Contract Number: **DE-EE0006839**

Title of Project: **ULTRA EFFICIENT LIGHT DUTY POWERTRAIN WITH GASOLINE LOW TEMPERATURE COMBUSTION**

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Final Report
This document details the work completed during Project DE-EE0006839 'Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion'. All tasks from the project's Statement of Project Objectives are discussed. Final demonstration data is also presented and discussed. Further project details can be found in the Quarterly Technicial Reports that were submitted during the course of the project and are stored on the EERE Project Management Center Website.

This report is broken into seven sections:
1. Overview and Executive Summary
2. Results Highlights
3. Project Timing and Milestones
4. Recommendations for Future Work
5. Publications and Presentations
6. Intellectual Properties
7. Project Records

The project team would like to sincerely thank the US Department of Energy for their support for this project, with special thanks to Gurpreet Singh, Ken Howden and Ralph Nine. Without this support, the progress made in the understanding and advancement of the GDCI technology would not have been possible.

1.0 Overview and Executive Summary:

Project

The goal of this project was to develop, implement and demonstrate a low temperature combustion approach called Gasoline Direct Injection Compression Ignition (GDCI) that provides high thermal efficiency with low NOx and PM emissions. The project target was to demonstrate a 35% fuel economy improvement over the baseline vehicle while meeting Tier 3 emissions levels.

At the start of this project, GDCI was a moderately mature combustion technology, due in large part to advances made during a Delphi Technologies program funded through an earlier Department of Energy Advanced Technology Powertrains (ATP) opportunity; under that earlier contract, DE-EE0003258, Delphi Technologies assembled a team with complementary industrial and academic experience, and led this team to advance the technology from the original fundamental work to the state of art embodied by a first-generation (Gen 1) multi-cylinder GDCI engine. Key activities during that project centered on engine and combustion chamber design, and development of fuel injection equipment, valvetrain and advanced controls. Performance results with the Gen 1 engine in a development vehicle demonstrated

that GDCI had the capability to operate using Low Temperature Combustion (LTC) over a broad speed-load range. Based on benchmarking work, efficiency for the Gen 1 GDCI engine compared favorably overall to production light-duty diesel engines.

The second DOE funded project, DE-EE0006839, focused on a number of technical risks and issues that were left to be resolved for GDCI to become a production-viable technology. These risks were:

1. GDCI combustion system refinement to achieve near-ideal air/fuel mixture preparation for high efficiency and low HC and CO emissions,
2. Transient control development for low temperature combustion with high EGR levels during real-world transient driving maneuvers and over a broader range of ambient conditions, and
3. Aftertreatment system design that is effective in dealing with the low-temperature challenges of a highly efficient engine.

The project was executed in two phases. Phase 1 leveraged the development vehicle from the Advanced Technologies Powertrain 1 (ATP1) project, DE-EE0003258. That vehicle was used as an initial test bed in the development of a high performance low temperature exhaust aftertreatment system. The vehicle was also used to develop calibration refinements for improved exhaust emissions and fuel efficiency.

Samples of a new GDCI development level engine, called Gen2 GDCI (and developed outside of the first DOE funded project), were also used during Phase 1 to develop refined controller hardware and control algorithms, as well as improved sensors and actuators. The Gen2 engine was then retrofitted into the development vehicle from the ATP1 project and used for controls refinement and calibration of GDCI to achieve improved cold start, drivability and robustness to real world environments and fuel variations.

During Phase 2 of the project, Gen3 versions of the GDCI engine were designed and built specifically for this project based on experience from the earlier engines. These engines were designed to be production-like in construction and, when combined with refined control systems and project specific low temperature exhaust aftertreatment, were intended to support the goal of meeting Tier 3 emissions levels at a vehicle level.

Though great progress had been made advancing the GDCI combustion process, and despite extensive presentations of our work on the technology at various conferences and in direct meetings with automotive companies, none of the US domestic automotive OEMs had shown an interest in adopting this combustion process as part of their technology planning as the project approached the Go/No-Go point at the end of Budget Period 3. As a result of this low-level of interest both

the US Department of Energy and Delphi Technologies received in this technology from domestic auto manufactures , Delphi Technologies elected a 'No-Go' status for the gate between Budget Period 3 and Budget Period 4 which terminated the project without spending any Budget Period 4 funds. The project team concluded that the dynamometer mapping of the most recent level of hardware, combined with the vehicle level simulation by Argone National Laboratory, was sufficient to document the capabilities and potential of the combustion process without spending the time and money to do the controls development and full calibration necesary for a demonstration vehicle.

Project Team

A team of engineers and scientists from various organizations was established and tasked with the project's Statements of Project Objectives. Regular meetings monitored the progress of the team, and adjusted tasks and action plans as required. The team consisted of individuals from the following organizations:

Delphi Technologies is an industry leader in advanced powertrain technology development. Delphi Technologies has major U.S. Technical Centers in Auburn Hills, Michigan, Rochester, New York, and Kokomo, Indiana that supported this project. These sites performed combustion controls and component development.

Oak Ridge National Lab tested and analyzed speciated exhaust emissions from the combustion process. They contributed key emissions characterization information and analyses over the course of the program to help ensure that the demonstration vehicle capabilities.

Umicore, a leading materials technology group and one of the world's leading producers of catalysts used in emission systems for both light-duty and heavy-duty vehicles, developed high performance low temperature exhaust aftertreatment catalysts specifically for the GDCI process and this project. Umicore worked with Delphi Technologies and ORNL to establish a systems level approach to low temperature combustion emissions.

The University of Wisconsin provided detailed spray characteristics for the project specific fuel injectors developed at Delphi Technologies.

Argonne National Labs (ANL) supported the project in the last year for vehicle simulation studies. The objective was to simulate the GDCI Gen3 engine in a variety of vehicles with differing powertrain options and compare the results to baseline SI engines and full hybrid powertrains for various vehicle classes.

The team of Delphi Technologies, ORNL, Umicore and University of Wisconsin engineers and scientists during the final quarter (Q4 2018) of the project included:

Keith Confer	Principal Investigator
Peter Olin	Project Director
John Storey	ORNL Co-Principal Investigator
David Moser	Umicore Technology Leader
Jaal Ghandhi	University of Wisconsin Co-Principal Investigator
Mark Sellnau	Project Technology Leader Combustion systems
Gregg Roth	Engineering Manager – Controls Systems
James Sinnamon	Combustions Systems Engineer
Wayne Moore	Gasoline Systems Engineer
Matt Foster	Combustion Systems Engineer
Kevin Hoyer	Engine Modeling
Don Johnson	Controls, algorithms and calibration
Frans Theunissen	Calibration Engineer
Jeremy Kraenzlein	Software Development Engineer
Samuel Lewis Sr.	ORNL Analytical Development Chemist
James Parks II	ORNL Emissions and Catalysis Research
Melanie DeBusk	ORNL Research
Scott Curan	ORNL Research and Development Staff

Results Summary

Phase 1

Gen1 Vehicle

The team leveraged the Gen1 development vehicle from the Advanced Technologies Powertrain 1 (ATP1) project to quickly make progress on understanding the technical issues to be tackled in ATP2. Gen 1 GDCI vehicle emissions testing in cooperation with Oak Ridge National Lab was completed in February, 2015 at Delphi's Auburn Hills Customer Technology Center. A variety of instrumentation, test equipment and sampling methods were employed using both Delphi and ORNL equipment. The vehicle was equipped with an inert catalyst for this testing so that engine-out species and concentrations would remain substantially unaltered and tailpipe measurements could be considered equivalent to engine-out measurements. This data was used to design and specify the Gen3 aftertreatment system. During this testing, a 31% combined fuel economy improvement over the baseline vehicle was demonstrated.

Subsequent calibration efforts improved the final Gen1 combined fuel economy to 32% above the baseline vehicle. Additional detail is included in the results section.

Test Cycle	Fuel Economy (mpg)	Improvement over Baseline
EPAIII	34 (E10)	33 %
HWFET	55 (E10)	30 %
Combined	42 (E0)	32 %

Table 1: ATP2 Gen 1 vehicle fuel economy and performance improvement summary as of July 2015.

Gen2 engine

The Gen 2 GDCI engine was developed by Delphi Technologies outside of Department of Energy funded projects, however, the Gen 2 engine was used in Phase 1 of this project.

Builds of the project's Gen 2 GDCI engines were completed at Delphi Technologies in early 2015. The Gen 2 engine system included a new Delphi fuel system, valvetrain, thermal management system, aftertreatment system, piston and ring pack, and lubrication system. Special design features were included to reduce both motoring and firing friction.

The first Gen 2 GDCI engine was installed on a performance dynamometer at Delphi Technologies technicial center in Auburn Hills, Michigan for steady state dynamometer testing at various speed and load conditions covering a broad operating range. The engine showed significant improvements relative to the first generation GDCI engines. BSFC improvements were derived mostly from reduced firing friction. ISFC of the Gen 2 engine was very low and showed the opportunities for an efficient powertrain if mechanical losses could be minimized. The design of the Gen 3 GDCI engine leveraged these learnings.

A Gen 2 engine was also built and installed in the vehicle from the ATP1 project. This Gen 2 vehicle was used primarily for controls development.

Gen2 controls

Controls updates for Gen2 included a new engine controller, new sensors and actuators, as well as control algorithms to support the new engine hardware. One of the major control system modifications for the Gen2 GDCI vehicle was the Thermal Management System controls. The Gen1 mechanical engine-mounted water pump and thermostat control in the high temperature coolant loop were replaced with an electric water pump and dual ball valve flow control device. The objective was to obtain better control of the engine warm-up process during a cold start. The new TMS included multiple parallel flow paths and independent device

flow controls as shown in the figure below. Model-based controls were developed and implemented for this system and several subsystem and component HIL benches were assembled and used for controls development. These benches were also used for component characterization, and the data utilized for calibration of the component models.

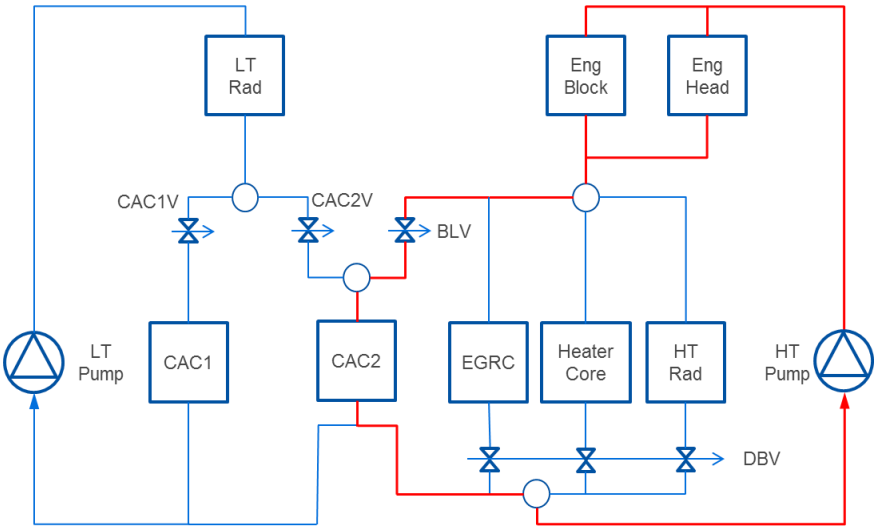


Figure 1: Coolant flow path of Gen 2.0 GDCI TMS in control mode 2

<u>Gen2 vehicle</u>

The project vehicle from ATP1 was retrofitted with a new Gen2 engine, thermal management system, aftertreatment system, control systems and lubrication system. Numerous new or updated control algorithms were developed, integrated, tested and calibrated. The completed Gen2 vehicle is shown in Figure 2 below as it was undergoing testing on a chassis dyno at Delphi CTCM technical facility.

Figure 2: Completed Gen2 GDCI vehicle undergoing testing on chassis dyno rolls at Delphi Technologies' CTCM in Auburn Hills, MI.

The primary focus of the work on this vehicle was to achieve and demonstate the targeted fuel economy improvement of 35% over the baseline vehicle. While there were aftertreatment system improvements implemented, that stage of development was not expected that vehicle emissions would meet the Tier 3 Bin30 target; for example, the vehicle was not equipped with an SCR NOx reduction system. Through extensive testing and calibration efforts, the vehicle achieved the fuel economy targets as noted in Table 2 below. As expected, the vehicle did not meet the Tier 3 Bin 30 emisions targets for any of the criteria pollutants.

Table 2: Gen 2 Vehicle Fuel Economy Performance

Test Schedule	Gen 2 Vehicle (mpg)	Baseline Vehicle (mpg)	Improvement (%)
City (EPAIII)	34.8	25.8	34.8
Highway (HWFET)	56.7	42.1	34.6
Combined	42.1	31.3	34.7

<u>Phase 2</u>

Phase 2 focued on a third generation of the GDCI engine. This Gen 3 level of GDCI engine was designed and built specifically for the project based on experience from the earlier engines. This engine was designed to be production-like in construction.

Several versions of the Gen 3 engine were evaluated during the course of the project. These engine variants were tested on a performance dynamometer at Delphi Technologies technicial center in Auburn Hills, Michigan for steady state dynamometer testing at various speed and load conditions covering a broad operating range. A Gen 3 engine was also packaged and installed in a project vehicle.

Gen3 vehicle

Another 2011 Hyundai Sonata was acquired for use in building the Gen3 development vehicle. The production powertrain was removed and a Gen 3 GDCI engine with custom ratio manual transmission and ancillary Gen3 systems were installed into the vehicle. This included the application of the second generation electronic control system, including new and updated electronic controllers and wiring harnesses. Ancillary systems include new Gen3 thermal management system, air & exhaust systems, and lubrication systems.

The Gen 3 vehicle control system was debugged: all system signals were checked for functionality and critical watchdog shutdown faults were tested to ensure protection of the vehicle hardware. A picture of the final vehicle engine compartment configuration is shown in Figure 4.

Vehicle first-fire was completed on February 16, 2018 and a stable idle was achieved on March 8, 2018. A warm-idle demonstration of the vehicle was conducted for visitors from the Department of Energy on March 19, 2018.

Figure 4: Gen 3 GDCI vehicle after debug testing completion.

Gen 3 Controls

To support the vehicle implementation of the Gen3 GDCI powertrain technology, the flexible controls architecture developed in ATP1 was adapted as needed for the new Gen3 hardware. The system continued to incorporate and improve Rapid Algorithm Development techniques using a high-capability controller (a dSPACE Microautobox II) along with a production Delphi Technologies GDi Engine Control Unit (ECU). This arrangement allowed use of production algorithms and software for systems that did not require significant development, while offering fast turnaround for algorithm prototyping on new or highly modified functions.

A high-speed interface between the Microautobox and the production ECU was utilized to enable the necessary data transfer rates. All of the Input / Output interfaces were connected via the production ECU (or I/O expansion boxes) so that production-style hardware interfaces could be utilized; this enabled use of a production implementation of the control system, requiring less re-work of the system. System throughput and computational resources have proven to be sufficient for GDCI engine control in the regions of operation necessary for demonstration of fuel economy and emissions performance of the Gen3 GDCI powertrain.

Additional hardware I/O needed to be added to the system to interface to the new Gen3 GDCI sensors, drivers / actuators, and instrumentation. This was facilitated with a distributed control architecture, linked by multiple CAN buses. A new custom hardware I/O module was developed and integrated into the distributed architecture, allowing the number of separate modules to be reduced from three to two while simulataneously increasing the number and capability of the I/O ports. This new I/O expansion module proved to be reliable and effective.

The watchdog controller continued to be utilized in the system to oversee the operation of the engine and act as a safety monitor for the engine, by continuously checking that particular parameters remain in their desired ranges. The scope of the watchdog monitoring was expanded to provide continuous monitoring of each of the catalysts in the aftertreatment system; catalyst overtemperature protection was also added. The catalyst protection system included an automatically triggered on-onboard nitrogen purge system.

The new Gen 3 thermal management system for the vehicle was improved over the Gen 2 system. It retained the high and low temperature coolant loops with independent radiators, dual coolant pumps and dual ball valve high temp loop control from Gen2. It included a triple loop intake air temperature control with a dual-element post-supercharger charge air cooler with independent control of each element. Additonal coolant loops were added for cooling the urea dosing valve, high flow and low flow EGR valves, and a liquid-cooled A/C condenser as shown in Figure 5 below. Significant effort was put forth to develop a model based control system for thermal manangement, including state estimators and fast response sensors for improved transient control of intake air temperature, which is a key parameter for combustion phasing.

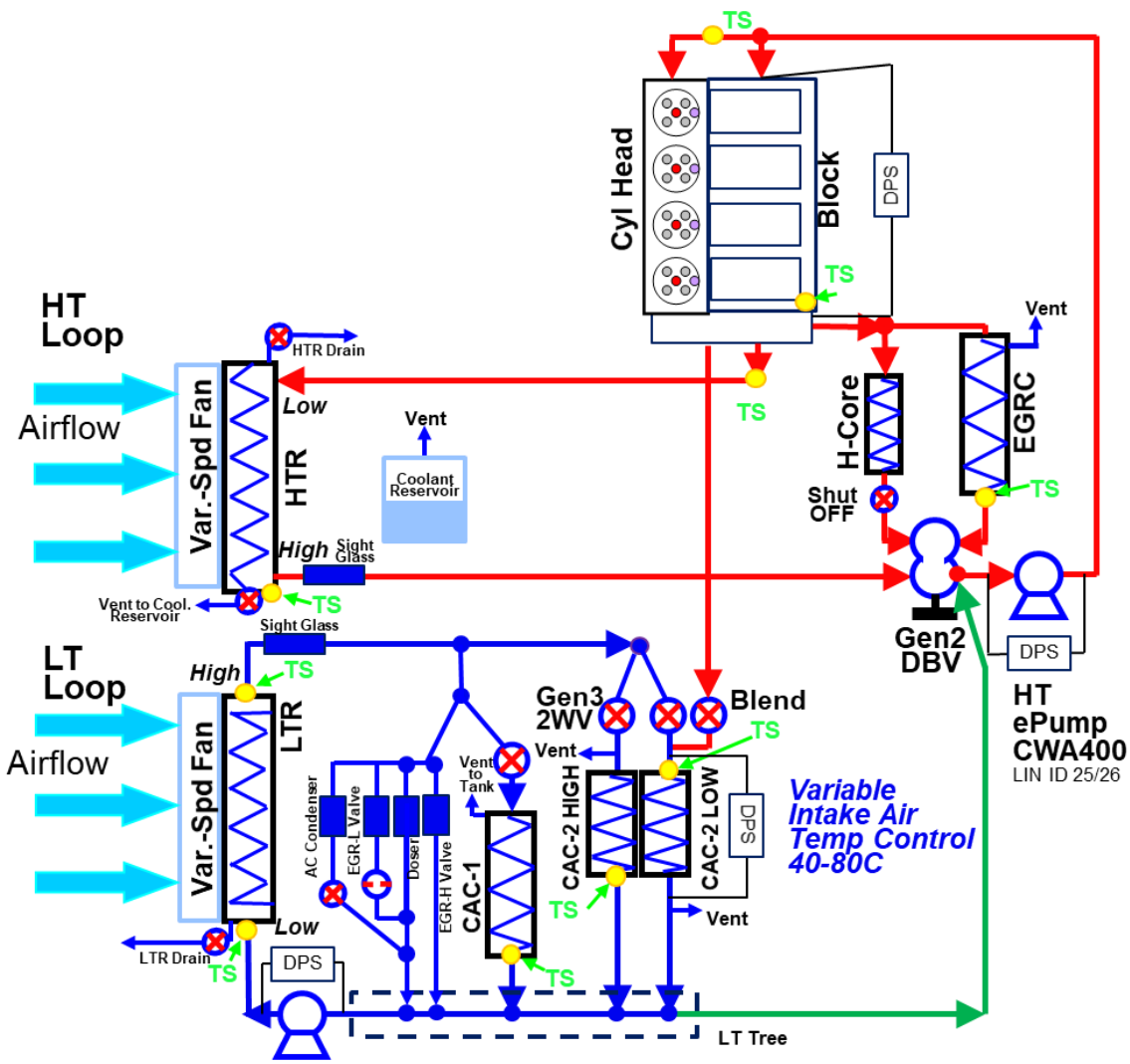


Figure 5: Gen3 Vehicle Thermal Management System with sensors.

The Gen3 air and exhaust systems included a new high-effectiveness intake air heater, a dual path cooled high flow / low flow EGR system along with significant improvements to the aftertreatment system, such as a Pre-turbo catalyst, a Gasoline Oxidation Catalyst / HC Trap, a GPF (if deemed necessary for particulate control) and a urea-based SCR system. The Pre-Turbo Catalyst (PTC in the Figure 6 below) was mounted directly to the integrated exhaust manifold to minimize light-off time after a cold start. The SCR system included a urea doser which sprayed onto a series of plates for improved evaporation.

New transient control systems were developed for intake air temperature control, which included expanded fast control using both the coolant controls and the intake air heater for fast response. A transient thermal model of the IAH was developed and incorporated into a model-based control for improved transient response

accuracy and for the purpose of protecting the heater from failure due to overtemperature. A photo of the new intake air heater undergoing bench testing for model calibration is included in Figure 7. This system allowed the use of variable intake air temperature targets as a function of engine speed and load. For SCR system control, an engine-out NOx model was developed along with a model-based urea dosing control. Boost control was carried over from Gen2, with modified calibrations. Parallel path EGR control was developed and simulated.

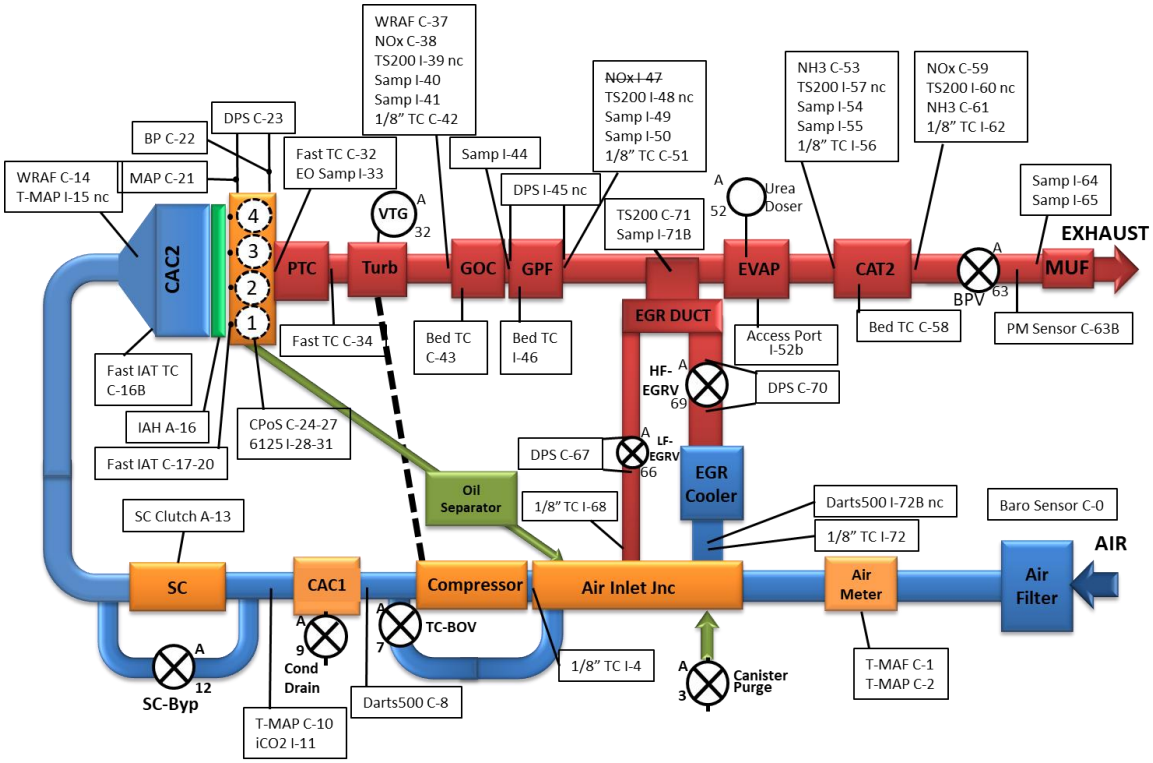


Figure 6: Gen3 Vehicle Air and Exhaust System with sensors

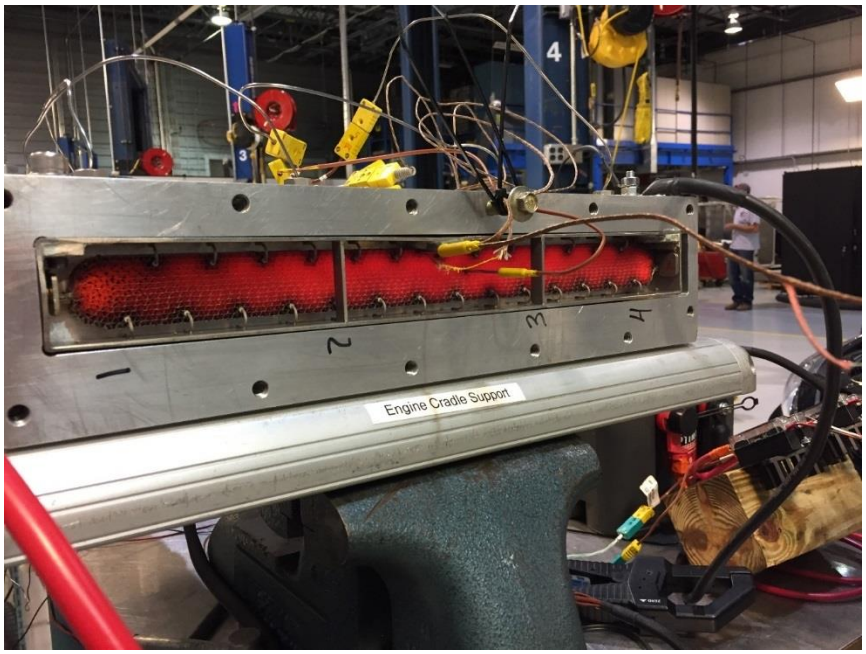


Figure 7: Gen3 Intake Air Heater undergoing bench test for model correlation.

A urea storage tank with pump, level sensors and fill ports was mounted in the spare tire well of the trunk as shown in Figure 8. This system was adapted from an existing OEM application and was larger than needed for a production application. Also visible in this photo is the catalyst over temperature protection system, brake vacuum pump and various instrumentation.

Figure 8: Trunk-mounted urea dosing supply tank.

The Gen3 engine lubrication system included independently controlled piston oil squirters for piston cooling. A novel new control system was develop and implemented that commands piston oil cooling based on the thermal state of that cylinder, as indicated by the combustion feedback system. The vehicle was also fully instrumented for the planned testing.

Gen3X

An updated version of the Gen3 GDCI engine, called Gen3X, was built and installed on the dynamometer at Delphi Technologies. The main features of the engine were:

- Simplified Thermal Management with Fast Intake Air-Blend Temperature Control
- Higher compression ratio of 16.8
- New GDCI-Diffusion combustion strategy for high load
- Fast electric intake air heater (IAH) for fast cold starts

The Gen3X engine is less complex and less costly than the previous Gen3 engine, and has lower fuel consumption and higher output. Due to new combustion strategies, the engine is also easier to control and more robust.

