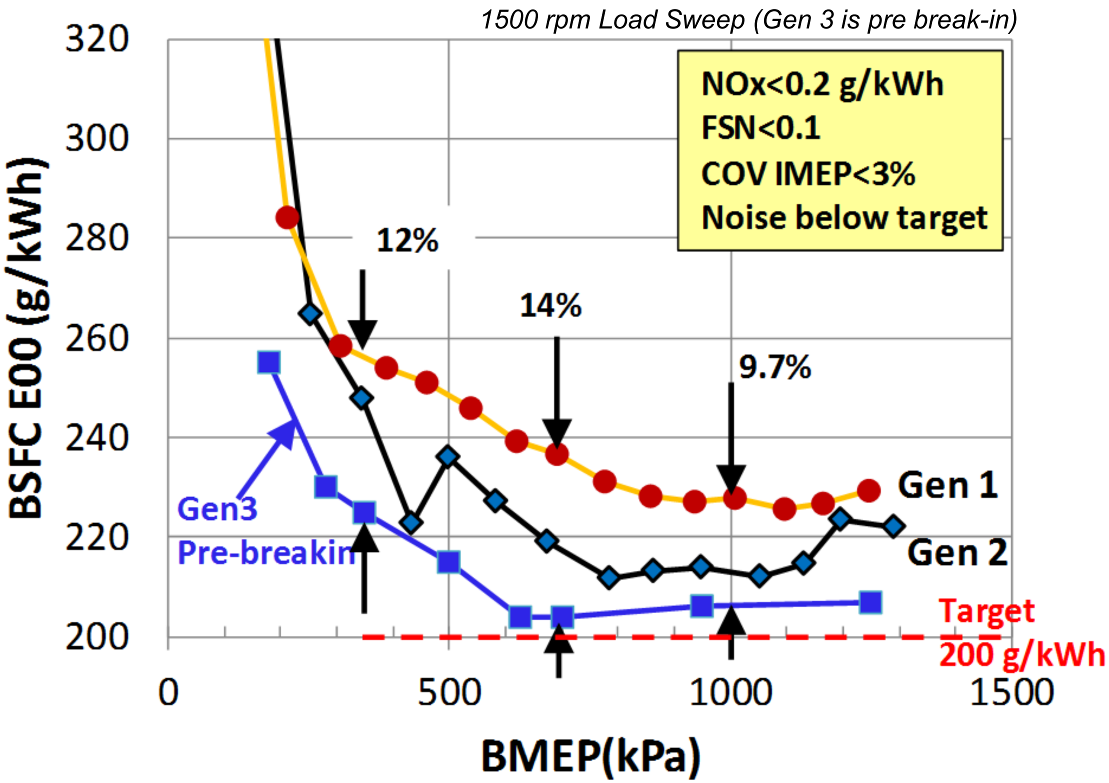
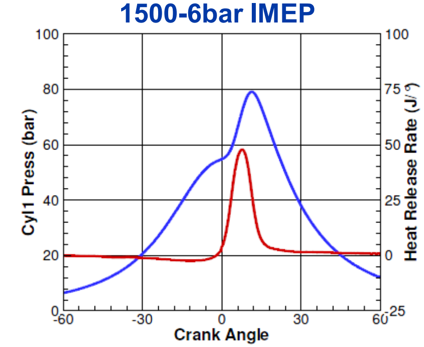
Technical Accomplishments and Progress: Dynamometer Testing – Gen 3 GDCI

- 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



Typical Comb Characteristics
1500-6bar IMEP



The Gen3 multicylinder GDCI engine has been built and is undergoing Engine dynamometer break-in – Early results are very encouraging.

