Final Report

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Project Title: **The Application of High Energy Ignition and Boosting/Mixing Technology to Increase Fuel Economy in Spark Ignition Gasoline Engines by Increasing EGR Dilution Capability**

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EXECUTIVE SUMMARY

This report summarizes activities conducted in support of the project “The Application of High Energy Ignition and Boosting/Mixing Technology to Increase Fuel Economy in Spark Ignition Gasoline Engines by Increasing EGR Dilution Capability” under COOPERATIVE AGREEMENT NUMBER DE-EE0005654, as outlined in the STATEMENT OF PROJECT OBJECTIVES (SOPO) dated May 2012.

The objective of this project was to develop and demonstrate the application of key enabling technologies involving ignition, intake charge boosting, cooled exhaust gas recirculation (EGR) quality & mixing, fuel injection, and charge motion systems. These enabling technologies have been shown to allow a boosted spark ignition gasoline engine operating with extensive EGR dilution to achieve a significant fuel economy benefit relative to conventional naturally aspirated gasoline engines.

The specific enabling technologies selected for evaluation in this project were …

- Dedicated EGR
- 2 Spark Plugs per Cylinder
- High Compression Ratio enabled by Low Surface-Volume Ratio Combustion System
- Tumble Intake Port and Swirl Control Valve
- Dual port fuel injection (PFI) + gasoline direct injection (GDI) Fuel Injection System
- Variable Geometry Turbocharger (VGT)

A full vehicle simulation was conducted using the baseline current production midsize GM vehicle equipped with the baseline engine & transmission using the FTP City/Hwy/US06 drive cycles. A “virtual” vehicle is modeled utilizing key characteristics such as vehicle mass, rolling resistance, aerodynamic drag, transmission gear ratios and vehicle axle ratio. A map of engine fuel consumption as a function of engine speed and load is then mated to the vehicle model. The analysis tool then models the vehicle driving the relevant emissions certification cycle and maintaining the desired vehicle speed as a function of time. At each time step, the analysis assesses the engine fuel consumption in each possible gear state to determine the most efficient shift schedule (subject to constraints such as minimum engine speed). The fuel consumption at each time step is integrated to obtain the fuel consumption estimate for the entire drive cycle.

This simulation enabled the selection of 11 engine speed – load points that represent ~95% of the fuel energy used during these drive cycles. The selected 11 engine speed-load points were used during engine dynamometer testing to represent “weighted” vehicle fuel economy.

In order to establish the performance of a current state of the art cooled low pressure loop (LPL) EGR system, such a system was designed, manufactured and installed on a current GM 2.0L turbocharged engine. This engine configuration was tested in the test cell at the selected engine speed-load points and at full load to establish fuel consumption and full load performance. This testing enabled the contribution of the selected enabling technologies to fuel consumption and full load performance improvement to be evaluated, not only to the baseline normally aspirated engine, but to a current state of the art cooled LPL EGR application.

An extensive engine redesign was executed in order to most effectively apply the selected enabling technologies. The redesigned engine was tested with two different combustion systems in order more clearly understand the performance benefits and deficiencies of the selected combustion systems.

Testing was first conducted using all enabling technologies with the proposed 2 spark plug / 3 valve per cylinder combustion system. Fuel efficiency was very significantly improved, as projected, achieving a 9.6% improvement relative to the 2010 2.4L naturally aspirated baseline engine. Full load performance was similar to the 2.4L naturally aspirated engine but well below projections. Data analysis indicated that the 2 spark plug / 3 valve per cylinder combustion system delivered improved light load fuel efficiency due to reduced combustion duration as projected. But this combustion system was very knock limited at high load fuel efficiency points and full load. It was determined that the overall performance of this combustion system was unacceptable when all operating modes were considered.

Testing then proceeded with all enabling technologies implemented and a new cylinder head design featuring a more conventional 1 spark plug / 4 valve per cylinder combustion system. This engine configuration exhibited further fuel efficiency improvement achieving an 11.4% improvement relative to the 2010 2.4L naturally aspirated baseline engine. While this combustion system did demonstrate a small fuel efficiency penalty at low loads compared to the 2 spark plug / 3 valve per cylinder combustion system, it was much more efficient at high load resulting in the net fuel consumption gain noted. Full load performance was also much improved matching projections and significantly exceeding the performance of the 2010 2.4L naturally aspirated baseline engine. The benefits demonstrated with this combustion system were primarily due to improved knock performance leading to more efficient combustion phasing.

COMPARISON of ACCOMPLISHMENTS to GOALS and OBJECTIVES:

Goals and Objectives

The objective of this project was to develop and demonstrate the application of key enabling technologies involving ignition, intake charge boosting, cooled EGR quality & mixing, fuel injection, and charge motion systems. These enabling technologies have been shown to allow a boosted spark ignition gasoline engine operating with extensive EGR dilution to achieve a significant fuel economy benefit relative to conventional naturally aspirated gasoline engines.

The enabling technologies are part of a solution that is capable of introduction in the U.S. in the near- to medium-term and is consistent with current and anticipated future emission standards while maintaining or exceeding competitiveness with alternate technologies.

Accomplishments

- A vehicle system model was developed to identify key fuel economy relevant engine operating conditions under various vehicle driving cycles.
- 1D engine models were developed to assist with specification of components and performance prediction using GT-Power commercial software. Engine models developed and evaluated included the Baseline 2.4L, a turbocharged 2.0L engine equipped with a low pressure loop (LPL) EGR system, and a turbocharged 2.0L engine designed specifically to operate efficiently using dedicated EGR and the additional identified enabling technologies.
- A suitable turbocharged 2.0L GM engine was updated with the novel high energy, extended duration ignition system and low pressure loop (LPL) EGR system as determined by simulation. Design work confirmed that the systems added to the engine are capable of installation in the engine compartment of a current mid-size GM vehicle. The engine was installed in the test cell and developed to achieve the highest possible thermal efficiency based upon the EGR dilution tolerance established with the novel high energy ignition system.
- A suitable turbocharged GM engine was extensively redesigned to optimally update the engine with the specified key enabling technologies and the appropriate dedicated EGR system. Design work confirmed that the systems added to the engine are capable of installation in the engine compartment of a current mid-size GM vehicle. The engine was installed in the test cell and developed to achieve the highest possible thermal efficiency based upon the EGR dilution tolerance established through the use of Dedicated EGR along with the addition of the key enabling technologies.

- A suitable Turbocharged 2.0L GM engine was extensively redesigned to effectively update the engine with an alternate combustion system solution based on the results of the previous work phases. Engine dynamometer testing was conducted to optimize the function of the enabling technologies and data was generated for final vehicle fuel economy simulation results. A final vehicle simulation was conducted using the engine dynamometer data to establish performance to objectives
- A 11.4% fuel consumption improvement was demonstrated relative to a 2010 2.4L naturally aspirated baseline engine through vehicle simulation of a current GM mid-size vehicle using measured test cell data
- The enabling technologies are part of a solution that is capable of introduction in the U.S. in the near- to medium-term
- The enabling technologies are part of a solution that is consistent with current and anticipated future emission standards
- GM's assessment is that the enabling technologies are part of a solution that is capable of maintaining or exceeding competitiveness with alternate technologies.