The Gen3X dynamometer engine was fitted with a high-pressure diesel fuel injection system. This was required to reduce smoke at higher loads to meet program targets (FSN<0.1). A new "degreened" gasoline oxidation catalyst (GOC) was installed on the engine without a gasoline particulate filter (GPF). The engine was recalibrated over the operating map using E10 gasoline (RON91) under warmed up operating conditions. Low-pressure EGR and an SCR catalyst were used to reduce NOx emissions to near zero tailpipe levels. Tailpipe NMHC and CO emissions met program targets of 10ppm and 50ppm, respectively. These steady-state, warmed-up engine dynamometer testing results demonstrate significant progress on emissions control.

Initial dynamometer tests of the 2.2L Gen3X GDCI engine included break-in tests and a load sweep conducted at 1500rpm. BSFC as a function of BMEP is shown in Figure 9. In this comparison, there are 4 versions of the Gen3 engine. Of the Gen3 versions, the first tests with inert exhaust aftertreatment (ATS) system exhibited minimum BSFC of 205 g/kWh. However, with an active ATS system, about a 2 percent penalty was observed. This was attributed to oxidation of fuel in the gasoline oxidation catalyst (GOC) ahead of the EGR system. Without an active ATS, this unburned HC and CO would be returned to the combustion system to make torque. The upper curve in Figure 9 shows the results of detailed calibration mapping. As can be seen, there is a significant fuel consumption penalty on the Gen3 engine when all the necessary constraints for calibration mapping are applied.

The bottom curve in Figure 9 shows data for the final Gen3X engine configuration. Minimum BSFC was 195 g/kWh at 9 bar BMEP. The engine utilized a new GDCI-diffusion combustion strategy for higher loads. The engine was found to be very easy to operate and control. The load capablility was also much higher than for the previous Gen3 engine due to the favorable boost characteristics achieved by emulating a VIC VNT turbo, through the use on the dyno engine of two turbochargers with different compressor wheels.

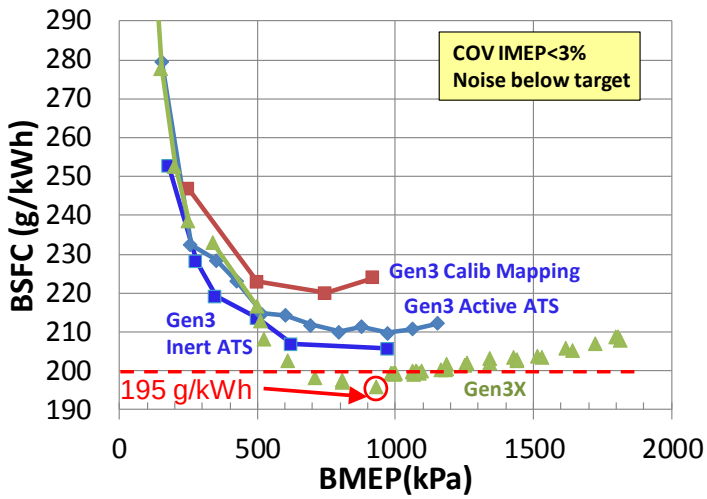


Figure 9. Preliminary load sweep at 1500rpm for the Gen3X GDCI engine.

The BSFC contour plot is shown in Figure 10. Tests were run at 650rpm (idle) up to 3500rpm (data plotted up to 3000rpm). Load ranged from 1bar to 21bar IMEP. For IMEP of 4 bar and below, single injections with GDCI combustion was used with heavy exhaust rebreathing and elevated inlet air temperature (IAT) up to 75 degrees. For 5 bar IMEP and above, double injections were used with 2-stage GDCI-diffusion combustion strategy. The first stage was an very clean GDCI combustion event. The second stage utilized a GDCI-diffusion combustion, which had higher NOx and PM emissions. The second stage extended the burn duration and reduced combustion noise. Burn duration could be easily controlled by Qsplit and injection timing.

Minimum BSFC for this test was 194 g/kWh (43% BTE) measured at 1750rpm-12bar IMEP. Notably, BSFC of 210 g/kWh (40% BTE) exteneded across a very large portion of the operating map from 5 to 20 bar IMEP. This is very important for engine down-speeding and up-loading to achieve the best vehicle fuel economy. At low loads down to 1 bar IMEP, BSFC was also excellent .

As shown in Figure 10, the engine could produce high torque because of the absence of knock and pre-ignition limits. For these initial tests, torque was limited by an exhaust temperature limit of 600 degree C. The low-load torque capability of the engine was exceptional. The engine easily produced 20bar IMEP at 1200rpm.

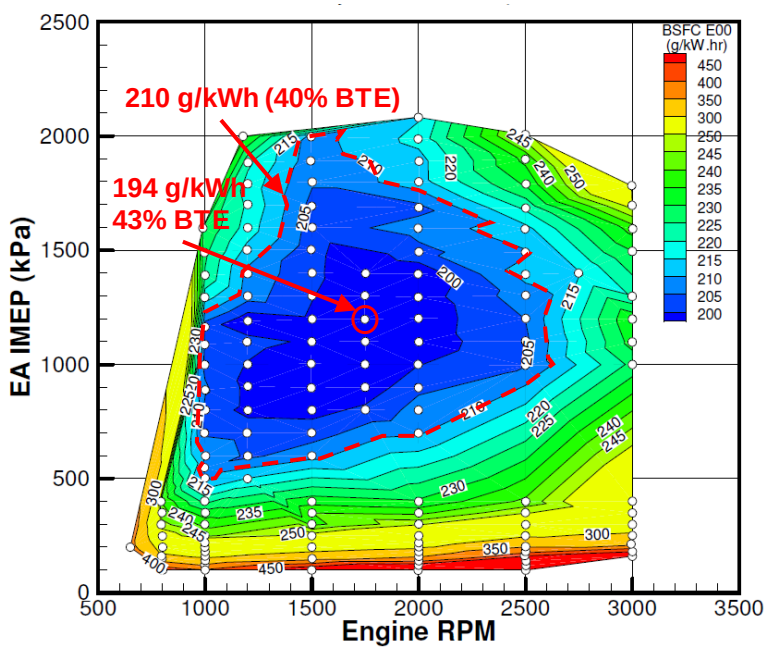


Figure 10. Initial BSFC contour map for Gen3X GDCI engine using a prototype GDi fuel system, tested up to 500 bar, and a single-stage boost system with a new GDCI-diffusion combustion strategy for high load.

Gen3X simulated upgrades

As testing proceeded in the dyno on the Gen 3X engine, potential enhancements to it were evaluated in simulation. In particular, a version of the Gen3X engine with thermal barrier coatings (TBC) was simulated. Based on the simulation results and an efficiency loss analysis, the addition of such thermal barrier coatings has the potential to improve brake thermal efficiency from 43.5% up to 48%. Using simulation, an engine map was created for the Gen3X engine with the thermal barrier coatings, and the data was provided to Argonne National Labs (ANL) for vehicle-level simulation work.

Argone Natl Lab simulations

The Gen3X GDCI engine and the Gen3X engine with the Thermal Barrier Coatings were simulated at 12 speed-load operating points to create an engine map for the FTP drive cycle. The work flow included first developing correlated engine models for the Gen3X engines using real dynamometer test data and cylinder pressure data at each test point. For the Gen3X engine with the Thermal Barrier Coatings the heat transfer multipliers for heat loss in the cylinder were reduced by 50% to simulate the expected effects of applying the thermal barrier coatings.

Reduced in-cylinder heat losses increased the cylinder pressure and enable greater work extracton during the expansion stroke. Reduced in-cylinder heat losses also increased exhaust temperatures and improved turbocharger work. Finally, the simulation results for the 12 operating points were used to fit an engine maps for the Gen3X engine and the Gen3X engine with the Thermal Barrier Coatings. These maps were provided to Argonne for vehicle simulations.

Figure 11 shows simulated fuel economy (MPG) for the US FTP city, highway, and combined cycles for a midsized vehicle. The baseline shown is a contemporary 1.6L SI turbocharged engine with variable intake valve lift and timing. There are three Gen3X powertrains shown in the figure. The Gen3X with 6 automatic transmission, the Gen3X with 8 automatic transmission and 12V start-stop, and the Gen3X with 8 automatic transmission 48V starter generator, exhibited 35.9%, 45.4%, and 50.9% combined fuel economy improvement, respectively, over the baseline. The fuel economy data is unadjusted but includes a 15% cold start correction for Phase I. While full emissions compliance were established, these results show that the Gen3X GDCI engine has potential as ultra-efficient internal combustion engines operating on US market gasoline (RON91).

Results for the simulated Gen3X GDCI engine with the Thermal Barrier Coatings are shown in the 5th and 6th bars in Figure 2.2.2 (labelled 'Gen3XTBC'). For the simulated Gen3X engine with the Thermal Barrier Coatings and 12V start-stop, the simulation predicts about 68% improved unadjusted combined fuel economy over the baseline. For the simulated Gen3X GDCI engine with the Thermal Barrier Coatings and 48V integrated starter generator, the simulation predicts about 78% improvement over the baseline. This amounts to unadjusted combined simulated fuel economy of 64 MPG.

As a comparison to full hybrid technology, vehicle simulations were also conducted for a power-split hybrid powertrain and a parallel hybrid powertrain. These results are shown on the right side of Figure 11. The Gen3X and simulated Gen3X Thermal Barrier Concept engines compare favorably with these advanced powertrains. Notably, the highway fuel economy of the Gen3X enigne and the simulated Gen3X GDCI engine with the Thermal Barrier Coatings exceed the highway fuel economy of the full hybrids.

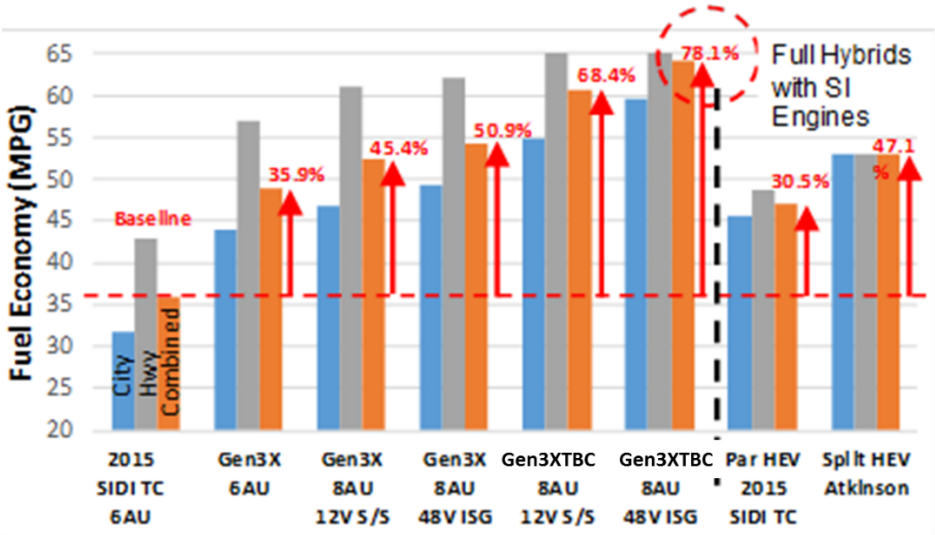


Figure 11. Vehicle simulation results for the 2.2L Gen3X GDCI engine with various powertrain technologies compared to baseline engine and full hybrid engines (Argonne).

Future Work

A number of areas remain to be addressed on the path of developing GDCI into a production-viable technology. Among them:

- Cold Start Emissions: Although significant progress was made in the development of an after-treatment system for GDCI engines, HC in particular remain a challenge, due to the extremely low exhaust temperatures and the slow warm-up of the engine during cold starts. Thus, further development of engine and aftertreatment hardware, as well as controls, will be needed to reduce HC emissions sufficiently.

- Egine Controls: Although the engine controls developed during the GDCI work were sufficient to allow the vehicle to be evaluated for fuel economy and emissions on FTP tests, further work is required to develop robust engine controls --- in particular transient controls – to maintain both stable and efficient engine operation, as well as achieve appropriate levels of driveabiltiy:
    - For the entire engine operating range, including to account for and be robust to part-to-part variation, vehicle-to-vehicle variation, variation in environmental conditions (e.g., temperature, altitude, humidity), part aging and variations in pump fuel.
    - In the presence of the operation of ancillary systems such as the evaporative emissions system, the crankcase ventilation system, and

systems that can introduce loads on the engine (e.g., air conditioniong, rear defrost).

- Diagnostic algorithms will need to be developed for the hardware configuration of the GDCI engine, based on an investigation and understanding of the emissions implications of each component, as well as the regulatory agency(ies) interpretation of the system and any specific functional monitors that may be required.

2.0 Results Highlights:

Task 1.1 Engine-out Emissions evaluation from ATP1 Vehicle

Gen 1 GDCI vehicle emissions testing in cooperation with Oak Ridge National Lab was completed in February, 2015 at Delphi Technoloies' Auburn Hills Customer Technology Center. A variety of instrumentation, test equipment and sampling methods were employed using both Delphi and ORNL equipment. Figure 1.1.1 shows the overall layout of the test equipment as arranged in the Delphi Vehicle Emissions Lab (VEL) during the testing. Note that the vehicle was equipped with an inert catalyst for this testing so that engine-out species and concentrations would remain substantially unaltered and tailpipe measurements could be considered equivalent to engine-out measurements.

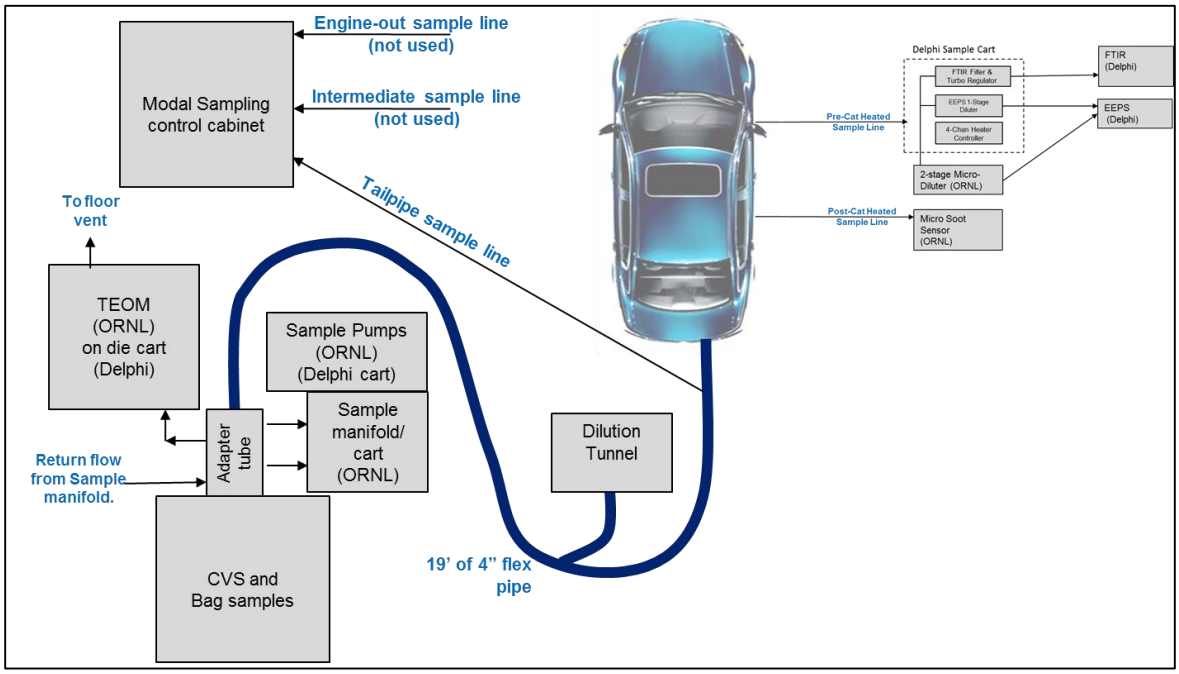


Figure 1.1.1: General layout of Gen 1 GDCI vehicle emissions sampling equipment used in conjunction with ORNL.

As noted in the figure above, instrumentation included a Fourier Transform Infrared spectroscopy (FTIR) analyzer, an Engine Exhaust Particle Sizer (EEPS), a Micro Soot Sensor (MSS), a Tapered Element Oscillating Microbalance (TEOM), and a custom sample manifold system in addition to the standard modal and bag emissions sampling instrumentation.

The sample system contained sets of four individual sample ports with which various sample collection techniques were employed. These included Teflow filters, 2, 4-Dinitrophenylhydrazine (DNPH) cartridges, Empore™ extraction disks, and gaseous sample canisters.

All methods were utilized on a variety of drive cycles including FTP75 (City), HWFET (Highway), US06 (high speed), SC03 (Air Conditioning) and a steady-state 2000 rpm / 2 bar BMEP test point. Additional data was collected regarding vehicle operating conditions using on-board data collection computers. Analysis of the data collected was completed and detailed results were included in the quarterly reports. This information was used in the design of the Gen2 and Gen3 aftertreatment systems.

Fuel economy results for the FTP75 test (average of one run) and HWFET test (average of 3 runs) is shown in Figure 1.1.2. The FTP75 fuel economy performance is 14% less than the previous data collected during ATP1 on this

vehicle when it was tested in a warmed-up condition. Engine temperature was found to rise more slowly than for the baseline SI engine, and thus the cold start fuel economy penalty is longer. The HWFET fuel economy improved by 7% as compared to the previous data collected during ATP1.

Delphi GDCI Vehicle Fuel Economy (mpg)	As of
	2/6/15
Cycle	Avg.
City - (EPAIII, Room Temp, uncorrected E10 fuel)	**33.15**
Hwy (uncorrected E10 fuel)	**62.37**
Percent Improvement over Baseline	
City - EPAIII, Room Temp	**26%**
Hwy	**43%**
CAFE method Combined FE (Room Temp)	**43.26**
Percent Improvement over Baseline	
Combined FE comparison (Room Temp, corrected to E0)	**31.0%**

Figure 1.1.2: Fuel Economy summary data observed during emissions testing.

Standard emissions measurements were taken with the Delphi Technologies' VEL equipment and the results are summarized in Figures 1.1.3 thru 1.1.10.

Hydrocarbon emissions are summarized in Figure 1.1.3 for the three FTP runs that were completed. Two of the runs are noted as invalid (due to engine shutdowns); however their results are very similar to the valid (fourth) run. As with all of the following emissions charts, the information presented is Bag data that has been weighted for each Phase of the test. Also, an inert catalyst was used in this testing, so bag numbers should be very similar to engine-out numbers.

Phase 2 is the highest contributor to total emissions and is approximately twice the amount of Phase 1 and 3 individually. This became a key focus item in the subsequent calibration activities. Phase 1 and 3 emissions are similar, indicating that a cold engine were not the main contributor to engine-out emissions.

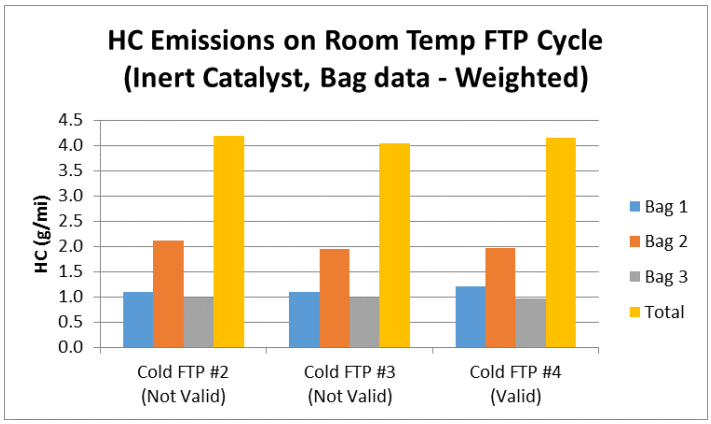


Figure 1.1.3: Hydrocarbon Emissions summary from the FTP75 testing

Carbon Monoxide emissions (shown in Figure 1.1.4) follow a similar trend to hydrocarbons, as expected, with a slightly more pronounced reduction in Phase 3 due to the warmer engine operating conditions. Phase 2 data also indicates the need to focus on CO emissions control.

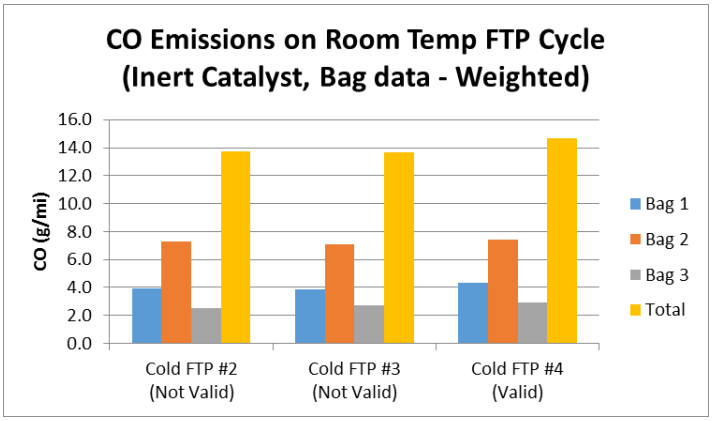


Figure 1.1.4: Carbon Monoxide Emissions summary from the FTP75 testing

Figure 1.1.5 provides the Oxides of Nitrogen emissions; it demonstrated a pronounced trend of higher Phase 2 emissions and thus a clear target for improvement efforts. Contrary to HC and CO, Phase 3 NOx emissions are higher than Phase 1, so additional effort was spent at that operating condition as well.

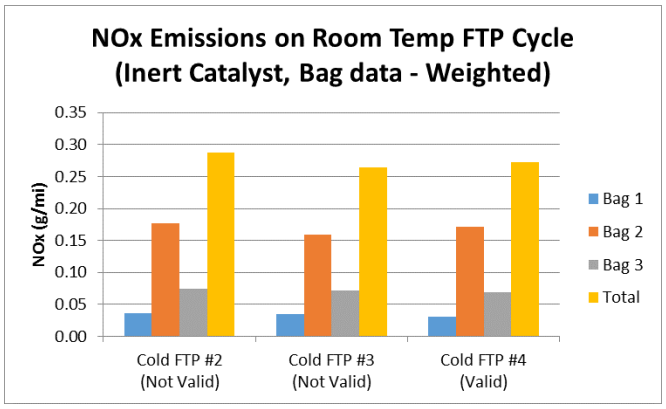


Figure 1.1.5: Oxides of Nitrogen Emissions summary from the FTP75 testing

CO2 emissions and Fuel Economy are shown in Figures 1.1.6 and 1.1.7. Only the final FTP test (Cold FTP #4) is considered a valid test due to the engine shutdowns and trace errors in the other two tests.

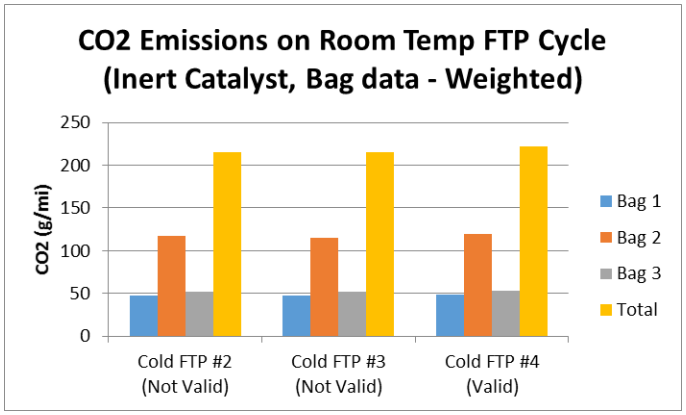


Figure 1.1.6: Carbon Dioxide Emissions summary from the FTP75 testing

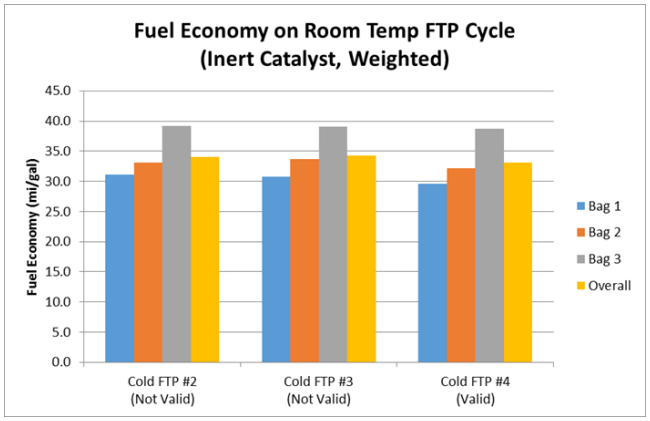


Figure 1.1.7: Fuel Economy summary by Phase from the FTP75 testing

HWFET emissions and fuel economy are given in Figures 1.1.8 and 1.1.9 and showed that HC and CO emissions on the highway cycle are about 1/3 that of the FTP. NOx emissions are similar to the FTP, and fuel economy is nearly double that of the FTP test.

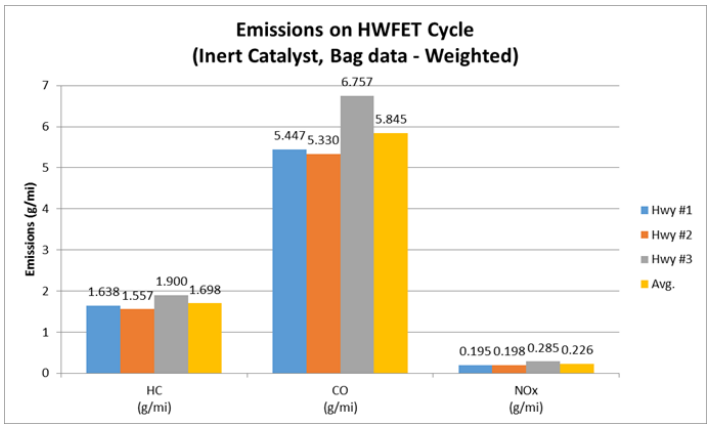


Figure 1.1.8: Emissions summary from the HWFET testing

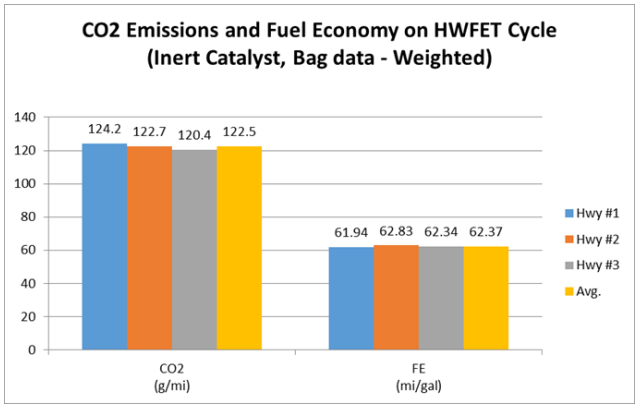


Figure 1.1.9: Fuel Economy summary from the HWFET testing

Figure 1.1.10 gives a comparison of measured emissions as a ratio to the Tier 3 Bin 30 standard, with the target therefore a ratio of 1. It was not expected that the vehicle would meet the Tier 3 standard since it has an inert catalyst and there had not been work to that point on the base engine calibration since the final testing conducted for ATP1. Tier 3 standards combine the NMOG and NOx emissions into a single target value. Engine out NMOG and NOx emissions are high and combine to create a poor ratio for those constituents. Formaldehyde emissions are also high and represent a significant challenge for the combustion and

aftertreatment systems. CO is quite reactive and should respond well to catalysis. PM performance is closest to meeting the standard and will improve with the Gen 2 aftertreatment system and improved calibrations. For this plot, the PM Mass emissions as reported by the Micro Soot Sensor were used.