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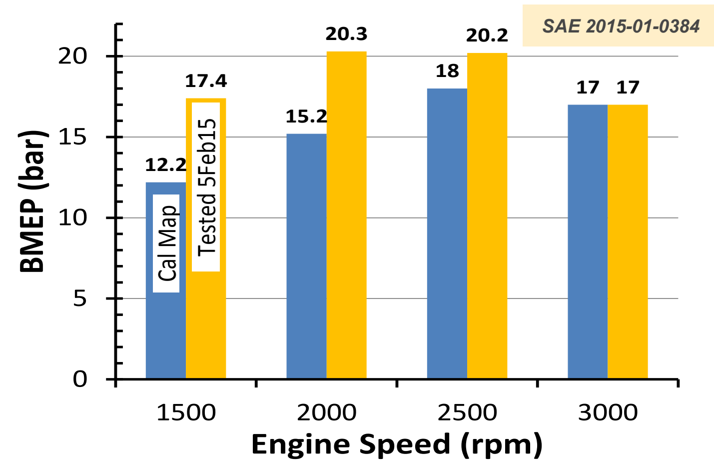
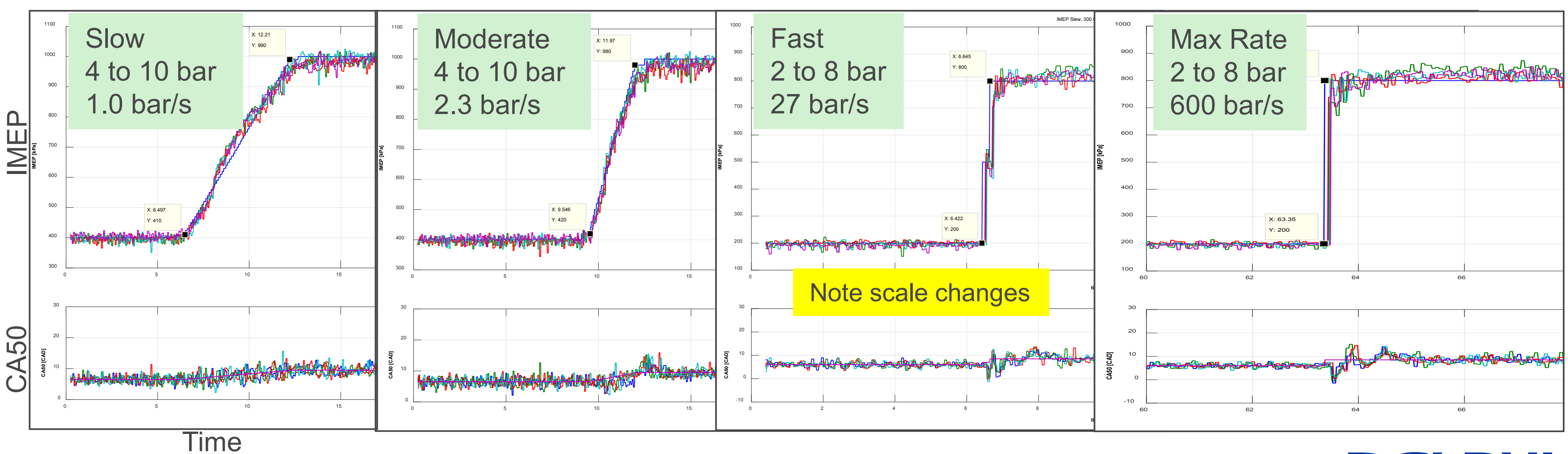
Responses to Previous Year Reviewers' Comments

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.





Responses to Previous Year Reviewers' Comments

- 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:

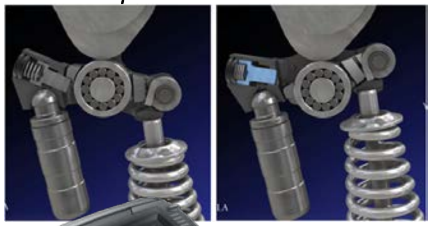
  - The project team has connected with other researchers doing similar work. In the past year Argonne National Lab, Sandia National Lab, Lund University and Oakridge National Lab have all visited and overviewed the GDCI progress and equipment. Discussions have recently begun with Co-Optima with the hopes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

Delphi DSF Valvetrain



VW 1.8L EA888

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, TN

Automotive OEM Alliance Partners

OEM 'Alliance' formed to provide project guidance and 'path to production' feedback. (Consult)

OEM 1
OEM 2

University of Wisconsin Madison - University

Characterization testing of gasoline fuel injectors. (Test)

Madison, WI

Umicore Autocat USA – Tier 1 Supplier

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

Auburn Hills, MI

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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

Gen3 mockup engine installed in a test vehicle

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

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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.