DETAILED ACTIVITIES and RESULTS SUMMARY

Phase 2 – Initial Simulation

Vehicle Simulation:

A vehicle simulation of a current mid-size GM vehicle equipped with the baseline 2.4L naturally aspirated (NA) 4-cylinder engine was conducted using the current U.S. Federal City/Highway/US06 test cycles. A "virtual" vehicle is modeled utilizing key characteristics such as vehicle mass, rolling resistance, aerodynamic drag, transmission gear ratios and vehicle axle ratio. A map of engine fuel consumption as a function of engine speed and load is then mated to the vehicle model. The analysis tool then models the vehicle driving the relevant emissions certification cycle and maintaining the desired vehicle speed as a function of time. At each time step, the analysis assesses the engine fuel consumption in each possible gear state to determine the most efficient shift schedule (subject to constraints such as minimum engine speed). The fuel consumption at each time step is integrated to obtain the fuel consumption estimate for the entire drive cycle.

The engine speed and load operating points were compiled over these vehicle test cycles and the fuel energy used was determined. Based on this work, 11 engine speed and load operating points were established that represent approximately 95% of the fuel energy used by the mid-size GM vehicle during these test cycles. These engine speed and load points formed the basis for engine testing to establish fuel consumption performance of the 2.4L NA 4-cylinder baseline engine and the technologies under study.

Construct 1D GT-Power model of the Baseline Engine:

This task was conducted to establish initial correlation between simulation results and engine dynamometer test results. This engine simulation model was run at the speed and load test points determined from the vehicle simulation work to establish predicted baseline fuel consumption performance for the mid-sized GM Vehicle.

Construct 1D GT-Power Model of the Turbocharged 2.0L LPL EGR Engine:

Construction of this simulation model was completed. The model of the GM turbocharged engine that is the basis for this version was acquired from within GM. The low pressure loop (LPL) EGR system was defined and added to the engine simulation model. The engine simulation model was run at the speed and load test points determined from the vehicle simulation work to establish predicted fuel consumption performance of this turbocharged 2.0L LPL EGR engine in the mid-sized GM Vehicle. The result of this performance simulation was compared to the baseline engine in the Project Milestone Report documenting Phase II results.

Construct 1D GT-Power Model of the Turbocharged 2.0L Engine Specified with Dedicated EGR and Key Enabling Technologies

Construction of this simulation model was completed. The model of the GM turbocharged engine that is the basis for this version was acquired from within GM. The Dedicated EGR system was defined and added to the engine simulation model as were the additional key enabling technologies. The engine simulation model was run at the speed and load test points determined from the vehicle simulation work to establish predicted impact on engine fuel consumption performance of Dedicated EGR and additional key enabling technologies applied to the Turbocharged 2.0L engine in the mid-sized GM Vehicle. The result of this performance simulation is also compared to the baseline engine in the Project Milestone Report documenting Phase 2 results.

The Performance Test Results Phase 2 Report was submitted. Summary as follows:

Quantity and Description of Property Tested

Phase 2 Results of Initial 1-D Engine and Vehicle Simulations

Test Completion Date and Location

October 5, 2012, GM Global Powertrain Engineering, Pontiac, Michigan

OEM Specification Evaluated and Performance Test Result

Specification Description	***Pass/Fail***
Vehicle Simulation	Pass
Conventional LPL EGR Engine Simulation	Pass
Dedicated EGR & Key Enabling Technologies Engine Simulation	Pass

Phase 3 – Baseline Engine Testing and DCO® Ignition System Evaluation

Evaluation of GM Baseline 2.4L Ecotec Engine:

The 2.4L Ecotec engine was delivered, installed in a test cell and the baseline test matrix was fully executed. A specific laboratory grade 91 RON E10 test fuel was acquired. The engine was instrumented for temperatures, pressures, and flow rates to establish a comprehensive baseline of the engine. The fully instrumented engine was installed in a test cell with control of inlet air temperature / pressure / humidity, exhaust back pressure, and engine speed / load. An emission sampling system was installed for post catalyst and engine out emissions measurements. Emissions measurements were conducted with a Horiba Mexa 7100DEGR exhaust emissions analysis system. Cylinder pressure analysis was conducted with an internally controlled software program.

The engine test matrix was determined by vehicle simulation in Phase 2 to best represent engine fuel consumption over the Federal City/Highway/US06 drive cycles. This matrix includes 11 modes. Each mode was weighted based on vehicle fuel consumption simulations and the required engine speed and load necessary to match with the vehicle transmission and drive line constraints. Best BSFC points were determined at each of the 11 modes. Best BSFC was determined by performing sweeps of intake and exhaust cam phasers at each speed / load condition. The spark timing was adjusted to MBT, or knock limited spark advance (KLSA). The KLSA was determined by the ECU. The user commanded spark timing would be advanced into audible knock and the knock logic in the control system would retard timing to be at an acceptable knock intensity level. MBT spark advance was used when possible and determined by locating the 50% mass fraction burned location of the engine between 6-8 CAD after top dead center. There was a slight variation from cylinder to cylinder in the location of 50% mass fraction burned especially when stability was negatively impacted due to intake and exhaust cam phaser changes. The full load curve from 1250 rpm to 6700 rpm was acquired to verify performance. Full load performance was established using the production calibration. Full load data at the test site was found to be 1.3 % higher than the published SAE full load curve on average. This provided high confidence in engine operation and test cell acquisition.

Analysis of the data was also conducted, including a carbon and oxygen balance across the engine to verify fuel flow, air flow, and emissions results. Calculations including combustion efficiency and brake specific emissions were applied for each data run acquired. Cylinder pressure acquisition was taken concurrent with every engine performance run. Cylinder pressure analysis provided detailed information on combustion behavior in all 4 cylinders. The primary metrics of interest are: peak pressure, the net indicated mean effective pressure (nIMEP), gross IMEP, pumping IMEP, combustion rates and durations, combustion stability and the polytropic exponents for the compression and expansion process.

Assessment of the engine model and engine test demonstrated strong agreement in terms of brake specific fuel consumption (BSFC) for the 11 mode points. The measured modal average BSFC was within 2% of the simulated estimations, expressing strong fidelity between simulation and experiment.

Evaluation of GM 2.0L Turbocharged engine updated with the novel DCO® high energy, extended duration ignition system and low pressure loop (LPL) EGR system

The GM 2.0L Turbocharged Ecotec engine was delivered and installed in the test cell. The low pressure loop (LPL) EGR system hardware was installed on the test engine. The control system was updated to include position feedback control of the EGR valve. The control logic was updated to use model feedback of EGR dilution and actual feedback from an intake O_2 sensor calibrated to EGR rate located just before the compressor inlet. The actual EGR rate was quantified by measuring the intake CO_2 concentration and the exhaust CO_2 concentration.

The DCO® Ignition System coils and the mounting hardware were installed on the test engine. The software architecture embedded control system was completed. The DCO® ignition system used the dwell signals from the ECU to trigger the DCO® events for each cylinder. The DCO® system provided the capability of achieving longer duration ignition events which have been shown to improve kernel development at high dilution operating conditions. The system is configurable on a cycle by cycle basis and operates at 48 VDC. The precise timing of the gate on the IGBT is what makes the DCO® effective as a long duration ignition event with a single breakdown.

The DCO® controller was calibrated to produce a DCO® event with breakdown occurring when the main ECU is commanding breakdown. The energy and duration of the DCO® event is configurable on a cycle-by-cycle basis.