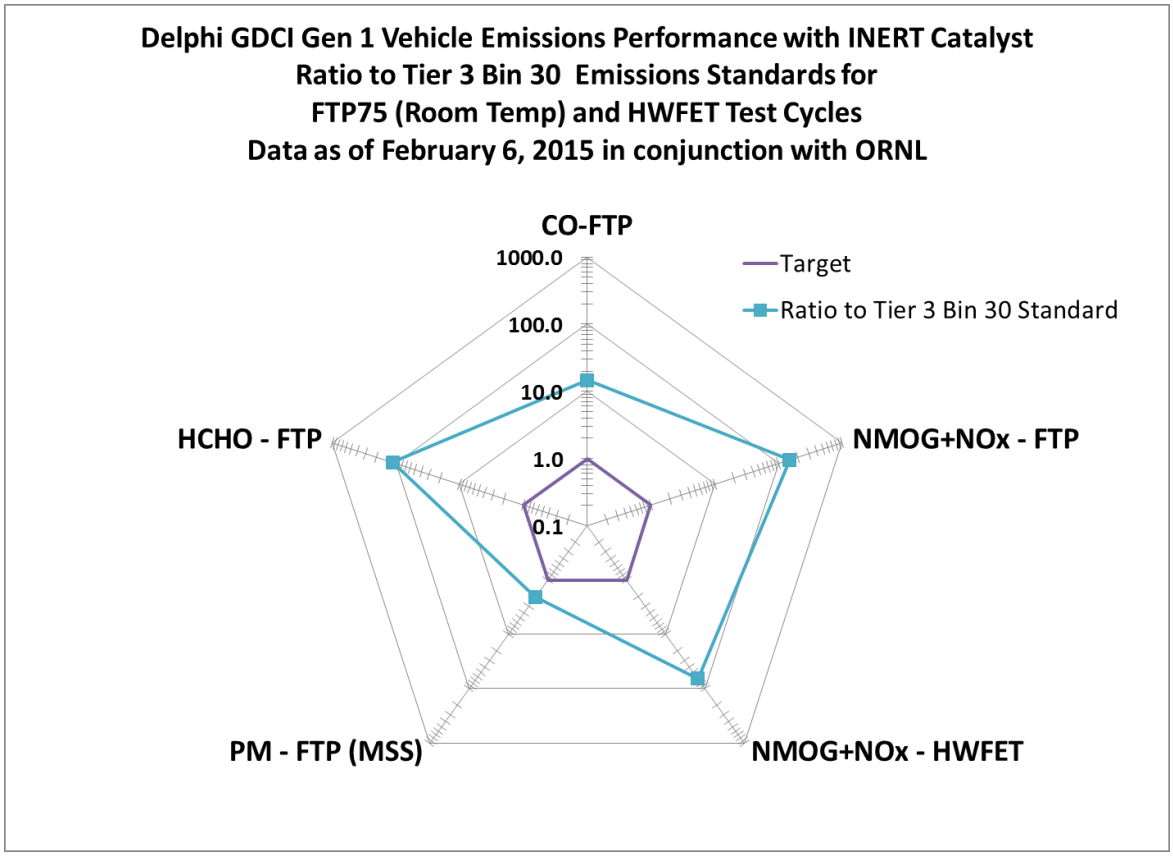


Figure 1.1.10: Summary of emissions performance relative to Tier 3 Bin 30 standard. NOTE: Vehicle had an inert catalyst installed for this testing to facilitate correlation of engine-out and tailpipe emissions measurements so there was no catalysis of pollutants from the aftertreatment system. The vehicle was not expected to meet emissions requirement in this configuration.

Task 1.2 GDCI Single Cylinder Engine Development

Delphi Technologies' GDCI single-cylinder engine was upgraded to Gen 2.0 GDCI hardware. The Gen 2.0 cylinder head, injection system, valvetrain, and piston were installed. A photo of this engine is shown in Figure 1.2.1. The Labview engine controller and software were also modified for GDI pump control and rail pressure control. The EGR cooler system was redesigned to improve EGR control.

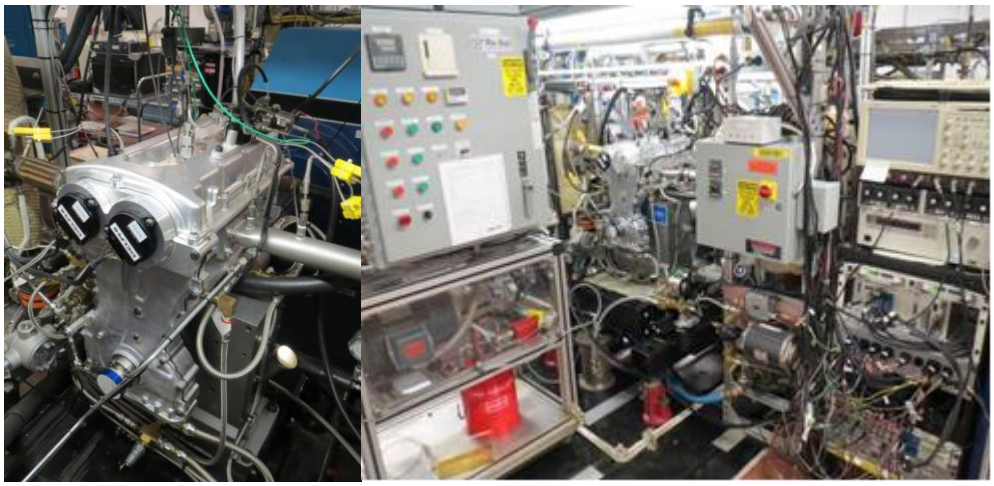


Figure 1.2.1 – Photo of Gen 2.0 GDCI single-cylinder engine at Delphi Technologies

In early 2015, tests were conducted at 800, 1500, and 2000 rpm over a range of loads. As shown in Figure 1.2.2, ISFC was very good over the load range with minimum ISFC of 169 g/kWh at 2000-11bar IMEP. This equates to 50.6% indicated thermal efficiency. At idle conditions, ISFC and COV IMEP increased considerably as combustion efficiency decreased. Combustion phasing, duration, and noise were in reasonable ranges for these tests.

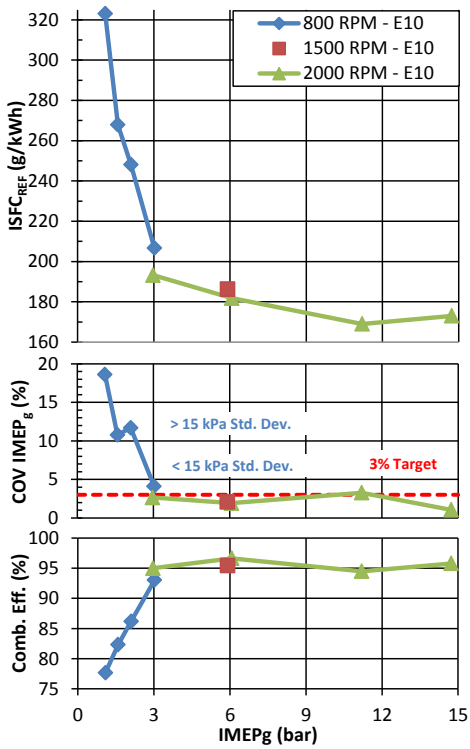


Figure 1.2.2 – Measured ISFC, COV IMEP, and Combustion Efficiency of Gen 2.0 GDCI single-cylinder engine.

Task 1.3 Engine and Vehicle Simulation

Simulation tools were used throughout the project to evaluate numerous aspects of the GDCI operation and to support controls development . Examples in Phase 1 include:

One-dimensional engine simulations were performed at full load using GT Suite to determine the best turbocharger and supercharger for GDCI engines. Five different turbocharger maps from two suppliers, and three different supercharger maps from two other suppliers were simulated. The simulations included various turbo rack settings, supercharger drive ratios (DR), and EGR levels, which produced various boost levels and associated BMEP.

A model-based control (MBC) strategy was also developed for the GDCI thermal management system (TMS) with the aid of co-simulation. A detailed GT Suite model of the complete GDCI thermal management system was developed and coupled to Matlab Simulink for transient control simulation. Simulations were completed that showed cooling capacity of the thermal management system at full-

load torque and power. The low-temperature radiator was enlarged, and improved coolant control valves were incorporated as a result of the simulation work. Detailed transient simulations were also conducted to demonstrate intake air temperature control and EGR transient control. Fast and accurate control of both EGR and intake air temperature were critical to the success of the GDCI concept.

Transient co-simulations of inlet air temperature control were also conducted for six different acceleration/cruise/deceleration transients to cover a typical range for the US FTP drive cycle.

Task 1.4 Spray Characterization & Spray Model Validation

Spray chamber testing of the GDi injectors was done at University of Wisconsin-Madison. Backlit and Schlieren spray imaging was completed for a range of chamber pressures and temperatures for various injection pressures and injection quantities. Eample results for high fueling level (25mm3 per shot) at the high chamber pressure and temperature condition are shown in Figures 1.4.1 through 1.4.3.

Spray images in Figure 1.4.1 show the liquid fuel evaporates very quickly and vaporized fuel penetrates without interaction among adjacent plumes. Liquid penetration results are shown in Figure 1.4.2. At conditions representative of the late compression stroke for a high compression engine, the liquid fuel does not penetrate further than approximately 20mm at any injection pressure. The fast vaporization of gasoline fuel is a major advantage over diesel fuels and greatly helps avoid wall wetting in compression ignition engines. Vapor penetration results are shown in Figure 1.4.3. As expected, vapor penetration exceeds liquid penetration. Due to spray momentum effects, vapor penetration is greater at higher injection pressures. At injection pressure of 500bar, vapor penetration is approximately 50mm.

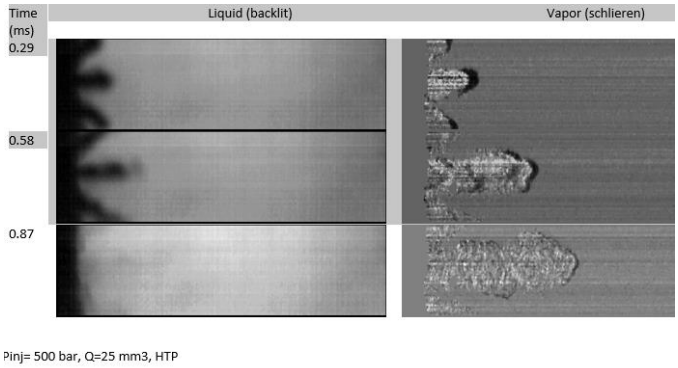


Figure 1.4.1. Images of an isolated fuel spray plume at three times after start of injection in the Delphi spray chamber at 40 bar, 650 K and fuel pressure of 500 bar.

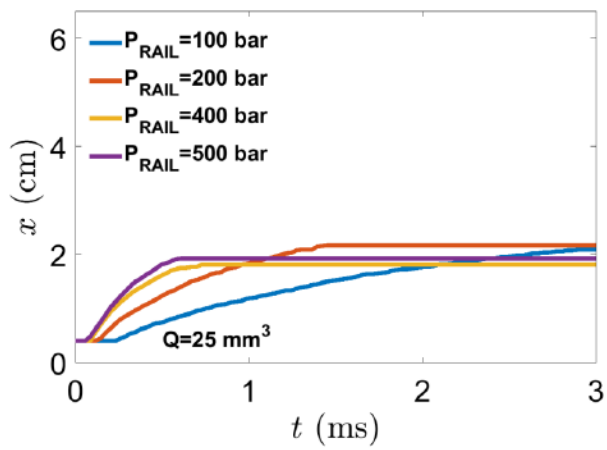


Figure 1.4.2. Liquid penetration as a function of injection pressure for injected quanitity of 25mm3 at chamber pressure and temperature of 40 bar and 650 K, respectively.

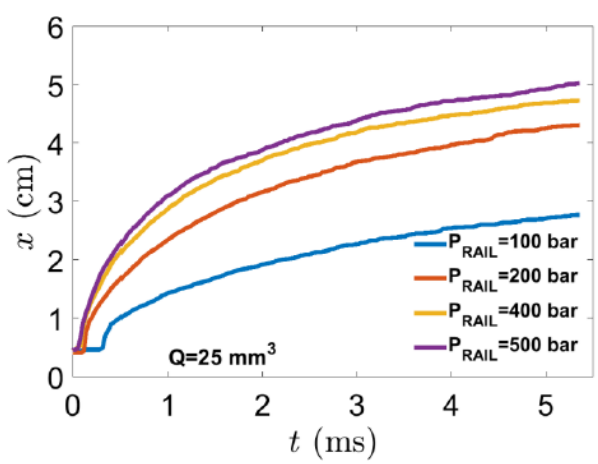


Figure 1.4.3. Vapor penetration as a function of injection pressure for injected quanitity of 25mm3 at chamber pressure and temperature of 40 bar and 650 K, respectively.

Task 1.5 GDCI Gen2 engine build

The Gen 2 GDCI engine was developed by Delphi Technologies outside of Department of Energy funded projects, however, the Gen 2 engine was used in Phase 1 of this project.

Builds of the project's Gen 2.0 GDCI engines were completed at Delphi Technologies in early 2015. The Gen 2.0 engine system included a new Delphi Technologies' fuel system, valvetrain, thermal management system, aftertreatment system, piston and ring packs, and lubrication system. Special design features were included to reduce both motoring and firing friction. A photo of the engine with base engine information is shown in Figure 1.5.1.

New GDCI injectors were fabricated at Delphi Technologies for testing on Gen 2.0 engines. The injectors featured higher maximum operating pressure (MOP), higher injection rates, and various spray angles. The injectors were bench tested and calibrated prior to engine tests. The thermal management system had features for cold starts and fast warm-up of the engine and aftertreatment system. The system also provides variable intake air temperature (IAT) control, which is useful to extend the operating load range of the engine. Labview engine controls and software were developed for engine heat up and intake air temperature control in the dynamometer test cell.

	2011 Gen I GDCI	2014 Gen II GDCI
Engine Type	4-valve Comp. Ignition	
Fuel	RON 91 E10	
Displacement	1.8 L	
Bore × Stroke	82 × 85.2 mm	Longer rod
Comp. Ratio	~ 15	~15.5
Piston	Texan	Omega
Cyl Pres Rating	200 bar	
Injection	Multi-hole GDI Central Mount	GDI Multi-hole
DOHC Type II Valvetrain	Intake & Exhaust Cont.-Var Mechanical	Exhaust Only
Swirl & Squish	Min. mixture motion	
Boost	2-Stage (Super & Turbo)	
EGR	Low-Pres-Loop w/Cooler	

Figure 1.5.1 – Base engine data and photo of the Gen 2.0 GDCI engine at Delphi Technologies.

Task 1.6 Gen 2 MCE engine dyne debug and mapping

The first Gen 2.0 GDCI engine was installed on a performance dynamometer at Delphi Technologies' technicial center in Auburn Hills, Michigan for debug and preliminary tests. A photo of the Gen 2.0 GDCI engine installation in test cell is shown in Figure 1.6.1. Labview engine controls and software were updated and sensors and actuators were interfaced and calibrated. Static tests were performed on the engine cooling system.

Preliminary motoring engine tests were conducted to determine friction characteristics of the Gen 2.0 engine (One objective of the Gen 2.0 GDCI engines was reduced motoring and firing friction).

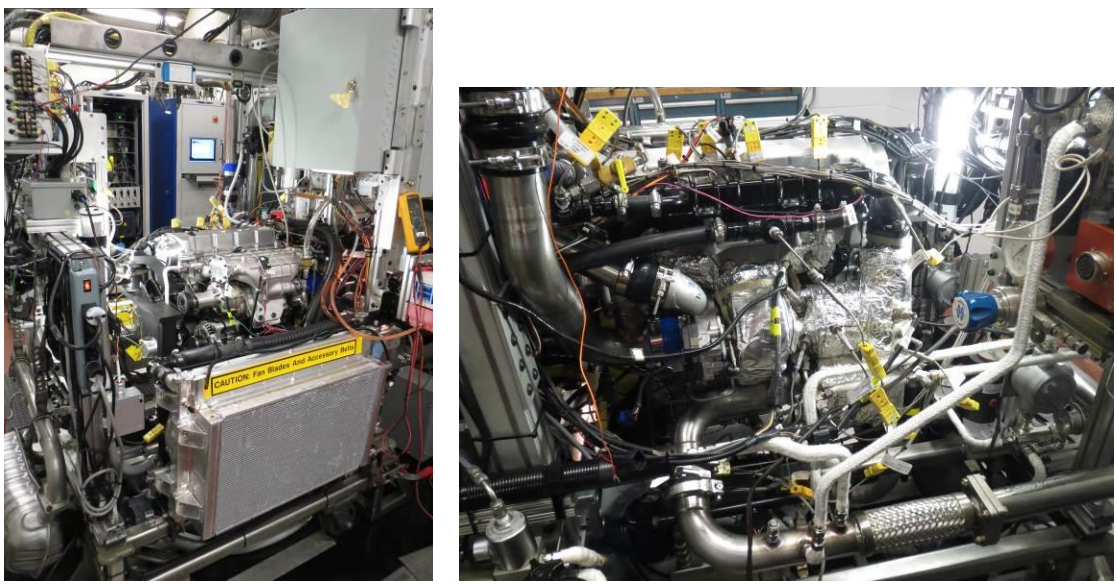


Figure 1.6.1 – First build of Gen 2.0 GDCI engine installed in a Delphi Technologies' test cell.

The Gen 2 engine was evaluated by conducting a load sweep at 1500 rpm. For this test, IMEP was varied from 1 to 15 bar. Data was collected that met project targets for NOx < 0.2 g/kWh, PM < 0.1 FSN, COV IMEP < 3%, and CNL. Targets for CNL were defined as a function of engine speed and load. Tests were also conducted at loads of 5 to 7 bar IMEP with relaxed project targets for ISNOx (<1

g/kWh) and smoke (< 0.25 FSN). This provided a significant BSFC benefit at this intermediate load range.

Figure 1.6.2 shows a BSFC comparison for the Gen2 and Gen 1 engines. The Gen 2 engine exhibited improved BSFC of over 11% at 4 bar BMEP and over 6% at 10 bar BMEP. The engine exhibited low BSFC of 211 to 215 g/kWh over a wide load range from 8 to 11.5 bar BMEP. Between 5 and 7 bar BMEP, an additional 5% BSFC improvement was realized by relaxing the NOx and smoke constraints. This could be realized if NOx aftertreatment was included on the powertrain. At low loads of 2 to 3 bar BMEP, the supercharger may be declutched for significant BSFC benefit (Figure 1.6.2).

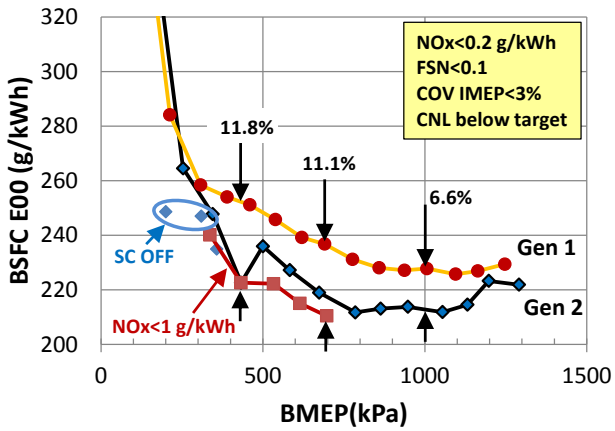


Figure 1.6.2. BSFC for 1500 rpm load hook for Gen 2 and Gen 1 GDCI engines.

The Gen 2 GDCI engine was also tested on a steady state dynamometer at five speed and load conditions covering a broad operating range. The engine was semi-optimized by manually adjusting various control parameters. An efficiency loss analysis was then conducted.

Table 1.6.1 lists the five operating points, the measured BSFC, the BSFC improvement relative to the Gen 1 GDCI engine, ISFC, and $FMEP_{NET}$. $FMEP_{NET}$ represents the mechanical losses of the firing engine minus the estimated mechanical losses of the supercharger. At the lowest load conditions (800 RPM-2 bar IMEP and 2000 RPM- 2.3 bar IMEP) boost was not required and the engine was operated naturally aspirated with the supercharger declutched. Exhaust rebreathing was used for 800 RPM-2 bar, 2000 RPM- 2 bar, and 1500 RPM- 6bar.

Table 1.6.1. Five test conditions for the efficiency loss analysis.

RPM-IMEP	Op. Cond.	$BSFC_{E00}$	Impvmt	$ISFC_{E00}$	$FMEP_{NET}$
		g/kWh	%	g/kWh	kPa
800-2bar	Idle	282.4	24.4	249.8	22
2000-2bar	Global Point	248.1	7.1	206	32
1500-6bar	Low Load	230	8.4	191.5	50
2000-11bar	Medium Load	218.4	5	177.9	119
1750-14bar	Min BSFC	211.9	3.2	178.6	131

For all five test points, the BSFC of the engine was very low with significant improvements relative to the first generation GDCI engines. BSFC improvements were derived mostly from reduced firing friction, FMEPNET, which resulted from multiple base engine design changes. ISFC of the Gen 2 engine was also very low and showed the opportunities for an efficient powertrain if mechanical losses can be minimized. The design of the Gen 3 GDCI engine leveraged these learnings.

Task 1.7 – GDCI Gen 2 Controls Development

Development of the Gen2 control system included the refinement of the control system architecture, upgraded controller hardware, new control algorithms, as well as improved sensors and actuators for the Gen 2 GDCI demonstration engines. Control function upgrades included fuel control, charge air control, thermal management control plus the development of new aftertreatment controls. Engine simulation, prototyping and software development using the HIL bench were also completed.

Gen 2 vehicle controls pre-work on Gen 1 vehicle

For the Gen 2 Intake Air Temperature (IAT) control, the feed-forward Charge Air Cooler 2 (CAC2) coolant flow rate calculation was replaced by a heat exchanger effectiveness model. The model used estimated supercharger outlet gas temperature, estimated supercharger gas flow rate, newly added CAC2 coolant inlet temperature measurement, and desired IAT as inputs. Figure 1.7.1 shows the profile of the calculated feed-forward coolant flow rate during engine transient operation. It reflects the engine speed/load variation, and can provide fast control command.

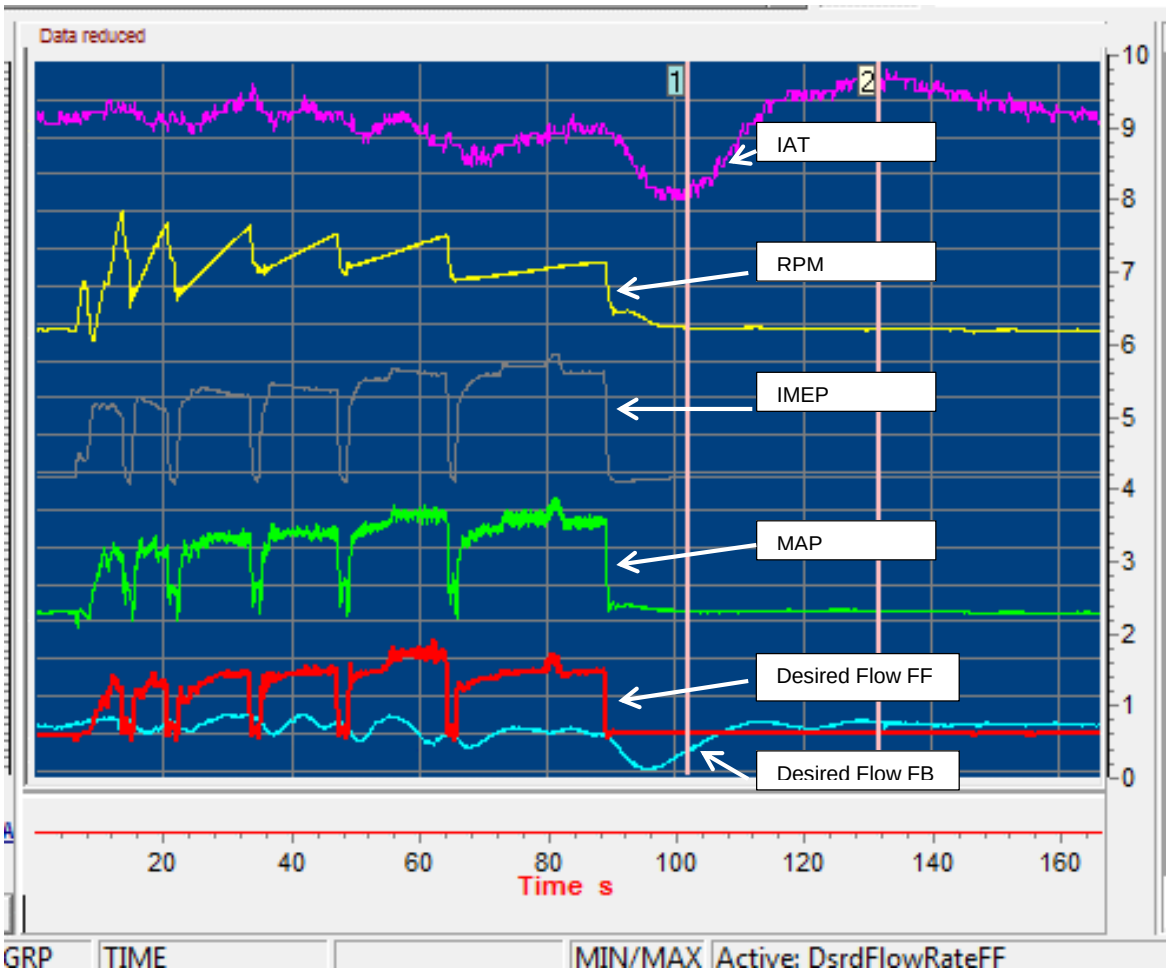


Figure 1.7.1: Feed-forward and feedback CAC2 coolant flow rate during transients

<u>Gen 2 engine controls on hardware in the loop (HIL) Bench</u>

A new Delphi Technologies' engine controller (MT92.1) was selected for Gen2 vehicle development. This controller had improved processor speed, dual cores, and increased memory. Upgraded MicroAutoBox (MABx) interface hardware was implemented which had significantly more throughput than the Gen 1 interface, for improved system performance. All controllers and interfaces were developed and verified on the HIL bench prior to implementation on the Start Cart and vehicle.