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

Technical Backup Slides

Project ID: ACE094
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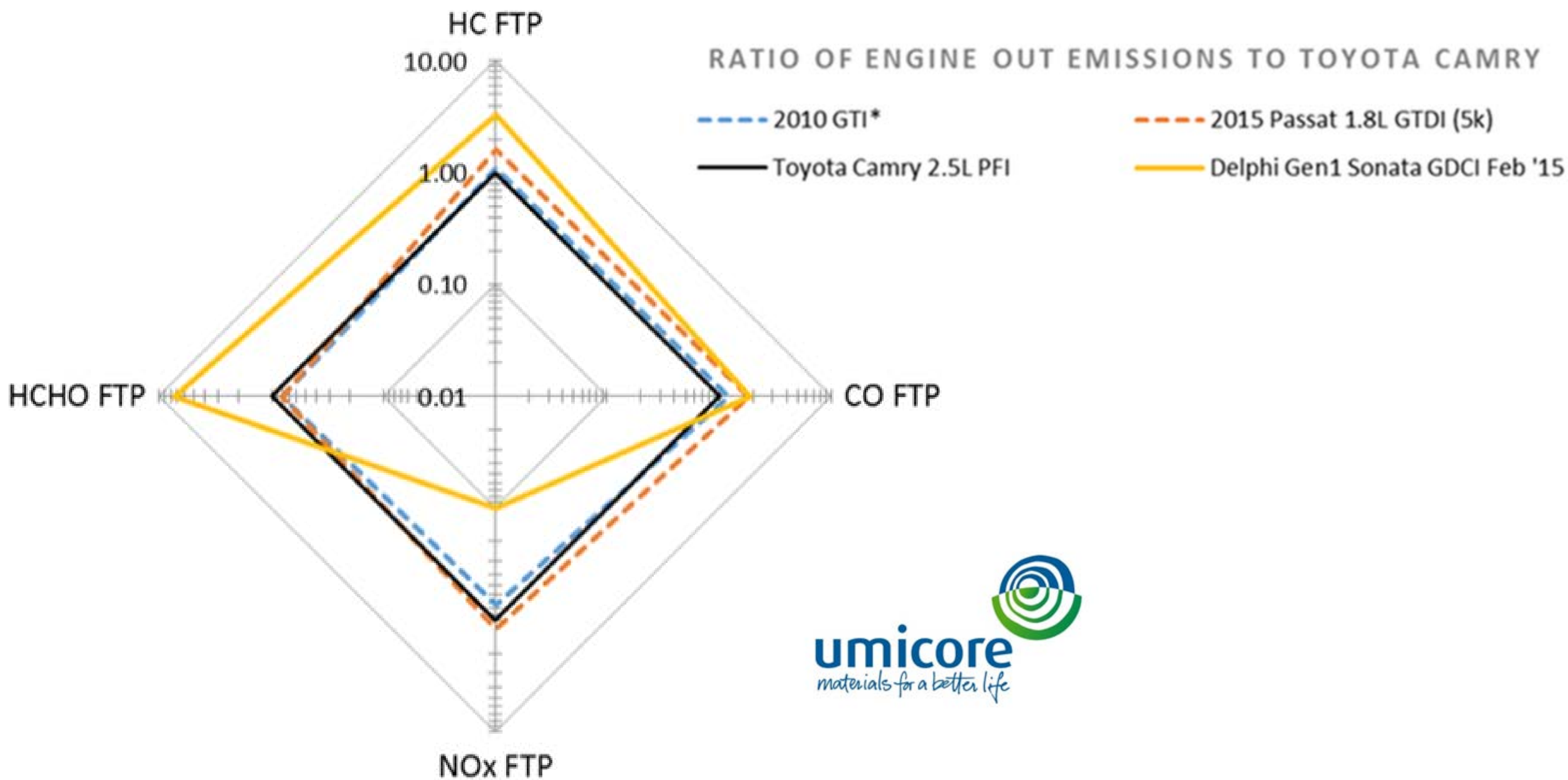
Technical Accomplishments and Progress:
Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