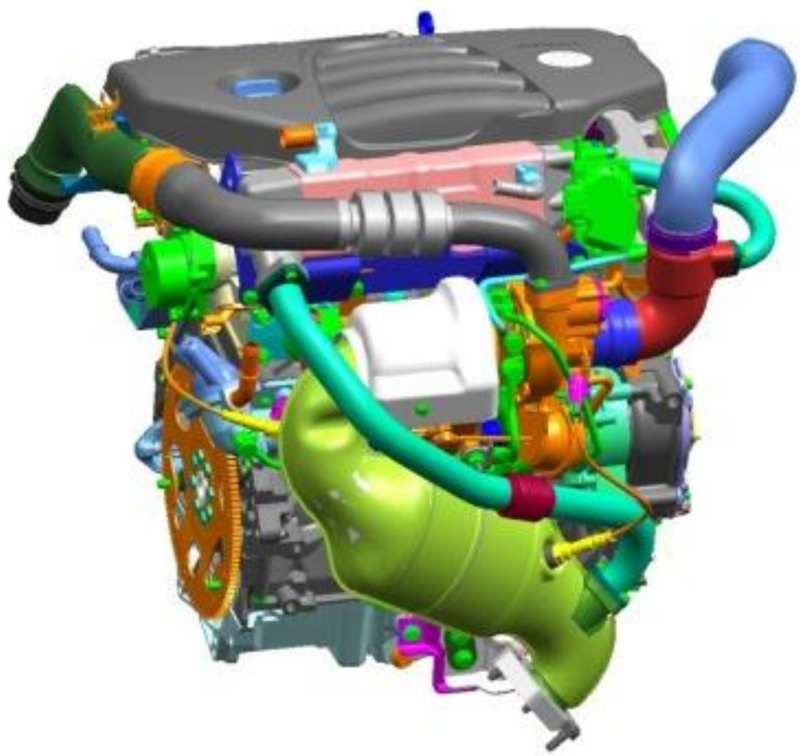


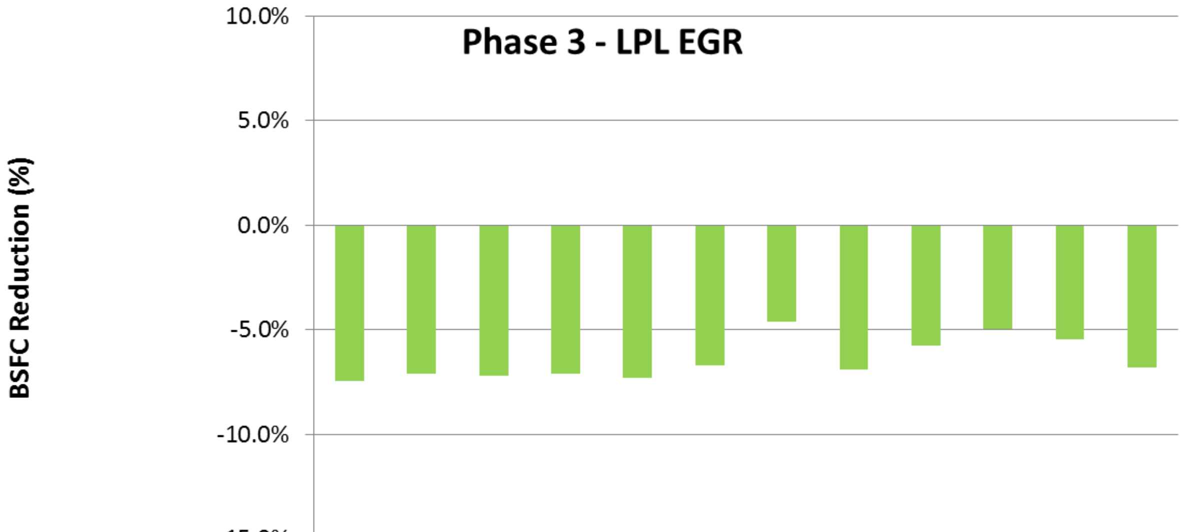
FIGURE 1: Phase 3 Engine

Engine, LPL EGR, and DCO® Performance testing was completed for the turbocharged GM 2.0L 4-cylinder engine specified with 11:1 compression ratio, high energy – extended duration DCO® ignition system and a baseline (LPL) cooled EGR system. The best BSFC points were determined at each of the initially determined 11 modes. These initially determined 11 speed-load operating points were deemed to be acceptable as the full load performance of this engine configuration was similar to the baseline engine. Therefore no final drive ratio adjustment was possible while still meeting vehicle performance requirements.

Best BSFC was determined by performing sweeps of intake and exhaust cam phasers in conjunction with cooled external EGR and turbocharger boost (as required) at each speed / load condition. The spark timing was adjusted to MBT, or knock limited spark advance (KLSA).

Engine test cell measurements were collected as noted in the baseline engine testing summary.

The fuel consumption and performance of the Phase 3 2.0L turbocharged engine specified as described above is shown below compared to the 2.4L naturally aspirated baseline engine at full load and the selected 11 mode points.



	1380/35	1570/69	1415/93	1400/118	1415/146	1700/173	1700/199	1980/80	1850/132	1980/146	2265/226	OA
Comparison to 2010 2.4L	-7.4%	-7.1%	-7.2%	-7.1%	-7.3%	-6.7%	-4.6%	-6.9%	-5.8%	-5.0%	-5.5%	-6.8%