Task 1.8 Gen2 aftertreatment

A Gen 2.0 aftertreatment system was designed and fabricated for Gen 2.0 GDCI engines. The system included a "log-plenum" exhaust manifold, a first oxidation catalyst with increased volume, a second oxidation catalyst with increased volume, a bean pipe and a backpressure valve. The header cone and bean pipe were redesigned using CFD tools for improved flow uniformity. The catalyst formulation and cell size were also improved for higher HC and CO conversion efficiency and lower space velocity. The system was packaged under hood for vehicle use and was equipped with a complete array of sample taps, automotive grade sensors, fittings, and gaskets. No NOx aftertreatment was included at this stage of the development. A photo of the system is shown in Figure 1.8.1.

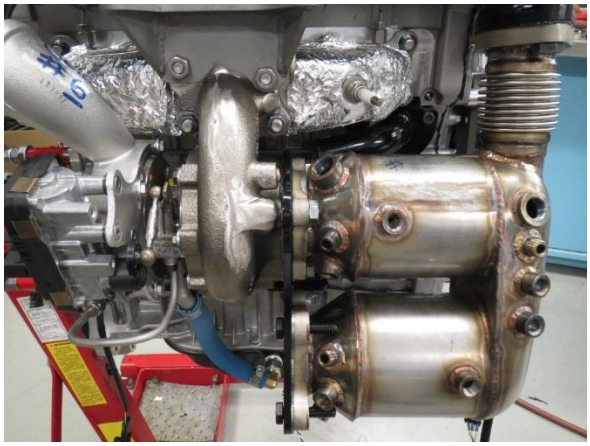


Figure 1.8.1 – Photo of Gen 2.0 aftertreatment system.

Task 1.9 – GDCI Gen 2 Vehicle

This task included the build, controls integration, calibration and testing of a Gen 2 GDCI powertrain installed in the ATP1 vehicle test platform. Development of refined control algorithms and Gen 2 specific calibrations were also completed. Testing and evaluation included emissions and fuel economy testing.

Vehicle Build & Integration of Technologies

A Gen2 engine, full Gen 2 thermal management system, upgraded control hardware and all supporting systems were installed in the ATP1 Gen1 vehicle. The upgrade was completed in Q2 2016.

Thermal Management System Control for Gen 2 GDCI Engine

In the previous vehicle configuration, the low temperature loop (LTL) and high temperature loop (HTL) of the thermal management system (TMS) were controlled separately. The LTL was only used to maintain intake manifold air temperature (IAT), while HTL e-pump was used for engine coolant temperature (CLT) control. Beginning with the Gen 2 vehicle, the hardware in both the LTL and the HTL was significantly changed with a number of additional valves added to permit independent control of coolant flow through various thermal management devices. The dual ball valve (DBV), CAC1 and CAC2 flow control valves, and a blending valve (BLV) were added between the LTL and HTL, as shown in Figure 1.9.1.

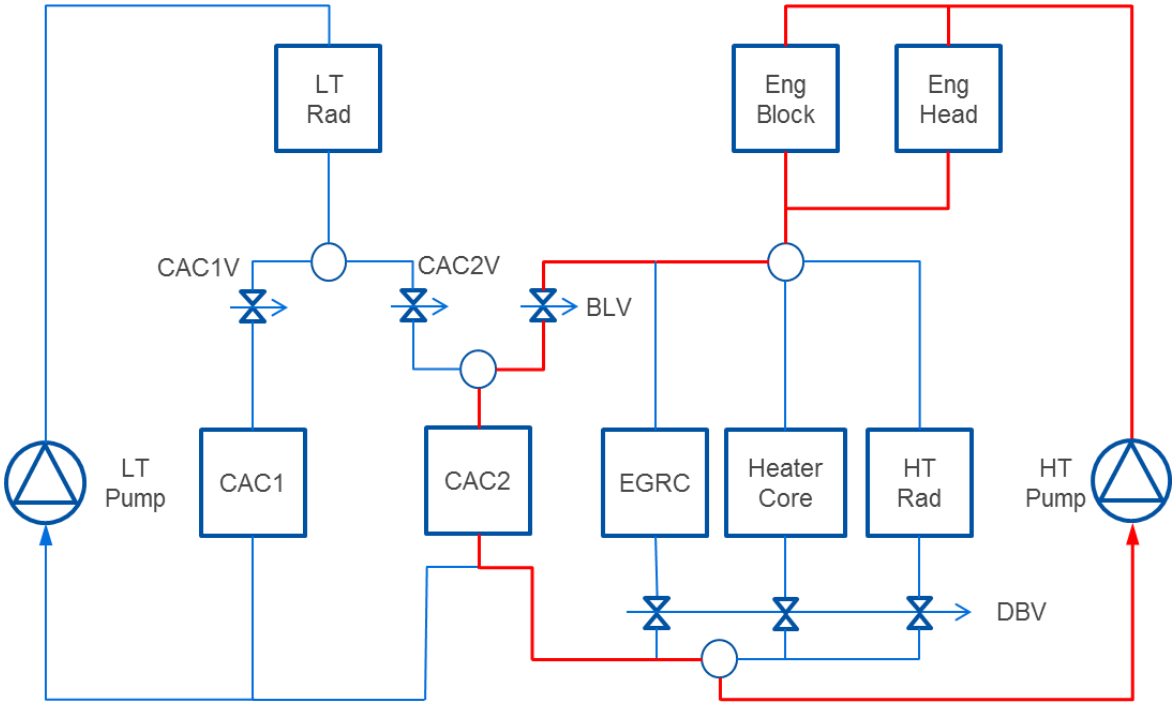


Figure 1.9.1: Coolant flow path of Gen 2 GDCI TMS in control mode 2

In order to take advantage of the new features of the Gen 2 engine thermal management system (TMS), the TMS control strategy was completely re-designed. The new concept controlled the TMS using several modes. Figure 1.9.2 shows the stateflow chart of the modes, as well as the mode switching strategy, which was based on engine operating conditions (mainly a function of IAT and CLT). The new strategy allows different interactions between the low temperature loop (LTL) and

high temperature loop (HTL) in some modes to achieve optimal thermal management and conservation of thermal energy during warm-up.

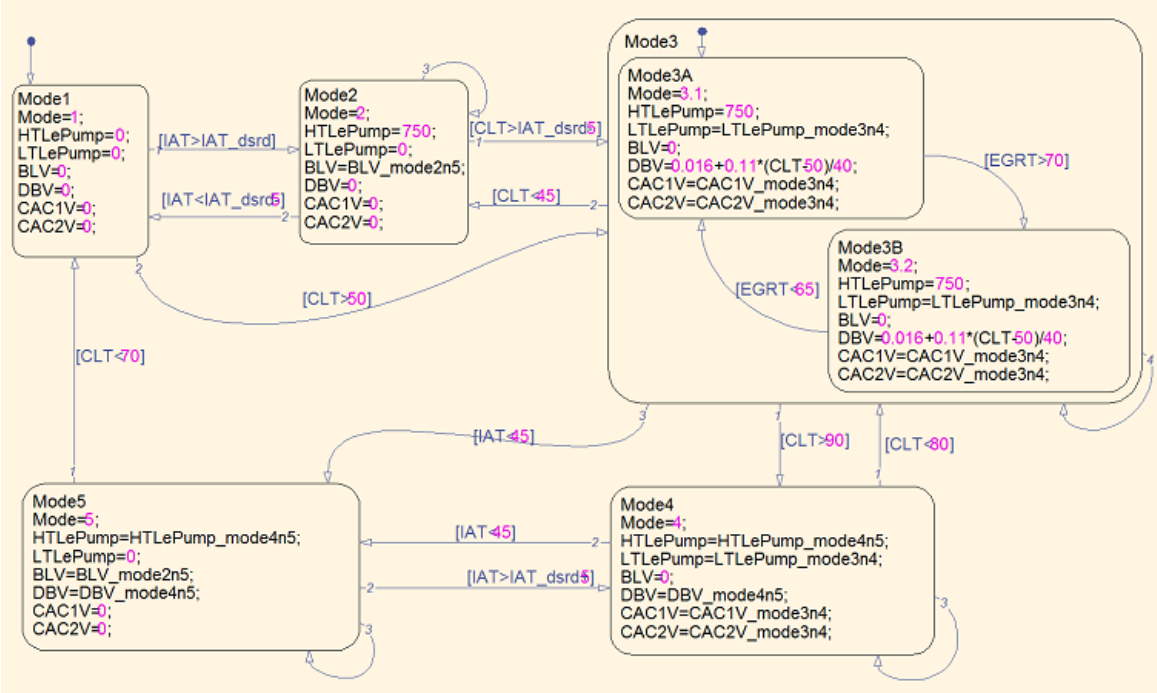


Figure 1.9.2: Stateflow chart of TMS control modes.

<u>Gen 2 Vehicle Calibration:</u>

Steady-state calibration of the Gen 2 vehicle was completed. The calibration work focus was on the FTP75 speed / load range from 1000 to 3000 rpm and from 0 to 12 bar IMEP.

Most of the Gen2 calibration work was focused on improving fuel economy. Since a significant portion of the engine load is from the supercharger, the calibration was focused on lowering the manifold air pressure (MAP) targets. Lower MAP values have a negative effect on promotion, and so strategies were developed and implemented to counter the lower promotion:

1. For low and mid loads, increased rebreathe and increased intake-O2% where needed thererfore different calibration desired values for MAP, Rebreathe dP, and Intake O2 were employed.

2. For high engine loads the exhaust cam position was closed to avoid scavenging and to optimize the turbo rack position for boost from the turbocharger instead of the supercharger.

Other Gen2 calibration differences related to improving fuel economy were:

- Idle rpm lowered from 1000 rpm to 750 rpm
- Fuel cut-off on deceleration (DFCO) enabled

Poor combustion performance at the exit of deceleration fuel cut-off and during gear shifts in general were addressed by a calibration that closed the rebreathe cam during gearshifts and fuel cut-off. This dramatically improved general drivability, though other challenges remained to be addressed forcold engine operation.

Steady State Vehicle Indicated Specific Fuel Consumption

Gen2 vehicle calibration improvements in the FTP75 speed / load range from 1000 to 3000 rpm, and from 0 to 12 bar IMEP, focused on improving fuel economy in the 1000-2000 rpm range and on stable combustion in the 2000-3000 rpm range. The calculated ISFC in [g/kWh] (based on measured airflow, exhaust lambda and IMEP(gross)) for the 1000-3000 rpm and 2-8 bar IMEP range is shown below in Figure 1.9.3.

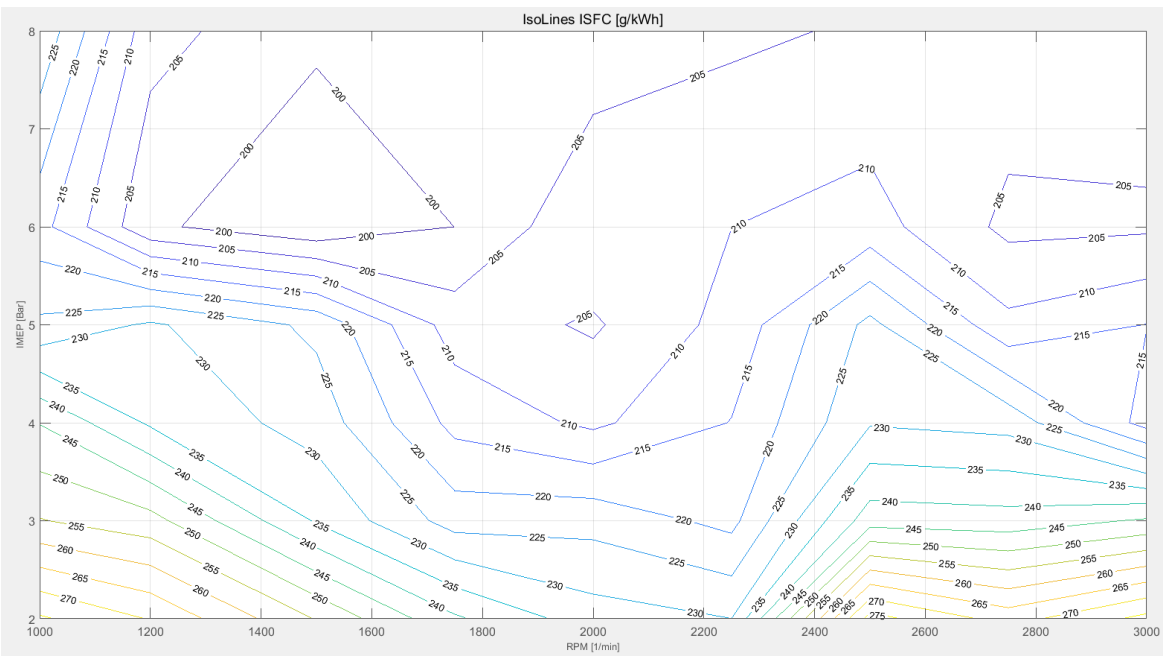


Figure 1.9.3: Calculated ISFC of Gen 2 vehicle over low-mid load operating range

Gen2 Vehicle Level Fuel Economy and Emissions Testing

City and Highway cycle fuel economy and emissions testing at Delphi Technologies on the Gen 2 vehicle were completed in August of 2017. Testing consisted of multiple runs of room temperature start EPAIII and HWFET tests. Modal data was used for reporting on this round of testing.

Vehicle fuel economy was evaluated using E10 Tier 3 certification fuel. The Gen 2 vehicle demonstrated a 35% improvement in combined fuel economy over the baseline vehicle running the same fuel. Table 1.9.1 provides the comparison data.

Table 1.9.1: Gen 2 Vehicle Fuel Economy Performance

Test Schedule	Gen 2 Vehicle (mpg)	Baseline Vehicle (mpg)	Improvement (%)
City (EPAIII)	34.8	25.8	34.8
Highway (HWFET)	56.7	42.1	34.6
Combined	42.1	31.3	34.7

Gen 2 vehicle emissions performance was not improved over the previous Gen 1.8 vehicle. This was due, in part, to utilizing the same aftertreatment hardware as was used on Gen 1.8 (with no NOx treatment capability) and also due to additional cold starting difficulties experienced on Gen 2. Cold start and cold idle quality had deteriorated, with significant emissions generated during that period. The Gen 3 engine design addressed these shortfalls of the Gen2 design.

Figure 1.9.4 is a comparison of Gen 2 Vehicle emissions levels relative to the Tier 3 Bin 30 emissions target. Significant improvements (one or two orders of magnitude) were still required for NMOG, CO and NOx, and the Gen 3 aftertreatment system was designed to address these challenges.

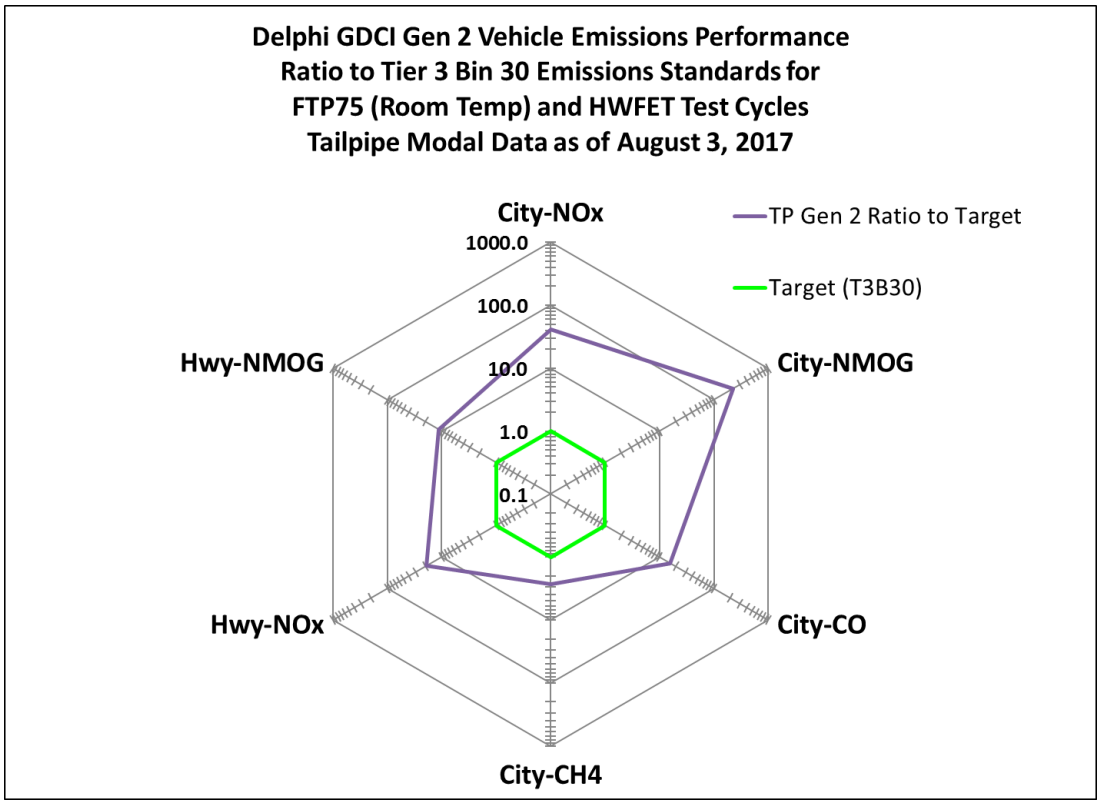


Figure 1.9.4: Gen 2 Vehicle Emissions performance relative to T3B30 target

Task 2.1 Gen 3 GDCI Simulation

<u>Boost System Development for Gen3 Engines</u>

The boost system was known to be the largest source of recoverable efficiency loss for GDCI engines, with the primary loss mechanism being pumping work of the supercharger bypass flow. One solution simulated was a variable supercharger drive to operate the supercharger just fast enough to produce the target MAP. For high load operation, an improved match of the turbocharger was also sought to improve torque and power.

One-dimensional engine simulations were performed at full load using GT Suite to determine the best turbocharger and supercharger for Gen3 engines. Five different turbocharger maps from Borg Warner and Honeywell, and three different

supercharger maps from Eaton and IHI were simulated. The simulations included various turbo rack settings, supercharger drive ratios (DR), and EGR levels, which produced various boost levels and associated BMEP. It was assumed that supercharger bypass flow was zero, as would be the case for a continuously-variable supercharger drive. A model of the 2.22L long-stroke Gen3 engine was developed for these simulations. Detailed results and analysis of these simulations can be found in the project quarterly reports starting in Q2 2016.

Simulation of Gen3 Combustion System at Part Load A primary goal of the GDCI injection and combustion systems is a 'wetless' injection process. Fuel wetting of the piston surfaces slows the fuel atomization and evaporation processes and leads to higher smoke emissions. Mixing of fuel in the bulk cylinder gases helps avoid cool zones near chamber walls that may impede complete oxidation of fuel. This is especially important for late injection timings when the piston is approaching top-dead-center (TDC). Careful matching of injection and spray characteristics to piston bowl geometry is essential.

An important factor is the injector spray angle. Converge Software was used to optimize the injector spray angle for a preferred Gen3 piston bowl. One preferred injection strategy was a premixed double injection in which a portion of the fuel was injected during the intake stroke, and the remainder was injected late on the compression stroke. Simulations were performed over a wide range of injection timings to predict propensity for piston wetting.

A typical CFD model for the Gen3 injection process is shown in Figure 2.1.1. The piston bowl is an open design with a low piston pip for high penetration distance. The long stroke of the Gen3 engine effectively increased the TDC clearance between injector and piston for late injections.

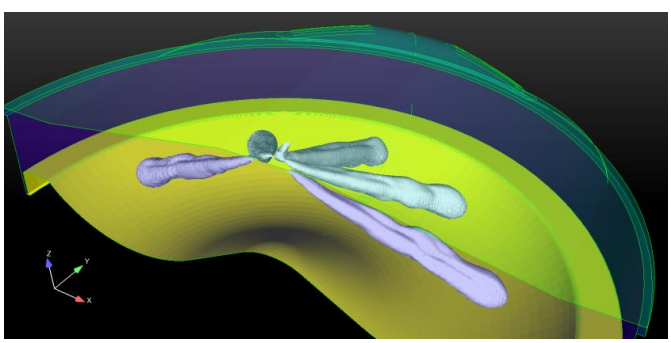


Figure 2.1.1. Converge simulation of the injection process for Gen3 combustion system showing vapor plumes for half of the cylinder simulation domain.

Simulation results are shown in Figures 2.1.2 a-d. Figure 2.1.2 a shows the mass of fuel injected and the mass of fuel vapor produced as a function of crank position

for various injection timings. Due to high cylinder gas temperatures, vaporization is very fast and is notably fastest for the latest injection timings simulated.

Predicted piston wetted mass normalized by total injected mass is shown in Figures 2.1.2 b, c, and d, respectively, for spray angles (SA) of 115, 125, and 130 degrees (included). For a relatively narrow spray angle of 115 degrees (Fig. 2.1.2 b), piston wetting occurred for all start of injection (SOI) timings and persisted through TDC and the combustion process. While difficult to simulate, these fuel puddles can be expected to produce significant smoke emissions. For a spray angle of 125 degrees (Figure 2.1.2 c), wetting was improved considerably, especially for injection timings later than 45 CAD btdc. A spray angle of 130 degrees (Figure 2.1.2 d) produced the best results with practically no piston wetting for injection timings later than 45 CAD btdc. On this basis, injectors with spray angles of approximately 130 degrees should exhibit the best smoke characteristics for late injection operation.

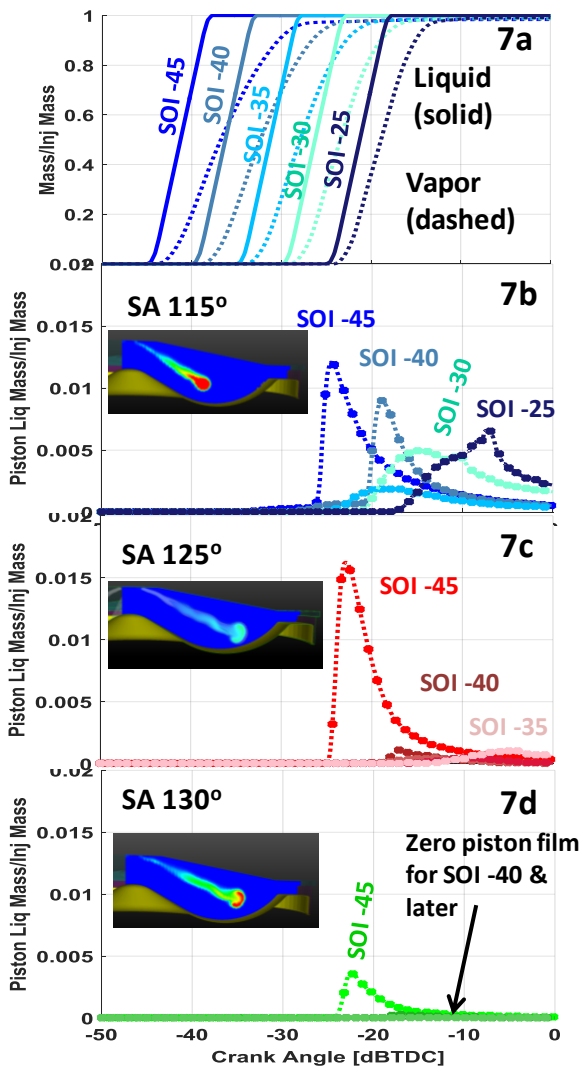


Figure 2.1.2 *a-d. Injection profiles and predicted piston wetting for three spray angles and various late injection timings*

Simulation of Gen3 Combustion System at High Load Simulations were also performed to develop combustion and injection strategies at high load. The objective was to provide efficient and clean combustion at high load operating conditions while meeting constraints for peak cylinder pressure (PCP) and combustion noise. Design factors include the fuel injection quantity, timing and pressure along with injector geometry and flow rate. At high load operating conditions, the time available for fuel mixing (ignition delay) is reduced because cylinder pressure and temperature are high. The challenge being addressed through simulation is to achieve a combustion event that is properly phased and of sufficient duration to not exceed cylinder pressure and noise limits.

One combustion strategy found to work well consisted of injection of a small amount of premixed fuel (0-20%) followed by diffusion combustion. Converge software was used to simulate this process for the Gen3 GDCI combustion system (Figure 2.1.3.) The figure shows simulated liquid droplets, gas temperature [K], and CO concentration [kg/m^3] at top dead center. It shows that combustion occurs in the bulk gases and that liquid droplets have limited penetration and avoid wetting the piston surface. It also shows that very little fuel is trapped in the piston topland volume, which helps keep HC emissions low.

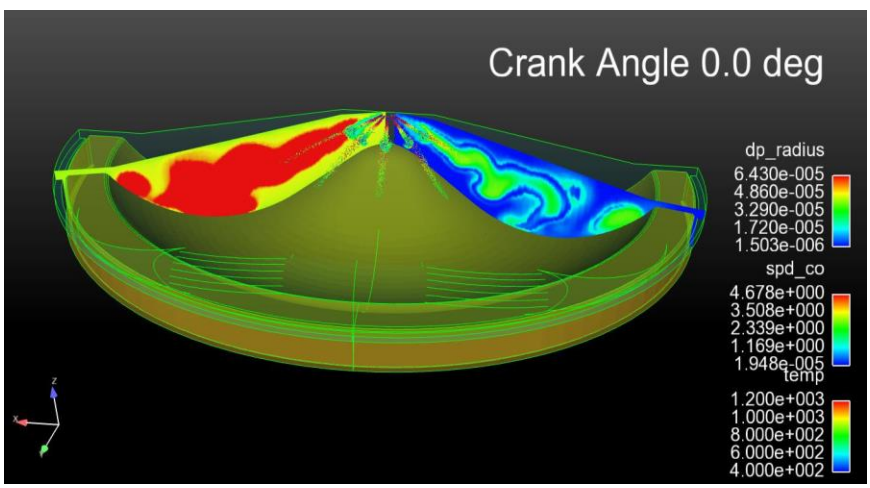


Figure 2.1.3*. Converge simulation of high load combustion process for Gen3 combustion system showing droplet size (plumes), gas temperature (left), and CO concentration (right).*

Further CFD studies were performed using Converge software to investigate this late-injection, diffusion-mode strategy with the Gen3 GDCI injection and combustion systems. This injection strategy is similar to conventional diesel in which one or

more late pre-injections are combined with a large main injection; it proved to be very effective for high-load operation of the GDCI engines. This approach showed lower combustion noise and required less EGR, while maintaining low smoke levels. The purpose of the pre-injected fuel is to release heat using GDCI combustion before the main injection occurs. This increases cylinder temperature and pressure in preparation for the main injection. The main injected fuel then burns in a diffusion mode with relatively long combustion duration for reduced combustion noise. Detailed simulations were conducted to refine this approach. Data and analysis for this research are documented in the projects quarterly reports beginning in Q3 2017.

Gen3 Single Cylinder Engine Development A Gen3 single-cylinder engine was built that featured a high-pressure injection system for testing high-load injection strategies. The engine was installed in EDL1 at Delphi Technologies' technicial center in Auburn Hills and was used for limited high-load injection strategy testing.