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



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

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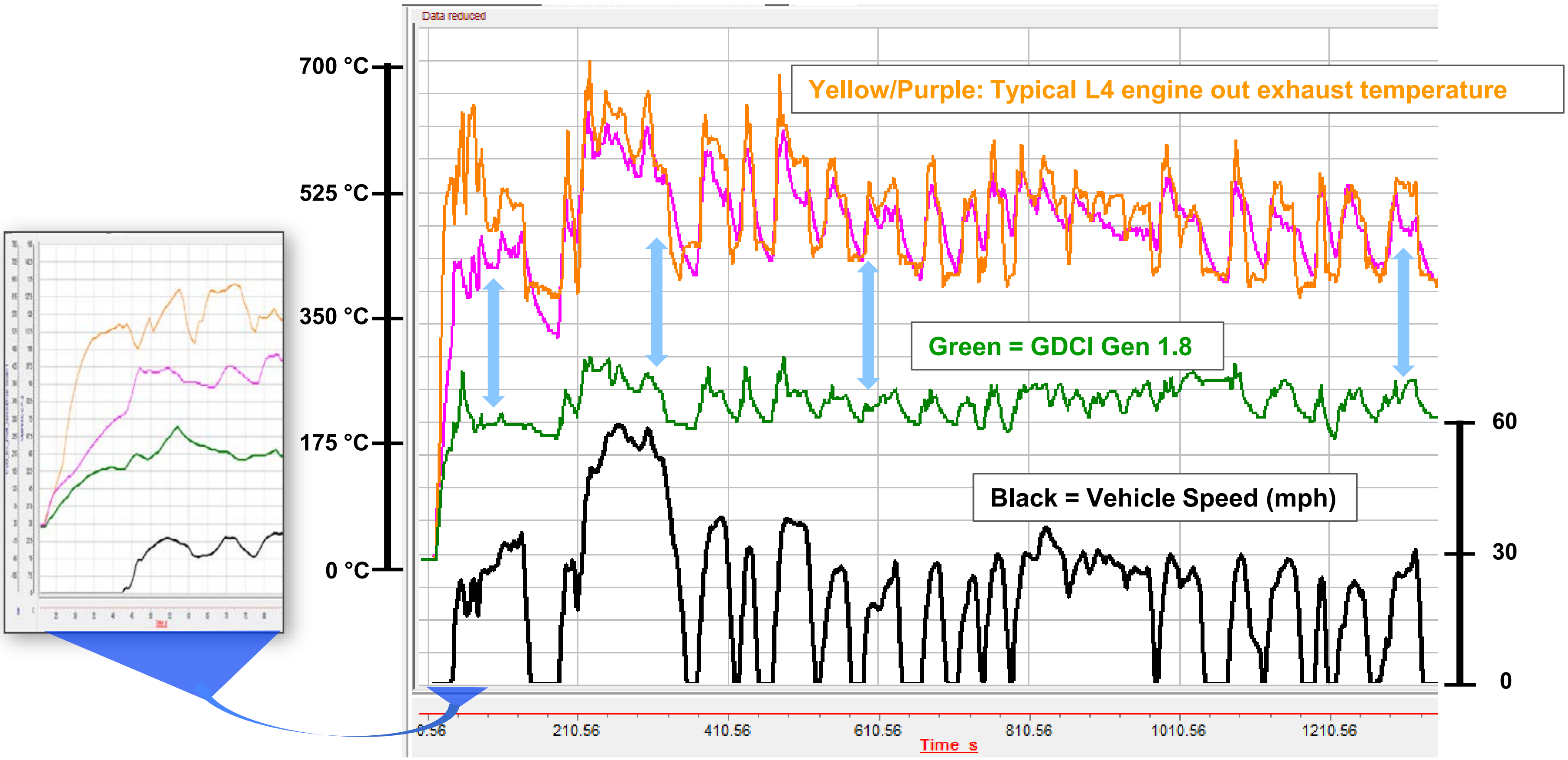
Technical Accomplishments and Progress:
Hardware Design: Gen 3 MCE exhaust aftertreatment architecture

- 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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