FIGURE 2: Phase 3 Fuel Consumption Results

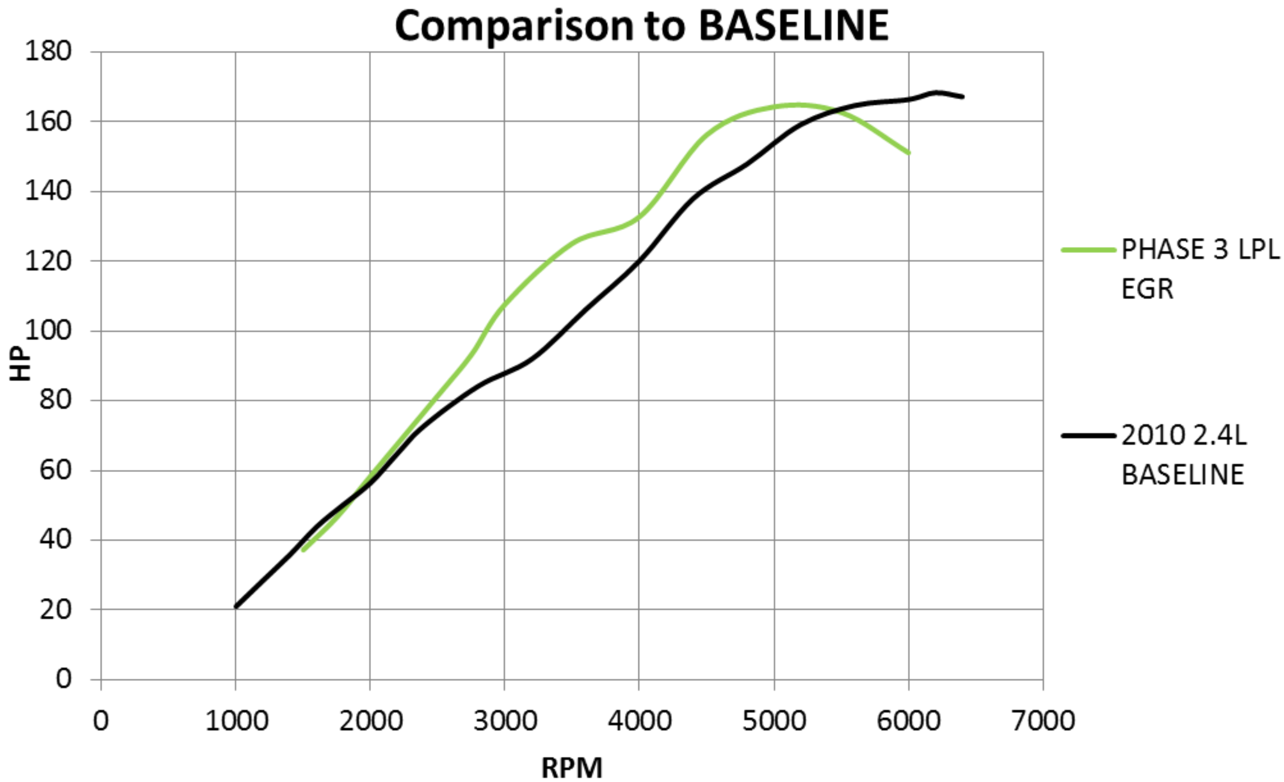


FIGURE 3: Phase 3 Performance Results

An assessment was completed of simulation and engine test results achieved with the 2.4L naturally aspirated baseline engine compared to the Phase 3 2.0L turbocharged engine with 11:1 compression ratio, low pressure loop cooled EGR and DCO ignition. The results demonstrated strong agreement between simulation and engine test results in terms of brake specific fuel consumption (BSFC) differences over the 11 mode points. The measured modal average BSFC improvement for the 2.0L turbocharged engine with 11:1 compression ratio, low pressure loop cooled EGR and DCO ignition compared to the 2.4L naturally aspirated baseline was predicted through simulation to be 2.4% while the engine testing resulted in a 3.2% improvement. This result illustrated strong fidelity between simulation and engine testing with the simulation results slightly more conservative regarding the predicted improvement.

The Performance Test Results Phase 3 Report was submitted. Summary as follows:

Quantity and Description of Property Tested

Phase 3 Results of design, testing, development, and analysis of novel DCO ignition system applied to initial GM 4-cylinder engine configuration with baseline EGR/mixing solution

Test Completion Date and Location

July 26, 2013, Southwest Research Institute, San Antonio, Texas

Testing Equipment Description

Description
Engine dynamometer for engine calibration and emission control development. Includes full emission measurements including particulate matter

Test Procedure Conducted

Engine dynamometer fuel consumption and performance test procedures conducted at Southwest Research Institute, San Antonio, TX

OEM Specification Evaluated and Performance Test Result

Specification Description	***Pass/Fail***
Fuel Consumption testing, development, and analysis of novel DCO ignition system applied to initial GM 4-cylinder engine configuration with baseline EGR/mixing solution	Pass
Full Load Performance testing, development, and analysis of novel DCO ignition system applied to initial GM 4-cylinder engine configuration with baseline EGR/mixing solution	Pass

Phase 4 – Initial Key Enabling Technologies Development

Evaluation of GM 2.0L Turbocharged Engine Specified with Dedicated EGR and Key Enabling Technologies

The GM 2.0L Turbocharged Ecotec engine was extensively redesigned in order to effectively implement the selected enabling technologies. The design and analysis activities supporting this extensive redesign included the following engine subsystems:

1. Work was completed on the detail design and analysis of the new cylinder head in order to implement the innovative ignition strategy of two spark plugs per cylinder.
2. Work was completed on the design of a new camshaft timing drive and valvetrain system.
3. Work was completed on the layout and detail of the exhaust system incorporating an innovative application of a Dedicated EGR bypass concept.
4. Work was completed on the design required to implement the application of an innovative variable geometry turbocharger to this gasoline engine.
5. Work was completed on the intake system with swirl control valves.
6. Work was completed on the layout and detail design of an innovative charge air cooler combined with a pulse suppression mechanism.
7. Work was completed on the piston top design that complements the combustion chamber and achieves the desired compression ratio.

Part Acquisition was completed in support of the extensively redesigned Phase 4 engine:

- PFI Injectors
- Pistons
- Exhaust Valves
- Camshaft Timing Drive
- Cylinder Head Casting (3-Valve)
- Cylinder Head Machining (3-Valve)
- Intake Manifold
- High pressure fuel line
- DI Fuel Rail
- PFI Fuel Rail
- PFI Fuel Injectors
- Swirl Plate Actuator
- VGT Turbocharger
- Cam Cover (3-Valve)
- Front Cover

- Exhaust Manifold
- Dedicated EGR Piping - Cooler
- Dedicated EGR Mixer
- Dedicated EGR Bypass Valve
- EGR Cooler Tanks
- Ignition Coils
- Intake Valves
- Exhaust Valve Retainers, Springs, Seats
- Intake Cam (3-Valve)
- Exhaust Cam (3-Valve)

FIGURE 4: Phase 4 Engine

FIGURE 5: Phase 4 Engine Installed in Test Cell

Electronic Controls Development in support of Phase 4

New electronic engine control functions were developed to support the key enabling technologies added. These new engine control functions were developed to coordinate engine control with the original GM engine control module. The key enabling technologies added included:

- ✓ Design optimization for use of Dedicated EGR
- ✓ Combustion system incorporating 12.0:1 CR, low S/V ratio and 2 spark plugs/cylinder
- ✓ Enhanced charge motion
- ✓ GDI + PFI fuel system
- ✓ Variable geometry turbocharger
- ✓ Dedicated EGR bypass valve

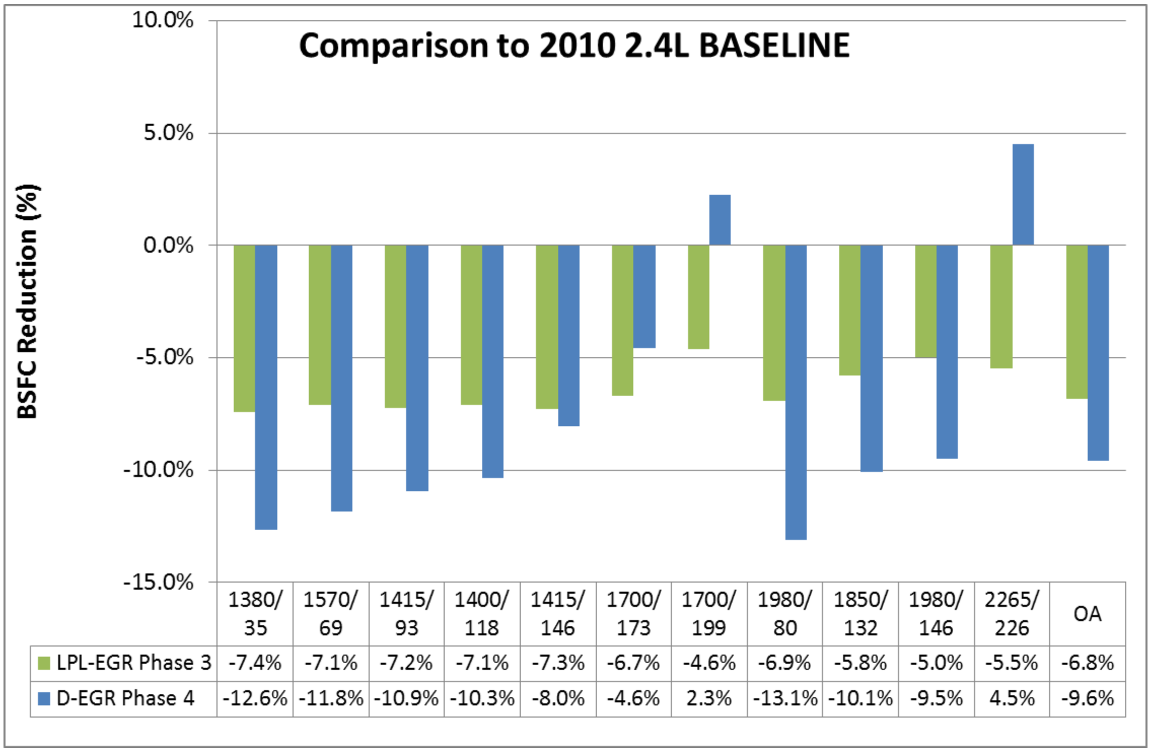
Engine, Dedicated EGR, Dual PFI + DI fuel system, and dual spark plug ignition performance testing was completed for the turbocharged GM 2.0L 4-cylinder engine specified as noted above. The best BSFC points were determined at each of the 11 modes. These initially determined 11 speed-load operating points were again deemed to be acceptable as the full load performance of the Phase 4 engine configuration was again similar to the baseline engine. Therefore no final drive ratio adjustment was possible while still meeting vehicle performance requirements.