Task 2.2 Engine and Vehicle Simulation

Vehicle Simulation - Propulsion System Efficiency (PSE) approach
During a collaboration session with a domestic OEM, their team shared a vehicle / propulsion system performance analysis method that provides information on the fundamental energy requirements to move a vehicle through a drive cycle using a simplified analysis method involving only the longitudinal vehicle dynamics as represented by the vehicle coastdown data. The required energy is then compared to the actual fuel energy used, and an overall Propulsion System Efficiency (PSE) is calculated. This approach normalizes vehicle fuel consumption data and allows direct comparison of powertrain efficiency amongst dissimilar vehicles and engines.

The analysis method itself is proprietary to the OEM, so an alternative simulation method was developed for this project in Simulink. A flowchart of the simplified model is shown in Figure 2.2.1 below. The Vehicle Demand Energy is calculated in the top yellow block labeled "Tractive Force, Torque, Power, Energy". The model was also extended to transmission and engine performance data which are used in conjunction with a BSFC-based Gear Shift Optimizer to provide the shift points for optimum fuel economy.

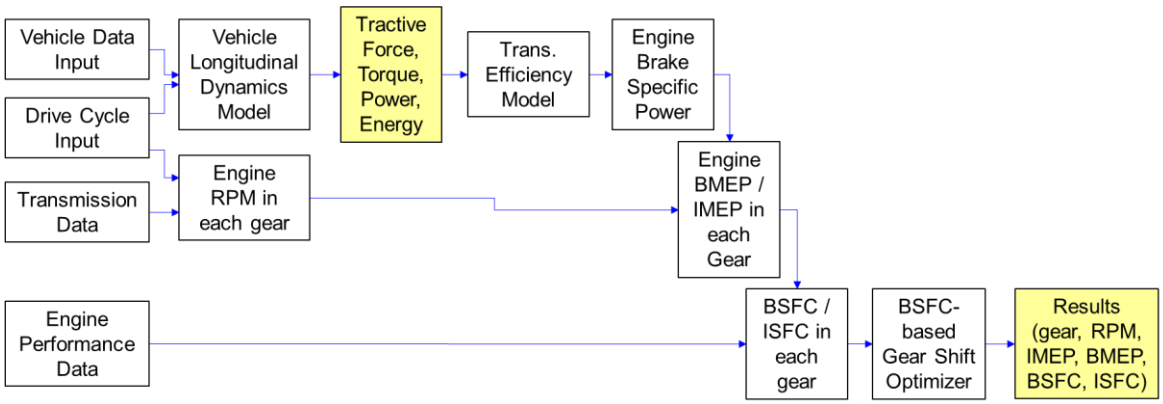


Figure 2.2.1: Vehicle Demand Energy model data flow.

The model was used to analyze the required engine torque and speed to meet the FTP75, HWFET and US06 drive cycle requirements. The simulation identified three critical points in the US06 cycle with particularly high speed and/or IMEP requirements:

- Cycle 3: 11.0 bar IMEP @ 3275 rpm
- Cycle 3: 18.2 bar IMEP @ 2050 rpm
- Cycle 8: 17.3 bar IMEP @ 2350 rpm

These speed / load requirements were within the planned engine capabilities, and were considered when executing calibration activities for vehicle drivability calibration.

The Vehicle Demand Energy model was updated to provide additional simulation outputs including vehicle fuel economy and engine-out emissions. This model used vehicle loss coefficients and vehicle test weight information from the EPA vehicle test data website to calculate the force required to move the vehicle through a transient drive cycle with the resulting Force and vehicle speed combined to determine the required power at the wheel. Transmission overall gear ratios were then used to calculate the required engine speed and brake torque for each of the transmission gear ratios. The optimum gear, based on minimum fuel consumption, was selected for each time step in the simulation. Finally, fuel consumption and engine-out emissions were calculated based on steady-state engine dyno mapping data. These parameters were integrated for the duration of the test cycle and summarized. The model also included cold-engine offsets, the magnitude of which was based on previous experience with Gen 2 GDCI vehicle testing.

The model was used in conjunction with preliminary Gen 3 engine dyno mapping data to predict fuel economy and engine out emissions for the planned test vehicle (2011 Hyundai Sonata with custom 6 speed manual transmission). Since the

preliminary data available at the time of the simulation work consisted of a limited operational range, additional dyno data was used to extend the performance map to higher speeds and loads, with blending of the data where appropriate.

Model Simulation Results

The results of the simulation using the Gen 3 engine in the 2011 Hyundai Sonata (target vehicle for DOE project) are summarized in Table 2.2.1 below. The results confirmed the expected benefits of the Gen 3 GDCI engine in terms of fuel economy and low engine-out NO_x emissions. It also confirmed that high HC aftertreatment efficiency (>99% average) would be required to meet Tier 3 Bin 30 tailpipe emissions standards.

Although a 25% penalty was assessed for Phase 1 cold engine effects, the impact of a cold start catalyst heating strategy and the electrical load imposed by the intake air heater were not included. This makes the simulation data overly optimistic, and it was therefore considered an "upper bound" for vehicle performance. The simulation also did not include transient control system lags, which can negatively impact performance.

The simulation results were compared to the measured baseline vehicle performance data to make an assessment of potential vehicle performance. Table 2.2.2. summarizes this comparison. The HWFET performance shows 37% improvement over the baseline vehicle, which is consistent with program targets of 35%. The FTP75 performance was substantially above the 35% target (and substantially above Gen 2 vehicle performance), which supports the observation mentioned above that the simulation is overly-optimistic on the FTP75 drive cycle. Note: baseline vehicle is 2009 PFI Hyundai Sonata with manual 5 speed transmission.

Table 2.2.1: Results of VDE Model Simulation of Gen 3 Vehicle Fuel Economy and Engine-out Emissions.

Test Cycle	Parameter	Units	Phase 1	Phase 2	Phase 3	Weighted
FTP75	Fuel Economy	mpg	38.3	47.1	47.9	45.5
	E.O. HC	g/mi	2.99	2.55	2.39	2.45
	E.O. CO	g/mi	9.08	9.45	7.26	7.83
	E.O. NO_x	g/mi	0.049	0.044	0.039	0.041

HWFET	Fuel Economy	mpg				62.1
	E.O. HC	g/mi				1.88
	E.O. CO	g/mi				4.35
	E.O. NO_x	g/mi				0.034
Combined	Fuel Economy	mpg				51.7

Table 2.2.2: Comparison of VDE Model Simulation of Gen 3 Vehicle to Measured Data on Baseline Vehicle.

Test Cycle	Parameter	Units	Gen 3 Simulation	Baseline Vehicle	Percent Improvement
FTP75	Fuel Economy	mpg	45.5	26.0	75 %
HWFET	Fuel Economy	mpg	62.1	45.4	37 %
Combined	Fuel Economy	mpg	51.7	32.2	61 %

<u>Simulation of Gen3X and Gen3X Thermal Barrier GDCI Concept Engine</u>

Gen3X calibration mapping data shown in Figure 2.2.2 was provided to Argonne National Labs (ANL) for vehicle simulation studies. The objectives were to simulate the GDCI Gen3X engine in a variety of vehicles with differing powertrain options, such as a 6-speed automatic transmission (6AU), an 8-speed automatic transmission with 12V start/stop (8AU 12V S/S), and an 8-speed automatic transmission with 48V integrated starter generator (8AU 48V ISG). Results were

compared to a baseline SI engine and full hybrid powertrains for each vehicle class.

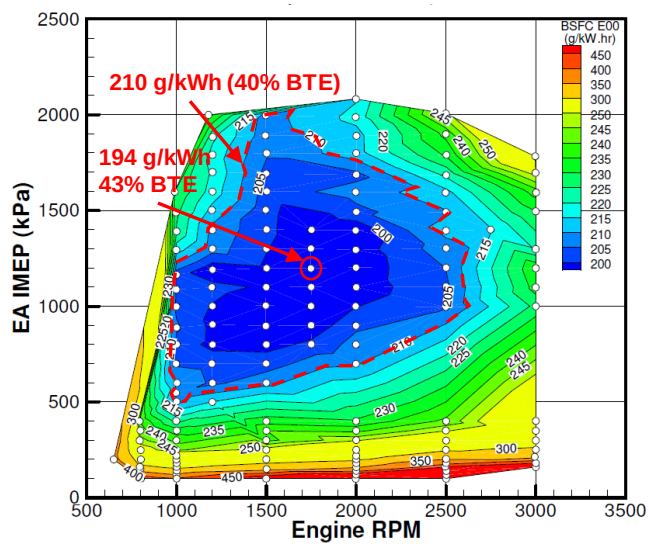


Figure 2.2.2. Initial $BSFC_{00}$ map for Gen3X GDCI engine using a 500 bar GDi fuel system, a single-stage boost system, and a new GDCI-diffusion combustion strategy.

Additionally, the Gen3X engine with Thermal Barrier Coatings was simulated at 12 speed-load operating points to create a new engine map for the FTP drive cycle to expore future potential upgrades of the GDCI engine. The work flow included first developing correlated engine models for the Gen3X engine using real dynamometer test data and cylinder pressure data at each test point. Then the heat transfer multipliers for heat loss in the cylinder were reduced by 50%. This basically reduced heat transfer by 50% relative to the tested Gen3X engine as expected if thermal barrier coatings were applied.

Reduced in-cylinder heat losses increase the cylinder pressure and enable greater work extracton during the expansion stroke. They also increase exhaust temperatures and improve turbocharger work. No detrimental effect on volumetric efficiency was observed in simulation. Finally, the simulation results for the 12 operating points were used to fit an engine map for the Gen3X engine with the Thermal Barrier Coatings. This map was provided to Argonne for vehicle simulations.

Figure 2.2.3 shows simulated fuel economy (MPG) for the US FTP city, highway, and combined cycles for a midsized vehicle. The baseline shown is a contemporary 1.6L SI turbocharged engine with variable intake valve lift and timing. There are three Gen3X powertrain configurations shown in the figure. The Gen3X with 6AU, the Gen3X with 8AU 12V S/S, and the Gen3X with 8AU 48V ISG, exhibited 35.9%, 45.4%, and 50.9% combined fuel economy improvement,

respectively, over the baseline. The fuel economy data is unadjusted but includes a 15% cold start correction for Phase I. While full emissions compliance has not yet been established, these results show that the Gen3X GDCI engine has potential as ultra-efficient internal combustion engines operating on US market gasoline (RON91).

Results for the simulated Gen3X GDCI engine with the Thermal Barrier Coatings are shown in the 5th and 6th bars in Figure 2.2.3 (labelled 'Gen3XTBC'). For the simulated Gen3X engine with the Thermal Barrier Coatings and 12V start-stop, the simulation predicts about 68% improved unadjusted combined fuel economy over the baseline. For the simulated Gen3X GDCI engine with the Thermal Barrier Coatings and 48V integrated starter generator, the simulation predicts about 78% improvement over the baseline. This amounts to unadjusted combined simulated fuel economy of 64 MPG.

As a comparison to full hybrid technology, vehicle simulations were also conducted for a power-split hybrid powertrain and a parallel hybrid powertrain. These results are shown on the right side of Figure 2.2.3. The Gen3X and Gen3X Thermal Barrier Concept engines compare favorably with these advanced powertrains. Notably, the highway fuel economy of the Gen3X enigne and the Gen3X GDCI engine with the Thermal Barrier Coatings exceed the highway fuel economy of the full hybrids.

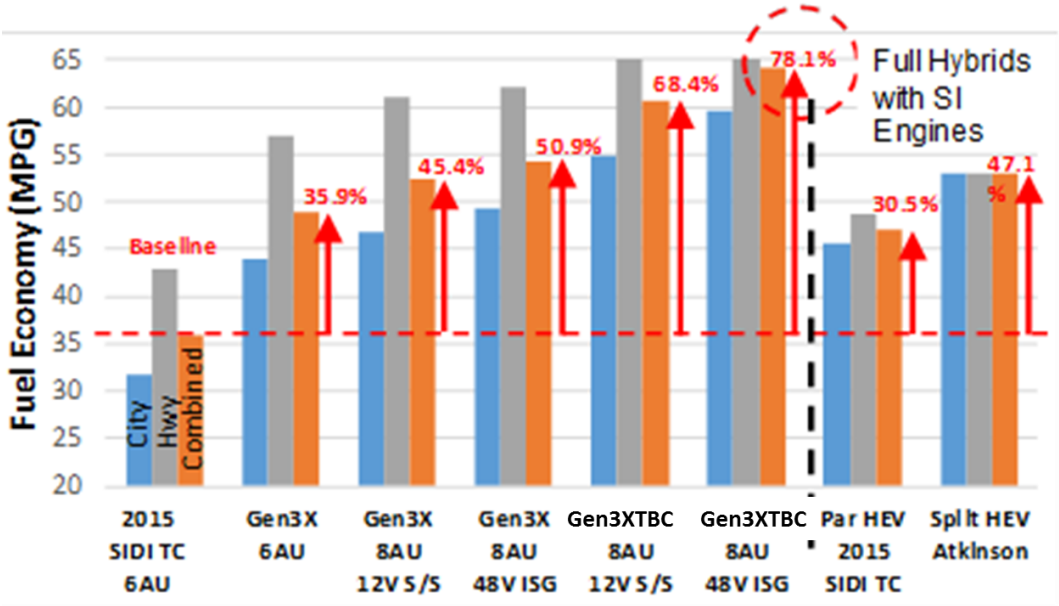


Figure 2.2.3. Vehicle simulation results for the 2.2L Gen3X GDCI engine with various powertrain technologies compared to baseline engine and full hybrid engines (Argonne).

Task 2.3 Benchmark GDI Engine

Benchmarking of the GDCI engines was done at several times and in several ways during the course of the project. A 1.8 L VW EA888 turbocharged engine upgraded with Delphi Technologies / Tula Technology Dynamic Skip Fire system was mapped at Delphi Technologies' technical center in Rochester, New York. Also, working with Argonne National Labs, comparisons were made to the DOE baseline 2015 SI turbocharged engine. Various vehicle simulations were performed for these engines (as reported in Task 2.2 above). However, a particularly relevant representation of the GDCI performance is in comparison to published data for the new Toyota 2.5L TNGA engines compared to test results for the Gen3X GDCI engine from mid-2018.

The BSFC contour plot for the Gen3X is shown in Figure 2.3.1 as reported in the Q3 2018 project report. Tests were run at 650rpm for idle and up to 3500rpm in this test (data plotted up to 3000rpm). Load ranged from 1bar to 21bar IMEP. For IMEP of 4 bar and below, single injections with GDCI combustion were used with heavy exhaust rebreathing and elevated IAT up to 75 degrees. For 5 bar IMEP and above, double injections were used with 2-stage GDCI-diffusion combustion strategy. Minimum BSFC for this test was 194 g/kWh (43% BTE) measured at 1750rpm-12bar IMEP. Notably, BSFC of 210 g/kWh (40% BTE) covered a large portion of the operating map from 5 to 20 bar IMEP.

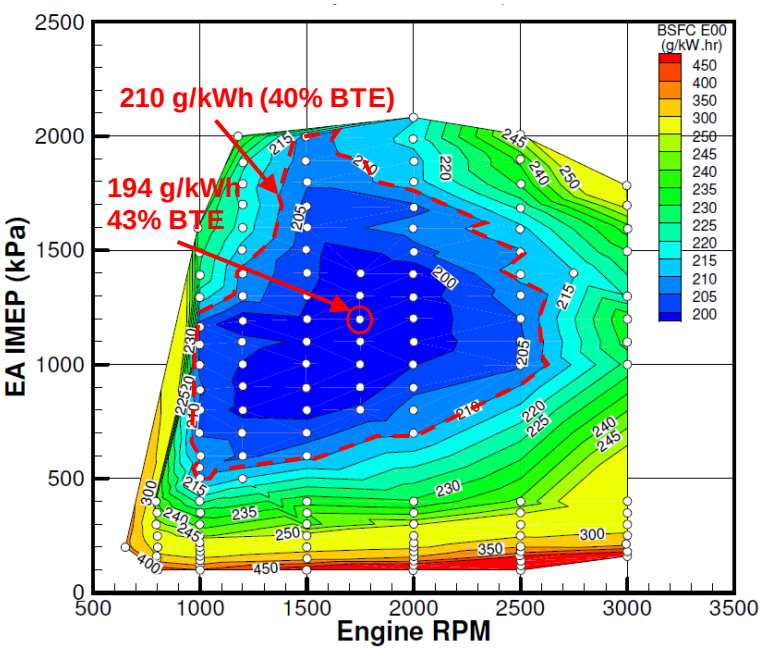


Figure 2.3.1. Initial BSFC contour map for Gen3X GDCI engine using a prototype GDi fuel system, tested up to 500 bar, and a single-stage boost system with a new GDCI-diffusion combustion strategy for high load.

By comparison, the BSFC contour map of the 2018 2.5L Toyota TNGA engine is shown in Figure 2.3.2. This engine received attention at the 2018 SAE World Congress and was claimed by Toyota at the time to be the most efficient gasoline engine in the world. It is a naturally aspirated engine and has a maximum BTE of 40%, which is measured at 2500rpm and almost maximum load. By comparison, the Gen3X engine produces 40% or higher BTE from 5 to 20bar BMEP on the same RON91 gasoline fuel.

Figure 2.3.3 shows specific power (kW/L) as a function of maximum BTE (%) from the 2018 Toyota SAE paper 2018-01-0370. This shows progress for SI engines over recent years as brake thermal effiency (BTE) and specific power improved. The new 2.5L Toyota TNGA engine family (HEV, NA, and turbo) represents impressive progress for SI engines. The inclination in the slope of the trend line for the TNGA family and for the 2007 and 2015 trend lines in the figure is due to knock, preignition, and dilute limit constraints suffered by all SI engines. Due to the injection strategy for GDCI engines, they do not have these fundamental limitations and consequently exhibit higher BTE and specific output.

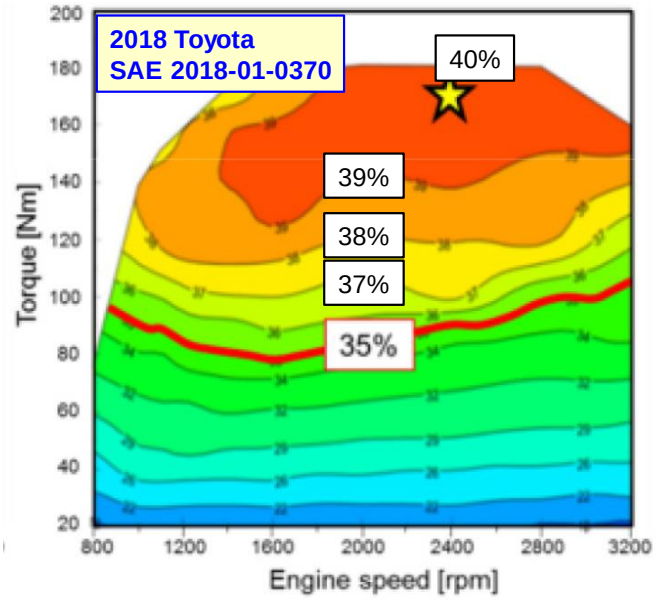


Figure 2.3.2. BSFC contour map of the 2018 2.5L Toyota TNGA spark ignited engine [SAE paper 2018-01-0370].

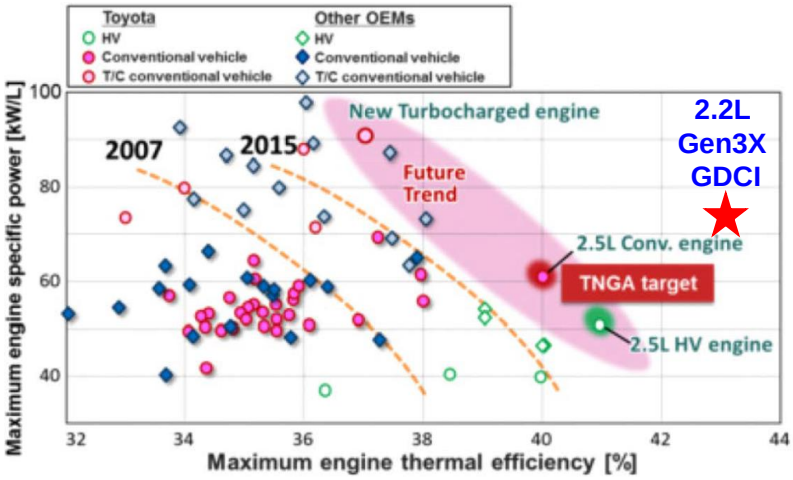


Figure 2.3.3. Specific Power (kW/L) as a function of maximum BTE (%) for SI engines, the 2018 2.5L Toyota TNGA spark ignited engine, and, based on simulation results and associated analysis, for the Gen3X GDCI engine [SAE paper 2018-01-0370].

Task 2.4 Multi Cylinder Engine (Gen3) Design and Build

A Gen 3 level of a GDCI engine was designed and built specifically for this project based on experience from the earlier engines. This engine was designed to be production-like in construction and would be the end deliverable of the project. Several versions were of the Gen 3 were evaluated during the course of the project.

Gen3 Cyl Heads: Detailed structural analysis of the cylinder head design was performed to confirm low stress levels throughout the cylinder head for boltup, thermal, and pressure loading. High cycle fatigue analysis indicated good fatigue characteristics. All cylinder heads were machined, finished, inspected, and bench tested.

Gen 3 Valvetrain: The project specific valvetrain systems were installed and tested on a performance valvetrain stand at Delphi Technologies' Technical Center in Rochester, New York. These tests confirmed proper valvetrain lash, oil flow, and friction.

Fast Electric Intake Air Heaters: The Gen 3 cylinder heads were designed with an electric intake air heater system for fast heating of the intake air. The heater assembly inserted into the cylinder head a short distance upstream of the intake

valves. The system was simulated extensively, for improved cold start and catalyst lightoff characteristics.

Exhaust Manifold: The Gen3 GDCI cylinder head also features a compact, integral exhaust manifold for use with a close-mounted pre-turbo catalyst (PTC). The exhaust manifold was air gap insulated without water cooling. Special fiberglass insulation was fabricated for the outside of the cylinder head to further insulate the exhaust manifold.

Gen3 Fuel System: The Gen3 GDCI engine also featured a higher pressure fuel system with new pump, rail, and injectors. The system featured new high pressure injectors and a log rail with maximum operating pressure of over 500 bar. The fuel pump was relocated to the valve cover and driven by the intake camshaft (eliminating the Gen2 cambox). Due to the higher fuel pressure and higher structural loads on the system, structural analysis was performed to insure low stresses in all fuel system components.

Hot-side EGR Valve: New EGR valves were fabricated for the Gen3 GDCI engines for operation at the upstream, hot-side of the EGR cooler to minimize deposit accummulation. Special shaft bushings and seals were developed for improved alignment of the butterfly blade on the shaft, and adaptations made to control axial motion of the valve to prevent sticking. The electric drive motor and electronics were cooled by engine coolant.

Low-Leakage Supercharger-Bypass Poppet Valve: New low-leakage poppet valves were fabricated for the Gen3 engines. Low leakage is important during engine cranking, cold starts, and idle to maximize boost levels from the supercharger. The valves featured a pressure-balanced dual poppet design.

Thermal Management System: The thermal management system was updated with a new Gen3 CAC-2 cooling module and the new Gen3 CAC-1 module (see Figure 2.4.1.). Both coolers were signicantly more compact that Gen2 coolers. More details of the Gen 3 Thermal Management system can be found later in this report in 'Task 2.6 GDCI Gen 3 Demonstration Vehicle' in the section labelled 'GDCI Gen 3 Vehicle Controls Development'

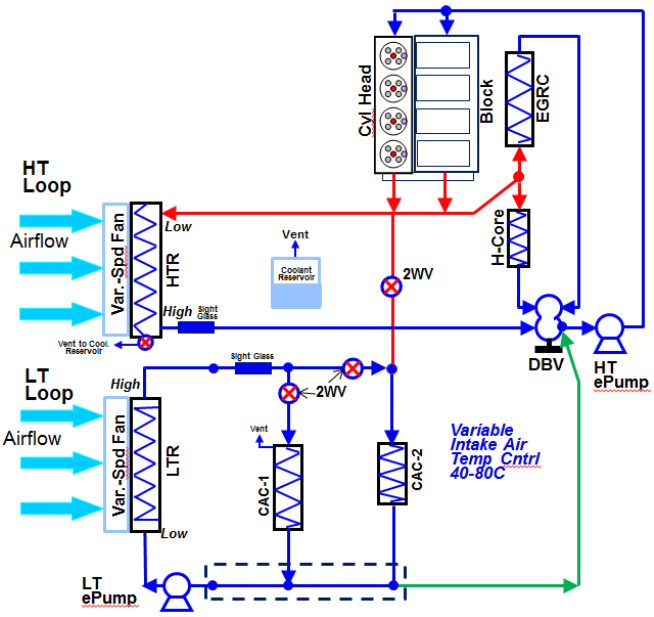


Figure 2.4.1. Schematic of Gen3 thermal management system (TMS).

<u>Gen 3 Aftertreatment:</u> The Gen3 aftertreatment system was developed with a tailpipe emissions target of Tier3-Bin30. The system included a close-coupled pre-turbo oxidation catalyst, a post-turbo HC trap/oxidation catalyst and an SCR catalyst. A schematic of the system concept is shown in Figure 2.4.2. The system was designed for very fast light-off of the pre-turbo oxidation catalyst.

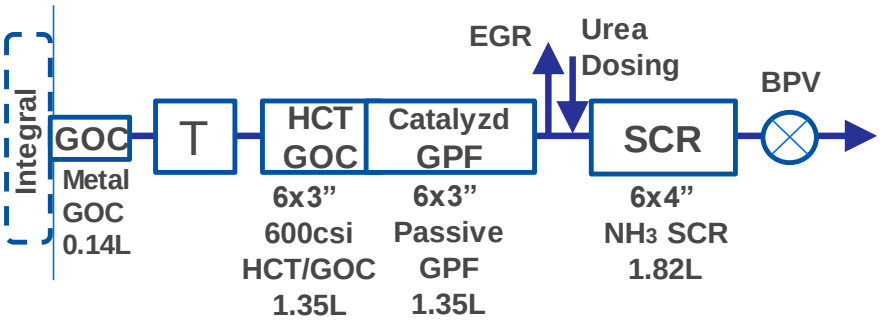


Figure 2.4.2 Schematic of the Gen3 aftertreatment system.

The pre-turbo oxidation catalyst features a metal monolith capsulated in a cylindrical mantle with an air gap construction for good thermal insulation. CFD simulation of the exhaust flow within the cylinder head and exhaust manifold was used to achieve minimum uniformity index of 92% at the pre-turbo oxidation catalyst inlet.

1D models of the aftertreatment system were used to develop the aftertreatment systems, as was 3D modeling and simulation of the SCR dosing system and SCR catalyst. Figure 2.4.3 shows an example NH3 concentration for one configuration in a steady-state simulation.