Best BSFC was determined by performing sweeps of intake and exhaust cam phasers in conjunction with Dedicated EGR cylinder operating conditions, Dual PFI + DI fuel system settings and turbocharger boost (as required) at each speed / load condition. The spark timing was adjusted to MBT, or knock limited spark advance (KLSA).

Full load testing was also completed while optimizing the same control parameters.

Engine test cell measurements were collected as noted in the baseline engine testing summary.

The fuel consumption and performance of the Phase 4 2.0L turbocharged engine specified as noted above is shown below compared to the Phase 3 2.0L turbocharged engine and the 2.4L naturally aspirated baseline engine at full load and the selected 11 mode points.



	1380/ 35	1570/ 69	1415/ 93	1400/ 118	1415/ 146	1700/ 173	1700/ 199	1980/ 80	1850/ 132	1980/ 146	2265/ 226	OA
LPL-EGR Phase 3	-7.4%	-7.1%	-7.2%	-7.1%	-7.3%	-6.7%	-4.6%	-6.9%	-5.8%	-5.0%	-5.5%	-6.8%
D-EGR Phase 4	-12.6%	-11.8%	-10.9%	-10.3%	-8.0%	-4.6%	2.3%	-13.1%	-10.1%	-9.5%	4.5%	-9.6%

FIGURE 5: Phase 4 Fuel Consumption Results

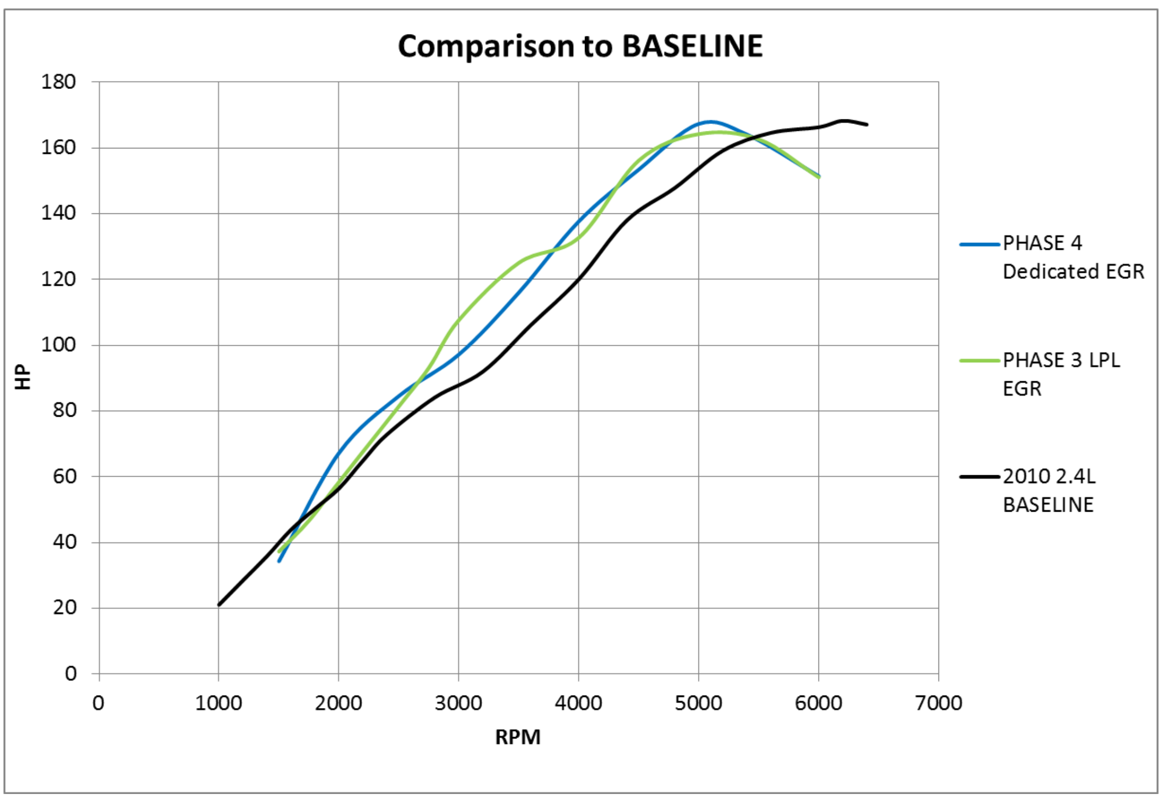


FIGURE 6: Phase 4 Performance Results

The 9.6% overall weighted fuel consumption improvement of the Phase 4 engine compares favorably with the 6.8% improvement recorded by the Phase 3 engine when compared to the 2010 2.4L normally aspirated baseline engine.

It can be observed that the fuel economy performance of the Phase 4 engine is worse than the 2010 baseline engine at test points 7 and 11. This was determined to be a result of poor knock limited combustion performance.

The power output of the Phase 4 engine was below expectations. This was the result of poor knock limited combustion performance at low speed and non-optimal exhaust valve timing at high speed.

Development of ignition timing strategies between the two spark plugs was evaluated in an attempt to mitigate the poor knock limited combustion performance. Operation on one spark plug at a time and staggered timing between the two spark plugs were not found to be effective in resolving the issue.

The Performance Test Results Phase 4 Report was submitted. Summary as follows:

Quantity and Description of Property Tested

Phase 4 results of design, testing, development, and analysis of a 3-valve, 2-spark plug per cylinder combustion system and initial key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration

Test Completion Date and Location

August 4, 2014, Southwest Research Institute, San Antonio, Texas

Testing Equipment Description

Description
Engine dynamometer for engine calibration and emission control development. Includes full emission measurements including particulate matter

Test Procedure Conducted

Engine dynamometer fuel consumption and performance test procedures conducted at Southwest Research Institute, San Antonio, TX

OEM Specification Evaluated and Performance Test Result

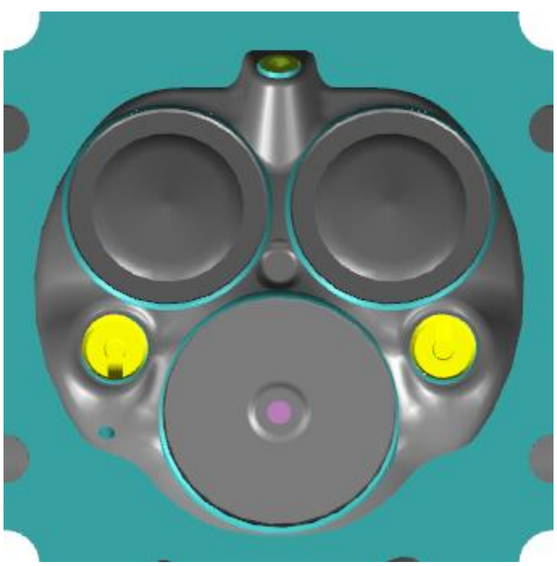
Specification Description	*Pass/Fail*
Fuel Consumption testing, development, and analysis of a 3-valve 2-spark plug per cylinder combustion system and initial key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration	Pass
Full Load Performance testing, development, and analysis of a 3-valve 2-spark plug per cylinder combustion system and initial key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration	Pass

Phase 5 – Alternate Combustion System with Key Enabling Technologies Development

The cylinder head of the Phase 4 GM 2.0L Turbocharged Ecotec engine was fully redesigned in order to effectively implement the alternate, optimized 4-valve 1-spark plug per cylinder combustion system in conjunction with the remaining selected enabling technologies.