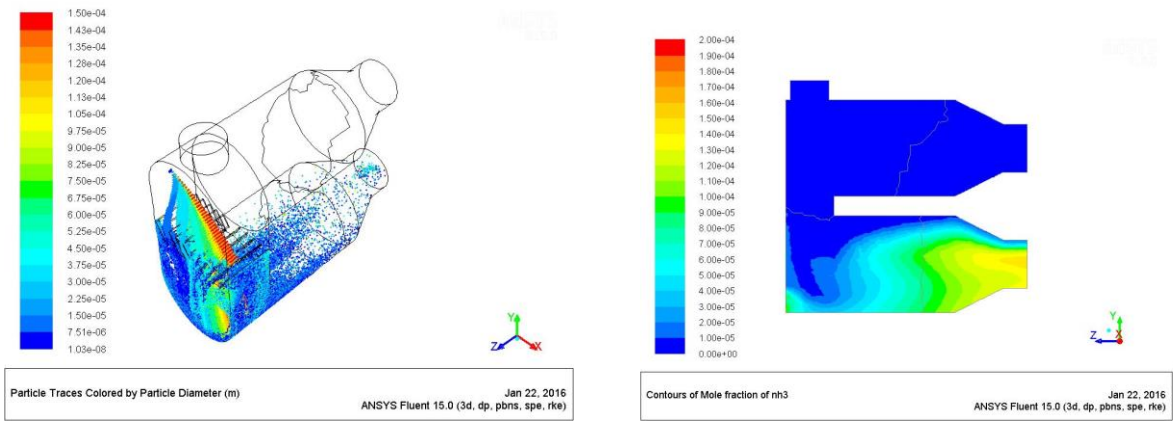


Figure 2.4.3 Preliminary 3D simulation of Gen3 SCR system (particle traces (left) and NH3 concentration (right).

Based on the detailed CFD simulations of various SCR dosing systems and configurations, it was decided to adopt the Daimler 2015 OM654 urea evaporator on the Gen3 GDCI engines. The evaporator was acquired, digitally scanned, and packaged in the Gen3 system. Figure 2.4.4 shows a CAD rendering of the final Gen3 aftertreatment system.

Catalyst sizes, substrates, and washcoats were selected based on simulation and discussions with Umicore experts. Figure 2.4.5 shows a photograph of the Gen3 aftertreatment system on a dynamometer engine at Delphi Technologies.

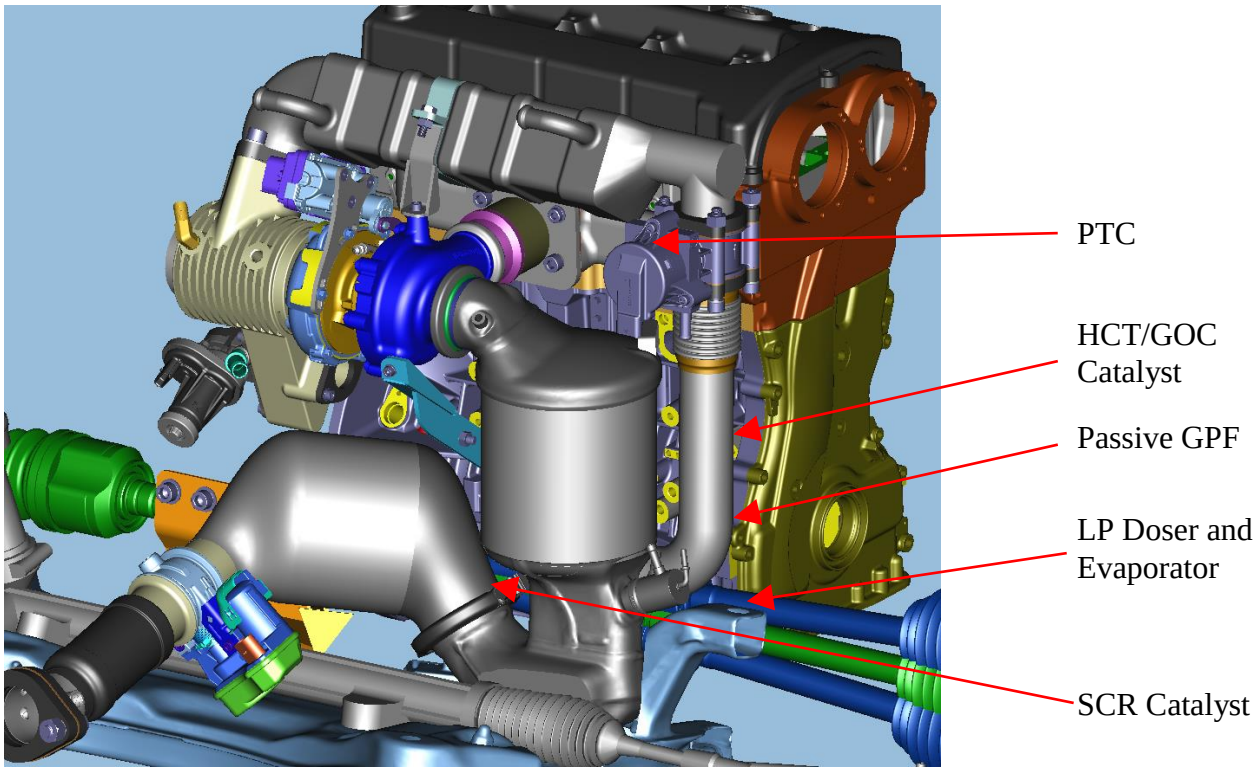


Figure 2.4.4 CAD rendering of the Gen3 aftertreatment system.

Figure 2.4.5 Photograph of the Gen3 aftertreatment system on dynamometer engine at Delphi.

Task 2.5 GDCI Gen 3 Multi-cylinder Engine Testing

During break-in testing of the first Gen3 GDCI engine on the dynamometer in early 2017, test data were recorded. The data was not considered optimized but did meet program requirements for engine out emissions (NOx<0.2g/kWh, FSN<0.1) and combustion stability (COV IMEP<3%). Results for this preliminary load sweep at 1500rpm are shown in Figure 2.5.1 along with previous data for the Gen1 and Gen2 GDCI engines. The Gen3 engine was significantly more efficient than the Gen2 engine across the load range. The measured BSFC in the mid-load range was close to the 200 g/kWh BSFC target.

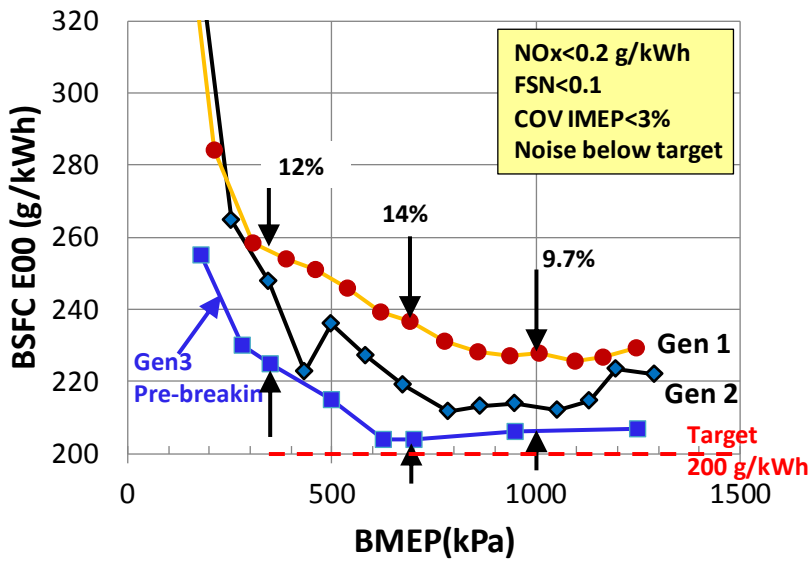


Figure 2.5.1 BSFC as a function of BMEP at 1500rpm for Gen1, Gen2, and Gen3 GDCI engines at Delphi Technologies.

Dynamometer testing of the Gen3 GDCI engine continued through 2017 as planned but was interrupted for several months due to dynamometer service and repair as well as emissions bench concerns, and failure of the supercharger on the test engine. Only limited engine testing was possible during this time, however progress was made, such as testing of new GDCI injectors.

Once the problems were overcome, dynamometer testing of the Gen3 GDCI engine was focused on calibration mapping and characterization of the aftertreatment system. To assist in this effort, a new procedure was developed to conduct

calibration mapping of the Gen3 engine, given the many degrees of freedom for the fuel injection, boost, thermal, aftertreatment and valvetrain systems.

In mid-2018, an updated version of the Gen3 GDCI engine, called Gen3X, was built and installed on the dynamometer at Delphi Technologies. The main features of the engine were:

- Simplified Thermal Management with Fast Intake Air-Blend Temperature Control
- Higher compression ratio of 16.8
- New GDCI-Diffusion combustion strategy for high load
- Fast electric intake air heater (IAH) for fast cold starts

The Gen3X engine was less complex (to reduce production costs) than the previous Gen3 engine, and, due to different combustion strategies, easier to control.

The Gen3X dynamometer engine was fitted with a high-pressure diesel fuel injection system to reduce smoke at higher loads to meet program targets (FSN<0.1). A new "degreened" gasoline oxidation catalyst (GOC) was installed on the engine without a gasoline particulate filter (GPF). The engine was recalibrated over the operating map using E10 gasoline (RON91) under warmed up operating conditions. Low-pressure EGR and an SCR catalyst were used to reduce NOx emissions to near zero tailpipe levels. Tailpipe NMHC and CO emissions met targets of 10ppm and 50ppm, respectively. These steady-state, warmed-up engine dynamometer testing results demonstrated significant progress on emissions control.

Dynamometer tests of the 2.2L Gen3X GDCI engine included a load sweep conducted at 1500rpm. BSFC as a function of BMEP is shown in Figure 2.5.2.1. In this comparison, there are 4 versions of the Gen3 engine. Of the Gen3 versions, the first tests with inert exhaust aftertreatment (ATS) system exhibited minimum BSFC of 205 g/kWh. However, with an active ATS system, about a 2 percent penalty was observed. This was attributed to oxidation of fuel in the gasoline oxidation catalyst (GOC) ahead of the EGR system. Without an active ATS, this unburned HC and CO would be returned to the combustion system to make torque. The upper curve in Figure 2.5.2 shows the results of detailed calibration mapping. As can be seen, there is a significant fuel consumption penalty on the Gen3 engine when all these constraints are applied.

The bottom curve in Figure 2.5.2 shows data for the Gen3X engine configuration. Minimum BSFC was 195 g/kWh at 9 bar BMEP. The engine utilized the GDCI-diffusion combustion strategy for higher loads. The engine was found to be very easy to operate and control. The load capablility was also much higher than for the previous Gen3 engine due to the favorable boost characteristics achieved by emulating a VIC VNT turbo, through the use on the dyno engine of two turbochargers with different compressor wheels.

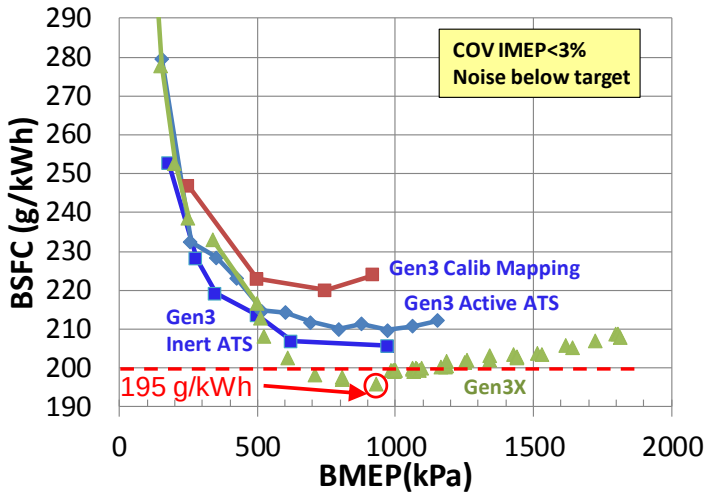


Figure 2.5.2. Preliminary load sweep at 1500rpm for the Gen3X GDCI engine.

Tests were conducted on the engine with full lean control and without EGR. The BSFC contour plot is shown in Figure 2.5.3. Tests were run at 650 rpm for idle and up to 3500 rpm in this test (data plotted up to 3000 rpm). Load ranged from 1 bar to 21 bar IMEP. For IMEP of 4 bar and below, single injections with GDCI combustion was used with heavy exhaust rebreathing and elevated inlet air temperature (IAT) up to 75 degrees. For 5 bar IMEP and above, double injections were used with 2-stage GDCI-diffusion combustion strategy. The first stage was a very clean GDCI combustion event. The second stage utilized a GDCI-diffusion combustion, which had higher NOx and PM emissions, but extended the burn duration and reduced combustion noise. Burn duration could be easily controlled by Qsplit and injection timing.

Minimum BSFC for this test was 194 g/kWh (43% BTE) measured at 1750rpm-12bar IMEP. Notably, BSFC of 210 g/kWh (40% BTE) covered a very large portion of the operating map from 5 to 20 bar IMEP. This is very important for engine down-speeding and up-loading to achieve the best vehicle fuel economy. At low loads down to 1 bar IMEP, BSFC was also excellent and was over 30% less than typical spark-ignited gasoline engines.

As shown in Figure 2.5.3, the engine could produce high torque because of the absence of knock and pre-ignition limits. For these tests, torque was limited by an exhaust temperature limit of 600 degree C. The low-load torque capability of the engine was very good. The engine easily produced 20 bar IMEP at 1200 rpm. At 1000 rpm, as fueling was being increased to 17 bar IMEP, the engine propshaft failed. However, the single-stage turbocharge had ample airflow to create more torque at these low speeds.

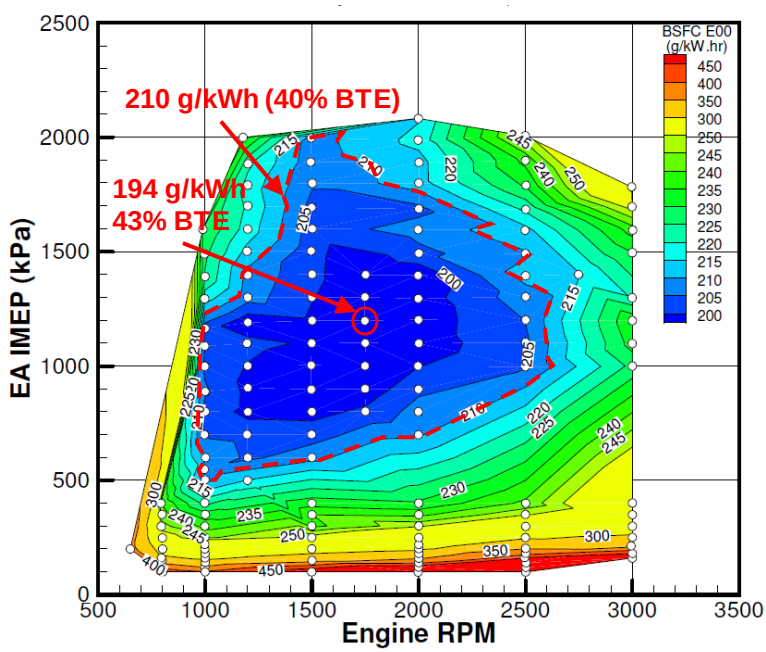


Figure 2.5.3. Initial BSFC contour map for Gen3X GDCI engine using a prototype GDi fuel system, tested up to 500 bar, and a single-stage boost system with a new GDCI-diffusion combustion strategy for high load.

Dynamometer tests of the final version of the GDCI development engines, a 2.2L Gen3X-DFI (Diesel Fuel Injection) GDCI engine, were completed to finish out the project in late 2018. The purpose of these tests was to evaluate the combustion system at the higher injection pressures necessary to better control smoke emissions. The engine was equipped with a prototype Diesel Fuel Injection (DFI) system.

Delphi Technologies' DFI 1.5 injectors were assembled locally with special nozzles and needles developed previously for the Gen1 GDCI engine. The nozzles had 10 holes with a spray angle of 130 degrees (included). These injectors were then flow calibrated in the Delphi Technologies' prototype injector facility. A diesel unit pump (DUP) 2.20b was installed on the cylinder head cover and driven by the 4-lobe cam on the intake camshaft. The cam lobes where designed for the previous GDI fuel pump, which had larger plunger diameter than the DUP pump. Consequently, the stroke of the pump was too low to achieve the target 1800 bar fuel pressure for the DUP pump. Tests were conducted for fuel pressures up to 1100 bar.

The main features for the Gen3X-DFI GDCI engine are listed below:

- 1800 bar Diesel Fuel Injection System with DUP 2.20b Fuel Pump
- Simplified Thermal Management with Fast Air-Blend Temp Control

- Cold-side Low-pressure EGR Valve
- Higher Compression Ratio (16.8:1)
- GDCI-Diffusion Combustion Strategy for High Load
- Fast Intake Air Heater (IAH) for Cold Starts
- Water-cooled Integral Exhaust Manifold (switchable)
- Lean Aftertreatment System including Preturbo Catalyst, Hydrocarbon Trap, Optional GPF, a Close-coupled SCR Catalyst and an Underfloor SCR Catalyst.

The Gen3X-DFI engine as tested is shown in Figure 2.5.4.

Figure 2.5.4. Gen3X-DFI GDCI engine installed in test cell at Delphi Technologies.

These engine tests were also important to evaluate exhaust temperatures and the performance of the aftertreatment system. The use of a gasoline particulate filter (GPF) proved to be optional for GDCI and it was decided not to use a GPF for these tests. At each operating point, parametric tests were conducted to semi-optimize the calibration for MAP, IAT, EGR, urea dosing, and injection pressure, Qsplit, and timing. While only a partial map for warmed-up conditions was completed, results covered most of the FTP drive cycle, as shown in Figures 2.5.5 through 2.5.14. These results indicated that exhaust temperatures were sufficiently high and tailpipe emissions were sufficiently low to meet the program emissions targets.

Figure 2.5.5 shows steady-state exhaust temperatures at the GOC catalyst located 1" from the brick face. These temperatures are relatively constant over the load range tested and are sufficient for good catalyst activity. For IMEP of 1 to 2 bar, catalyst temperatures were above 250 degree C due to use of exhaust rebreathing and elevated inlet air temperature.

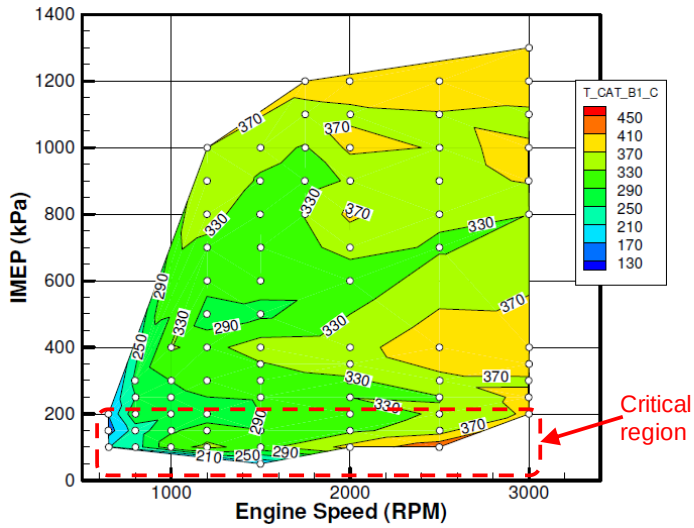


Figure 2.5.5. GOC catalyst temperature 1" from the brick face for Gen3X-DFI under warmed-up operating conditions.

Figure 2.5.6 shows engine out (EO) indicated specific hydrocarbon emissions (ISHC) for the test. For most of the operating range, ISHC was in the 1 to 3 g/kWh range, which was much lower than for previous GDCI engines and is similar to modern diesel engines. Only at IMEP below 2 bar did ISHC levels increase somewhat.

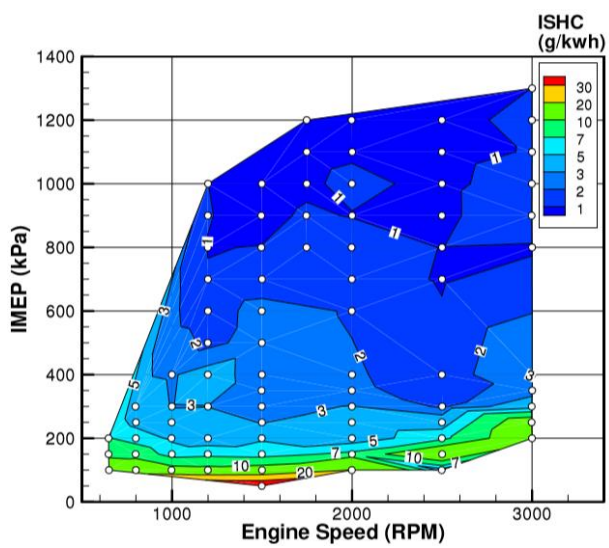


Figure 2.5.6. EO ISHC emissions for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.7 shows tail pipe (TP) non-methane hydrocarbon (NMHC) emissions for the test. The goal for these tests was to achieve NMHC less than the 10 ppm target

defined for the project. This was approximately accomplished with initial settings. Results showed that low EO HC combined with a close-coupled GOC catalyst can produce low tailpipe HC emissions.

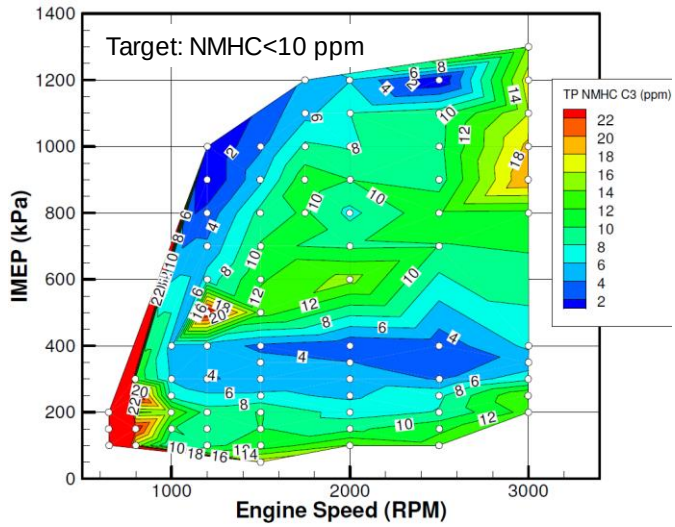


Figure 2.5.7. Tailpipe NMHC emissions for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.8 shows EO ISCO for the test. Overall ISCO levels are low and indicate good burnout of the fuel-air mixture in the combustion process. ISCO exhibits a load dependence with decreasing emissions at higher loads. For the lowest loads below 2 bar IMEP, ISCO increases somewhat, as is typical for GDCI combustion.

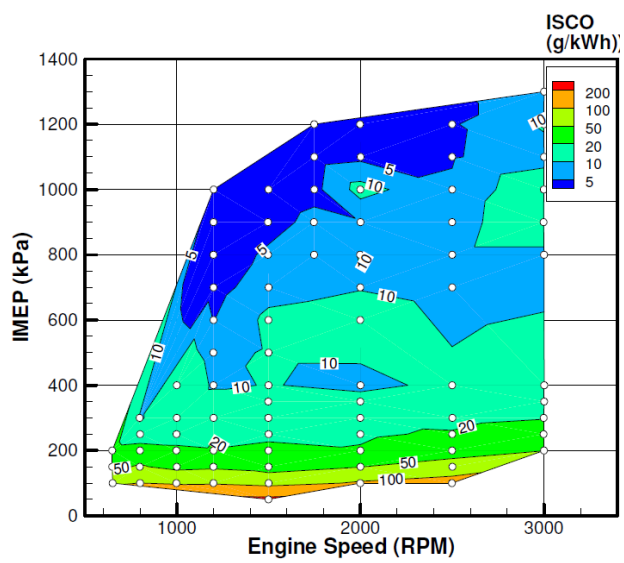


Figure 2.5.8. EO ISCO emissions for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.9 shows TP CO emissions for the test. The CO target of 50 ppm on average was relatively easy to achieve for this system. .

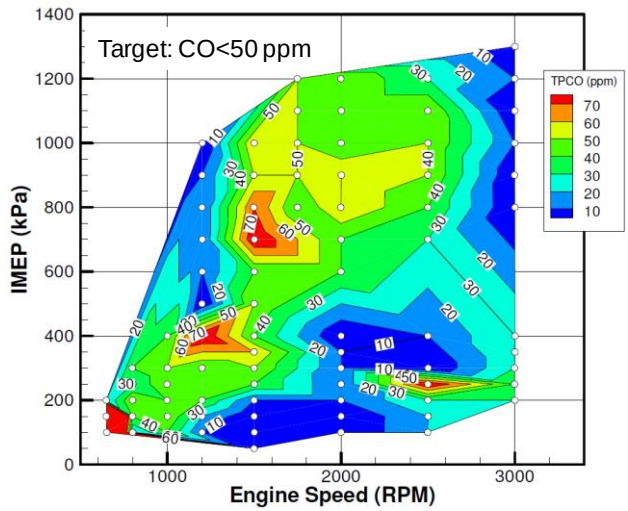


Figure 2.5.9. Tailpipe CO emissions for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.10 shows the exhaust temperature 1" back from the face of the SCR catalyst. This catalyst was mounted close-coupled at the exhaust side of the engine and exhibited temperature characteristics similar to the GOC catalyst a short distance upstream. It is known that SCR catalysts operate down to 200 degree C and lower, but operate at best efficiency in the 300 degree C range. The data shows that the SCR temperatures were sufficient for high NOx conversion efficiency.

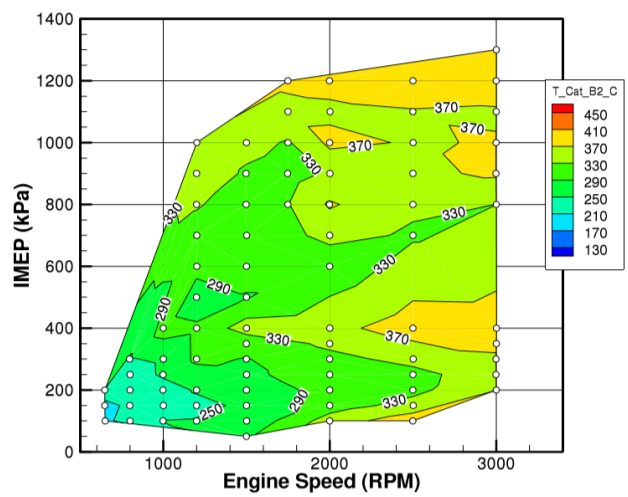


Figure 2.5.10. SCR catalyst temperature at 1" back from the catalyst face for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.11 shows EO ISNOx emissions for the test. For 4 bar IMEP and below, EO NOx was very low due to use of PPCI combustion (single injection). NOx in this range was less than 0.5 g/kWh. Very little urea was needed to reduce NOx at this level. For 5 bar IMEP and above, GDCI-diffusion combustion is used. As more fuel is added to the 2nd-stage combustion event, NOx emissions increased to the 2 or 3 g/kWh range. Further reduction in EO ISNOx can be expected with refined EGR and injection settings.

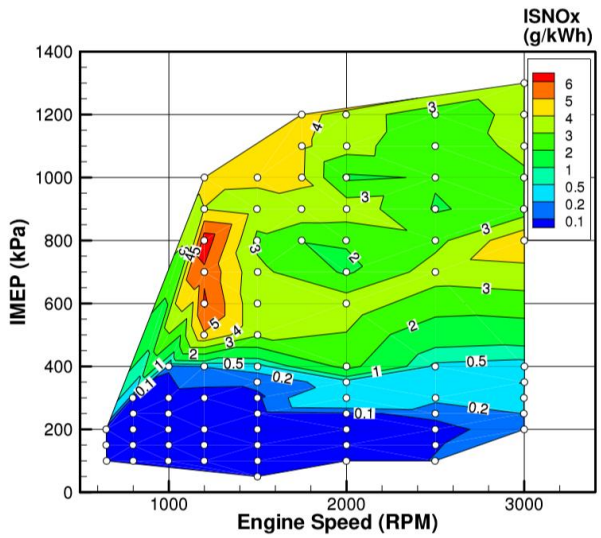


Figure 2.5.11. EO ISNOx emissions for Gen3X-DFI under warmed-up operating conditions.

Figure 2.5.12 shows TP NOx emissions for the test. For this test, it was decided to evaluate if near-zero NOx could be achieved with the system over the operating map. Urea dosing was manually increased until TP NOx was less than 1 ppm. As shown in Figure 2.5.2.9, near zero TP NOx was possible at most of the operating conditions tested. These steady-state, warmed-up dyno results are below the 10 ppm target defined for the project.

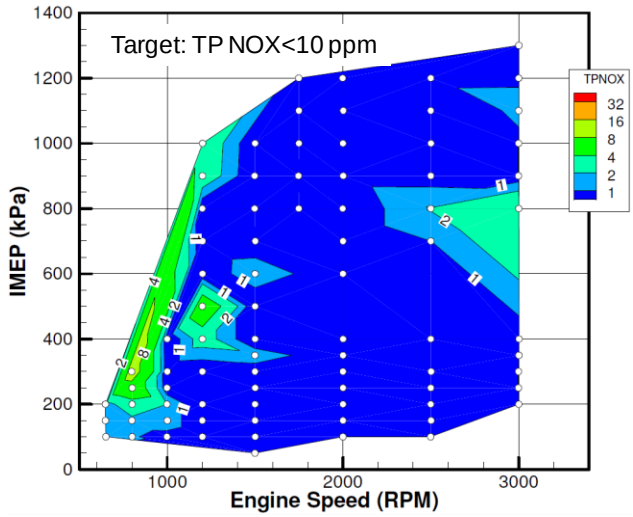


Figure 2.5.12. TP NOx emissions for Gen3X-DFI under warmed up operating conditions.

The urea dosing levels needed to achieve these levels are shown in Figure 2.5.13. The urea solution used was the industry standard diesel emissions fluid (DEF) available across the United States.

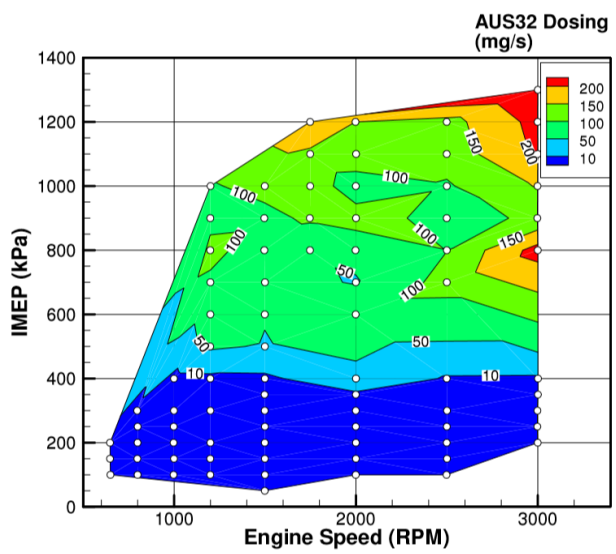


Figure 2.5.13. Urea dosing rate (mg/s) for Gen3X-DFI under warmed up operating conditions.

Figure 2.5.14 shows exhaust smoke as measured by an AVL 415S smoke meter without a GPF. Similar to trends for TP NOx, smoke levels are extremely low for the low-to-medium load range due to use of PPCI combustion (single injection). For higher loads with GDCI-diffusion combustion, smoke levels could be controlled with higher injection pressure and were typically less than 0.1 FSN, which was the target for this calibration. This entire test was limited by the available fuel pressure of 1100

bar. Higher fuel pressure (1800 bar) is needed to achieve low smoke emissions at the highest loads.

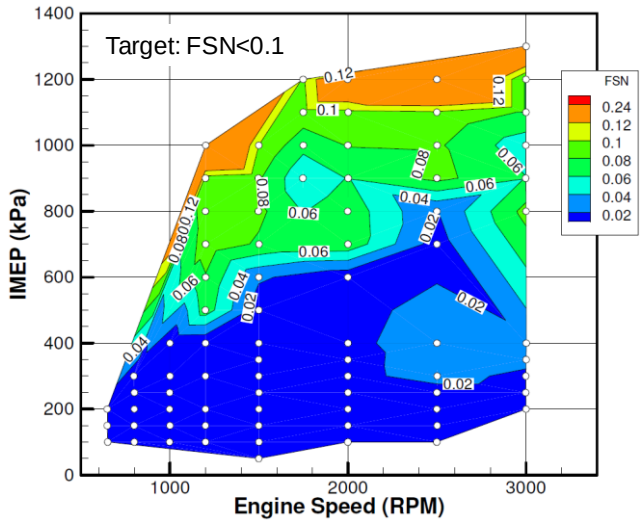


Figure 2.5.14. Smoke emissions for Gen3X-DFI without a GPF as measured by an AVL 415S smoke meter.

<u>Noise Characteristics of Gen3X-GDi Engine</u> Noise characteristics of the Gen3X GDCI engine are very different from typical SI or diesel engines. Importantly for Gen3X engines, the new GDCI-diffusion combustion process enables the ability to tailor the heat release to achieve quiet combustion at all conditions. During calibration testing, combustion noise levels were tuned subjectively based on audible noise levels in the test cell. For the tests reported in this section, the engine was equipped with the original 500 bar GDi fuel injection system. Results are shown in Figures 2.5.15 and 2.5.16.

The left graph of Figure 2.5.2.13 shows combustion noise in dB as measured by an AVL Combustion Noise Meter. The right graph shows maximum pressure rise rate (MPRR) from cylinder pressure data. The amount of heat release in the first stage combustion controls the MPRR (right graph). MPRR depends on speed and load and exceeds 10bar/CAD at loads of 10 to 15bar IMEP. In the test cell, combustion noise was generally not audible to a person standing near the engine.

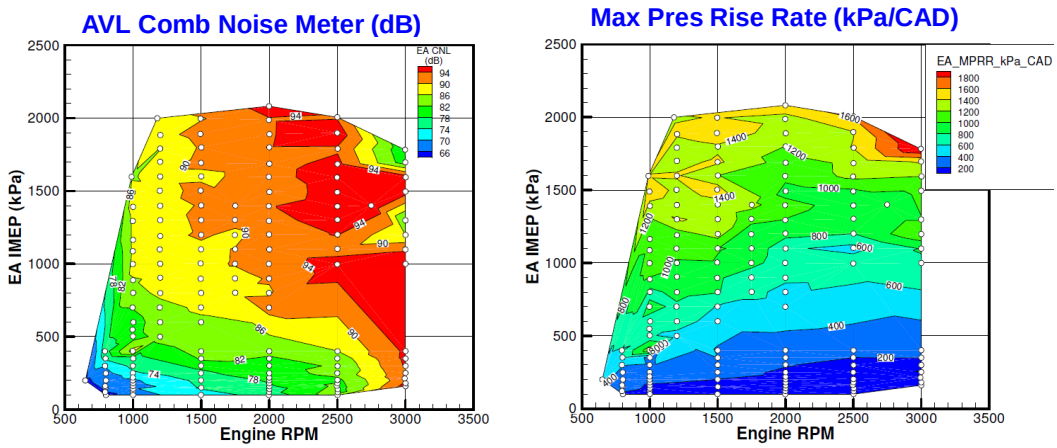


Figure 2.5.15. Combustion noise (dB) measured with AVL Combustion Noise Meter and maximum pressure rise rate (kPa/CAD) for the 2.2L Gen3X-GDi GDCI engine.

While the DOE ACEC Combustion Noise Guideline was not used for calibration of the engine, the results show that the ACEC guideline was essentially met at the operating conditions tested. Figure 2.5.2.14 shows noise data at 2000 rpm for the Gen3X-GDi engine compared to the ACEC maxiumum (orange) and minimum (blue) noise targets. This is an important achievement and demonstrates that quiet combustion is possible for GDCI combustion technology.

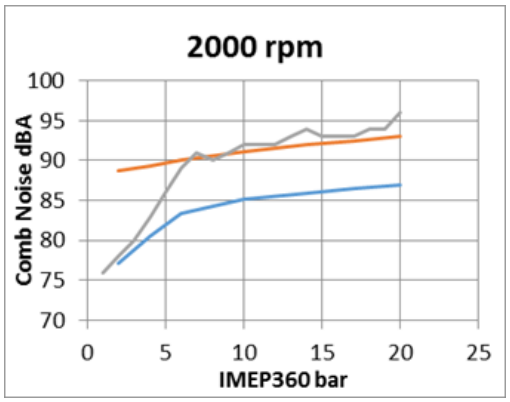


Figure 2.5.16. Combustion noise (dB) (grey) for the Gen3X-GDi engine at 2000 rpm compared to the maximum (orange) and minimum (blue) noise targets based on the DOE ACEC Combustion Noise Guideline.

In summary, the dynamometer test results for the Gen3X engine variations demonstrated the ability to meet program targets for emissions on the dynamometer engine. Overall results are favorable while meeting warmed-up tailpipe program targets for NMHC, CO, NOx, and FSN. The data shows that the GDCI-diffusion combustion process, the associated injection strategies, and the prototype

aftertreatment system are feasible. Initial tests were completed up to 12 bar IMEP. Further testing would require a 1800 bar injection system.

Task 2.6 GDCI Gen 3 Demonstration Vehicle

GDCI Gen 3 Vehicle Controls Development

Second generation Electronic Controls were developed for the Gen3 GDCI vehicle with refined system architecture, controller hardware, control algorithms, as well as improved & additional sensors and actuators. Algorithms updated included fuel control, EGR control, thermal management control and the development of new aftertreatment controls focused on emissions reduction targeted for Tier 3 requirements.

Additional hardware I/O (HWIO) needed to be added to the system to interface to the new Gen3 GDCI sensors, drivers, actuators, and instrumentation. This was facilitated with a distributed control architecture, linked by multiple CAN buses. A new custom HWIO module was developed and integrated into the distributed architecture, allowing the number of separate modules to be reduced from three to two while simulataneously increasing the number and capability of the I/O ports. This new I/O expansion module proved to be reliable and effective.

The watchdog controller continued to be utilized in the system to oversee the operation of the engine and act as a safety monitor for the engine should certain monitored parameters go out of their desired ranges. The scope of the watchdog monitoring expanded to provide continuous monitoring of each of the catalysts in the aftertreatment system; catalyst overtemperature protection was also added. The catalyst protection system included an automatically triggered an onboard nitrogen purge system.

The Gen3 thermal management system for the vehicle was improved over the Gen2 system. It retained the high and low temperature coolant loops with independent radiators, dual coolant pumps and dual ball valve high temp loop control from Gen2. It included a triple loop intake air temperature control with a dual-element post-supercharger charge air cooler with independent control of each element. Additonal coolant loops were added for cooling the urea dosing valve, high flow and low flow EGR valves, and a liquid-cooled A/C condenser as shown in figure 2.6.1 below. Significant effort was put into developing a model based control system for thermal manangement, including state estimators and fast response sensors for

improved transient control of intake air temperature, which is a key parameter for combustion phasing.

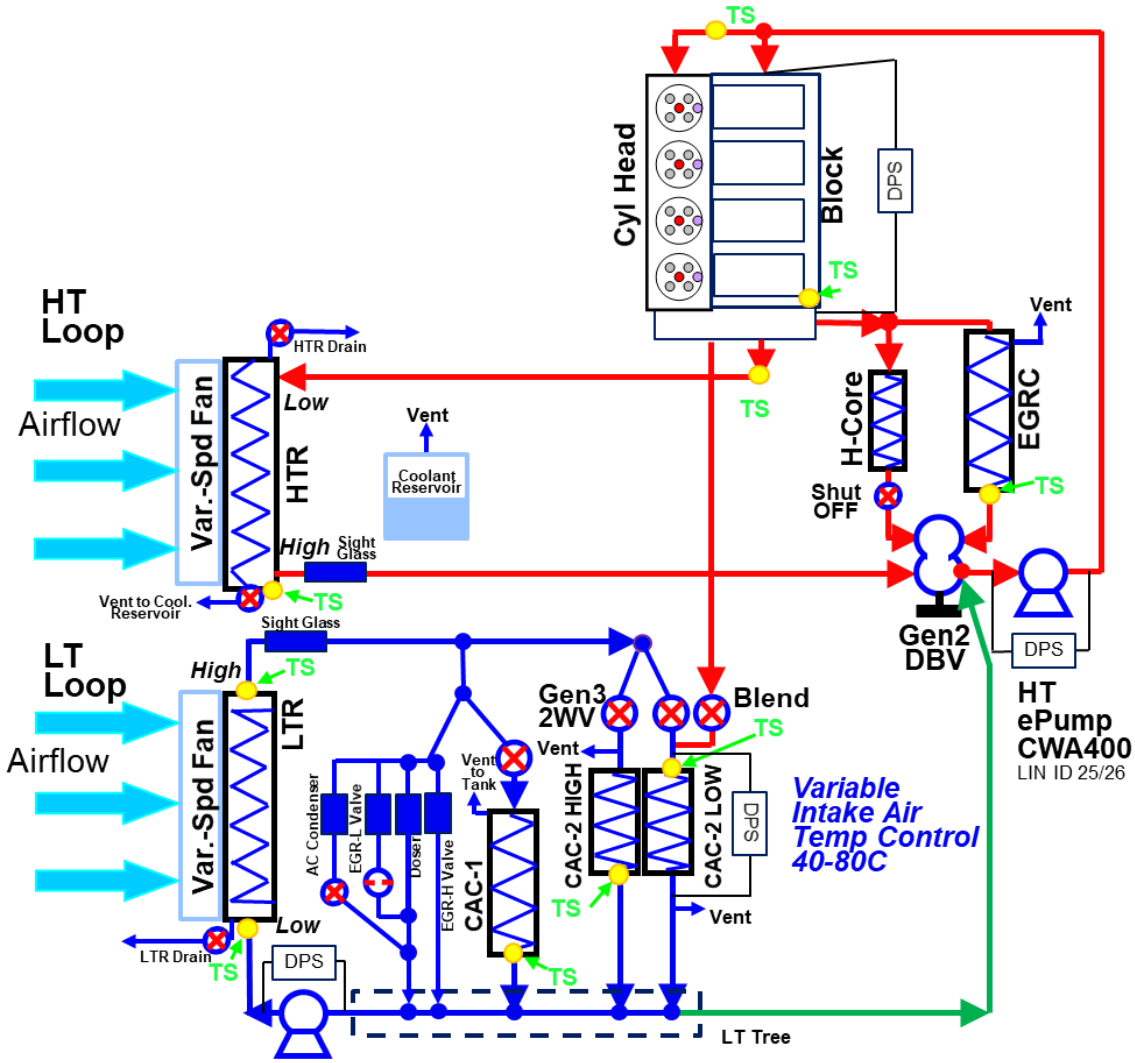


Figure 2.6.1: Gen3 Vehicle Thermal Management System with sensors.

The Gen3 air and exhaust systems include a new high-effectiveness intake air heater, a dual path cooled high flow / low flow EGR system along with significant improvements to the aftertreatment system, which now includes a Pre-turbo catalyst, a Gasoline Oxidation Catalyst / HC Trap, a GPF (if deemed necessary for particulate control) and a urea-based SCR system. The Pre-Turbo Catalyst (PTC in the Figure 2.6.2 below) was mounted directly to the integrated exhaust manifold to minimize lightoff time after a cold start. The SCR system included a urea doser which sprayed onto a series of plates for improved evaporation. New transient control systems were developed for intake air temperature. Boost control was

carried over from Gen2, with modified calibrations. Parallel path EGR control was developed and simulated.

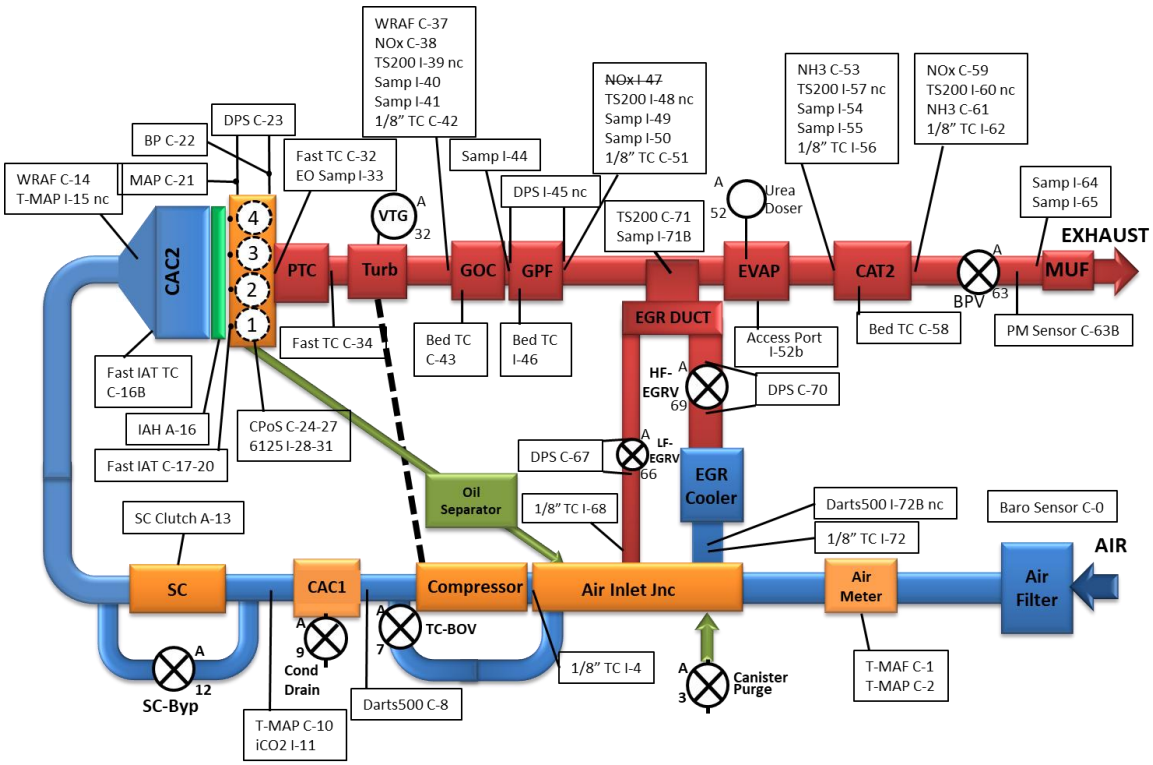


Figure 2.6.2: Gen3 Vehicle Air and Exhaust System with sensors

Development of the Selective Catalyst Reduction (SCR) system on the HIL bench was completed and the interfaces to the Gen 2 SCR controller and the MABx were tested and verified.

To support accurate calculation of the Charge Reactivity Index, a real-time cylinder pressure trace filtering method was developed to enable consistent and stable calculations of the polytropic indices for compression and expansion. It facilitated instantaneous calculation of polytropic indices and created opportunity for more accurate combustion phasing calculations and better prediction of the top dead center compression-induced temperature and pressure. These parameters strongly influence the start of the combustion phasing for a given oxygen content, fuel dispersion and chemistry. Detailed overview of this important work was included in the projects quarterly reviews.

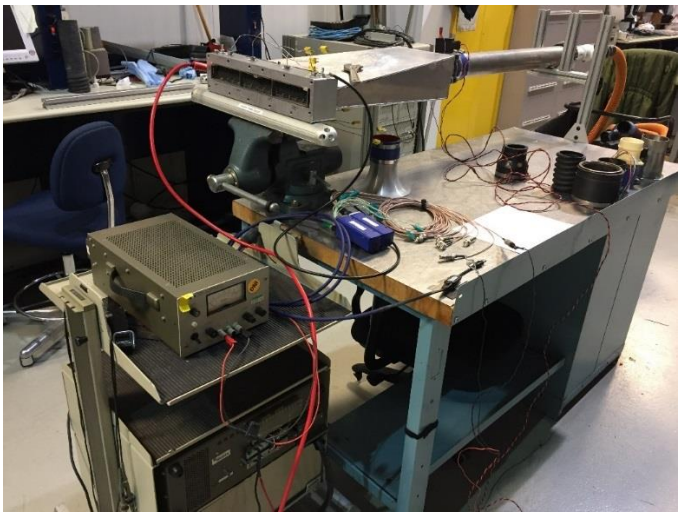
The Gen 3 Intake Air Heater (IAH) was a single device whereas the Gen 2 engine used four individual heater elements. Located in the intake manifold, the power of the heater (2.3kW) and its design allowed better heat transfer to the air entering

the engine. The heater was used for cold start and engine warming. Controls were designed for use of the heater during preheat as well as for the interface of the heater control with thermal management system control.

The IAH control strategy used a preheat period, before cranking, to accumulate heat in the heater foil. The preheat was mainly defined by the duration and the voltage applied to the heater. At the end of the preheat period, the engine starter engages and the engine starts. A measured intake air temperature (IAT) become the value to control during the warming phase, where a PI controller ensured the correct voltage regulation for the targeted temperature. During this phase, depending on the gas temperature coming out of the supercharger, the power of the heater was reduced until the gas temperature coming out of the supercharger is greater than the targeted IAT. The control switched to a mode where the heater was only powered during transient phase if it was required, from a low IAT to a high IAT, compensating for the temperature lag in the second charge air cooler because of thermal inertia.

The IAH control was continuously monitored by an IAH foil temperature model. The objective of the model was to estimate the temperature of the heater foil so that precautions could be taken to avoid heater damage due to excessive temperature. The model developed was a 0D thermal model of the IAH foil temp to minimize throughput requirements in the controller. In addition it included a calculation of the maximum allowable duty cycle of the heater to maintain a calibrated foil temperature limit as an automatic safety.

This model was evaluated in simulation for a variety of input conditions, including a typical start sequence. Intake air heater model calibration, however, was conducted using several bench procedures to extract appropriate calibration values. Figure 2.6.3 shows an image of the bench test setup (upper photo), the heater undergoing a high power test (middle photo) and transient data collected during that test (lower portion of figure).



Engine Cradle Support

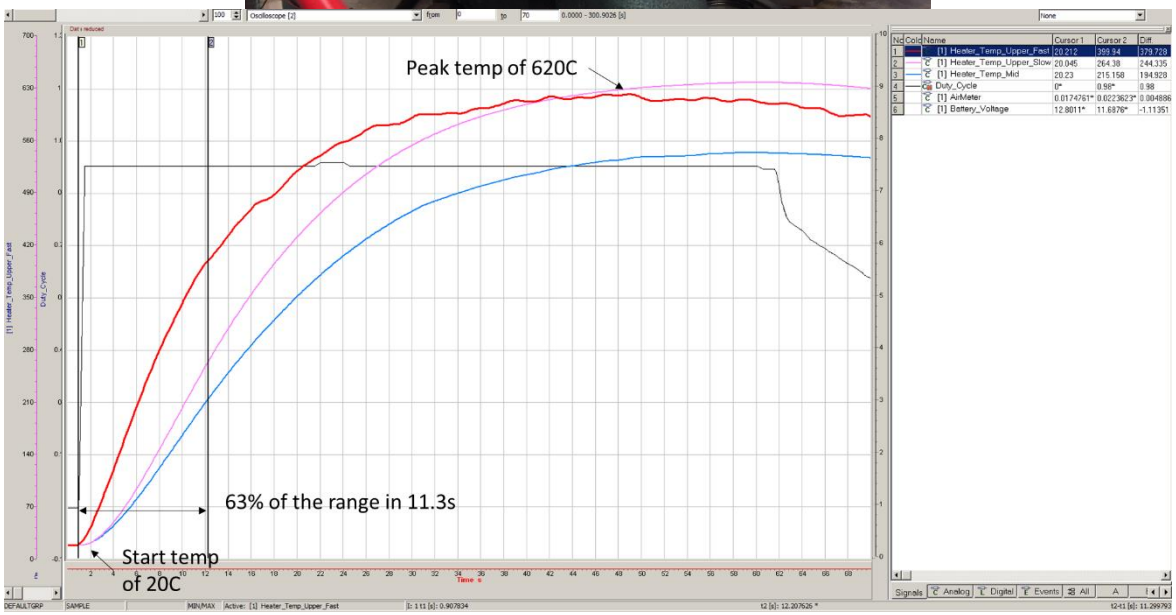

Peak temp of 620C
63% of the range in 11.3s
Start temp of 20C

Figure 2.6.3: Bench testing to determine calibration parameters for Intake Air Heater foil temperature model. Top two pictures are the test setup and Gen 3 IAH undergoing high power test, lower plot is data collected during that test.

Gen3 vehicle

Another 2011 Hyundai Sonata was acquired for use in building the Gen3 development vehicle. The production powertrain was removed and a Gen 3 GDCI engine with custom ratio manual transmission and ancillary Gen3 systems were installed into the vehicle. This included the application of the second generation electronic control system, including new and updated electronic controllers and wiring harnesses. Ancillary systems included the new Gen3 thermal management system, air & exhaust systems, and lubrication systems.

The Gen 3 vehicle control system was been debugged and the vehicle was operated. All system signals were checked for functionality, and critical watchdog shutdown faults were tested to ensure protection of the vehicle hardware.

Vehicle first fire was completed on February 16, 2018 and a stable idle was achieved on March 8, 2018. A warm-idle demonstration of the vehicle was conducted for visitors from the Department of Energy on March 19, 2018.

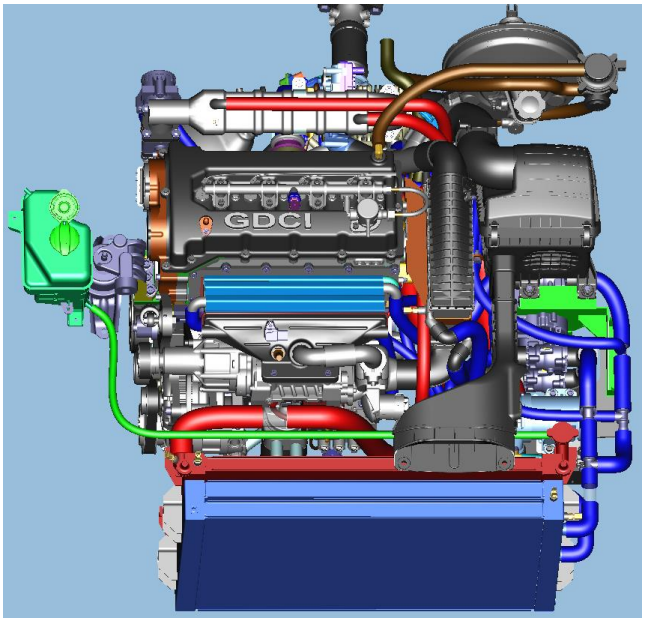


Figure 2.6.4: CAD rendering of the Gen3 powertrain package.