The Phase 4 and Phase 5 combustion systems are shown below:

PHASE 4



PHASE 5

The design and analysis activities supporting this cylinder head redesign included the following engine subsystems:

1. Work was completed on the detail design and analysis of the new cylinder head in order to implement the alternate optimized 4-valve 1-spark plug per cylinder combustion system.
2. Work was completed on the piston top design that complements the alternate combustion chamber and achieves the desired compression ratio.

Part Acquisition was completed in support of the extensively redesigned Phase 5 engine:

- Pistons
- Exhaust Valves
- 4-Valve Cylinder Head Casting
- 4-Valve Cylinder Head Machining
- 4-Valve Cam Cover
- Exhaust Valve Retainers, Springs, Seats
- 4-Valve Intake Cam
- 4-Valve Exhaust Cam

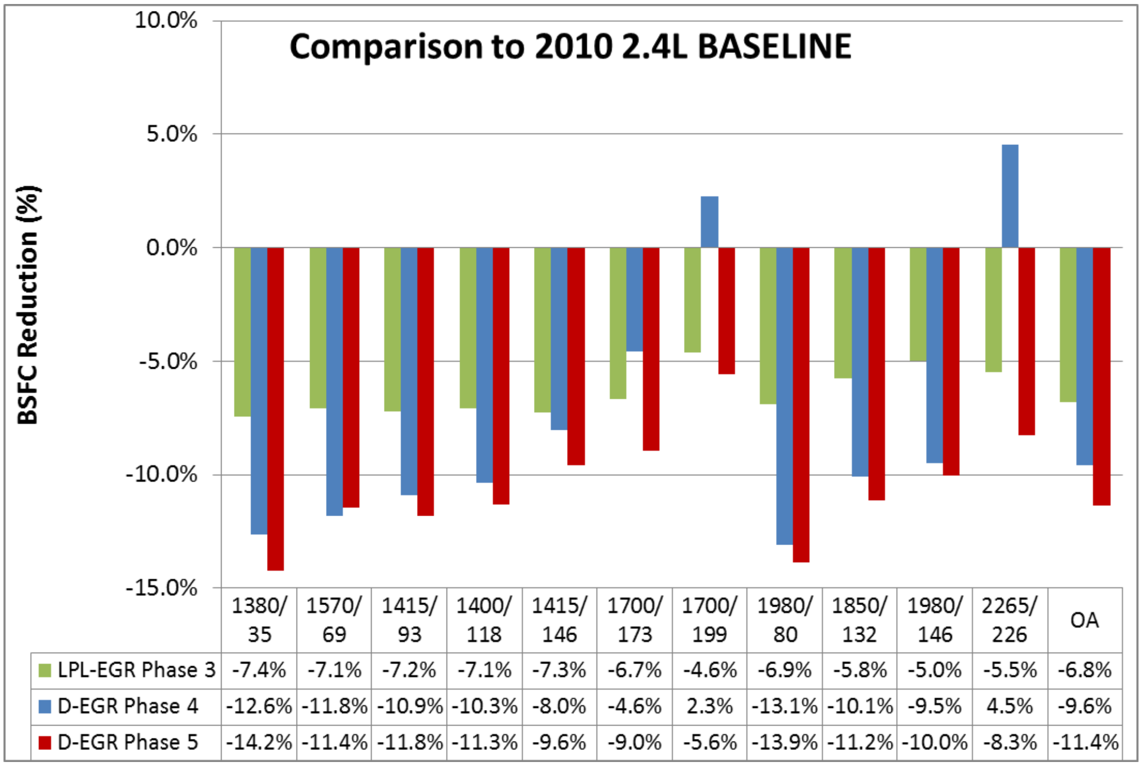
Engine, Dedicated EGR, Dual PFI + DI fuel system, and DCO® ignition Performance testing was completed for the turbocharged GM 2.0L 4-cylinder engine specified as noted above. The best BSFC points were determined at each of 11 modes. In this instance, the initially determined 11 speed-load operating points were revisited as the full load performance of the Phase 5 engine configuration was superior to the baseline engine. Unfortunately, the benefit of the increased performance could not be fully realized due to the fact that the baseline 2.4L NA engine was already operating near the minimum rpm NVH limit of this engine-vehicle combination. Therefore only a small 6% final drive ratio adjustment was possible in this case. Further vehicle fuel consumption improvement should be possible with a displacement reduction of the Phase 5 engine to more closely match the performance of the baseline engine.

Best BSFC was determined by performing sweeps of intake and exhaust cam phasers in conjunction with Dedicated EGR cylinder operating conditions, Dual PFI + DI fuel system settings and turbocharger boost (as required) at each speed / load condition. The spark timing was adjusted to MBT, or knock limited spark advance (KLSA).

Full load testing was also completed while optimizing the same control parameters.

Engine test cell measurements were collected as noted in the baseline engine testing summary.

The fuel consumption and performance of the Phase 5 2.0L turbocharged engine specified as noted above is shown below:



	1380/ 35	1570/ 69	1415/ 93	1400/ 118	1415/ 146	1700/ 173	1700/ 199	1980/ 80	1850/ 132	1980/ 146	2265/ 226	OA
LPL-EGR Phase 3	-7.4%	-7.1%	-7.2%	-7.1%	-7.3%	-6.7%	-4.6%	-6.9%	-5.8%	-5.0%	-5.5%	-6.8%
D-EGR Phase 4	-12.6%	-11.8%	-10.9%	-10.3%	-8.0%	-4.6%	2.3%	-13.1%	-10.1%	-9.5%	4.5%	-9.6%
D-EGR Phase 5	-14.2%	-11.4%	-11.8%	-11.3%	-9.6%	-9.0%	-5.6%	-13.9%	-11.2%	-10.0%	-8.3%	-11.4%

FIGURE 7: Phase 5 Fuel Consumption Results

Fuel consumption results are shown compared to the 2010 2.4L normally aspirated baseline engine.

The 11.4% overall weighted fuel consumption improvement of the Phase 5 engine compares favorably to the 9.6% improvement demonstrated by the Phase 4 engine and 6.8% improvement observed with the Phase 3 engine when compared to the 2010 2.4L normally aspirated baseline engine.

It can be observed that the fuel economy performance of the Phase 5 engine recorded at test points 6, 7, and 11 resolved the performance issue experienced with the Phase 4 engine at these points. This improvement was primarily due to improved resistance to knock.

Results of full load performance testing of selected enabling technologies applied to the redesigned GM 4-cylinder engine updated with an advanced dilution system and an alternate combustion system (Phase 5) are shown graphically in **Figure 8**.

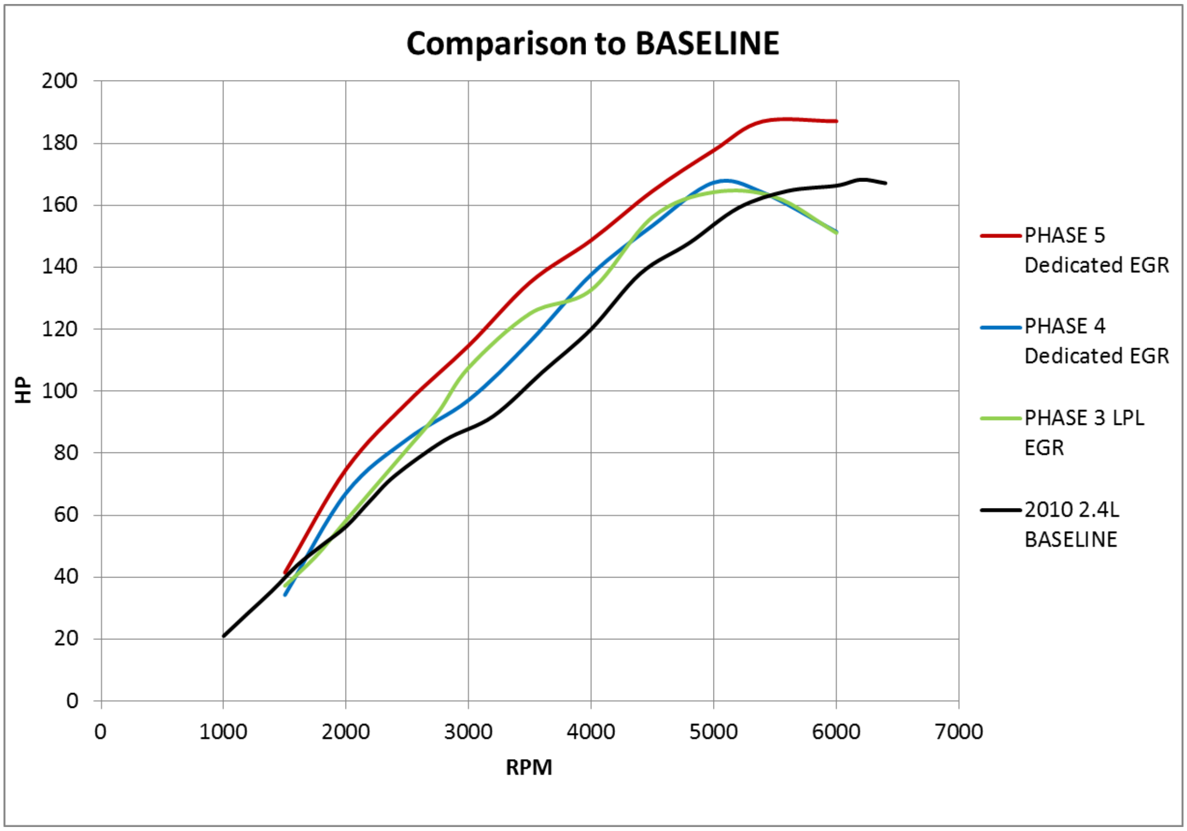


FIGURE 8: Phase 5 Full Load Performance Results

Full load performance results are shown compared to the 2010 2.4L normally aspirated baseline engine.

The full load performance of the Phase 5 engine clearly exceeds the full load performance of the Phase 4 engine and the Phase 3 engine. The improvement demonstrated over the Phase 4 engine was primarily due to improved resistance to knock.

The full load performance of the Phase 5 engine also clearly exceeds the project objective of achieving performance equivalence when compared to the 2010 2.4L normally aspirated baseline engine.

The Performance Test Results Phase 5 Report was submitted. Summary as follows:

<u>Quantity and Description of Property Tested</u>

Phase 5 Results of design, testing, development, and analysis of the final 4-valve 1-spark plug per cylinder combustion system and specified key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration

<u>Test Completion Date and Location</u>

March 30, 2015, Southwest Research Institute, San Antonio, Texas

<u>Testing Equipment Description</u>

Description
Engine dynamometer for engine calibration and emission control development. Includes full emission measurements including particulate matter

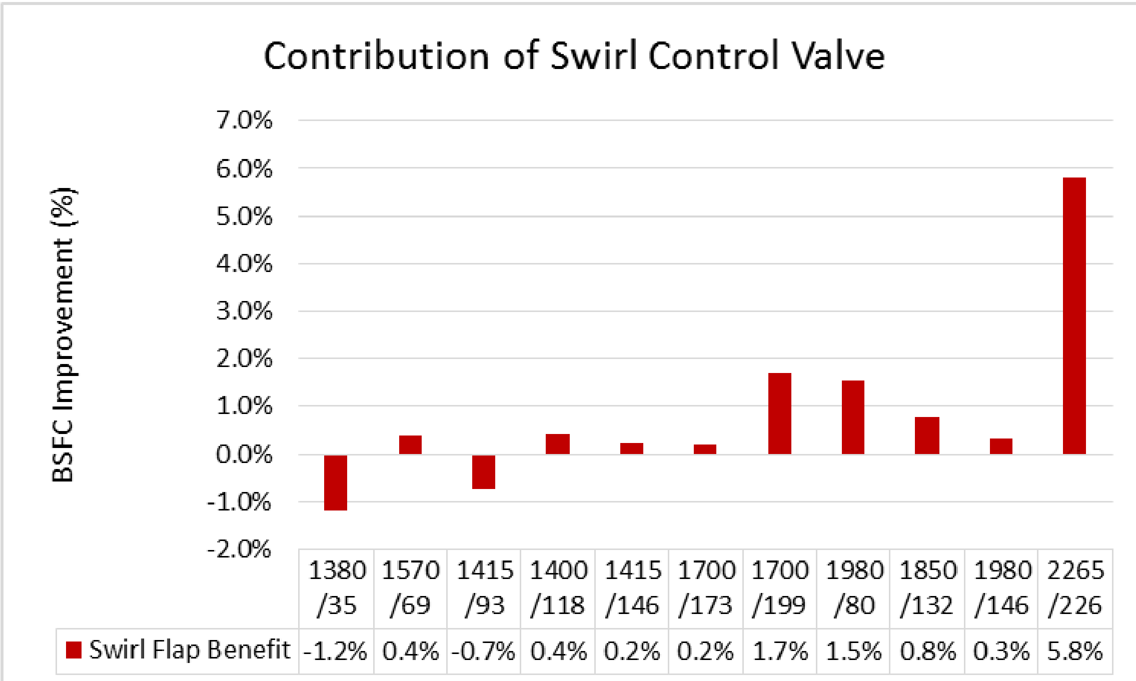
<u>Test Procedure Conducted</u>

Engine dynamometer fuel consumption and performance test procedures conducted at Southwest Research Institute, San Antonio, TX