Figure 2.6.5: Gen3 engine installed in a test vehicle.

In May of 2018, the US Department of Energy, Delphi Technologies and Argonne National Laboratory (ANL) established a plan to have Argonne create simulations of a selection of vehicle platforms that would explore the potential of GDCI beyond the project scope of a single mid-size sedan.

During a project quarterly review in August 2018, the US DOE and Delphi Technologies concluded that the dynamometer mapping of the most up to date level of hardware, combined with the vehicle level simulations by Argonne National Laboratory, would be sufficient to document the capabilities and potential of the GDCI combustion process and the Gen 3 vehicle work would be halted without spending the time and money to do the controls and full calibration necessary for a demonstration vehicle as originally planned for the project.

3. Project Timing and Milestones

Project Management and Planning

Regular planning and status review meetings were held during the course of this project. All project reporting and presentations were carried out, on time, by the project team.

Schedule Status and Termination:

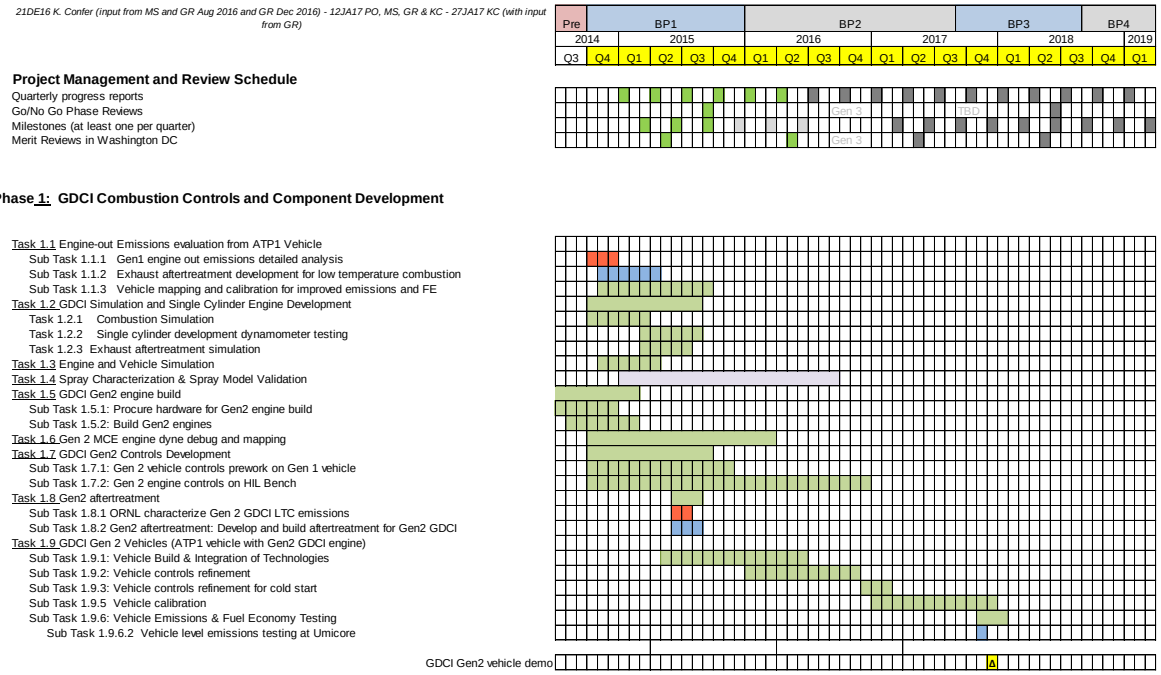
In a project review on March 5th, 2018, representatives of the US Department of Energy and Delphi Technologies discussed the low level of interest in the Gasoline Direct-injection Compression Ignition technology expressed by the US based automotive OEM's. Despite the great progress that had been made advancing understanding and control of the GDCI combustion process - progress that Delphi Technologies made a concerted effort to disseminate through presentations at numerous automotive conferences and meetings with many different potential customers - none of the US domestic automotive OEMs expressed interest in adopting this combustion process as part of their technology planning for production programs. Our understanding during the project review and from other such meetings and discussions, is that the US Department of Energy received similar feedback from OEM's.

On May 2nd, 2018, the US DOE, Delphi Technologies and Argonne National Laboratory (ANL) discussed a plan to have Argonne create simulations of a selection of vehicle platforms that would explore the potential of GDCI beyond the project scope of a mid-size sedan. Delphi Technologies has supported that activity by providing the necessary data to ANL, and through discussions with ANL regarding the simulation results. As the work with ANL proceeded, the US DOE and Delphi Technologies had a detailed discussion at a project quarterly review meeting on August 27th 2018 regarding how to best document the potential of the GDCI low temperature combustion approach without spending the time and money to do the controls and full calibration necessary for a demonstration vehicle as originally planned for the project. Based on this discussion, it was concluded that the dynamometer mapping of the most up to date level of hardware, combined with the vehicle level simulations by Argonne National Laboratory, would be sufficient to document the capabilities and potential of the GDCI combustion process.

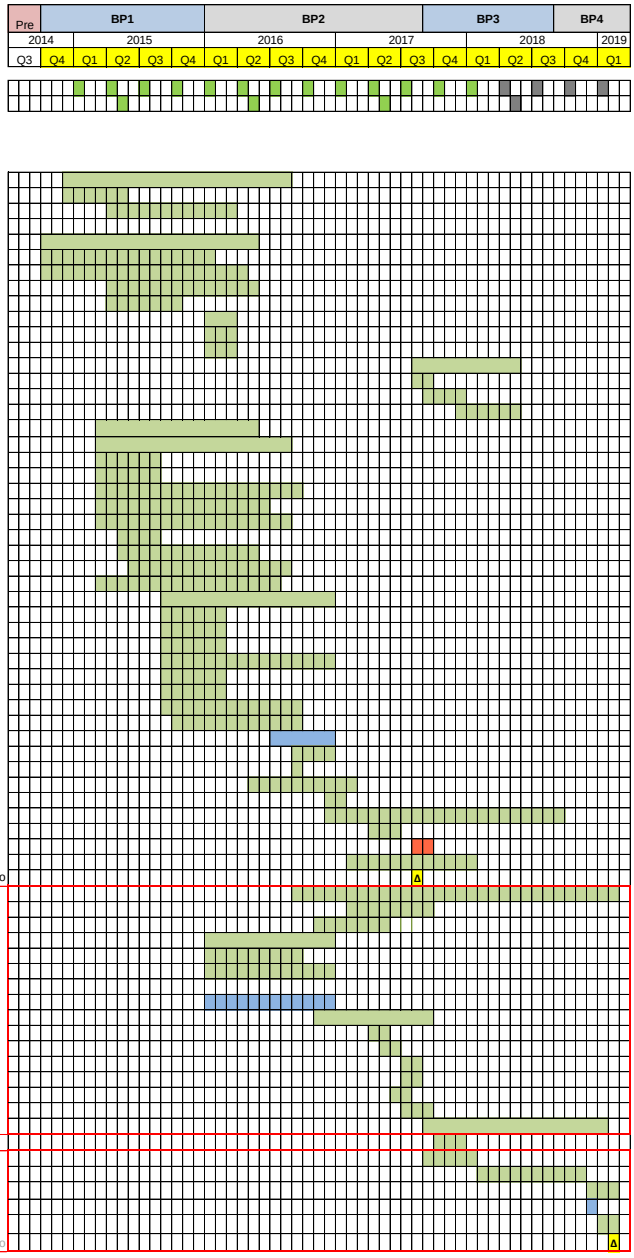
Therefore, as a result of the lack of interest both the US Department of Energy and to Delphi Technologies have seen in the technology from domestic auto manufactures, Delphi Technologies elected a 'No-Go' status for the gate between Budget Period 3 and Budget Period 4; the project has been terminated without

spending any Budget Period 4 funds. The project team concluded work on the project on December 28th 2018 with the dynamometer mapping of the most recent level of GDCI hardware. This data, combined with the vehicle level simulation by Argonne National Laboratory, documents the capabilities and potential of the GDCI low temperature combustion process.

Project Timing



21DE16 K. Confer (input from MS and GR Aug 2016 and GR Dec 2016) - 12JA17 PO, MS, GR & KC - 27JA17 KC (with input from GR)



Area in red boxes shows Budget Period 4 tasks which were effected by No-Go

Milestones:

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	Passed
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 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 rough assembled and ready for final wiring and plumbing	Q2 2017	Complete
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	Passed
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	Tests completed at Delphi
Subtask 2.6.5.2	Vehicle drive simulation	Milestone	Gen3 GDCI vehicle drive simulation performed and estimated fuel economy and emissions performance available	Q1 2018	Complete
Task 2.3	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.	Q2 2018	Complete
Subtask 2.6.5.1	MCE full dyno mapping	Go/No-Go	Multi-cylinder engine mapping of Gen3 GDCI engine on performance dynamometer is completed for use on vehicle calibration. Data used as a Go/No Go gate for the full vehicle calibration activities	Q2 2018	No Go
Subtask 2.5.2	Characterization testing (Steady State)	Milestone	Gen3 GDCI engine characterized on performance dynamometer and data available.	Q3 2018	Complete
Sub Task 2.6.6.1	Vehicle level emissions testing at Umicore	Milestone	Gen3 vehicle tested for aftertreatment emissions performance at Umicore's test site for verification of emissions performance and prep final tuning of emissions-related calibrations to meet Tier 3 emissions performance.	Q4 2018	NA due to No Go
Subtask 2.6.6.2	Vehicle level Fuel Economy and Emissions testing at OEM	Milestone	Gen3 vehicle, with final calibrations, tested for fuel economy and emissions performance	Q1 2019	NA due to No Go

Cost Status:

DOE / NETL		
Contract # DE-EE0006839		Total Contract
Current Funded Amount:	$8,116,102	$9,392,865
% of Funding Spent	96.53%	

		Total
Billing Period		10/1/14 - 1/31/19 Cummulative
Direct Material		$1,609,862
Direct Labor- PT		$5,106,884
Direct Labor E&S		$26,517
Fringe Benefits		n/a
Overhead - PT	176.87	$9,032,548
Overhead - E&S	128.23	$37,584
Travel		n/a
Equipment		$0
Other Direct Costs		$1,549,913
G & A	27.37	$4,745,100
Lower Tier Subcontract Costs		$37,615
Prior Bill Adjustments		$0
Privately Funded by Delphi		$0
Total		$22,146,023
Delphi Cost Share (BP3)	60.74%	$14,311,462
Invoice Amount		$7,834,561

4. Recommendations for Future Work

A number of areas remain to be addressed on the path of developing GDCI into a production-viable technology. Among them:

- Cold Start Emissions: Although significant progress was made in the development of an after-treatment system for GDCI engines, HC in particular remain a challenge, due to the extremely low exhaust temperatures and the slow warm-up of the engine during cold starts. Thus, further development of engine and aftertreatment hardware, as well as controls, will be needed to reduce HC emissions sufficiently.

- Egine Controls: Although the engine controls developed during the GDCI work were sufficient to allow the vehicle to be evaluated for fuel economy and emissions on FTP tests, further work is required to develop robust engine controls --- in particular transient controls – to maintain both stable and efficient engine operation, as well as achieve appropriate levels of driveabiltiy:
    - For the entire engine operating range, including to account for and be robust to part-to-part variation, vehicle-to-vehicle variation, variation in environmental conditions (e.g., temperature, altitude, humidity), part aging and variations in pump fuel.
    - In the presence of the operation of ancillary systems such as the evaporative emissions system, the crankcase ventilation system, and systems that can introduce loads on the engine (e.g., air conditioniong, rear defrost).
    - Diagnostic algorithms will need to be developed for the hardware configuration of the GDCI engine, based on an investigation and understanding of the emissions implications of each component, as well as the regulatory agency(ies) interpretation of the system and any specific functional monitors that may be required.

5. Publications and Presentations

Paper titled *"GDCI Multi-cylinder Engine for High Fuel Efficiency and Low Emissions",* Sellnau et al., SAE 2015-01-0834, was submitted to the SAE for publication and presentation at the SAE World Congress in April 2015.

Presentation of paper titled "GDCI Multi-cylinder Engine for High Fuel Efficiency and Low Emissions", Sellnau et al., SAE 2015-01-0834, was presentated by Mark Sellnau at the SAE World Congress on April 22nd, 2015.

Presentation titled *"Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion",* was presented by K. Confer on June 11th, 2015 in Washington DC.

Symposium Presentation titled: "GDCI Technology Advancements for Ultra Low CO2 Emissions," by Mark Sellnau (invited speaker) at 2015 SAE GCI Symposium, Capri, Italy, Sept 2015.

Presentation Titled: "GDCI for High Efficiency and Low Emissions," by Mark Sellnau (invited speaker) at 13th International Conference on Engines for Vehicles, Stony Brook University, Port Jefferson, NY, June 2015.

"Development of Electrical-Electronic Controls for a Gasoline Direct Injection Compression Ignition Engine", Johnson et al., SAE 2016-01-0614, SAE World Congress, April 2016

"Second Generation GDCI Multi-cylinder Engine for High Fuel Efficiency and US Tier 3 Emissions", Sellnau et al., SAE 2016-01-0760, SAE World Congress, April 2016

"Development of Electrical-Electronic Controls for a Gasoline Direct Injection Compression Ignition Engine", Johnson et al., SAE 2016-01-0614, SAE World Congress, April 2016

"Second Generation GDCI Multi-cylinder Engine for High Fuel Efficiency and US Tier 3 Emissions", Sellnau et al., SAE 2016-01-0760, SAE World Congress, April 2016

Presentation titled *"Ultra Efficient Light Duty Powertrain with Gasoline Low Temperature Combustion"* was presented by K. Confer on June 9th, 2016 in Washington DC.

2017 DOE Vehicle Technologies Review: *ACE094 Merit Review DE-EE0006839* presentation given by Keith Confer, Washington, DC on June 9th 2017

SAE 2018-01-0902 – Sinnamon, Aggoune, Sellnau, Hoyer "Transient Control of Thermal and EGR Systems for Third Generation GDCI Multi-Cylinder Engine"

SAE 2018-01-1150 – Malaczynski and Foster – "Wavelet Filtering of Cylinder Pressure Signal for Improved Polytropic Exponents, Reduced Variation in Heat Release Calculations and Improved Prediction of Motoring Pressure & Temperature"

SAE 2018-01-0901 - Sellnau, M., Hoyer, K., Moore, W., Foster, M., et al., 'Advancement of GDCI Engine Technology for US 2025 CAFE and Tier 3 Emissions, '

Project update presentation to USCAR September 13th, 2018 in Southfield, MI by Mark Sellnau and Keith Confer.

SAE 2019-01-1154 Sellnau, M. et al., "*Pathway to 50% Brake Thermal Efficiency using GDCI.*" Completed. To be presented at SAE World Congress April 2019

6. Intellectual Properties

DOCKET	S - Number	Title	Inventors
DP-322031	S-141,459	GDCI LATE INJECTION STRATEGY FOR TRANSIENT EGR ERROR COMPENSATION AND FULL LOAD GDCI OPERATION	SELLNAU, MARK C.; MOORE, WAYNE R.; SINNAMON, JAMES F.
DP-322168	S-141,460	FAST-IAT-ESTIMATION-BASED GDCI COMBUSTION TIMING CONTROL	YANG, XIAOJIAN; ROTH, GREGORY T.
DP-322548	S-142,113	FAST INTAKE AIR HEATER SYSTEM FOR GASOLINE DIRECT INJECTION COMPRESSION IGNITION ENGINE	SELLNAU, MARK C.
DP-322674	S-143,894	LOW-COST HIGH-EFFICIENCY GDCI ENGINES FOR LOW OCTANE FUELS	KOLODZIEJ, CHRISTOPHER P.; SELLNAU, MARK C.
DP-322829	S-144,418	FAST ENGINE EXHAUST TEMPERATURE ESTIMATION USING DYNAMIC OBSERVER	YANG, XIAOJIAN
DP-322832	S-144,419	OPTIMUM FUEL AIR MIXTURE QUALITY DETERMINATION USING CYLINDER PRESSURE MEASUREMENT IN PARTIALLY PREMIXED COMPRESSION IGNITION INTERNAL COMBUSTION ENGINES	KOLODZIEJ, CHRISTOPHER P.; HOYER, KEVIN S.; FEDEWA, ANDREW
DP-323348	S-150,896	GDCI NOx AFTERTREATMENT CONTROL SYSTEM AND METHOD	ROTH, GREGORY T.; AGGOUNE, Karim
DP-324192	S-148,220	INTERNAL COMBUSTION ENGINE CONTROL METHOD	FEDEWA, ANDREW
DP-324202	S-148,221	SELECTIVE CYLINDER AFTERTREATMENT INJECTION	FEDEWA, ANDREW
DP-324598	S-148,400	SYSTEM AND METHOD FOR INTAKE AIR TEMPERATURE CONTROL IN GDCI ENGINES	SINNAMON, JAMES F.; SELLNAU, MARK C.
DP-324809	S-150,897	LOW-LOAD FUEL CONTROL STRATEGY FOR GASOLINE COMPRESSION IGNITION ENGINES	ROTH, GREGORY T.; THEUNISSEN, FRANS M.

7. Project Records

Included in this section is a synopsis of project activities from each quarterly report that were provided to the US Department of Energy during the course of the project. Each section is identified by the year and quarter of the report coverage.

Q4 2014

A project kick-off meeting was held at Delphi in Auburn Hills Michigan on October 8th 2014. Contract negotiations are ongoing for each of the project's Sub-recipient Agreements.

Engine and Aftertreatment
Multiple new Gen 2.0 multi-cylinder GDCI engines were built at Delphi. The first engine was installed in Delphi's performance test cell for debug. The Gen 2.0 aftertreatment system was designed, built, and assembled on the new Gen 2.0 GDCI multi-cylinder engines. For preliminary aftertreatment tests, the system was also installed on a Gen I GDCI engine running on a steady state dynamometer.

Contorls
Controls work focused on development of cold start algorithms and automated transition from starting to closed loop engine control.

Q1 2015

Contract negotiations were ongoing for each of the project's Sub-recipient Agreements.

Engine and Aftertreatment
The Gen 2.0 GDCI single-cylinder engine was tested over a range of speeds and loads. Preliminary results indicated very good fuel consumption and emissions. A Gen 2.0 engine ran in Delphi's performance test cell. Labview engine controls and software were developed for dyno engine heat up and thermal management. Engine tests were conducted at various operating conditions to confirm performance of the control system for testing.

Controls
Controls work focused cold start controls & calibration along with emissions sampling experiments that were conducted in conjunction with Oak Ridge National Laboratory.

Q2 2015

Contract negotiations were completed for both Umicore and University of Wisconsin-Madison. Negotiations with HATCI continued.

Engine and Aftertreatment
The Gen 2.0 GDCI multi-cylinder engine was tested gasoline at 1500rpm and 2000rpm. Preliminary results indicated good fuel consumption and emissions with significant BSFC reduction relative to the Gen I engines as well as reduced motoring friction and firing friction.

A next generation thermal management system was designed with custom radiators, coolant control valves, liquid cooled charge coolers, and electric water pumps. System and component models were developed and detailed simulations were conducted.
Controls
Controls work focused on calibration mapping and control algorithm development for improved fuel economy & emissions. Work began on Gen 2 Control System definition and development.

Q3 2015

Sub-recipient Agreement negotiations with HATCI continued.

Engine and Aftertreatment
Gen 2.0 GDCI multi-cylinder engine completed preliminary testing on an engine dynamometer.

Controls
Controls work focused on vehicle hardware updates to Gen2 content. Work continued on Gen 2 Control System development and implementation.

Q4 2015

HATCI reported that they would most likely not support the project but a final decision had not been reached during this reporting period. Delphi started the process of discussions with other potential OEM partners.

Engine and Aftertreatment
Fabrication of a new, project specific, Gen3 GDCI multi-cylinder engine began based on detailed simulations and analysis. An aftertreatment system for the Gen3 engines was being developed using simulation. The system featured a pre-turbo catalyst, a post-turbo HC trap and oxidation catalyst, and an SCR catalyst.

Controls
Vehicle algorithm and calibration modifications were developed to support the engine hardware updates from Q3 2015. Work continued on Gen 2 Electronic Control System development and implementation.

Q1 2016

HATCI has reported that they would not participate in the project, but a transfer of hardware was being negotiated to help the project meet its goals. Delphi continued discussions with other potential OEM partners.

Engine and Aftertreatment
Design, fabrication, and bench testing of the new Gen3 GDCI multi-cylinder engine continued. All cylinder heads were completed and passed all bench tests successfully. New approaches to optimization of the combustion system were developed.

Controls
Controls work focused on vehicle testing to understand and quantify errors in vehicle fuel economy testing that occurred during ATP1 and the initial portions of ATP2. Work began on algorithm and calibration modifications to support further engine hardware updates. Work continued on Gen 2 Electronic Control System development and implementation.

Q2 2016

The transfer of critical hardware from HATCI took place. Delphi continued discussions with other potential OEM partners.

Engine and Aftertreatment
Design and release of the Gen3 long-stroke blocks was completed for all components. Development of the GDCI boost system progressed with simulation

of new turbo and supercharger devices. Aftertreatment developments continued. A urea dosing system with SCR catalyst was simulated for various dosing sprays, mixers, and catalysts with realistic packaging. A vertical oxidation catalyst and horizontal SCR catalyst system was developed

Detailed emissions characterization was completed with researchers from ORNL for the Gen2 dynamometer engine. Engine dynamometer tests were conducted throughout the quarter to characterize various high pressure GDI injectors.

Controls
Work focused on algorithm and calibration modifications to support an engine hardware update to Gen 2 that began in January 2016. Work also continued on the electronic control system development and implementation for the Gen 3 vehicle.

Q3 2016

Engine and Aftertreatment
Fabrication of the new Gen3 GDCI multi-cylinder engine prodeeded. The cylinder blocks are being machined. Development of the Gen3 EGR system progressed as did development of the Gen3 thermal management system. Injector characterization tests were completed. The aftertreatment system was designed and packaged on the test vehicle. Catalyst specifications were determined with Umicore experts and procurement began. Engine dynamometer tests were conducted to develop an improved combustion strategy for part-load operation.

Controls
Controls work focused on modifications and debugging of the Gen 2 vehicle. Algorithm and calibration modifications to support the Gen 2 content were in progress. Algorithm development to support the new Gen 2 thermal management system hardware progressed.

Q4 2016

Engine and Aftertreatment
Fabrication of the first Gen3 GDCI multi-cylinder engine was completed. The first Gen3 aftertreatment system was built.

Controls

Work focused on algorithm development and calibration activities of the Gen 2 vehicle. Algorithm development and calibration to support the new thermal management system hardware neared completion. A mockup Gen3 engine was used for vehicle package development. Extensive electrical wiring was completed and electrical debug work begun.

Q1 2017

Engine and Aftertreatment
Preliminary dynamometer testing of the first Gen3 GDCI multi-cylinder engine was begun.

Controls
Work focused on calibration activities of the Gen 2 vehicle and electronic controls preparation for the Gen 3 vehicle. Calibration to support the Gen 2 thermal management system hardware was completed. Work continued on the Electronic Control System hardware and software implementation for the Gen 3 vehicle.

Q2 2017

Engine and Aftertreatment
The Gen3 GDCI angine and aftertreatment system performed well in preliminary dynamometer tests.

Controls
Work focused on calibration activities of the Gen 2 vehicle and electronic controls and software preparation for the Gen 3 vehicle.

Q3 2017

Engine and Aftertreatment
Dynamometer testing of the Gen3 GDCI engine was interrupted for about three months due to dynamometer service and repair. Only limited engine testing was possible during this reporting period. Simulations were performed on the Gen3 GDCI engine using various boost systems and some design refinements to the Gen3 GDCI engines were studied in CAD.

Controls

Work focused on vehicle integration, electronic controls, algorithms and software preparation for the Gen 3 vehicle. The Gen 3 engine was being installed in the vehicle and wiring updates are in progress.

Q4 2017

Engine and Aftertreatment
Dynamometer testing was further interrupted due to ongoing emissions bench failures and a second failure of the supercharger on the test engine. Only limited engine testing was possible during this reporting period. New Gen3 GDCI injectors were tested on engine.

A diffusion combustion strategy involving double injection was explored to develop the high-load torque and power.

Controls
Work focused on vehicle integration, electronic controls, algorithms and software preparation for the Gen 3 vehicle. The Gen 3 engine was installed in the vehicle and auxiliary system installation & wiring updates were in progress.

Q1 2018

Engine and Aftertreatment
Dynamometer testing of the Gen3 GDCI engine proceeded with a focus on calibration mapping and emissions characterization. A new procedure for calibration mapping was developed and tested. The new GDCI-diffusion combustion strategy for high-load operation was simulated and tested on the Gen3 engine. An additional Gen3 multi-cylinder engine was built to be used for high-load strategy development and testing.

Controls
Work focused on vehicle electronic controls debug, algorithm completion and software for the Gen 3 vehicle. The Gen 3 vehicle was debugged and was functioning. Vehicle first fire was completed and vehicle was capable of warm idle operation.

Q2 2018

Engine and Aftertreatment
Calibration mapping of the Gen3 GDCI dynamometer engine continued. use of the "Phi-EGR" strategy, was tested. This improved "burn out" in the combustion chamber and increased combustion efficiency significantly allowing exhaust temperatures to be maintained at high levels down to low engine loads. Spray chamber testing of the latest GDi injector began at University of Wisconsin-Madison.

Due to an engine controller software problem, the dynamometer test engine was seriously damaged prior to completion of calibration mapping. A backup Gen3 engine had been prepared and was installed for use on high load strategy development and testing.

Q3 2018

Engine and Aftertreatment
A new version of the Gen3 GDCI engine, called Gen3X, was completed, and installed on the dynamometer and first tests were completed. Simulations were conducted on the Gen3X engine on design changes to reduce heat losses.

Vehicle simulations were conducted at Argonne National Laboratory using the 2.2L Gen3X engine map for a midsized passenger car, small and medium SUVs, and a pickup truck.

Controls
Work focused on vehicle simulation and modeling of an air charge reactivity index.

Q4 2018

Project testing wrapped up with the Gen3X dynamometer engine which was fitted with a high- pressure diesel fuel injection system to reduce smoke at higher loads.

Using simulation, an engine map was created for the Gen3X engine with the thermal barrier coatings, and the data was provided to Argonne National Labs (ANL) for vehicle-level simulation work. Results showed that a Gen3X engine with the thermal barrier coatings, with an 8-speed automatic transmission and with a 48V motor generator unit (MGU) would have approximately 78% better fuel economy (MPG) than a baseline 1.6L SIDI turbocharged engine with intake VVL in a midsized sedan.

Delphi Technologies elected a 'No-Go' status for the gate between Budget Period 3 and Budget Period 4, and so terminates the project on December 31st, 2018, without spending any Budget Period 4 funds.

Certification of Compliance: The author certifies that the information provided in this Research Performance Progress Report is accurate and complete as of the date shown.