<u>OEM Specification Evaluated and Performance Test Result</u>

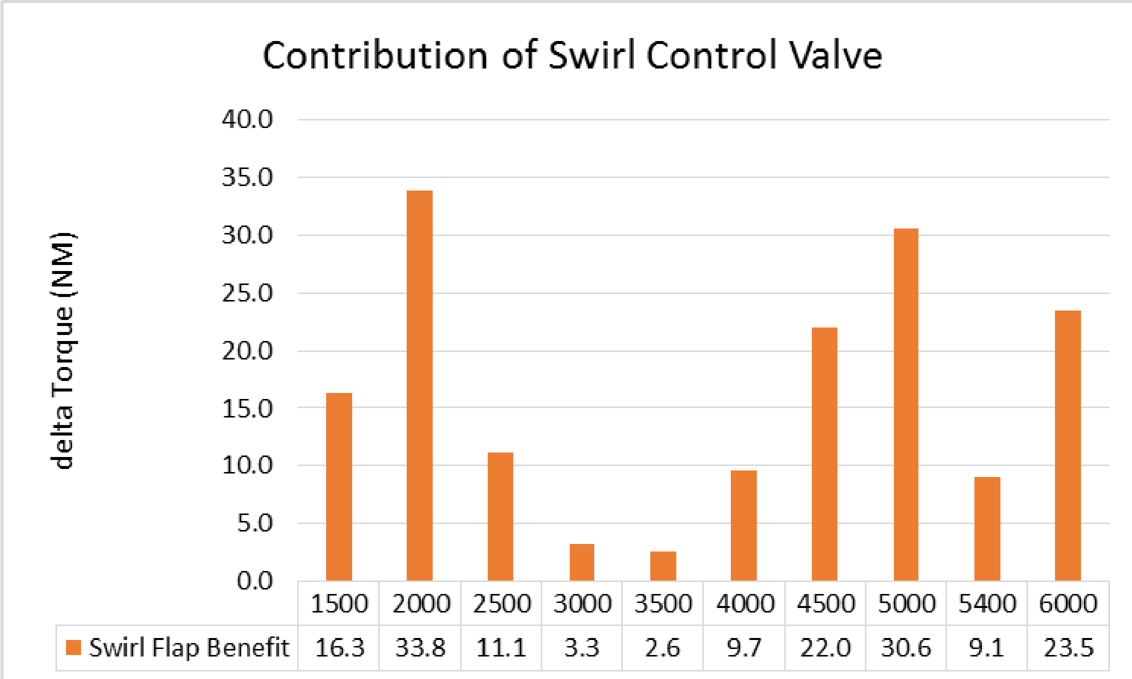
Specification Description	***Pass/Fail***
Fuel Consumption testing, development, and analysis of the final 4-valve 1-spark plug per cylinder combustion system and specified key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration	Pass
Full Load Performance testing, development, and analysis of the final 4-valve 1-spark plug per cylinder combustion system and specified key enabling technologies evaluated using a redesigned turbocharged GM 4-cylinder engine configuration	Pass

Contribution of Certain Key Enabling Technologies to Performance Improvement

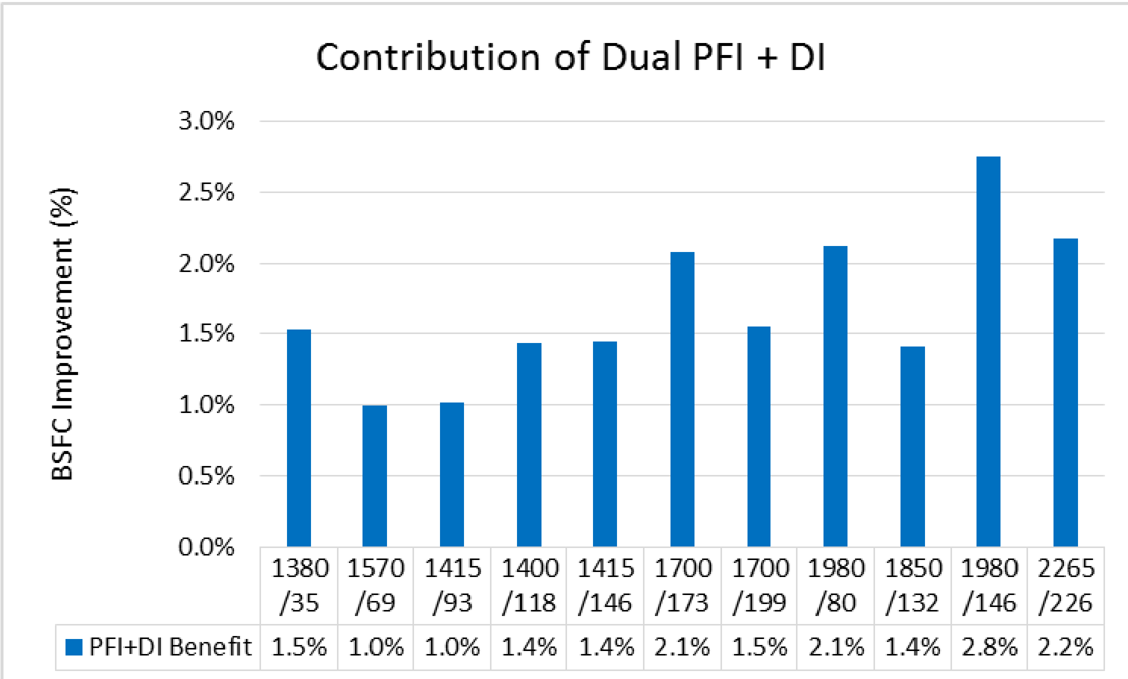


The benefit of the swirl control valve was determined by comparing performance of the fully optimized engine with the swirl control valve open and closed. Calibration parameter optimization was conducted in both cases.

It is apparent that the observed part load BSFC benefit is varied with the exception of one high speed-high load point. This high speed-high load point benefited from a significant improvement in knock limited CA50 with the swirl flap enabled.



It is apparent that the full load torque benefit is relatively large with the exception of the 3000-3500 rpm operating points. The benefit of the swirl control valve application was achieved primarily through improved combustion stability which allowed increased turbocharger boost prior to exceeding the combustion stability limit. The combustion stability benefit of swirl flap application varied with engine speed.



The benefit of the Dual PFI + DI fuel system was determined by comparing performance of the fully optimized engine operating with DI only to PFI + DI operation. Calibration parameter optimization was conducted in both cases.

It is apparent that a consistent observed BSFC benefit is achieved at all points using the PFI + DI fuel system. This benefit was achieve primarily through improved mixing.

Contribution of Variable Geometry Turbocharger (VGT)

The contribution of the Variable Geometry Turbocharger was not able to be measured directly as it was not possible to fit a standard turbocharger for comparison.

- The Variable Geometry Turbocharger was able to be controlled fully open for minimum contribution to pumping work during non-boosted operating points supporting reduced fuel consumption.

- Variable Geometry Turbochargers have clearly established transient boost response benefits over fixed geometry turbochargers. This can lead to improved fuel consumption through vehicle downspeeding strategies. Evaluation of this benefit will have to be quantified through further development as transient operation was beyond the scope of this work.

SUMMARY:

Final engine testing with all enabling technologies implemented accomplished a significant 11.4% fuel consumption improvement relative to the 2010 2.4L naturally aspirated baseline engine as projected at the initiation of the project. Full load performance was also much improved matching projections and significantly exceeding the performance of the 2010 2.4L naturally aspirated baseline engine.

The specific enabling technologies selected for evaluation in this project that were shown to contribute directly to this fuel consumption and performance improvement as projected were …

- Dedicated EGR
- High Compression Ratio enabled by Low Surface-Volume Ratio Combustion System
- Tumble Intake Port and Swirl Control Valve
- Dual PFI + GDI Fuel Injection System
- Variable Geometry Turbocharger

The specific enabling technology selected for evaluation in this project that did not contribute directly to a fuel consumption and performance improvement as projected was …

- 2 Spark Plugs per Cylinder